

Dissertation

Jan Thiesler

A true 3D-AFM head

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A true 3D-AFM head

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Abstract

Surface measurements in three dimensional (3D)-Nanometrology become more complex and demanding. 3D geometries of dense structures, narrow trenches and vias with steep side-walls cannot be measured completely in one orientation, which enlarges the measurement uncertainty. A small measurement uncertainty is desirable because accurate and absolute measurements allow the development of novel products and control processes around the world which leads to prosperity of mankind. As the complexity of small structures reaches the level of macroscopic parts, measurement tasks or processes that seem to be state of the art in the macroscopic world cannot be fulfilled or applied at the nanoscale, simply because the specific sensors required for those measurements are not developed [1].

The work-horse in dimensional nanometrology is the atomic force microscope (AFM) [2], [3] and modifications of it. This measurement tool uses a small bendable probe, which interacts with the surface of a sample. The surface forces deflect the cantilever probe elastically. The deformation of the probe is detected and used to trace the surface topography point by point. Multiple traces are usually rendered to a 3D appearing image of the topography of the sample surface. Without further data processing this image contains image artifacts such as the dilation with the apparent tip apex geometry, which is immanent to the principle of probing with a tip. Consequently, sharp features appear rounded, trenches appear narrower and sidewall angles of structures appear with the cone angle of the tip of the probe. Especially for narrow trenches, critical dimensions (CD) and steep sidewalls the CD-AFM was invented. Despite the use of a special probe with flared tip apex and dual-axis tip control this AFM shows limits and cannot probe in true 3D.

Within this thesis a novel sensor is developed which can be applied to measure 3D topographies at the nanoscale in one measurement. Based on the CD-AFM working principle a new cantilever-based probe is modified to be sensitive for three orthogonal spatial directions (3D), enhancing state of the art probing by an additional degree of freedom. The novel cantilever-based probe is denoted as the 3D-Nanoprobe. It is optimized for isotropic stiffness to reduce tip-slipping during probing and its overall stiffness is adapted to the compliant flared tip, to improve sensitivity for slender and small tip geometries. Essential for the 3D-Nanoprobe is, it is selective for three orthogonal directions of tip apex displacements, by means of the developed and optimized structure. The 3D-Nanoprobe consists of two head sections, optimized for an optical detection system. The head sections are connected by flexure hinge structures, to balance the mechanical properties of the probe. In this work, the 3D-Nanoprobe is used in contact mode for true 3D-probing. The resonance frequencies of the 3D-Nanoprobe are separable and above 70 kHz for fast probing and allow other operating modes in the future. The 3D-Nanoprobe is applied in a novel 3D-AFM head and verified to be a true 3D-sensor for 3D-Nanometrology. The optical detection system of the 3D-AFM head is a hybrid combination of a differential working interferometer and a dual optical lever. The interferometer mainly detects the first head section's displacement of the 3D-Nanoprobe in vertical z-direction. The dual optical lever detects the inclination angles of the second head section induced by bending and torsion of the flexure hinges due to tip apex displacements in horizontal x- and y-directions. After calibration the developed true 3D-AFM head shows a selectivity ratio to register 3D tip apex displacements in spatial directions of about 50:1 and a probing repeatability of <1 nm in x-, y-, z-directions.

Zusammenfassung

Taktile Oberflächenmessungen in der dreidimensionalen (3D)-Nanometrologie werden immer komplexer und anspruchsvoller. Typische 3D-Geometrien und Strukturen mit schmalen Gräben oder Vias mit steilen Seitenwänden können nicht vollständig in einer Orientierung gemessen werden, was die Messunsicherheit vergrößert. Da die Komplexität kleiner Strukturen das Niveau makroskopischer Teile erreicht und Wechselwirkungen mit der Oberfläche im nanoskaligen Bereich einen starken Einfluss auf die Art der Messung und Messstrategie haben, können Messaufgaben oder Messverfahren, die in der makroskopischen Welt Stand der Technik zu sein scheinen, nicht für den Nanometerbereich angewendet werden. Erschwerend kommt hinzu, dass die spezifischen Sensoren für diese Messungen nicht entwickelt sind [1]. In Übereinstimmung mit der ITRS und IRDS Roadmap ist eine Verringerung der Messunsicherheit notwendig, denn genaue und absolute Messungen ermöglichen die Entwicklung neuartiger Produkte und Kontrollprozesse auf der ganzen Welt, die derzeit einen starken Einfluss auf den Wohlstand der Menschheit haben. Das internationale Einheitensystem (SI) bildet hier die Grundlage für notwendige internationale Vergleiche. Die primären nationalen Normale, die dem Benutzer die Rückführbarkeit auf diese SI-Einheiten ermöglichen, werden von den nationalen Metrologie-Instituten (NMIs) vorgehalten und ermöglichen z.B. internationalen Handel und Wissenschaft. Das NMI von Deutschland ist die Physikalisch-Technische Bundesanstalt (PTB). Innerhalb der PTB ist die Abteilung 5 der Fertigungsmesstechnik zugeordnet, die das Rückgrat der industriellen Produktion bildet [4].

In dieser Arbeit wird ein neuartiger Sensor entwickelt, mit dessen Hilfe Proben mit nanoskaligen 3D-Topographien und steilen Seitenwänden in einer einzigen Messung bzw. Aufspannung gemessen werden können. Als Basis hierfür dient das vielfach in der dimensionellen Nanometrologie verbreitete Rasterkraftmikroskop (AFM)[2], [3] und dessen Modifikationen. Dieses Messinstrument verwendet eine kleine biegsame Sonde (Cantilever), die über ihre Spitze mit der Oberfläche einer Probe in Wechselwirkung tritt. Die Oberflächenkräfte lenken den freitragenden Bereich der Sonde elastisch aus. Die Verformung der Sonde wird detektiert und verwendet, um die Oberflächentopographie durch Scanbewegungen zu erfassen. Mehrere Scanlinien über die Oberfläche werden in der Regel zu einem 3D-ähnlichen Bild der Topographie der Probenoberfläche verarbeitet. Ohne weitere Datenverarbeitung enthält dieses Topographiebild Bildartefakte wie die Dilatation durch die Spitzengeometrie, die systemimmanent für das Rasterkraftmikroskop ist. Folglich erscheinen scharfe Konturen abgerundet, Gräben werden schmaler und Seitenwandwinkel von steilen Strukturen erscheinen unter dem Kegelwinkel der Spitze der Sonde. Speziell für schmale Gräben und Linienstrukturen mit steilen Seitenwänden bzw. critical dimension (CD) Messungen wurde das CD-AFM entwickelt. Trotz des Einsatzes einer speziellen aufgeweiteten Sondenspitze und einer zweiachsigen Regelung für den Scanbetrieb stößt dieses CD-AFM an seine Grenzen und kann nicht echt 3D messen [1]. Basierend auf dem Arbeitsprinzip des CD-AFM wird eine neue cantileverbasierte Sonde so modifiziert, dass diese für dreidimensionale Verschiebung der Sondenspitze sensitiv ist und den Stand der Technik der Rasterkraftmikroskope für CD Messungen um einen zusätzlichen Freiheitsgrad erweitert. Die cantileverbasierte Sonde wird als 3D-Nanoprobe bezeichnet und ist auf isotrope Steifigkeit hin optimiert, um das typische Rutschen der Spitze während der Antastung der Oberfläche zu reduzieren. Weiterhin verfügt die 3D-Nanoprobe über eine an die speziell aufgeweitete Sondenspitze angepasste Steifigkeit, um die Empfind-

lichkeit für schlanke, schmale, und somit nachgiebige Spitzengeometrien zu verbessern. Die aus-schlaggebende Kerneigenschaft der 3D-Nanoprobe ist jedoch, die Verschiebungen der Sondenspitze in allen drei Raumdimensionen selektiv und quasi ohne Übersprechen zu detektieren. Die 3D-Nanoprobe besteht aus zwei Kopfbereichen, die für optische Detektionsprinzipien optimiert sind. Die Kopfbereiche sind durch Festkörpergelenke verbunden. Position und Geometrie der Festkörpergelenke bestimmen hierbei maßgeblich die mechanischen Eigenschaften der entwickelten Sonde. Die mechanischen Eigenschaften der Sonde sind so optimiert, dass die 3D-Spitzenverschiebung nach einem Kalibrierungsprozess mit einem Selektivitätsverhältnis von typischerweise 50:1 detektiert werden kann. In dieser Arbeit wird die 3D-Nanoprobe im Kontaktmodus für echte 3D-Antastung verwendet. Darüber hinaus sind die Resonanzfrequenzen der 3D-Nanoprobe trennbar und liegen über 70 kHz, so dass eine schnelle Abtastung möglich ist und in Zukunft auch andere Betriebsarten möglich sind. Die 3D-Nanoprobe wird in einem neuartigen 3D-AFM-Kopf eingesetzt und als echter 3D-Sensor für die 3D-Nanometrologie durch Messungen verifiziert. Das eingesetzte optische Detektionssystem des 3D-AFM-Kopfes ist eine neue hybride Kombination aus einem differentiell arbeitenden Interferometer und einem dualen optischen Lichtzeiger. Das Interferometer erkennt die Verschiebung des ersten Kopfbereiches in vertikaler z-Richtung. Der duale Lichtzeiger erfasst die Neigungswinkel des zweiten Kopfbereiches, die sich aus der Biegung und Torsion der Festkörpergelenke zusammensetzen, die aufgrund der Verschiebung der Spitze in horizontaler x- und y-Richtung verursacht werden. Die Entwicklung wurde an zwei orthogonal zueinander orientierten Referenzproben mit vertikalen Seitenwänden getestet und zeigt eine Antastwiederholgenauigkeit von <1 nm in allen drei Raumrichtungen (x, y, z).

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1. Introduction

*Everything is nothing without material.*¹

The uppermost part or outer boundary layer of something is defined as a surface. Technically, all bodies or manufactured parts with a spatial geometry have a surface with an imperfect topography, which differs from the ideal. In dimensional nanometrology surface feature sizes and shapes are quantified at the micro- and nano-scale to measure e.g. product specifications and characterize samples. Numerous measurement tools and microscopes were developed over the decades to investigate and image topographies and dense structures [6]. A very versatile tool to probe the surface of a sample is the atomic force microscope (AFM) which belongs to the type of scanning probe microscopes [2], [3]. It can be applied to all kind of samples including insulators and transparent materials and works under normal lab conditions. The conventional AFM is today's workhorse in research and industry for quasi non-destructive measurements of localized nanoscopic features and relatively flat surfaces with high precision. A vertical resolution in probing direction down to a few ten picometers can be reached. As being a part of the tool set of precision engineering also surface properties are obtained frequently. Typically for tactile measurement principles the apparent sample topography is dilated by the cantilever tip apex geometry and surface forces, causing artifacts [10]. To probe high aspect ratio topographies special kind of AFMs, measurement modes and cantilever probes were developed (see **Figure 3.1**). A special kind of AFM is the so-called critical dimension (CD) or 3D-AFM. The CD-AFM uses a specific cantilever with a cylindrical and slender tip which is flared at the apex [11]. The tip shape, detection system and dual-axis tip control allows probing in two orthogonal directions (2D). Hence, the conventional vertical probing of the classical commercial AFM is enhanced by an additional horizontal (lateral) probing direction. This CD/3D-AFM is optimized for probing vertical side walls of 1D gratings and re-entrant structures, and is mainly applied in semiconductor industry, optics industry (e.g. computer-generated holograms) and at national metrology institutes (NMIs) [12], [13]. The NMI of Germany is the Physikalisch-Technische Bundesanstalt (PTB). Within PTB, the division 5 is assigned to precision engineering as the backbone for industrial production to provide traceability to the international system (SI) units via reference samples and measurements, allowing for instance international trades and science [4]. Typical critical dimensions of reference samples are in the range of ten to a few thousand nanometers.

Today's innovation in manufacturing process control and quality assurance is driven by the development pressure for stable sustainable processes with new materials for improved energy efficiency, effectiveness, conserving resources by increasing the yield, higher component durability and overall cost reduction. For instance, the lifetime of semiconductor devices is influenced by the sidewall roughness and gets increasingly important as the feature size of the device decreases. To control new processes in the industry innovative measurement tools are needed. With ongoing miniaturization and increasing complexity of the manufactured devices quality inspection becomes more and more challenging. Based on their detection principles and used cantilever probes AFMs have several limitations. Two of the main limitations when

¹Translated german proverb (source unknown): *Ohne Material ist alles nichts.*

applied to complex geometries are, that the tip might be too large to probe dense structures, and that available AFMs have no true 3D-sensitivity and no 3D-probing capabilities. This includes also the CD and 3D-AFMs, with only dual-axis tip control. Consequently, shape measurements of even simple 2D gratings are very challenging and are so far impossible to be measured accurately in a single measurement, because the probing direction may be orthogonal to the normal of the sample surface, which leads to unstable probing conditions and increases the measurement uncertainty [1], [5], [6].

At the macro-scale the versatile workhorse for quasi non-destructive measurements is the coordinate measuring machine (CMM) [88], whose concept can be adapted to measure small parts with micro-probes [89]. Mainly because of the relatively large tip size of usually more than $20\text{ }\mu\text{m}$, large probing force, unsatisfying stability, relatively slow probing speed and insufficient position resolution CMMs cannot be used to for measurements at the nanoscale.

Consequently, the aim of this work is to develop an AFM that has full 3D-probing capabilities, denoted as a true 3D-AFM. Inspired by the CMM's probing, the already specialized CD/3D-AFM is modified to measure arbitrary geometries at the nanoscale by developing a novel probe and new sensor head denoted as the true 3D-AFM head, to overcome the current limitations. The next chapter 2 details this aim, followed by the state of the art in chapter 3. In section 3.2, the AFM is introduced and the state of the art modifications for CD metrology the so-called 3D-AFMs are presented, with basic cantilever mechanics needed for the development of the novel probe. In addition, relevant detection principles are explained in detail in section 3.3 and applied to the task. Based on this, requirements for the novel probe in section 4.1 and sensor head in section 5.2 are identified. The novel probe denoted as the 3D-Nanoprobe is designed, mechanically described, simulated, optimized and manufactured in chapter 4 to meet the specifications to be applied in a true 3D-AFM. In chapter 5 the new true 3D-AFM head and the detection system is designed, manufactured, tested and verified. The 3D-AFM head is applied in a test setup at PTB laboratory in section 6.1 for CD metrology tasks. In chapter 6 the 3D-Nanoprobe is calibrated and the manufactured stiffness is measured, which verifies the optimization process and overall mechanical description of this built. Finally, in 6.4 the 3D-Nanoprobe is successfully applied for true 3D CD measurements of reference CD structures including pitch, side wall angle, line-width roughness and line-edge roughness measurements. The measurements are conducted in two orthogonal directions and demonstrate true 3D-probing capabilities of this novel true 3D-AFM head for 3D-Nanometrology.

2. Research scope and objectives

The overall goal in the advancement of scanning probe microscopes (SPM) in 3D-Nanometrology is to improve their precision and enhance measurement capabilities, by developing a novel kind of SPM tool, that detects an additional spatial degree of freedom for probing in true 3D to achieve the possibility to probe all geometries, which are reachable by a probe's tip, or dense complex features with steep or undercut sidewalls at the nanoscale, in one measurement.

In semiconductor industry and research micro- and nanoscale structures become more and more complex and dense. The driving force behind this miniaturization is, it saves resources (material and cost), is more compact and more cost-efficient, it increases product performance. Another benefit of the miniaturization is, it usually lowers the static and dynamic power consumption per gate of the semiconductor device [7]. With increasing complexity of the manufactured devices, control of the manufacturing processes becomes increasingly important and enables further down-scaling and improves reliability and yield. Obviously, for precise manufacturing process control, sensors are mandatory and used to take measurements for model based and physical based simulation of process parameters [8]. Measurement tools such as the critical dimension atomic force microscope CD-AFM or the CD scanning electron microscope (CD-SEM) are the main workhorses of the quality management of today's common manufacturing processes. In addition, various measurement technologies such as scatterometry (optical critical dimension (OCD) and mid-infrared critical dimension (IRCD) ellipsometry or Mueller Matrix spectroscopic ellipsometry (MMSE)) and X-ray fluorescence (XRF), CD Small Angle X-Ray scattering (SAX), 3D(tilting)-AFMs or destructive methods such as high resolution transmission electron microscopy (HRTEM) measurements are also applied and combined, because latest technology nodes oftentimes require an approach of hybrid measurement strategies to receive the relevant information of the sample [6].

For instance, the *3nm node* with lateral gate all around (LGAA) Field-effect transistors (FET) and FinFET structures are simply too complex and dense to be characterized with a tactile probing system today, if not impossible [16]. It would require very narrow and slender tips of less than 10 nm in diameter to reach into the very narrow trenches and re-entrant structures. This small tip diameter would make this tip very delicate and soft, which would lead to a very small detectable signal and inaccuracy of cantilever based probing (3.2.3). In the back-end of line and in-line tests of those semiconductors, buried structures or features simply cannot be measured by an AFM, as it is a surface metrology tool. But not all devices and process steps in semiconductor devices and lithography or research require a *3nm node* with a minimum pitch of about 24 nm [16]. For instance, based on the power specifications of I/O signals, gates and structures have to be larger and robust to meet physical requirements.

Complementary to the high-resolution images of the TEM and the fast measurements of the CD-SEM, the AFM is considered as non-destructive and direct measurement tool (unlike e.g. scatterometry) for measuring localized features, and is most used for reference metrology applications [6], [18], [17]. The main application of today's CD-AFM, besides use in research and development of new manufacturing processes, are highly precise and accurate measurements of computer generated holograms (CGH) structures and contours of reticles and photo masks for extreme ultraviolet (EUV) lithography machines and standards [19]. Consequently, several national metrology institutes (NMIs) have built their own metrological CD/3D-AFM which are traceable to the SI system of units e.g. [20], [21], [22]. Unfortunately, those ac-

curate measurements are very time consuming, which is the main disadvantage of the SPM principle for industrial use. With current advancement of quantum devices accurate reference metrology becomes more and more important, because quantum effects are oftentimes based on the absolute (not relative) geometries of the device. By that means, NMIs can contribute to a stable progress of the quantum revolution, because absolute and traceable measurements of complex 3D structures at the nanoscale with smallest possible uncertainty is crucial for this kind of novel devices, and can be seen as one of the requirements for an advancement of this technology.

Inherent to the measurement principle of the scanning process, the commercial AFM is considered as a slow measurement tool. Until now, rendering a true 3D-image takes at least 2 measurements from different orientations of a tilting-AFM or CD-AFM [23], [6]. The individual measurements have to be co-registered. This is more time consuming than one measurement and enlarges the uncertainty because of the registration (stitching) post-process. Consequently, it is desirable to develop an AFM which is capable of performing just one measurement with one orientation and characterize 3D geometries faster with higher accuracy. It may also be used as a direct reference tool for e.g. referencing algorithms or scatterometry samples. It can also be used to allow a comparison of different AFM measurement techniques to improve understanding of fundamentals, such as tip-sample interaction of 3D probing or clarify unwanted feedback in measurements and ensure agreement between instruments at the nano-scale and to improve hybrid measurement methods. A careful investigation on today's so-called 3D-AFM (mainly CD AFMs and tiling-AFM) revealed that they are actual 2D or (at best) 2.5D-AFM, since they lack 3D-sensitivity and 3D probing capabilities [9]. Because the nomenclature of a 3D-AFM is already in use (e.g.[18]), the expression *true 3D-AFM* is used instead. By that means, a tactile probing tool (SPM/ AFM) needs to be developed which measures true 3D at the nano-scale, similar to a μ CMM at the macro-scale.

To reach this goal, several key points are derived from [9] and have to be fulfilled and concatenated to build a true 3D-AFM:

1. The tip geometry of the probe must be applicable to probe in three orthogonal directions, also referred to x-, y-, and z-directions (axes).
2. The probe itself has to be suitable to be applied for 3D-probing and has to be selective for the three spatial dimensions (3D).
3. The detection unit has to be sensitive and selective for 3D.
4. The architecture of the scanner and controller to control the tip-sample position has to be operated in multiple axis (3D).
5. The probing trajectories for the measurements have to be planned in 3D by a special probing algorithm, because in contrast to a CMM the sample features are not visible.
6. The measured position data is processed as actual 3D-data by developed software (x,y,z data points).

In the past, the PTB has done lots of successful work in developing of CD-AFMs and 3D-AFMs [24], [18], [25]. By that means, several key points (4., 5. and 6.) were already addressed in the past.

Consequently, the aim of this work is to cover the remaining three requirements for true 3D tactile probing, thus true 3D measurements at the nanoscale, respectively develop a true 3D-AFM head.

The hypothesis of this thesis will argue, that a 3D detection system in combination with a novel structured probe is needed to form a true 3D-AFM head.

The main objectives are:

- Investigate state of the art SPM tools, measurement modes and relevant detection principles in 3D-Nanometrology and identify current limitations which are relevant for the 3D-AFM.
- Develop a novel kind of probe based on a cantilever design, that can be used to detect three independent and orthogonal (spatial) directions of tip displacements. The probe should have a quasi isotropic stiffness and sensitivity in 3D. The probe should be manufacturable by a rapid prototyping technology.
- Develop a novel kind of detection system in an AFM-head that is capable of selectively detecting the tip displacements of the developed probe in 3D. A microscope objective lens 50x must be used in the AFM-head for sample inspection.
- Experimentally test, characterize and validate the developed novel tool in a test setup to standardized samples. The samples are preferable traceably calibrated and should be used for routine measurements in critical dimensional metrology for comparison with the state of the art.

In the following, relevant devices and methodologies are explained and theories are presented. Based on this, limitations of the AFM are identified. The true 3D-AFM head is formed by the novel probe, the so-called 3D-Nanoprobe in chapter 4 and the detection system. The compatible detection system, according to the third objective, is developed and refined in chapter 5. The true 3D probing experiments of objective four can be found in the last chapter 6.

3. Theoretical background and state of the art

The following section will give an overview over the research field of microscopy tools, along with an introduction of devices, techniques and fundamentals which are relevant for this thesis. Special focus is given to a type of scanning probe microscope (SPM), the atomic force microscope (AFM). The AFM instrumentation and measurement methods, as well as commonly used individual components are explained in detail.

3.1. Microscopes

Microscopes are measurement tools or instruments, which allow to produce a (usually) magnified image of an object or sample surface. With a magnification coefficient greater than one the image of the sample appears enlarged. Details of the sample become apparent with sufficient resolution of the collected image. In 16th century the optical microscope was developed, however its invention cannot be attributed to a single person [215]. It uses a system of optical lenses to focus light from a sample surface to a detector, e.g. the human eye. The lens system can be separated into two parts, the microscope objective lens with a small focal length, and the tube lens with a large focal length. An image of the optical microscope is not shown here, it is shown later within **Figure 5.4**, as part of the developed true 3D-AFM head. The achievable magnification depends on the focal distances of the used lenses, quality of the optics and their distance to each other. For light in the visible range a magnification of about 1000 times is usually achieved. The achievable resolution is limited by the used wavelength of the light λ and for the conventional microscope by the diffraction limit to about $0.25 \mu\text{m}$. Based on the findings of *Airy* in 1834, the diffraction limit d_{refl} , represented by being able to separate two imaged points (*Abbe limit* $\epsilon_{\text{dif}}=1$ or *Rayleigh criterion* $\epsilon_{\text{dif}}=1.22$), is approximated by

$$d_{\text{dif}} = \frac{\epsilon_{\text{dif}} \lambda}{2n \sin \Theta} = \epsilon_{\text{dif}} \lambda / 2\text{NA} \quad , \quad (1)$$

where n is the refractive index of the medium, Θ the half cone opening angle of the focused light of the microscope objective lens, and NA the numerical aperture of the objective [26], [27], [28], [29]. Thus, using a smaller wavelength increases the resolution. This fact is used in the electron microscope (SEM) via the *de Broglie* wavelength of accelerated electrons. The SEM instrument is considered to be developed by Max Knoll and Ernst Ruska in 1931 [30]. In contrast to the conventional optical microscope, (most often) magnetic lenses in an electron column are used to shape an electron beam for sample inspection. The focused electron beam is scanned across the sample surface and the local interaction of the electron beam with the sample is used to collect an image. The image contrast depends on the accelerating voltage (wavelength), material and topography of the sample, and detector. A very narrow electron beam allows a resolution below a nanometer, depending on the material, with magnifications of up to about 10^6 [31].

Figure 3.1 shows a coarse overview of microscopes and microscope techniques with no claim to completeness. Today there are simply too many techniques. An overview can be found for instance in [32], [33], [34]. The instruments can be separated based on the working principle into the scanning and non-scanning instruments. The main difference to one another

is, that the scanning principle inverts the imaging principle of the non-scanning techniques. The non-scanning microscopes capture one image over the full field of view at a time. This measurement method is usually faster than the scanning technique, but shows limits in resolution as already mentioned and is restricted in the field of view. The usually slower operating scanning microscopes however acquire the image data point by point through a very small aperture, which is moved (scanned) over the sample. Very high resolution can be achieved by applying an aperture smaller than the resolution limit of the non-scanning microscopes. This scanning principle is used in tactile measurements to investigate the topography of samples, e.g. roughness.

For scanning probe microscopes (SPM) and stylus measuring devices (e.g. Profilometers) this aperture, and consequently the achievable lateral resolution, is determined by the tip shape (tip apex radius), where the vertical resolution is mainly determined by the position noise of the scanner and noise of the detection system of the probe. A smaller tip radius means a smaller aperture and thus a higher resolution. Depending on the tip-sample interaction and scanner, atomic resolution can be achieved [35]. The field of view is limited by the scan range.

The scanning probe microscopy (SPM) tool is considered to be invented in 1981 by Binnig and Rohrer [36] with the scanning tunneling microscope (STM), despite pre-existing instruments such as the *Topografiner* developed around 1972 [37]. The STM of Binnig and Rohrer allowed to image conductive surfaces at the atomic level and was rewarded shortly after its fundamental invention with the Nobel Prize in 1986. An electrically conductive probe with a sharp tip is brought close to a conductive sample surface. At close distances (usually smaller than 1 nm) a tunneling current is registered due to a bias voltage between the probe and sample. This current is used to measure the tip-sample distance in vertical direction. The tip-sample distance is kept constant via a feedback loop. In combination with a horizontal (lateral) scanning system the sample surface contour is traced and an image of the surface can be rendered. Because the STM is limited to conductive samples, the atomic force microscope (AFM) was invented. Stemming from the invention of the SPM, various tools were developed over the decades, as depicted in **Figure 3.1**.

In the following the AFM (**Figure 3.1**) is explained in detail and relevant information is given to further developments of this instrument, the CD-AFM and tilting-AFM.

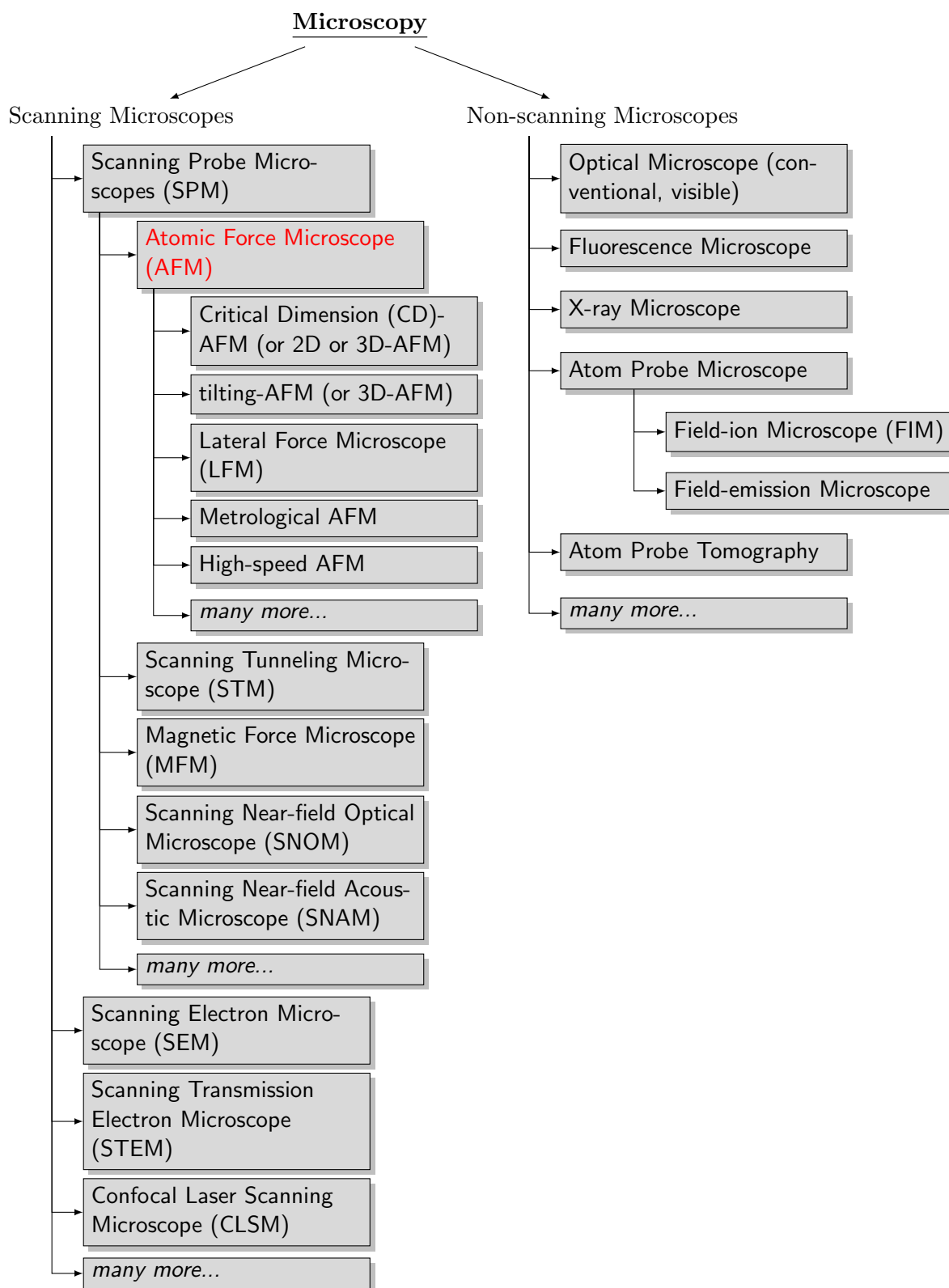


Figure 3.1: Organization chart of microscopy with the marked **AFM**, giving a brief and rough overview of microscopy without claim to completeness.

3.2. Atomic force microscope (AFM) and 3D-AFM

As indicated in **Figure 3.1 and 3.2** the AFM is a type of SPM tool. The first AFM is considered to be invented in 1985 by G. K. Binnig 1985 [2], accompanied by similar developments at that time, detecting atomic interaction forces [38], [39]. It was patented in 1986 [3]. This AFM setup was based on the relatively new invented STM [36], which was enhanced by thin gold foil cantilever probe with a diamond chipped piece attached to its free end. The SPM was used to detect the elastic deflections of the gold foil cantilever probe. The tip of the probe was brought into contact with the sample surface. The tip-sample interaction forces of the overlapping surface potentials deflected the cantilever probe. The measured cantilever probe deflection was controlled by a piezo actuator operated in closed-loop. For the first time a sharp non-conducting tip was applied to measure the surface topography on a non-conducting surface at the nanoscale in contact mode. About two years later *Albrecht and Quate* rendered an image of pyrolytic boron nitride (insulator) sample with atomic resolution under atmosphere (air) conditions [40]. In general, detecting tip-sample interaction forces (section 3.4) is the functional basis of any AFM. A 3D rendered image is measured by stacking line scans of a controlled tip-sample distance, following the contour of the sample surface. The horizontal trajectory of the line scan is denoted as the fast scan axis and the horizontal orthogonal oriented direction as the slow scan axis. Because the probe's tip is not infinitesimal small, the tip influences the measured geometry. As mentioned before, the tip dilates the samples surface and an apparent geometry is measured. Consequently, AFM images are always approximations of the sample surface [41], [42]. For accurate dimensional measurements of the sample geometry the effective tip shape, which includes physical tip shape and tip-sample interaction, is eroded after a tip calibration process with [25], [43], [44] or without [10] a special calibration sample (artifact) [45]. *VDI/VDE 2656 norm* gives an extensive introduction for calibrating of SPM tools and guides through the application of e.g. reference samples for tip characterization, which is important of commercial AFMs [46], [47]. Stemming up from this pioneer work, the AFM nowadays is the main work-horse for dimensional nanometrology and is applied in the research fields of physics, chemistry, biology, electro-chemistry, and mechanical engineering, healthcare and semiconductor industry for imaging and manipulation. Since it is commercialized for several decades now, the commercial AFM is relatively easy to operate and can be enhanced for various measurement tasks, to measure surface topographies and quantitative physical and chemical properties of the sample surface locally, directly and nearly without damage. General, measurement and operating modes are described in section 3.5. Measurements can be performed under vacuum, atmosphere at ambient pressure, and in liquids such as water. An overview of today's AFMs and components can be found in [48], [49], [50], [51], [52], [53], [54] and [55], without claim to completeness because available methods, tools, modifications and applications are simply too numerous to give a comprehensive overview. An overview of commercial and metrological AFMs can be found in [56].

Figure 3.2 shows a simplified sketch of an AFM with the commercially most often used detection principle, the optical lever. The z-deflection of the *cantilever* probe is transferred and amplified via the *laser beam* onto the segmented (quadrant) photo diode (*QPD*). The photo current is measured and the displacement signal of the laser spot on the QPD is used as a measure of the defection of the probe. The digital signal possessor (*DSP*) and control

unit registers the time dependent signals $S(t)$ of the *sensing unit* and controls the deflection of the *cantilever* and position on the *sample* with the *xyz-stage*. A personal computer *PC* is used to operate the instrument. The cantilever can be mechanically excited by the piezo elements (shaker piezos). A regular AFM consists of six main functional components. The first component is (at least) one scanning stage for relative tip-sample displacements in x-, y-, and z-directions.

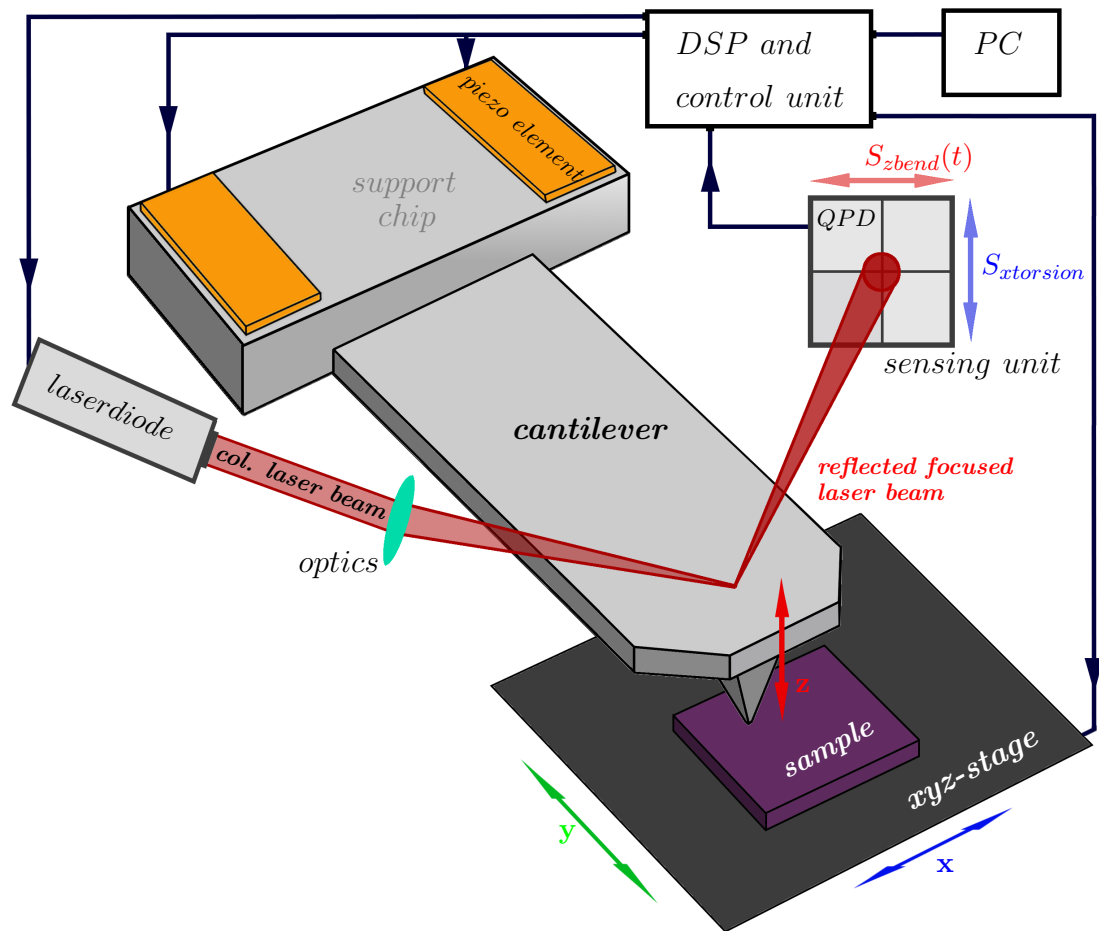


Figure 3.2: Simplified working principle sketch of the atomic force microscope with an optical lever detection unit as a 3D drawing.

This stage can also be realized by using combinations of multiple stages with different properties [57]. The xyz-stage (3-axis) can be considered as the core element of the AFM, because the stage properties such as bandwidth, motion degrees of freedom, scan speed, travel, dynamics and positioning noise, hysteresis of a bidirectional scan, creep, orthogonality of the axis and non-linearities of the scan trajectory, directly affect the scanning and probing result, based on its working principle. Inherent and undetected positioning noise and e.g. drift between the probe and sample lead to artifacts in the measured surface topography (noise is added to the measured topography). To reduce the noise influence and specifically non-linearities, hysteresis and drift of the actuators, the stages are usually operated in closed loop configuration with displacement sensors such as strain gauge sensors, interferometers, inductive sensors or capacitive sensors. The usual travel is about $100\text{ }\mu\text{m} \times 100\text{ }\mu\text{m} \times 10\text{ }\mu\text{m}$ in x-, y-, and z-direction, respectively, but can also be just a few micrometers [57] or several millimeters [56]. Most often, piezo ceramics are used as actuators, but also other actuator concepts are applied e.g. linear voice coil drives [24] or [61], which are also commercially available [62]. The axes guiding is usually accomplished via mechanical bearings such as flexure hinge mechanisms or by the actuator itself [57], [56].

The position is usually controlled via a matched proportional-integral-derivative (PID) controller, but can be manifold e.g. feed forward control or complex model based controller [58], [59]. The controller is the second component of an AFM, here denoted as *digital signal processor (DSP)* and control unit. To trace the surface accurately and avoid dynamic imaging artifacts, such as tip flight, edge overshoot, or unsampled surface regions, the control parameters and scan speed are usually adapted to the sample topography and measurement task. This adaptation can also be done with the help of artificial intelligence as shown in [60] for a PID controller or by a hybrid combination stage design [57]. In this work, the stages play a subordinate role, thus controller and stages and configurations are not discussed in detail, because it goes beyond the scope of this work. In our test setup the piezo stage scanner, and after calibration the probe's deflection, is controlled by a PID controller.

The third component is the probe, it is oftentimes denoted as a cantilever. It is a compliant, usually rectangular beam with a sharp tip and described in detail in section 3.2.1.

The fourth component is the detection unit which, as already mentioned, is most often based on an optical lever detection principle, because of robustness, stability and simplicity. It is depicted in **Figure 3.2** and was used for AFM first in 1988 [64]. It consists of a collimated laser light source of a few mW optical power, a focusing lens (optics) and a *sensing unit*. This *sensing unit* is usually a segmented photodiode with an amplifier circuit. By deflecting the probe, the center of the beam spot on the segmented photo-diode is displaced and an electrical bending signal $S_{zbend}(t)$ is measured indicating a bending angle α of the cantilever's tip region, which is an indirect measurement of the displacement of the tip apex in vertical or horizontal direction [72]. The displacement of the beam is assumed in a first approximation to be proportional to the tip's displacement. The signal is transferred to the DSP to control the tip-sample distance. Using a four quadrant photo-diode (QPD) enables registering bending and torsion deflection via $S_{xtorsion}$ of the cantilever probe [65], which is used for instance in FFMs or CD-AFM and is denoted as dual optical lever. An early overview of available detection principles is given in [66] and can also be found in 3.3 with focus on the optical lever and interferometer displacement detection. A comparison can be found in [63].

The probe and detection system constitute the AFM-head (sensor). The fifth component is

the software, which is represented by a personal computer *PC* in **Figure 3.2**. The *PC* is also the graphical user interface and calculates the scan trajectories and applies the probing algorithms of selected measurement or operating mode, displays measured data and stores them for post processing. The last component is the frame. Usually it is a mechanical frame which connects the *xyz-scanner*, AFM-head and sensors of the AFM setup. However, this frame concept can also be extended to metrological frames for referencing and traceability in metrological AFMs [24].

In general, relatively flat samples are measured with the commercial AFM, because unstable and quasi undetectable tip-sample interactions can lead to structural damage. For samples with high aspect ratios and vertical sidewall the CD-AFM and tilting-AFM (oftentimes denoted as 3D-AFM [23]) were developed. However, despite both not being able to probe in 3D, as explained in the following, there is even a third type of AFM which is also referred to as 3D-AFM. This AFM performs 3D mapping of surface regions of liquid solid interfaces with atomic resolution and is not discussed here [67].

The tilting AFM and classical commercial AFM use similar cantilever probes, however the probes for tilting AFMs have a negative tip set back (such as the ATEC-EFM probes [68]) and narrower support chips and to avoid contact with the sample surface. A regular support chip is depicted in **Figure 3.4**. The difference between a classical commercial AFM and tilting-AFM is, that the tilting AFM has an additional rotational stage for orienting (tilting) the tip or sample, to reach the areas of the sample topography that are undetectable by the commercial AFM [69], [23], [70]. **Figure 3.3 I** illustrates possible scan paths over a line structure of these AFMs with probing directions (*arrows*).

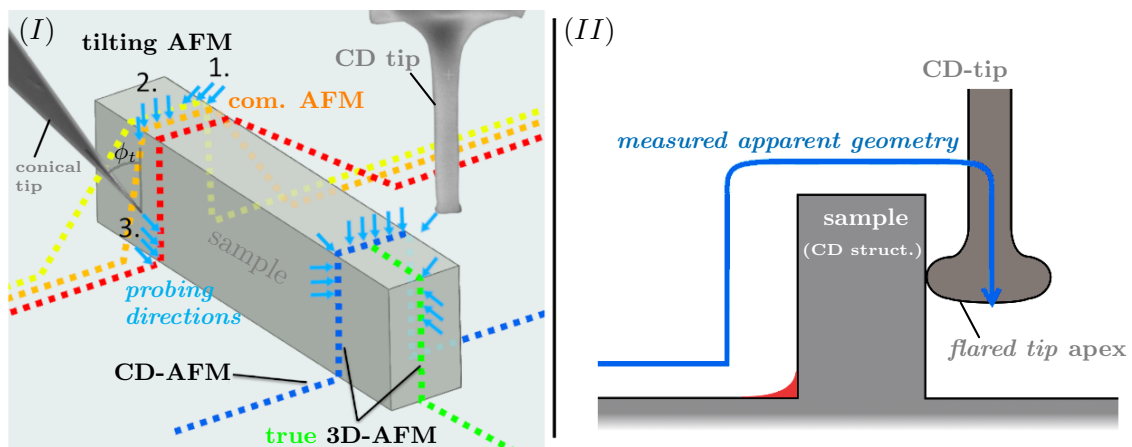


Figure 3.3: Types of AFM for dimensional Nanometrology (I) shows the typical scan paths (dotted lines) and probing directions (*light blue* arrows) of the commercial AFM (path 2., *orange*), the tilting AFM with scan paths 1., 2., and 3. (tilting angle ϕ_t) and their usual conical shaped tip, the CD-AFM (*blue* path) with the CD-tip cantilever probe and the scan paths of the true 3D-AFM (*blue* and *green*) which is to be developed in this work. (II) shows the tip dilation effect of the blunt CD-tip cantilever probe. The red area (meniscus) marks the unreachable footing of the structure due to the tip radius and vertical edge height of the CD-tip.

The commercial AFM (tip not shown) probes in z-axis direction and owing to the tip sample dilation, cannot probe the sidewalls (see scan path 2.). By tilting the probe relative to the sample by more than half of the cone opening angle of the probe's tip (up to about $\pm 40^\circ$ in [70]), the sidewalls, overhanging structures and sharp bottom corners can be probed by the sharp tip apex as shown by scan paths 1. and 3. in **Figure 3.3** with the *conical tip* [23], [19]. By stitching the single measurements (1., 2., 3.) of the same sample region, a 3D representation of the topography of the sample can be rendered [70]. The stitching process may have a direct impact on the measurement uncertainty [25]. In the literature these tilting AFMs are oftentimes also denoted as 3D-AFMs, despite having no 3D probing capabilities [23]. The same detection principle as in a commercial AFM is used. Thus, the bending deflection of the probe is registered and only the z-direction is controlled, making these AFM heads a 1D sensor.

A 2D sensor is used in the special CD-AFMs. These AFM heads detect two orthogonal tip displacement directions, the probe's torsion and bending deflection, respectively. The first developed CD-AFM was denoted as 2D-AFM [71] and [11] and were operated using dual-axis tip scanning (or servo) control. The early development of [71] used an 2D heterodyne interferometer with special modified probe and a so-called 3-point tip to probe vertical sidewalls. The development by [11] shortly afterward used a cantilever probe with flared CD-tip, which is excited for bending and torsion motion and the geometry is traced in a non-contact mode. Today, CD-AFMs are usually operated according to [11] and probing algorithms are specifically developed for this purpose. The cantilever is excited near its resonant frequency in vertical direction and dithered in horizontal direction to probe vertical sidewalls by dampening the probe's oscillation. The cantilever deflections are simultaneously registered via an dual optical lever, as presented first time in [65]. **Figure 3.3 I** shows this CD-tip and the scan path over a line structure by a *dotted blue line* and probing directions normal to the surface marked with *arrows*. This so-called vector approach probing is explained in section 3.5. **Figure 3.3 II** show the measured apparent geometry of the line structure in a cross section. The red area marks the undetectable area (sharp bottom corner) of the CD-tip owing to the tip-sample dilatation effect of the corner radius and vertical edge height with the sample geometry. Consequently, calibration of the CD-tip shape is indispensable for accurate CD metrology [25], [45]. The CD-tip cantilever probe is described in detail in section 3.2.3. CD-AFM probing directions are usually oriented in the x- and z-directions for best probing signal quality. This enables probing of aligned CD structures, where the main interaction force is in agreement with the probing direction, in one measurement with small uncertainty. According to the cantilever mechanics, described in 3.2.1, the optical lever bending signal is biased by tip displacements in y-direction, which can lead to unstable probing conditions and eventual tip breakage under certain probing conditions, described in section 3.2.1 and 3.5. By performing multiple line scan around a vertical oriented cylindrical structure or radius the approaching vector of the CD-tip deviates from the expected surface normal direction, which leads to unstable probing conditions and poor sensitivity. The known tip-slipping effect may also appear in horizontal direction enlarging measurement uncertainty, especially for compliant samples or tips [45]. Hence, CD-AFMs show best measurement performance for 1D grating, but the applicability is limited when using samples with complex geometries. Consequently, "... even current state-of-the art CD-AFM instruments do not have three-axis equivalence in terms of surface sensing, displacement accuracy, or tip position control. ..."

([1], p.2, line 41 ff).

To overcome these drawbacks, several approaches to true 3D-sensing or true 3D-AFMs have been made over the decades with promising results [12], [13], [20], [54], [72], [73], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84], [85], [86], [87] and [56]. Unfortunately, most of the systems are still under development.

This means, today's 3D-AFMs show no true 3D-sensing or 3D-probing capabilities as depicted in **Figure 3.3**. However, in coordinate measuring metrology (CMM) true 3D probing is common. Over the decades several CMMs were developed to measure small parts [88], unfortunately the tip apex diameter is too large, contact forces are too high and measurement speed is too slow, to be used for nanostructures in 3D-Nanometrology. A review of probes and sensors for the use in μ CMMs can be found in [89]. Consequently, there is a gap between CMMs and AFM which needs to be closed in order to probe samples with complex geometry at the nanoscale in one measurement.

3.2.1. AFM probe

The probe of an AFM is called a cantilever. Functionally, one cantilever can be split into three parts; the support chip, the cantilever body and the tip. The cantilever body is the main compliant part of the probe and is fixed at one side with the base to a rigid support chip with dimension of usually 1.6 mm x 3.4 mm x 0.3 mm in x, y, z, respectively, for handling and mounting [90]. The tip is located at the free very end of the cantilever body with a typical tip setback of about 10 μm , shown in **Figure 3.4**. In the literature the word cantilever is most often used to describe the cantilever body including the tip, without the support chip.

The commercial cantilever body is rectangular or triangular shaped with a size range from 2

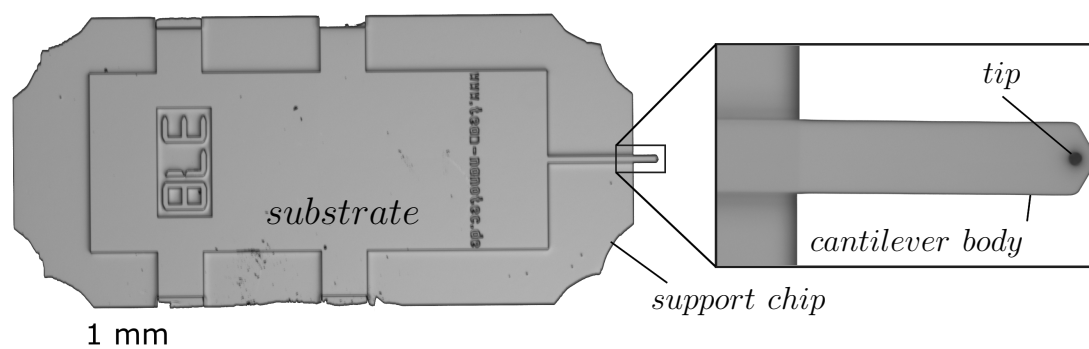


Figure 3.4: Cantilever (AFM probe) light microscope image from the bottom. The region of the tip is shown as a dark dot at the very end of the Cantilever with a length of about 120 μm in the detail.

mm down to about 10 μm in length. Usual cantilevers have lengths in the range of 50 μm to 250 μm with widths of 20 μm to 50 μm and thicknesses of 0.2 μm to 7 μm . Typical cantilever materials are metalloids such as mono-crystalline silicon (Si), ceramics such as silicon-dioxide, silicon nitride (Si_3N_4), metals such as gold and tungsten, and polymers such as SU-8, PMMA (polymethylmethacrylate) and many more. From the perspective of mechanical properties, the cantilever should have very low creep, low thermal expansion coefficient, low Young's modulus but great hardness, thermal stability, a low intrinsic loss coefficient (exception only for some high speed applications) and a high flexural fatigue strength and endurance limit. Single-crystal silicon has shown to be a good material in these applications. The lattice is highly linear elastic which can be used for a first easy mechanical description. Moreover single-crystal silicon shows very low creep and has a small hysteresis (low intrinsic loss coefficient). Because of the high hardness (MOHS 10) the material is very brittle. Pure and defect free crystals show good tensile strength and high endurance limits. Another advantage is, very highly purified silicon is widely used in the semiconductor industry and is therefore inexpensive and can be processed with lithography in batch processes. The cantilevers are manufactured by dry and wet etching of a silicon wafer substrate. After fabrication, the support chip with the cantilever body is isolated (broken off) from the wafer and the product is packaged. One disadvantage is, that silicon shows a small reflectance of light in the visible and infrared range. To improve signal quality for optical signal detection systems most cantilevers are coated by a thin (30 nm - 40 nm) aluminum or gold reflective coating. With material properties of silicon

and the geometries of the cantilever body the nominal stiffness ranges usually from 0.02 N/m to 100 N/m with first resonance frequencies from about 10 kHz to 300 kHz.

The tip can be made of a different material than the cantilever body material to combine mechanical properties of the cantilever body with particular properties or geometries of the tip. This allows for specific scanning modes or improved probing conditions. For additional wear resistance the tips are coated for instance with diamond like carbon (DLC) or can be gold coated or made of platinum silicide for conductive measurement modes. In special cases the very end of the tip can be functionalised by for instance proteins, depending on the requirements [91]. Colloidal, rounded (i.e. 50 nm radius), knife-edge or needle-like, cone shaped, pyramidal and even cylindrical shapes are common. **Figure 3.5** shows a selection of three common cantilever tips. The half cone opening angles of the cone shaped tips are in the range of about 10° to 22°. The half cone opening angles of the pyramidal or polygon shaped tips depend on the crystalline material, orientation and manufacturing process and is usually in the range of about 20° to about 30°. The common cantilever of the commercial AFM tapers to a sharp (about 15 nm radius) or super sharp (<2 nm) tip apex [92] with a tip apex aspect ratio (length:width) in the order of about 4:1. A special kind of cantilever tips are the so-called critical dimension (CD)-tips, which are cylindrical and flared at the very end and used for CD-measurements, specific for CD-AFM.

The mechanics of the cantilever body and CD-tip are described in the following section.

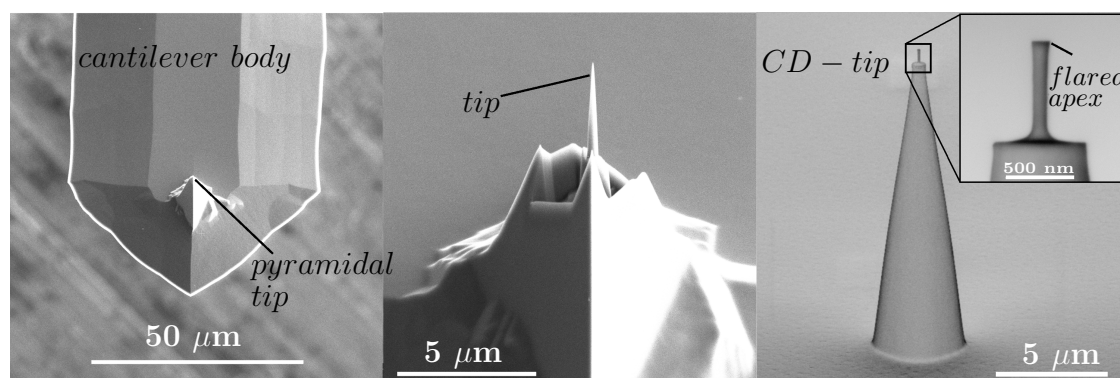


Figure 3.5: Three different tip shapes are shown in SEM: The *left* shows the free end of a cantilever, with common pyramidal silicon tip in an overview. A FIB manufactured high aspect ratio tip from a pyramidal tip is shown in the *middle*. On the *right* a cone shaped tip is shown with a special so-called CD-tip with flared apex (in detail). Images taken with VERIOS 5 HP SEM and HELIOS 5 UX.

3.2.2. Mechanical description of a cantilever probe

To describe the elastic deformation of the cantilever, simple beam mechanics are used in this section. The crystalline material allows a first approximation with simplified description of the material properties by Hooke's law and Poisson's ratio. Because the expected deformations are small (a few ten nanometers) compared to the length, linear elastic deformation can be used, when applied in the AFM. The deformation of the cantilever results from tip displacements under tip-sample interaction forces, whereas gravitational forces can usually be neglected because of the cantilevers small size (mass). The tip displacements can be described via the compliance, the inverted stiffness. The detectable deformation of the cantilever body under a tip displacement is described by its sensitivity. Both can be calculated from the material properties and the geometry of the cantilever. **Figure 3.6** shows a cantilever with a coordinate system x,y,z used in this work to describe the mechanics of the probes. The cantilever geometry is described by the width w , the thickness t , the length of the tip L_{tip} , cantilever body length L_{ges} and the effective length L_{eff} of the cantilever measured from the base to the tip in y -direction without overhang ($L_{overhang} = L_{ges} - L_{eff}$, which is also denoted as tip set back).

The general bending in z -direction of a simple linear elastic beam with isotropic material is described by:

$$M_z(y) = EJ_z \frac{d^2 u}{dy^2} \quad (2)$$

With the bending momentum $M_z(y)$, the Young's modulus E , the moment of inertia for bending in z -direction J_z , the displacement u and the direction of integration y . The bending momentum is replaced by $M_z = F_z \cdot (y - L_{eff})$ with a tip-sample interaction force F_z in z -direction. With a fixed and not angled base (substrate) the boundary conditions $u|_{y=0} = 0$ and $\frac{du}{dy}|_{y=0} = 0$ are applied after double integration, which result in the bending line of an Euler-Bernoulli beam:

$$u(y) = \frac{F_z}{6EJ_z} (3L_{eff} - y)y^2 \quad (3)$$

The maximum displacement is at the free end of the cantilever. With $y = L_{eff}$ the tip displacement Δz in z -direction is

$$u|_{y=L_{eff}} \rightarrow \Delta z = \frac{\Delta F_z L_{eff}^3}{3EJ_z}. \quad (4)$$

and the compliance in z -direction for a force F_z

$$c_{zz} = \frac{\Delta z}{\Delta F_z} = \frac{L_{eff}^3}{3EJ_z}. \quad (5)$$

With $J_z = \frac{wt^3}{12}$, this lead to

$$c = \frac{4L_{eff}^3}{Ewt^3}. \quad (6)$$

The inverse $1/c_{zz} = 1/c = k$ is oftentimes denoted as the **nominal stiffness of the can-**

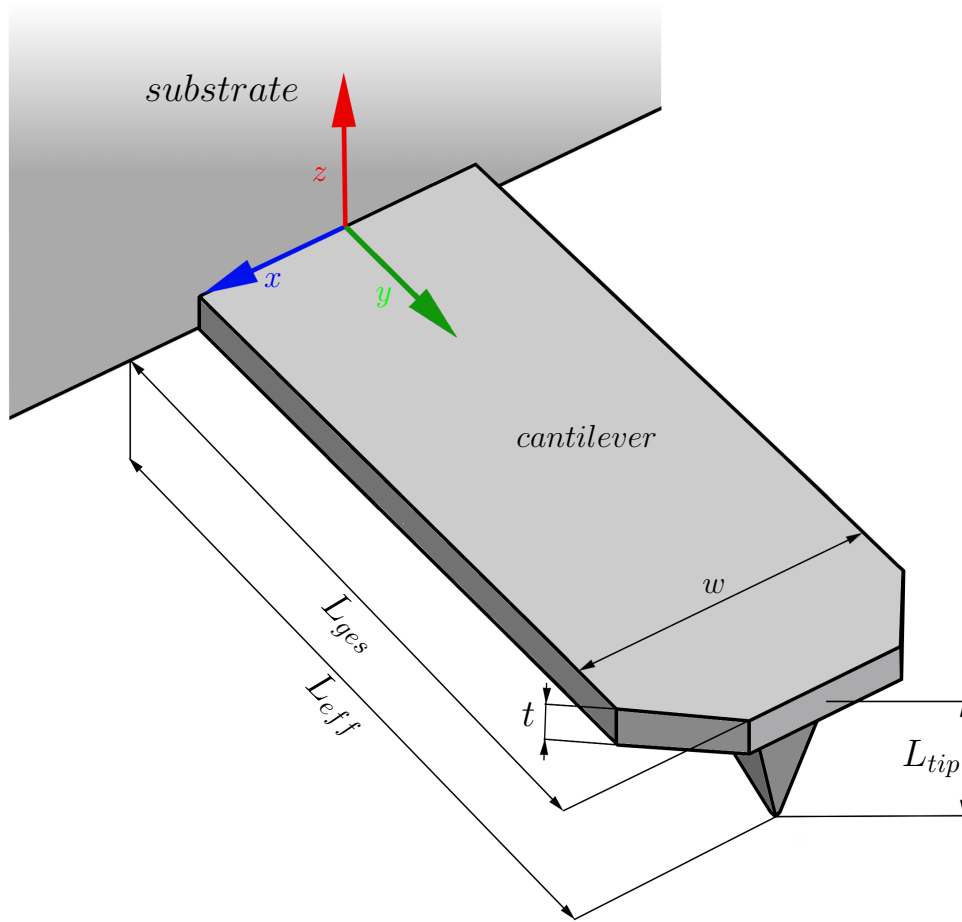


Figure 3.6: Cantilever probe of the AFM in a 3D drawing with relevant variables of the geometry and coordinates system of the probe of the mechanical model (own image adapted from [93] and [111]).

tilever. Even for a tip-less cantilever this is only partially correct, as will now be discussed. By inverting the compliance to get the stiffness one assumes that this is done in a 1D space, because the operation to receive the stiffness is to inverse the compliance. In addition, most cantilevers have a tip $L_{tip} \neq 0$ and the bending in z-direction causes a displacement of the tip apex in y-direction. This results in a mechanical based crosstalk between the z- and y-direction of the cantilever. By using the stiffness to describe the cantilever mechanical properties (e.g. for operating in contact mode) a displacement constraint is set. With the described crosstalk this would result in buckling of the cantilever body and affect the described stiffness k_z . For a correct description of a simple cantilever with a tip at the free end, all possible torsion, bending and displacements of a cantilever body and tip have to be taken into account in the three spatial dimensions. This can be described by the compliance matrix $\mathbf{C}$ and the inclination angle matrix $\mathbf{A}$. With the tip sample interaction force vector $\Delta \mathbf{F}$ and

$\Delta \mathbf{s} = \mathbf{C} \cdot \Delta \mathbf{F}$ this results in a vector of the tip displacement of

$$\Delta \mathbf{s} = \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix} = \begin{pmatrix} c_{xx} & c_{xy} & c_{xz} \\ c_{yx} & c_{yy} & c_{yz} \\ c_{zx} & c_{zy} & c_{zz} \end{pmatrix} \cdot \begin{pmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{pmatrix}. \quad (7)$$

The angle matrix is used to describe the detectable inclination angles of the cantilever body by a tip-sample interaction force. The dual optical lever detects the out of plane bending angle α in the in yz-plane and the torsion angles β around the y-axis. The in plane bending angle γ of the cantilever body in the xy-plane is not detectable by the conventional optical lever.

$$\begin{pmatrix} \Delta \alpha \\ \Delta \beta \\ \Delta \gamma \end{pmatrix} = \begin{pmatrix} a_{\alpha x} & a_{\alpha y} & a_{\alpha z} \\ a_{\beta x} & a_{\beta y} & a_{\beta z} \\ a_{\gamma x} & a_{\gamma y} & a_{\gamma z} \end{pmatrix} \cdot \begin{pmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{pmatrix}. \quad (8)$$

Figure 3.7 shows the possible elastic cantilever deformations and tip displacements under the tip-sample interaction force $\mathbf{F}$. The drawing is a visualization of the compliance matrix $\mathbf{C}$ and the tip displacements and possible motions can be compared with the coefficients of the compliance and angle matrices.

For instance, the result of a force in x-direction acting on the tip of the cantilever is shown in the sub figures in **Figure 3.7** (a), (d) and (g). In (a) the bending of the acting force and torsion of the bending momentum from the force acting on the tip apex are added to the tip displacement $\Delta x(x) = \Delta x_{bending} + \Delta x_{torsion}$. The tip displacement in x-direction is linear and significant ($\neq 0$) and is therefore calculated in the following. The displacement in y- and z-direction from a force in x-direction are not significant, because of the small displacement a small angle approximation is applied. The approximation neglects a cosine error (Taylor: second order) to the final result of less than 0.2 percent for a general commercial cantilever, which is considered as insignificant. By assuming the tip is located in the symmetry axes of the cantilever body the y- and z-forces in (b) and (c) have no torsional momenta and the effect on a the displacement in x-direction is zero.

In the following we will calculate every component of the matrix, the displacement of the tip, and all relevant motions for small deflections of the cantilever shown in (a), (e), (f), (h) and (i). The compliance of **Figure 3.7** (i) was calculated above. The following equations and mathematical description of a cantilever can also be found in similar form in [49], [93] and [94]. The displacement of the tip in y-direction in **Figure 3.7** (f) of F_z is calculated with the bending angle α_z , by the first derivative of the bending line by $\frac{du}{dy} = \frac{\Delta F_z}{2EJ_z}(2L_{eff} - y)y$. For small angles and a rigid tip the bending angle of the tip region is given by:

$$\alpha_z \approx \tan(\alpha_z) = \frac{du}{dy}|_{y=L_{eff}} = \frac{\Delta F_z L_{eff}^2}{2EJ_z} = \frac{3\Delta z}{2L_{eff}} \quad (9)$$

This bending angle is detected in most AFM using an optical lever detection method. With $\Delta z = cF_z$ one can rewrite it as

$$\alpha_z = \frac{3}{2L_{eff}} cF_z \quad (10)$$

which leads to the matrix component $a_{\alpha z} = \frac{3}{2L_{eff}} c$. With the length of the tip L_{tip} in z-

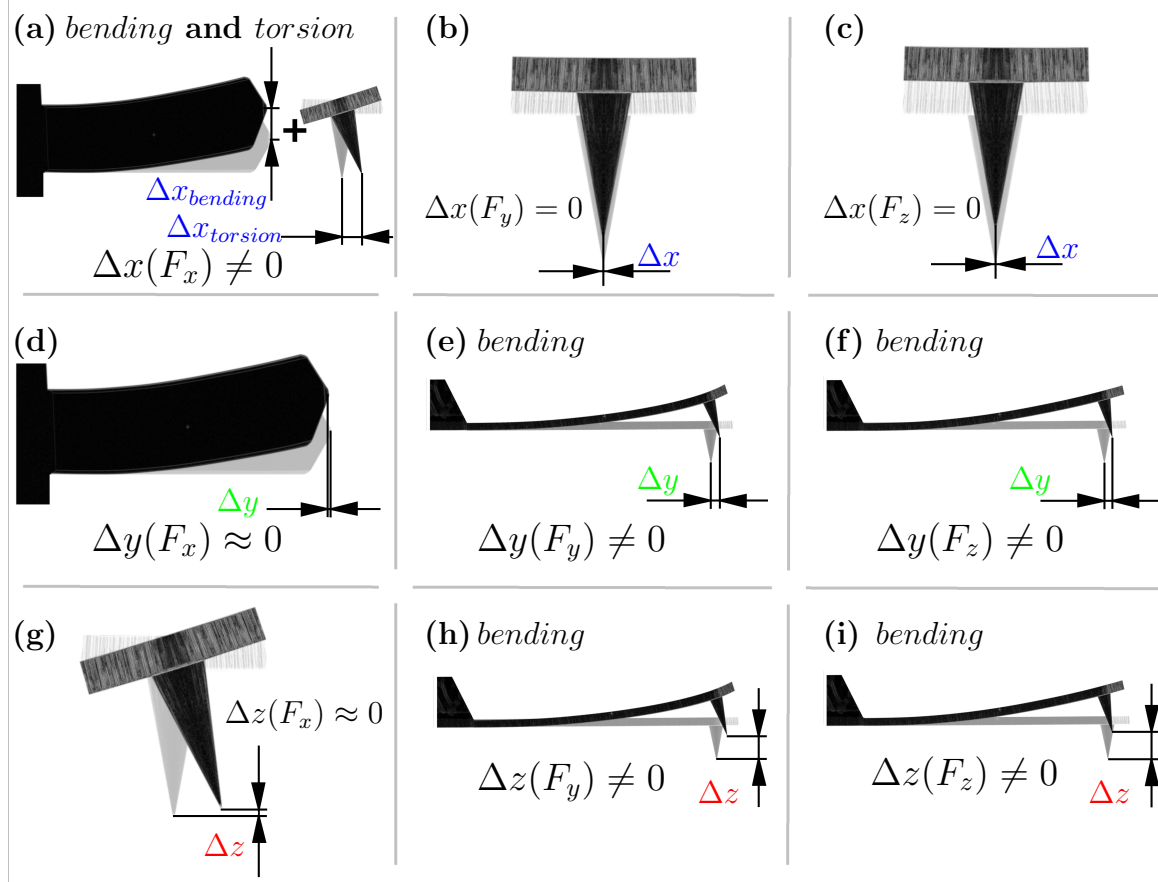


Figure 3.7: Graphical matrix shows the possible bending and torsion motions of the cantilever body and displacement of the tip in x, y, and z-direction, respectively.

direction, the crosstalk of z-displacement of the tip apex to y- direction is expressed for small angles by

$$\Delta y = \alpha_z L_{tip} = \frac{3L_{tip}}{2L_{eff}} c \cdot F_z \quad ; \quad c_{yz} = \frac{3L_{tip}}{2L_{eff}} c \quad (11)$$

Because F_z does not induce a torsion for a symmetrical positioned tip $a_{\beta z} = 0$ and the compliance is $c_{xz} = 0$. Similar applies for $a_{\gamma z} = 0$, because the direction of the F_z is perpendicular to the in plane bending x-direction.

Figure 3.7 shows the tip displacements in Δx , Δy and Δz in (b), (e) and (h) for a force acting on the tip apex lengthwise the cantilever body in y-direction F_y , respectively. The F_z acts via the tip length L_{tip} with a bending momentum of $M_y = F_y L_{tip}$ on the cantilever body. By replacing the bending momentum and rearranging (2) leads to

$$\frac{d^2 u}{dy^2} = \frac{F_y L_{tip}}{E J_z} \quad (12)$$

The same boundary conditions from the z-direction $u|_{y=0} = 0$ (cantilever fixed to the rigid

support chip) and $\frac{du}{dy}|_{y=0} = 0$ (no pretilt) are used. Double integration leads to the bending line of a beam under a bending momentum.

$$u(y) = \frac{F_y L_{tip}}{2EJ_z} y^2. \quad (13)$$

With $y = L_{tip}$ the crosstalk is described as

$$c_{zy} = \frac{\Delta z}{\Delta F_y} = \frac{L_{tip} L_{eff}^2}{2EJ_z} \quad (14)$$

Implementing (6) in the equation above results in

$$c_{zy} = \frac{3L_{tip}}{2L_{eff}} c. \quad (15)$$

which is the equal to c_{yz} , because the compliance matrix is symmetric. Using (13), the inclination angle is again given by the derivative of the bending line for small angles by:

$$\alpha \approx \frac{du}{dy}|_{y=L_{eff}} = \frac{F_y L_{tip} L_{eff}}{EJ_z} = \frac{2\Delta z}{L_{eff}}, \quad (16)$$

hence

$$a_{\alpha y} = \frac{3L_{tip}}{L_{eff}^2} c. \quad (17)$$

The tip apex displacement in y-direction is given via the bending angle at the tip by implementing $\Delta y = \alpha L_{tip}$. This leads to the compliance matrix component

$$c_{yy} = \frac{\Delta y}{\Delta F_y} = \frac{3L_{tip}^2}{L_{eff}^2} c. \quad (18)$$

Because the tip is assumed to be in the symmetry axes of the cantilever body, no momentum acts on the cantilever body for in-plane bending or torsion around y-axes as indicated by **Figure 3.7** (b). Consequently, the corresponding compliance and inclination angles are $c_{xy} = \frac{\Delta x}{\Delta F_y} = 0$, $a_{\beta y} = 0$ and $a_{\gamma y} = 0$.

The remaining tip apex displacements Δx , Δy and Δz for F_x , are shown in **Figure 3.7** in (a), (d) and (g), respectively. The superposition principle is used to combine the tip apex displacements of the in plane bending and the torsion for small angles, shown in (a). With $\Delta x = \Delta x_{bend} + \Delta x_{torsion}$ and $c_{xx} = \frac{\Delta x}{\Delta F_x}$ one can write

$$c_{xx} = c_{xxbend} + c_{xxtorsion}, \quad (19)$$

because the same force is applied on the tip apex.

The compliance component c_{xxbend} is received by coefficient comparison with (6) and the

moment of inertia for bending in x-direction $J_x = \frac{tw^3}{12}$. This leads to

$$c_{xxbend} = \frac{4L_{eff}^3}{Ew^3t} = \frac{t^2}{w^2}c. \quad (20)$$

The compliance component $c_{xtorsion}$ is modeled with $\Delta x_{torsion} = \beta L_{tip}$. Here β is the torsion angle of a torsion beam with the momentum $M_y = F_x L_{tip}$ and shear modulus $G = \frac{E}{2(1+\nu)}$ hence follows that

$$\beta = \frac{3L_{eff}M_y}{Gwt^3}. \quad (21)$$

With an assumed Poisson's ratio ν of about 0.33 of the material, the compliance can be written as:

$$c_{xx} = \left(\frac{2L_{tip}^2}{L_{eff}^2} + \frac{t^2}{w^2} \right) c \quad (22)$$

and detectable bending angle β is calculated from the inclination angle matrix coefficient

$$a_{\beta x} = \frac{2L_{tip}}{L_{eff}^2}c. \quad (23)$$

The not detectable horizontal deflection angle of the cantilever, is denoted as in-plane bending angle γ and is given by coefficient comparison, using (9) with

$$\gamma_x \approx \tan(\gamma_x) = \frac{du}{dy}|_{y=L_{eff}} = \frac{\Delta F_x L_{eff}^2}{2EJ_x} = \frac{3\Delta x_{bend}}{2L_{eff}}, \quad (24)$$

and therefore

$$a_{\gamma x} = \frac{3t^2}{2L_{eff}w^2}c. \quad (25)$$

Because $w > t$ this bending angle is small compared to α and $J_z \ll J_x$. This means $\Delta y \ll \Delta x$ and consequently $\Delta z(F_x) \rightarrow 0$ and $\Delta y(F_x) \rightarrow 0$. Because there is no bending in z-direction $a_{\alpha x} = 0$.

As a result, the cantilever is in good approximation mechanically described by the compliance matrix

$$\mathbf{C} = \begin{pmatrix} \frac{2L_{tip}^2}{L_{eff}^2} + \frac{t^2}{w^2} & 0 & 0 \\ 0 & \frac{3L_{tip}^2}{L_{eff}^2} & \frac{3L_{tip}}{2L_{eff}} \\ 0 & \frac{3L_{tip}}{2L_{eff}} & 1 \end{pmatrix} \cdot c \quad (26)$$

and the matrix of the inclination angles by

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} = \begin{pmatrix} 0 & \frac{3L_{tip}}{L_{eff}^2} & \frac{3}{2L_{eff}} \\ \frac{2L_{tip}}{L_{eff}^2} & 0 & 0 \\ \frac{3t^2}{2L_{eff}w^2} & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \cdot c. \quad (27)$$

A normal cantilever with a geometry of $L_{eff} = 130 \mu\text{m}$, $w = 35 \mu\text{m}$, $t = 4 \mu\text{m}$, $L_{tip} = 15 \mu\text{m}$ shows a compliance ratio of about 1:1:20 for $c_{xx}:c_{yy}:c_{zz}$ and a significant crosstalk of about 0.17:1 ($c_{yz}:c_{zz}$) [72]. For commercial AFMs this anisotropy is not important, the horizontal stiffness of the cantilever in combination with a stiff conical tip reduces the tip slipping effect, described in [95], [93]. For vertical and lateral (horizontal) probing with a compliant tip such as a CD-tip however it enhances tip slipping and sticking [96], and reduces the detectable bending and torsion (deflections) of the cantilever probe, as explicitly shown in [72]. This is also indicated by the inclination angle ratios of $a_{\beta x}:a_{\alpha y}:a_{\alpha z}$ with about 0.15:0.23:1 [72]. Thus, a rectangular cantilever is most sensitive for deflections induced by a force in z-direction. The large mechanical crosstalk can also lead to unstable probing conditions and in combination with a regular detection principle (e.g. optical lever) can lead to tip breakage as shown in [97]. Thus, for accurate true 3D probing the sensitivity needs to be balanced, and the tip slipping must be reduced by an isotropic stiffness ratio with minimal crosstalk to achieve stable probing conditions.

3.2.3. The cantilever probe for critical dimension (CD) measurements

The versatility of the AFM origins mainly from of the measurement method and choice of the probe. To probe vertical sidewalls a special cantilever with a CD-tip is used, e.g. [98]. **Figure 3.8** depicts the slender CD-tip in detail in an SEM image. The cylindrical CD-tip is located at the free end of the cantilevers tip cone. The tip is flared at the free end to probe undercut sidewalls and re-entrant structures. The free end of the cantilever is shown in a side view on the *left* in detail. The mechanical model to describe the CD-tip uses a simplified description with d = effective diameter and L_s = effective CD-tip length, as depicted in detail on the *right*. The tip length to width ratio is about 6:1. The flared CD-tip apex is made of silicon or wear resistant diamond-like carbon (DLC) deposited with an electron beam deposition (EBD) process [99]. This flared part can also be realized by a slight bend of the tip apex as it is been used for probing with carbon nanotube (CNT) tips to achieve a defined probing interaction [103]. Another kind of flared probes are the so-called *trident probes*, which are similar shaped but have sharpened extensions in the tip apex region to improve probing of sharp bottom corners [100], [101], [102].

Depending on the batch, the CD-tip usually tapers slightly to its base with a soft transition

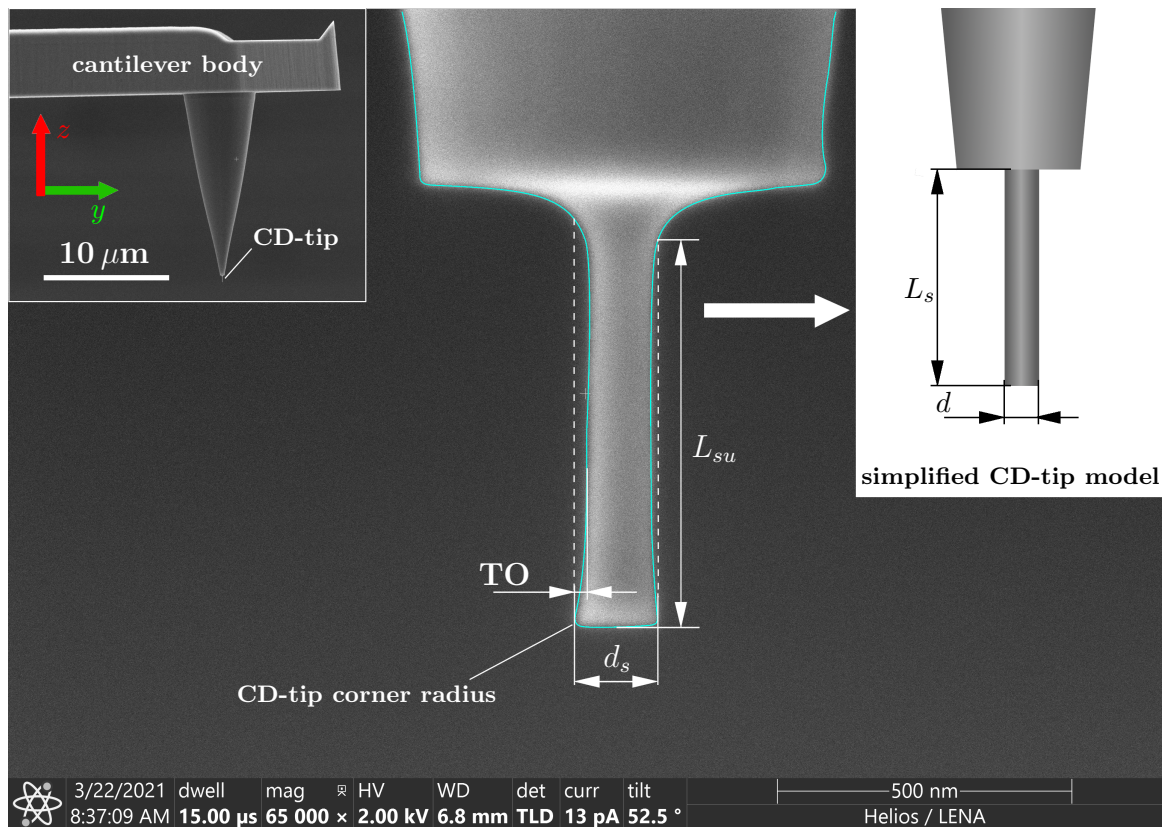


Figure 3.8: SEM image of the CD-tip of a CDR cantilever probe ([98]) for CD metrology with flared tip apex with a tip overhang (TO) of about 15 nm, tip apex diameter d_s , and usable CD-tip length L_{su} .

to the cantilever tip cone. This transition limits the probing depth in -z-direction and usable tip length L_{su} , as indicated by the dashed lines in **Figure 3.8**.

The tip overhang, which is determined by the tip diameter d_s and diameter of the shaft, varies with the nominal tip width and manufacturer. Nominal CD-tip diameters from about 850 nm down to 15 nm are available [104], [105]. The depicted CD-tip shows a tip overhang of about 15 nm. This tip overhang is also necessary, because usually the probe has an incident angle which limits probing depth in +y-direction. An upper corner of the sample structure geometry will not be able to interact with the CD-tip apex, instead it will probe the cylindrical shaft of the CD-tip. This is called shaft probing and leads to measurement artifacts as it can be seen in [106]. Depending on the geometry of the CD-tip apex, it also shows limits for probing sharp bottom corners of sample structures because the relatively blunt CD-tip simply cannot reach those areas, mainly because of its tip radius and vertical edge height, as indicated above in **Figure 3.3**.

During probing, the slender and compliant CD-tip is deflected by the tip-sample interaction forces [107]. This means, the total compliance of the cantilever $\mathbf{C}_{tot}$ is dominated by the compliance of the small and slender CD-tip $\mathbf{C}_s$, in combination with a stiff cantilever body $\mathbf{C}$ from (26) it is given by

$$\mathbf{C}_{tot} = \mathbf{C} + \mathbf{C}_s = \mathbf{C} + \begin{pmatrix} c_{Sxx} & c_{Sxy} & c_{Sxz} \\ c_{Syx} & c_{Syy} & c_{Syz} \\ c_{Szx} & c_{Szy} & c_{Szz} \end{pmatrix}. \quad (28)$$

The elastic deflections are taken into account by modeling higher order tip effects and tip calibration [107], [108], [25].

A simple linear elastic model can be used to describe, the compliance of the CD-tip in 3D, however every CD-tip has its individual geometry which is neglected here. The contact region of a tip-sample interaction is also neglected in this description, such as a shear contribution because of the slenderness of the CD-tip. The CD-tip can be described as a cylindrical rod depicted in **Figure 3.8** on the *right*. The CD-tip geometry is approximated by the effective CD-tip length L_s and diameter d . Because of the radial symmetry the horizontal compliance is $c_{Sxx} = c_{Syy}$. The following expressions are also similarly described in [93], [95] and [107]. The component c_{Szz} is given by the compression or elongation ϵ_z of the cylindrical tip and Young's modulus of the tip E_s with,

$$c_{Szz} = \frac{\Delta z}{\Delta F_z} = L_s \cdot \frac{\Delta \epsilon_z}{\Delta F_z} = L_s \cdot \frac{\Delta \sigma_z}{\Delta F_z E_s} = L_s \cdot \frac{1}{E_s A} = \frac{4L_s}{E_s d^2 \pi}, \quad (29)$$

under the assumption of normal stress σ_z , induced by the interaction force F_z . Consequently, the c_{Sxz} and c_{Syz} are zero. The linear-elastic model of an Euler-Bernoulli beam is used to describe the bending in horizontal x- and y-direction. It is given by

$$c_{Sii} = \frac{64L_s^3}{3E_s d^4 \pi}, \quad i = x, y. \quad (30)$$

The higher order effects of the CD-tip apex z-position change under bending due to a horizontal force is neglected, because the expected deformation is small compared to the CD-tip's length. Hence, all remaining components of $\mathbf{C}_s$ are approximated to zero and the compliance

matrix of a CD-tip is given by

$$\mathbf{C}_s = \begin{pmatrix} \frac{64L_s^3}{3Ed^4\pi} & 0 & 0 \\ 0 & \frac{64L_s^3}{3Ed^4\pi} & 0 \\ 0 & 0 & \frac{4L_s}{Ed^2\pi} \end{pmatrix}. \quad (31)$$

Today, CD-tips become increasingly smaller, because certainly only trenches can be probed which are wider than the CD-tip [213],[214]. Small CD-tips are more compliant than large CD tips, because the compliance of a structure is anti-proportional to its size, despite sharing the same aspect ratio of length to diameter. This has a strong effect on the sensitivity or detectable probing signal, because only the deflection of the cantilever body can be detected, not the CD-tip displacement. A detailed example of the impact of the CD-tip on the cantilever's total compliance is given in section 4.2. As already mentioned above, the compliance ratio between cantilever tip and body can be several orders of magnitudes. For instance, the sensitivity in x- and y-direction is reduced by a factor of about 200 for a 70 nm CD-tip [72]. Consequently, using a stiff cantilever probe with a narrow compliant CD-tip leads to a small detectable signal and presumable small signal to noise ratio. This inherent shortcoming is addressed in the works of [93], [109], [110] and is considered in the development of the novel probe [72], [106], [111].

3.3. Detection principles

Several detection principles were used and investigated to measure the probe deflection induced by the tip-sample interaction force. In the past, detection methods such as tunneling current sensing, capacitive sensing, homodyne and heterodyne interferometer displacement detection, polarization detection, external optical feedback into a laser-diode cavity, auto-focus sensors, piezoelectric self-sensing and many more were tested and used over the decades [66], [112], [113] and can be found with consideration of noise contributions in [114].

Most commonly, the deflection of a cantilever shaped probe is measured at the free end of the cantilever body with an interferometer or an optical lever [66]. A scheme of the optical lever detection method is shown **Figure 3.2**. Also an array sensor can be used instead of a segmented photo-diode as a sensor to measure the displacement of the reflected beam [112]. Both, interferometer and optical lever are optical detection methods. The interferometer detects the changes of the cantilever position and the optical lever detects the inclination angle of the cantilever beam locally at the focused spot. Both are precise and manageable detection methods and relatively easy to build and are selected as feasible to realize a 3D-sensor for true 3D-AFM use. To achieve highest stability a differential interferometer can be used, as described in [115], [116], [117]. In these setups the reference beam is focused on the support chip or base of the cantilever probe. Very low noise values are reported due the compact design and short deadpath, which might be a promising detection method for the novel AFM head. Another advantage of both of these detection principles is, that they are compatible with most commercial cantilever probes since they require only a reflective and even surface for probing, unlike other detection principles, e.g. capacitance sensing. In the past a combination of both detection methods was successfully tested and multi-dimensional tip-sample interaction forces were registered [85], [86], [87] and [56]. Unfortunately, the used probes and scan algorithms were not suitable for true 3D-probing.

The position resolution of each individual detection method is in the order a few 10 pm for static and dynamic modes [66] and is usually stable down to a few nanometers over hours, which obviously depends on the used probe (e.g. thermal noise) and measurement environment. In the following both detection principles are explained in detail.

Because optical detection principles are being used in this work, a simplified description of light can be found in section 3.3.1.

3.3.1. Description of Light

Light is a form of electromagnetic radiation and described as a wave in an electromagnetic field that carries a electromagnetic linear and angular momentum. The energy of the electromagnetic wave in free space is defined by its oscillation frequency ν . Interactions with the electromagnetic field and properties are described by the Maxwell equations [118]. Two electromagnetic waves can be super-positioned. In vacuum, electromagnetic waves travel with the speed of light c_0 and are not directly affected by static fields (electric or magnetic). With the oscillation frequency ν and traveling speed c_0 , the wavelength of a traveling free wave is defined as $\lambda_0 = \frac{c_0}{\nu}$. The direction of oscillation of the waves is perpendicular to the direction of propagation. The orientation of the oscillation can be expressed by a vector of the electric field, the direction is the polarization. If the orientation is random, the traveling wave is considered as non-polarized. If the oscillation is oriented in one plane the light is linear polarized.

By definition there are two orthogonal linear polarized components of a wave called s- and p-polarization. Elliptically polarized electromagnetic waves have a phase difference and difference in amplitudes of the s- and p-polarized wave components. If the amplitude of the s- and p- wave components is equal and the phase lag between them is $\pi/2$ the polarization is called circular. Multiple waves with the same phase can be added by using *Huygens-Fresnel* principle and form a so-called wavefront [119], which can be geometrically described by surfaces, which appear as lines in a 2D drawing. The propagation direction which is perpendicular to these constructed surfaces are so-called rays and can be used to describe classic optical paths in free space. The propagation (traveling) direction can be expressed by the (angular) wave vector $\vec{k}$, whereby $|\vec{k}| = \frac{2\pi}{\lambda}$, but can differ from the pointing vector (energy flux of the wave), given by the electric field vector $\vec{E}$ and magnetizing field $\vec{H}$ with $\vec{S} = \vec{E} \times \vec{H}$. For materials, which can be considered as isotropic, such as most glasses and air, the pointing vector aligns with the (angular) wave vector. Where the velocity is given by $c = \frac{c_0}{n}$, with n as the refractive index of the medium. Thus, a monochromatic sinusoidal traveling wave in vacuum (linear Maxwell equation) with the amplitude A_0 , phase φ , time t and position vector $\vec{r}$ can be expressed as

$$\psi(\vec{r}, t) = A_0 e^{i(\vec{k} \cdot \vec{r} - 2\pi\nu t + \varphi)} \quad (32)$$

Averaging over at least one period yields the optical (light) intensity. Simple wavefront forms are the plane wave (collimated parallel rays) and spherical wave (focused rays). With the development of quantum theory, electromagnetic waves interaction with media were found to be quantised (quantised electromagnetic field) [120]. These quanta are called photons and have no static mass. As a result the energy of a photon $E_{\text{photon}} = h\nu$ is proportional to the carried linear momentum (for most materials) with its vector pointing in the direction of the energy flow ($h = \text{Planck constant}$). In general the electromagnetic spectrum ranges from radio frequencies with large wavelength of hundreds of meters over infrared radiation to high energy gamma rays with picometer wavelength. The visible spectrum to the human eye ranges from about (violet) 380 nm to about (dark-red) 780 nm (wavelength) and is called visible light. Above 780 nm to 2500 nm there is the non-visible near infrared radiation (NIR) and below 380 nm the ultra violet (UV) radiation band. Within this work, visible white light (400 nm - 700 nm) for microscope illumination and lasers with wavelengths of about 635 nm, 670 nm and 1550 nm are used.

3.3.2. Displacement detection with interferometry

Interference describes the superposition of two coherent waves. Coherence is a measure of the similarity of the wave over a given time and can be expressed by the cross-correlation function (1 = fully coherent, <1 to >0 partially coherent, 0 = incoherent) of two waves in a time interval. Whereby coherence can be separated into spatial coherence and temporal coherence. Spatial coherence is dependent on the shape of the source (*van Cittert-Zernike* theorem [121], [122]), whereas temporal coherence is dependent on the spectrum of the source and can be explained by the *Wiener-Khinchin* theorem [123]. For a Gaussian spectrum the coherence length L_{coh} of a quasi monochromatic light source with the center wavelength λ and spectral line-width of the center wavelength $\Delta\lambda$ at full width at half maximum (FWHM)

is given by

$$L_{coh} = c_0 \Delta \tau \approx \frac{\lambda^2}{n_g \Delta \lambda}. \quad (33)$$

with the coherence time τ_{coh} , and n_g as the group refractive index. If n_g does not change over λ then it is equal to refractive index n of the medium (e.g. vacuum). This can be assumed in this work because in our setup lasers are used with $\Delta \lambda \ll \lambda$. The superposition of two or more at least partially coherent waves leads to constructive (in phase) and destructive (out of phase) interference over its coherence length. The intensity $I_0 = \frac{c_0 \epsilon_0 |\vec{E}|^2}{2}$ of two sine waves with perpendicular polarization which are interacting, expressed by field vector $\vec{E}_\perp = E_0(\cos(2\pi\nu t) + i\cos(2\pi\nu t + \Delta\phi))$ in complex notation, is given by

$$\langle |\vec{E}_\perp|^2 \rangle = E_0^2 \langle \cos^2(2\pi\nu t) + \cos^2(2\pi\nu t + \Delta\phi) \rangle. \quad (34)$$

By integration over an integer of time periods T the intensity is independent of $\Delta\phi$ because $\frac{1}{T} \int_0^T \cos^2(2\pi\nu t) dt = 1/2$. As a result perpendicular polarized waves do not interact with each other.

If the waves are parallel polarized (here linear) $\vec{E} = E_0(i\cos(2\pi\nu t) + i\cos(2\pi\nu t + \Delta\phi))$ the interaction is given by

$$\langle |\vec{E}_\parallel|^2 \rangle = E_0^2 \langle \cos^2(2\pi\nu t) + 2\cos(2\pi\nu t)\cos(2\pi\nu t + \Delta\phi) + \cos^2(2\pi\nu t + \Delta\phi) \rangle \quad (35)$$

The two waves interact with each other and the intensity depends on the phase difference $\Delta\phi$ and is proportional to $(1 + \cos(\Delta\phi))$. The interferometer shown in **Figure 3.9** is a simplified version, because the shown configuration can only detect interference fringe counts or velocity and is not sensitive for the sign or phase of the z-displacement of the moving mirror MM . The phase and sign can be detected via quadrature detection of the I_{PD} signal [124]. This can be achieved by using polarization or modulation (e.g. laser frequency modulation) of the source. Linear polarized laser light rotated at a 45° angle is used as a source, which is then circular polarized (quarter-wave plate rotated by 45°) and enters the beamsplitter BS . The detector PD is enhanced by a polarizing beam splitter and second detector, to detect the reflected polarization components. The orthogonal s- and p-polarized components I_{PDs} and I_{PDp} are detected by the photo-diodes individually as a sine and cosine, respectively, due to a change of the light paths and can be used to calculate the current phase $\Delta\phi = \text{atan2}(I_{PDs}/I_{PDp})$. They can also be displayed as the xy-parameters of a Lissajous figure with the shape of an ellipse [124]. The interferometer in this work uses a non-polarizing beam splitter and is relative insensitive to polarization changes. Thus, in the following expressions vector notation is not necessary and only light intensities are used to describe the interferometer signal. **Figure 3.9** shows a sketch of a *Michelson*-interferometer. The collimated monochromatic beam coming from a laser source is split by a beamsplitter (BS) and forms a reference arm (beam) and a measurement arm (beam). After reflection both intersect at the beamsplitter and interfere. The moving mirror (MM) reflects the measuring beam and can be displaced in z-direction. This displacement changes the optical path between those two beams, which intersect again at the beamsplitter (BS). Distinct changes of the optical paths are shown on the *right side*. By displacing MM by $\lambda/2$ the collected intensity I_{PD} of the interference pattern on the photodetector PD shifts by one fringe $2\pi = \lambda$. In the AFM the moving mirror (MM) is

replaced by a reflective probe. The interference pattern is detected, usually by a square-law photo-detector (PD). With ideal flat mirrors, perfectly perpendicular oriented mirrors and

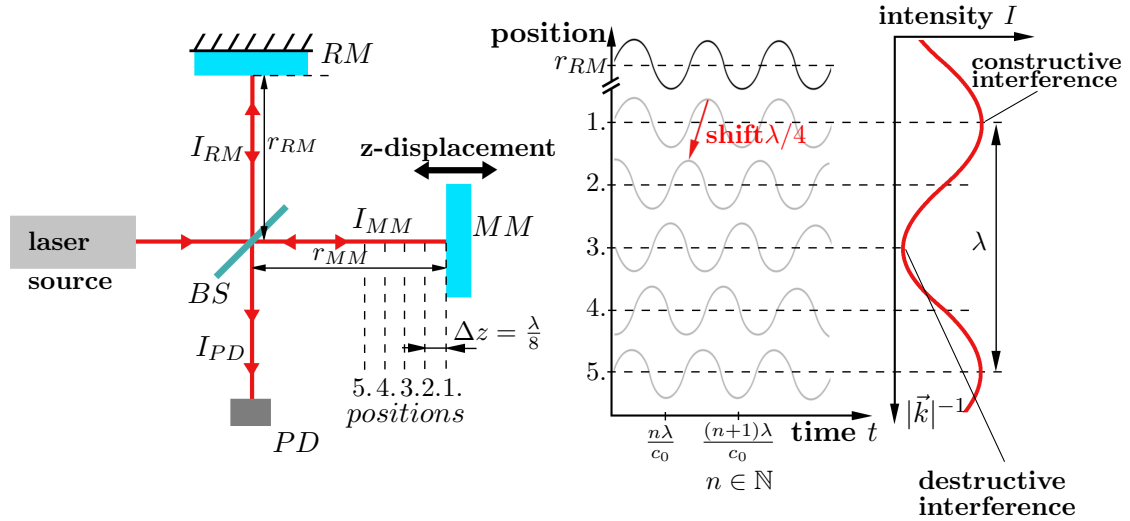


Figure 3.9: The *Michelson-interferometer* sketch is shown on the *left side*. The reference mirror (*RM*) reflects the reference beam with the fixed length r_{RM} .

monochromatic source and beamsplitter (BS) ratio of 50:50, the measurable intensities can be described by

$$I_{PD} = I_{MM} + I_{RM} + 2\sqrt{I_{MM}I_{RM}}\cos(\Delta\phi_r), \quad (36)$$

with a relative phase difference $\Delta\phi_r$ between the optical path of reference arm r_{RM} and the corresponding path r_{MM} of the moving mirror $\Delta\phi_r = \phi_{RM} - \phi_{MM} = 2k\Delta z = 2k(r_{RM} - r_{MM})$. This leads to the fundamental equation of a simple (double-path) interferometer of

$$\Delta z = \frac{\lambda_0}{2n_{medium}}(n + \frac{\Delta\phi}{2\pi}) \quad (37)$$

with n as the order/number of interference fringe (integer) and phase difference determined by a phase unwrapping algorithm, because of the unambiguous range of the phase of $0 \leq \Delta\phi < 2\pi$. The refractive index of the medium is given by n_{medium} . The minimal absolute length difference Δz between both interferometer arms is called dead path, since it does not change (or is not used) during displacement measurements. This dead path has a strong influence on the error of the displacement measurement of the interferometer because any effect that changes the refractive index of the medium n_{medium} in the optical paths of the interferometer (e.g. environment) has an influence on the wavelength. Consequently, it has an influence on the measured distance. In this work the refractive index of air n_{air} has a strong influence on the measured distance, because measurements are performed in a climatized laboratory under atmosphere. The main influence sources on the refractive index (also dispersion formular) of air are the ambient pressure, temperature, humidity and CO_2 (gas) level. Applying the correction formulars of *Edlén*, *Ciddor* or *Bönsch* mitigates this error [125], [126], [127].

Additional error sources are for instance misalignment of optical components, wavefront errors, ghost images, multiple reflections that form etalons between parallel optical surfaces (e.g. *Fabry-Perot interferometer*), Bessel-beams with higher order terms or non-uniform intensity distributions caused by apertures (*Airy disk* [26]) and optical elements, amplifier errors of e.g. gain error of the current to voltage converters of the detectors, phase-shift error, laser phase or intensity noise, thermal noise, vibrations, mechanical instabilities, stray light and dependent on the interferometer also errors in data evaluation. Most of these errors have a periodic influence in the 2π phase shift, consequently are measurable as periodic non-linearities of a linear displacement. Stable and periodic non-linearities can be corrected by e.g. least square algorithms fitting of the components of the quadrature detection. A distorted Lissajous figure (ellipse) is fitted to a unit circle. One frequently used method is the *Heydemann* correction algorithm [124]. This basic correction method can mitigate zero, first and second order non-linearities, but has no effect on higher order non-linearities. Those can be corrected with higher order models and look-up tables [128].

Absolute distance measurement

Most interferometers such as the *Michelson*-interferometer in **Figure 3.9** measure relative displacements. The displacement is only unambiguous within $0 \leq \Delta z < \lambda/2$. To measure absolute displacements a second sensor or wavelength can be used. This second wavelength is superimposed with the first to generate a longer unambiguous range. It forms a synthetic wavelength $\Lambda = \frac{\lambda_1 \lambda_2}{\lambda_1 - \lambda_2}$, which can be used to determine the absolute distance. With a small difference between λ_1 and λ_2 synthetic wavelengths of 1 mm to tens of meters can be generated. Another way for absolute distance measurements is to sweep the wavelength of the source $\lambda(t)$ over time.

$$\lambda(t) = \lambda - \Delta\lambda(t) \quad (38)$$

A detailed description can be found in [129], which is briefly summarized in the following. Rewriting and using $\Delta\lambda \ll \lambda$ leads to the simplified expression of the oscillation frequency ν of

$$\nu(t) = \frac{c_0}{\lambda - \Delta\lambda(t)} \approx \frac{c_0}{\lambda} \frac{\lambda + \Delta\lambda(t)}{\lambda} = \nu \left(1 + \frac{\Delta\lambda(t)}{\lambda} \right) . \quad (39)$$

Assuming a sinusoidal modulation of the laser wavelength with the frequency $f_{mod} = \frac{\omega_{mod}}{2\pi}$, an amplitude $a_0 = \frac{\Delta\lambda(t)}{\lambda}$ and a start phase ϕ_0 , ν can be written as

$$\nu(t) = \nu (1 + a_0 \cos(\omega_{mod}t + \phi_0)) \quad (40)$$

Substituting (40) into (36) leads to following expression of the detectable intensities of a wavelength modulated interferometer

$$I_{PD}(t) = I_0 \cos \left(\frac{2\pi n_{medium} \Delta z}{c_0} \nu (1 + a_0 \cos(\omega_{mod}t + \phi_0)) \right) . \quad (41)$$

In this work a setup with a diode laser is used. Because these lasers can drift over time, a

drift term $\xi_{drift}(t)$ and $\lambda = \lambda_0 + \Delta\lambda$ is implemented. Rearrangement of (41) leads to

$$I_{PD}(t) = I_0 \cos \left(\frac{2\pi n_{medium} \Delta z}{\lambda} (1 + a_0 \cos(\omega_{mod} t + \phi_0) + \xi_{drift}(t)) \right) \quad (42)$$

This expression has multiple higher order frequency components, which can be expressed by a *Jacobi-Anger expansion* with J_n as n -th order *Bessel functions* with $n \in \mathbb{N}$. By using the trigonometric addition formula $\cos(p+q) = \cos(p)\cos(q) - \sin(p)\sin(q)$, the detectable signal is given by

$$\begin{aligned} I_{PD}(t) = I_0 \cos(\phi_{path} + \xi_{drift}(t)) & \left(J_0\left(\frac{\phi_{path} \Delta \lambda}{\lambda}\right) - 2J_2\left(\frac{\phi_{path} \Delta \lambda}{\lambda}\right) \cos(2\omega_{mod} t + 2\phi_0) + \dots \right) \\ & - I_0 \sin(\phi_{path} + \xi_{drift}(t)) \left(2J_1\left(\frac{\phi_{path} \Delta \lambda}{\lambda}\right) \cos(\omega_{mod} t + \phi_0) \right. \\ & \left. - 2J_3\left(\frac{\phi_{path} \Delta \lambda}{\lambda}\right) \cos(3\omega_{mod} t + 3\phi_0) + \dots \right) \end{aligned} \quad (43)$$

with $\phi_{path} = \frac{2\pi n_{medium} \Delta z}{\lambda}$. Using a lock-in amplifier and a narrow bandpass filter for ω_{mod} , the signal of interest is given by

$$I_{PD}(t) = I_0 \cos \left(\frac{2\pi n_{medium} \Delta z}{\lambda} + \xi_{drift}(t) \right). \quad (44)$$

In reality filters are not perfect (suppression of sidebands) and the periodic non-linearity corrections can not compensate for higher order non-linearity terms, including because the phase position of the non-linearity might not be stable. As a result typical fluctuations of the displacements signal of an interferometer are shown as an example in **Figure 3.10**. These error signals are usually a few nanometers, but can be mitigated by a careful optical design or in case of wavelength modulation by using a different modulation function (linear).

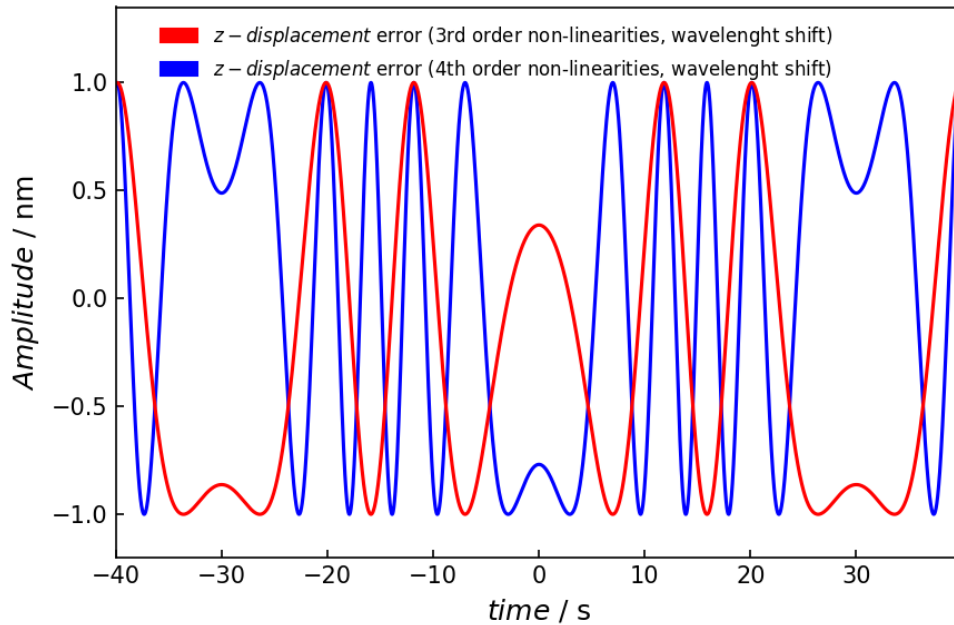


Figure 3.10: Simulated periodic non-linearities of an interferometer with a dead path of 23 cm, and an unstable center wavelength of about 1540 nm. The periodic drift of the wavelength was set to $0.5 \cdot 10^{-6}/\text{min}$, as an example.

3.3.3. The optical lever

The optical lever is one of the oldest detection principles known. It is based on the law of reflection, according to which the angle of reflection measured to the normal of the surface (mirror) is equal to the angle of incidence normal of the surface. Tilting this mirror surface, results in twice the tilt of reflected light beam. A detector mounted in a distance to the mirror intersecting the reflected beam, registers a change in position of the light beam. The achievable optical amplification for a collimated beam can be of several orders of magnitude without additional noise and is proportional to the lever, which is the distance between mirror and detector. For small angles, the displacement of the optical beam on the detector is nearly proportional to the tilting angle of the mirror surface. For focused light the quasi noiseless amplification is limited by the optical setup and beam properties. The length of the lever is determined by the focal length of the used focusing lens and the detected signal is almost independent of the distance between the lens and detector. An explanation of this detection principle can also be found in [56], [63], [64].

For AFM, mostly optical levers with focused light are applied, because of the small reflective area (a few $10 \mu\text{m} \times 10 \mu\text{m}$) of a cantilever probe. To register the largest signal, the light beam is usually focused on the area of the largest deflection of the probe, which is usually the free end of the cantilever. To describe the optical lever properties, the *Gaussian beam* is used as a model for the light beam [130]. An intensity distribution of a collimated *Gaussian beam* with the beam diameter D_{col} is depicted in **Figure 3.11** on the left side and can be described with the intensity dependent on the beam radius r as

$$I_{00}(r) = I_0 e^{-\frac{r^2}{\omega_0^2}} \quad (45)$$

with the center maximum intensity value I_0 and beam waist radius at $1/e^2$ intensity ω_0 .

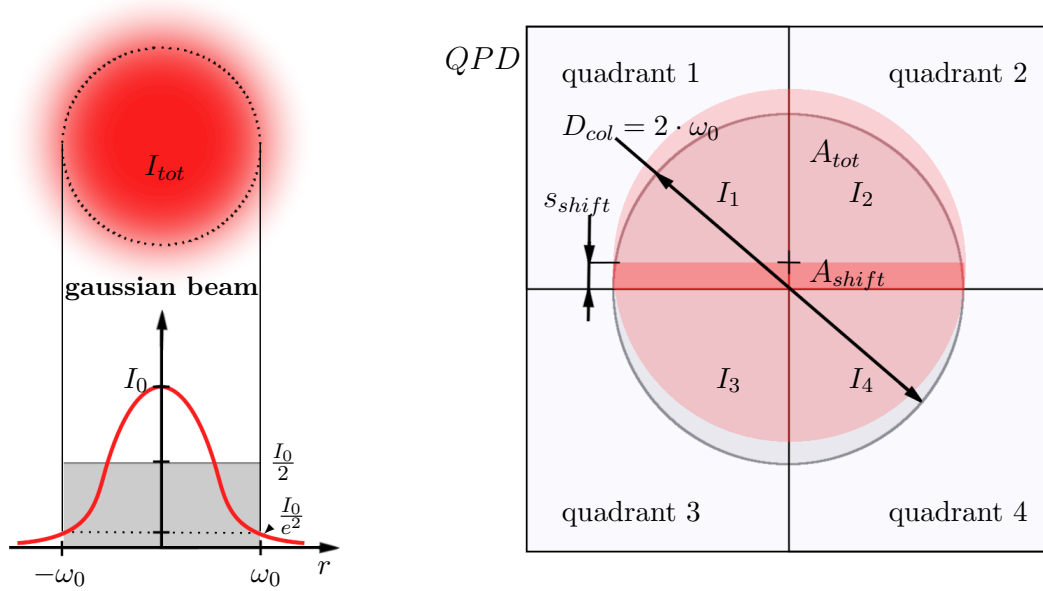


Figure 3.11: The Gaussian beam intensity distribution and the Quadrant Photodiode with maximum intensity I_0 and $\omega_0 =$ beam waist radius r at $1/e^2$ (13,6 %) intensity (*left side*). The total intensity of the light beam is given by $I_{tot} = I_1 + I_2 + I_3 + I_4$. Twice the beam waist radius defines the nominal collimated beam diameter D_{col} , which is used to describe an evenly spread intensity distribution on the quadrant photodiode (QPD), (*right side*) as an approximation. Illuminated areas are marked in red and gray as $A_{shift} = D_{col} * s_{shift}$ and A_{tot} .

This formula is only valid for large spot diameters $d_{spot} = 2\omega_0 \gg \frac{\lambda}{n}$ or weak and non-convergent beams, where n is the refractive index of the medium and λ the wavelength. In general, the *Gaussian beam* diverges/converges with propagated distance z_{prop} by

$$\omega(z_{prop}) = \omega_0 \sqrt{1 + \left(\frac{\lambda z_{prop}}{\pi \omega_0^2} \right)^2} \quad (46)$$

The beam diverges/converges nearly linearly far from the focus (beam waist), as is often used in geometrical ray optics. In AFM displacements of the probe are small compared to the beam waist length. The minimum spot size d_{spot} of a focused *Gaussian beam* with focal length f and beam diameter D_{col} is described, using beam divergence [130], by

$$d_{spot} = \frac{4\lambda f}{\pi D_{col}} \quad (47)$$

Figure 3.12 shows the ideal focus spot size for different D_{col} and focal length f . Applied to the optical lever, the beam is reflected at the beam waist by the probe and detected by a segmented photodiode in the AFM head. The total intensity I_{tot} of the beam, is split by the segments of the photo-diode. Each segment is separated by a small gap of about $50 \mu\text{m}$. Two segments, four quadrants or position sensitive diodes or even individual photodiodes can be used. In this work a Quadrant Photo-Diode (QPD) is used. In **Figure 3.11** quadrant (1

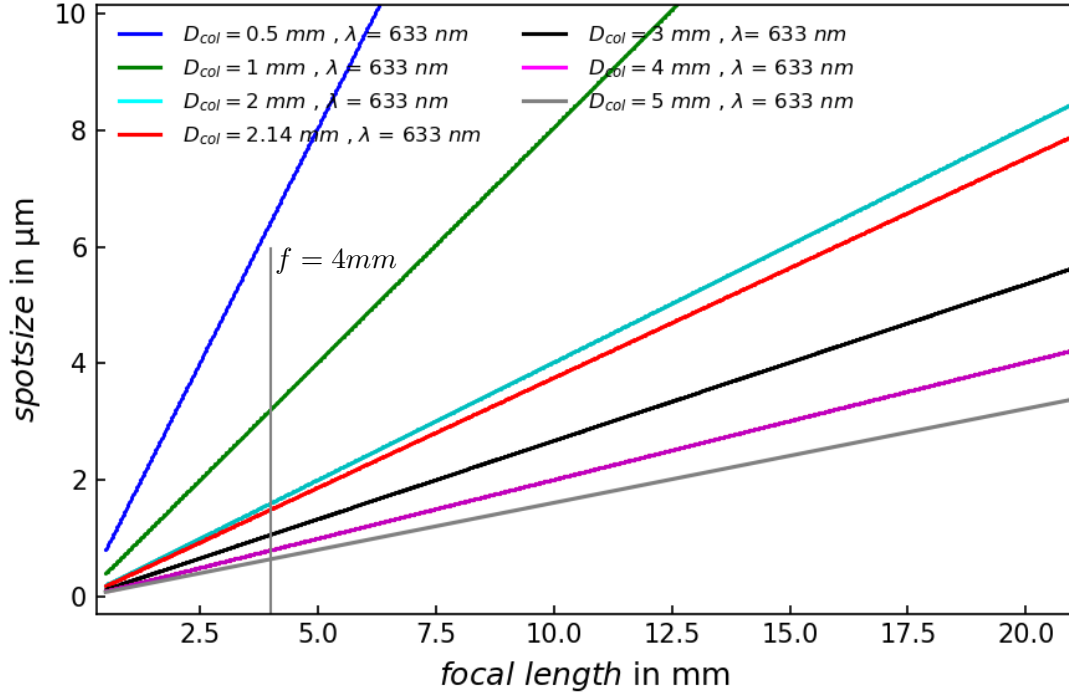


Figure 3.12: Spot sizes of a *Gaussian beam* for focal lengths f and collimated beam diameters D_{col} .

to 4) detect an intensity I_1 to I_4 . Neglecting the gap $I_{tot} = I_1 + I_2 + I_3 + I_4$. Based on the photoelectric effect of a silicon based photodiode, the individual segment generates a photo-current. Each photo-current is usually amplified by a current-to-voltage amplifier to generate a voltage signal proportional the light intensity illuminating the photodiodes surface. The four signals are processed by summing and differential amplifiers to get the total intensity $I_{tot} = I_{SUM}$, and two orthogonal beam position signals. According to **Figure 3.11** the normalized top-bottom (TB) and normalized left-right (LR) beam position signals are given by

$$\frac{\Delta I_{TB}}{I_{SUM}} = \frac{(I_1 + I_2) - (I_3 + I_4)}{I_{SUM}} = \frac{\Delta V_{TB}}{V_{SUM}} \text{ and } \frac{\Delta I_{LR}}{I_{SUM}} = \frac{(I_1 + I_3) - (I_2 + I_4)}{I_{SUM}} = \frac{\Delta V_{LR}}{V_{SUM}}. \quad (48)$$

where V_{TB} , V_{LR} and V_{SUM} are the corresponding detectable current-to-voltage amplified voltage signals. To give a first approximation and a simple formula of the optical lever principle we use following simplifications. First, the gap of the photo-diode is neglected,

because it is usually small compared to the D_{col} . Second, only the light inside the nominal collimated beam diameter D_{col} is used in the description, with a flat top intensity distribution. This is done, because due to apertures in the optical path and rotational symmetry of the intensity distribution. Indicated by the gray areas in **Figure 3.11**, the intensity of a flat top beam profile with a nominal D_{col} is about half of the *Gaussian beam* profile intensity I_0 . Third, the beam is assumed to be located in the center of the QPD and the intensities I_1 to I_4 are equal. The beam will only be shifted by a small distance $s_{shift} \ll D_{col}$ and does not reach the corner areas of the QPD and thus remains in the photosensitive area. In first approximation, by neglecting the spot's corner curvature, the displacement signal is proportional to the displacement of the beam on the QPD. The rotational symmetry and simplification of an evenly spread intensity distribution in the area $A_{tot} = \pi D_{col}^2/4$ gives the normalized signal

$$S_{sig} = \frac{2A_{shift}}{A_{tot}} = \frac{\Delta I}{I_{tot}} \quad (49)$$

for an off-center shifted beam with e.g. $\Delta I = \Delta I_{TB}$ and $A_{shift} = s_{shift} \cdot D_{col}$. By treating each quadrant individually in the differential amplification of the quadrants, $\pm A_{shift}$ is detected, which is represented by a factor of 2 in (49). The linear approximation for small bending inclination angles α of a cantilever probe for a optical lever with a focal length f is given by

$$s_{shift} = 2\alpha f. \quad (50)$$

The detectable beam shift on the QPD under the assumption of a proportional dependency of cantilever tip displacement e.g. Δz to the beam shift and cantilever mechanics (10) is given by

$$s_{shift} = \frac{4}{3} \frac{\Delta z}{L_{eff}} f. \quad (51)$$

Implementing (51) into (49) results in

$$S_{sig} = \frac{16}{3} \frac{\Delta z f}{\pi L_{eff} D_{col}} \quad (52)$$

Finally, with (47) and with $S_{sig} = \Delta V_{xy}/V_{SUM}$ this results in

$$\Delta V_{xy} = \frac{8}{3} \frac{\Delta z}{L_{eff}} \frac{d_{spot}}{\lambda} V_{SUM}. \quad (53)$$

Where V_{xy} is either the top to bottom V_{TB} or left to right V_{LR} displacement voltage signal of the beam position on the QPD. The expression (53) shows the important dependencies of the optical lever signal using focused light on a probe. The properties can be separated in three parts, which are $\frac{\Delta z}{L_{eff}}$, $\frac{d_{spot}}{\lambda}$ and V_{SUM} and can be mainly attributed to mechanics, optics and electric/electronic, respectively. Generally, a large signal-to-noise ratio (SNR) is required to measure small probe displacements. Consequently, all parameters of (53) need to be optimized for a large signal, low noise and excellent long term stability. A large probe displacement leads to a large detectable signal. Applied to the AFM, the parameter Δz is usually influenced by thermal noise (Brownian motion) of the probe, tip-sample interaction, environmental noise (e.g. acoustic), mechanical stability of the setup and position noise of

the used stage. The thermal noise and tip-sample interaction are influenced by the stiffness of the cantilever and temperature [131]. In this work, neither of these influence factors can be changed due to the optimization of the probe for stable probing, environmental conditions in the lab and used test setup. The parameter L_{eff} can be attributed to the geometry of the used probe, which means the detected signal is proportional to the displacement of the cantilever probe and inversely proportional to the probe's length. This means shorter cantilever probes tend to have a larger sensitivity. By sectioning the novel probe, as depicted in section 4, this length is shortened, hence the signal is improved. In addition, L_{eff} is also influenced by the location of the spot on the probe. By using a thermo-symmetrical design and thermally conductive material with thermal inertia in the new AFM head, fluctuations of the spot location are reduced, as presented later in section 5.2 and 5.4.

With a larger spot size diameter d_{spot} on the cantilever probe the signal gets proportionally larger, consequently the spot should be chosen as large as possible for the best signal. Expression (47) shows, that the diameter of the spot is influenced by the focal length and diameter of the collimated beam, both are determined by the focusing lens. Moreover, d_{spot} is influenced by the beam quality. Consequently, in our setup high quality lenses are chosen. When the spot is too large or the probe's width is too small, artifacts such as interference can occur or stray light can be reflected back from the sample surface onto the QPD during measurement. Those artifacts overlay with the measured sample geometry, resulting in measurement errors. A suitable spot size diameter is about half of the cantilever probes width.

As λ is determined by manufacturer's specification of the light source, it cannot be optimized, but can be improved by exchanging the source. The commonly used silicon photodiodes have a smaller yield for shorter wavelength and a maximum at about 900 nm. Visible light is frequently chosen for safety reasons and practicability during adjustment.

The last optimization parameter is V_{SUM} , it implies using a large amplification and low noise electrical circuit. A large amplification gain does not seem intuitive as the voltage signal V_{xy} can be normalized by V_{SUM} , but should be adopted to the dynamic range of the signal acquisition system to reduce quantization noise. This will be considered in the design of the new 3D-AFM head and probe (see section 5.3).

3.3.4. Simulation of the optical beam on the QPD

A simulation, based the specification of commercially available parts, was used to build a more accurate model for the optical lever for calculating and estimate non-linearities of the detection system. A *Gaussian beam* with a monochromatic wavelength of 633 nm (HeNe-Laser) was modeled. The beam is assumed to be collimated to $D_{col} = 2.24$ mm and passes through an aperture of 2.5 mm, to eliminate stray light. The microscope objective lens (*50X Mitutoyo Plan Apo NIR*) is treated as ideal with the nominal aperture of 4.9 mm in a 100 mm distance from the QPD surface. The beam interacts with the QPD with an area of 5 mm x 5 mm and with a gap of 30 μ m (e.g. S5980, *Hamamatsu*). The *python* toolbox *LightPipes 2.1.3* [133],[132] was used for the simulation. A grid size of 4096 rays x 4096 rays was used and the beam was shifted in horizontal x-direction by 2.5 mm to the edge of the QPD in 1 μ m increments. The image of the light intensity of the centered beam on the QPD is shown in **Figure 3.13**, with the beam intensity profile shown in **Figure 3.14**. The apertures cause

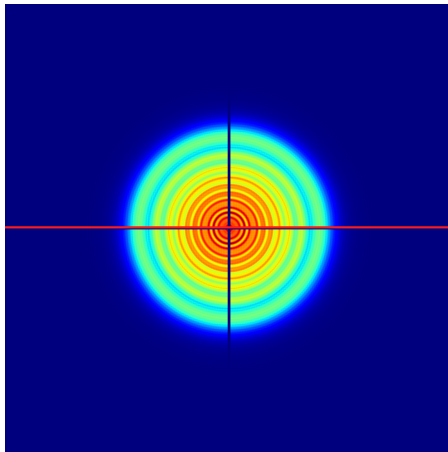


Figure 3.13: Optical simulation of intensity of the collimated laser beam on the QPD. The cross marks the gaps of the quadrants.

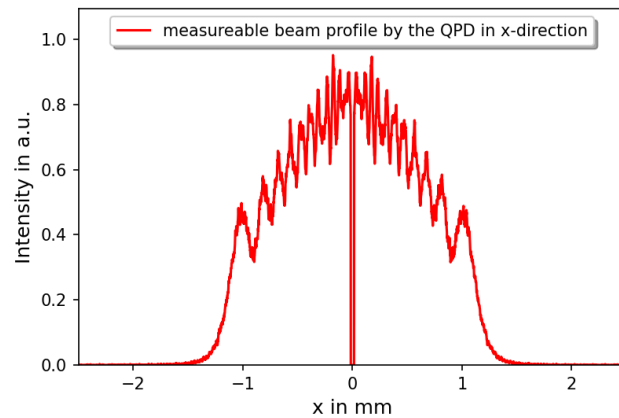


Figure 3.14: Optical simulation of the detectable intensity profile in x-direction of the centered, collimated laser beam of $D_{col} = 2.24$ mm on the QPD with apertures. The dip at $x = 0$ mm represents the area of the gap of the diode segment in y-direction.

an interference pattern in the beam intensity profile (*Airy disks*) and contribute to the non-linearity of the detection system. The detection system is similar to the AFM head detection system described later in this work (section 5.2).

Figure 3.15 shows the result of the simulation. The beam was shifted from left to right (LR) in +x-direction. The beam was not shifted in top to bottom (TB), in y-direction. The LR and TB signals are normalized to the actual total intensity (I_{SUM}) collected by the QPD. The summation (SUM) signal of the centered beam was normalized to the total intensity at the start of the simulation. The SUM signal slightly increases in value by 1.8% when the beam is shifted to 1.25 mm. This shows the contribution of the gaps, the inactive areas of the photodiode. From $x = 1.25$ mm to $x = 2.5$ mm the SUM signal decreases to about 50%

because the beam is shifted over the edge of the active area of the photodiode. As expected, the TB signal is constant. The LR signal increases up to about $x = 1.25$ mm and decreases when the beam is shifted over the edge of the QPD. Because non-linearities of the LR signal can be considered to be large for shifts $x > D_{col}/10$, the optical lever should only be used for LR and TB signal offsets $< \pm 10\%$. **Figure 3.16** shows the LR and TB signals close to the center position of the beam in detail. The non-linearity of the LR signal is $< 0.2\%$ with a ten times smaller non-linear crosstalk to the orthogonal TB signal of $< 0.025\%$. This small crosstalk shows the influence of the beam's circular shaped interference pattern and influence of deviations of the simulation (possibly due to limited resolution).

The beam displacement sensitivity of this QPD is the slope of the signal curve in displacement

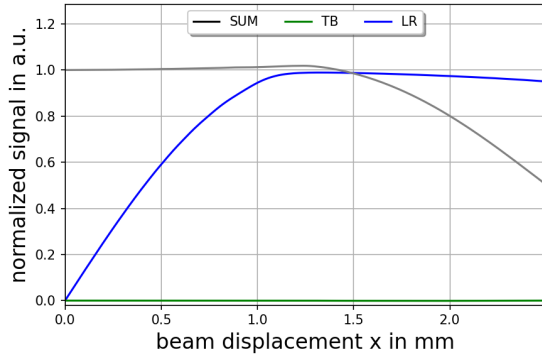


Figure 3.15: Optical simulation of the collimated laser beam on the QPD. The beam is shifted in x-direction over the QPD surface and the normalized intensity of left to right LR signal, top to bottom TB signal and total SUM signal is calculated for the 4096×4096 rays.

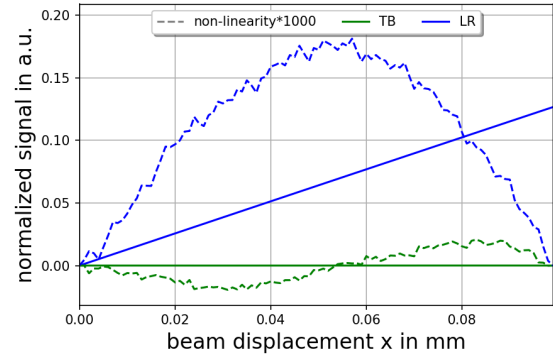


Figure 3.16: Simulated quasi linear region of the shifted collimated laser beam on the QPD. The non-linearities are below 0.2% .

direction. Here the LR signal shows a slope of $1.28 \frac{1}{mm}$. The TB signal shows the same value for a beam shift in the orthogonal y-direction (symmetry). Because the LR Voltage signal is normalized by the summation of the total intensity voltage signal of the four quadrants V_{SUM} , the relative detectable Voltage signal of an ideal QPD circuit in this specific setup (which is used later in this thesis) is given by

$$S_{QPDx} = V_{SUM} 1.28 \cdot 10^{-6} \frac{1}{nm} \Delta x_{QPD}. \quad (54)$$

and

$$S_{QPDy} = V_{SUM} 1.28 \cdot 10^{-6} \frac{1}{nm} \Delta y_{QPD}, \quad (55)$$

with Δx_{QPD} and Δy_{QPD} as orthogonal beam displacements on the QPD. In conclusion, the non-linearity of the optical lever principle can be considered as negligible, if during measurement only a conservatively chosen $\pm 10\%$ part of the total displacement signal range is

used. The optical lever with a QPD measuring the beam position in two orthogonal x- and y-directions is called a dual optical lever and is applied in the developed 3D-AFM head.

3.4. Surface interaction forces

There are four currently known fundamental interaction forces. The long range interaction by gravity and electromagnetism and the short range interaction by the weak interaction and strong interaction of and within particles (atoms). The weak and strong interaction are nuclear forces of the atom ranging only a few femtometers and are not within the scope of this thesis. This applies equally to the classical gravitational force field F_G , because for small objects and small distance changes, this force has usually not to be taken into account. The empirical law of the universal gravitational force (field) was published in 1687 by *Sir I. Newton* [134] and is given by:

$$F_G(r) = -G \frac{m_1 m_2}{r^2}. \quad (56)$$

It is proportional to the masses m_1 and m_2 and inversely proportional to the square of the mass center distance of both masses. The gravitation constant is given by $6.67430(15) \cdot 10^{-11} \frac{m^3}{kgs^2}$ [135]. Recent investigation for very close ranges (distances) of the inverse-square law of the gravity force seem to show no violation of this law [136], [137], [138], [139]. Consequently, changes of gravitational forces have almost no impact on AFM measurements. As an example, a conventional silicon cantilever with $120 \mu m$ length and $35 \mu m$ width and $3 \mu m$ thickness has a total static mass of about 30 ng. Thus, dynamic interaction with another body by a scanning motion of a few ten micrometer has a negligible effect on the resultant force F_G . Consequently, gravitation does not seem to be relevant as a surface force and is not taken into account.

The remaining electromagnetic force is the dominant force for the probe's tip-sample interaction. In the classical way the electromagnetism is described by the Maxwell equations [118]. In the beginning of the 20th century the electromagnetic field was discovered to be quantized and the interaction of charge particles can be described with photons, with the help of quantum electrodynamics [140], [120], [141]. A treatment of the fundamental nature of the surface interaction forces is not within the scope of this thesis. In following, relevant surface forces to dimensional AFM measurements of two interacting surface potentials, mainly of the same material (e.g. silicon-silicon), are categorized and interaction models are explained and possible impacts on the measurements discussed.

The general description of the interaction between two atoms or small molecules can be described by the 6,12 Lennard-Jones (pair) potential (LJP) [142]². A good overview on the development of this expression can be found in [143]. **Figure 3.17** shows the LJP.

It describes the potential between two particles over their separation distance r , with binding energy ϵ_b and is given by

$$V_{LJP}(r) = 4\epsilon_b \left(\left(\frac{\sigma_{LJP}}{r} \right)^{12} - \left(\frac{\sigma_{LJP}}{r} \right)^6 \right) \quad (57)$$

with σ_{LJP} as the closest distance where the inter-molecular potential between the two particles is zero, often denoted as *van der Waals radius*, which is half the distance between non-bonding particles (atoms, e.g. silicon about 0.2 nm). With increasing distance the binding

²Unquestionably, the inter-nuclear distance and simplified potential shape is influenced by the complex interacting atomic orbitals, the binding type (*metallic bond, ionic bonds, covalent bonds, e.g. covalent radius of silicon about 0.11 nm*) and the atomic lattice *e.g. silicon diamond cubic lattice constant about 0.543 nm*.

energy becomes minimal (approaches zero). The inflection point of the potential curve at $2^{1/6} \cdot r \approx 1.12 \cdot r$ marks the balance point between the attractive and repulsive forces of the interaction. The attractive part of the LJP is defined by *van-der-Waals* forces and the repulsive part by the *Pauli exclusion principle* for forbidden states [144]. The strong repulsive potential is a quasi force induced by the exclusion [145] and scales with $1/r^{12}$ relative to the nucleus. The attractive part (*van-der-Waals* forces) of the pair potential was determined empirically. The potential can be expressed by $V_{vdW}(r) = -\frac{C_{vdW}}{r^6}$, with C_{vdW} as *van-der-Waals* coefficient.

Today, the attractive or repulsive inter-atomic *London dispersion force* (*dispersion* [150]),

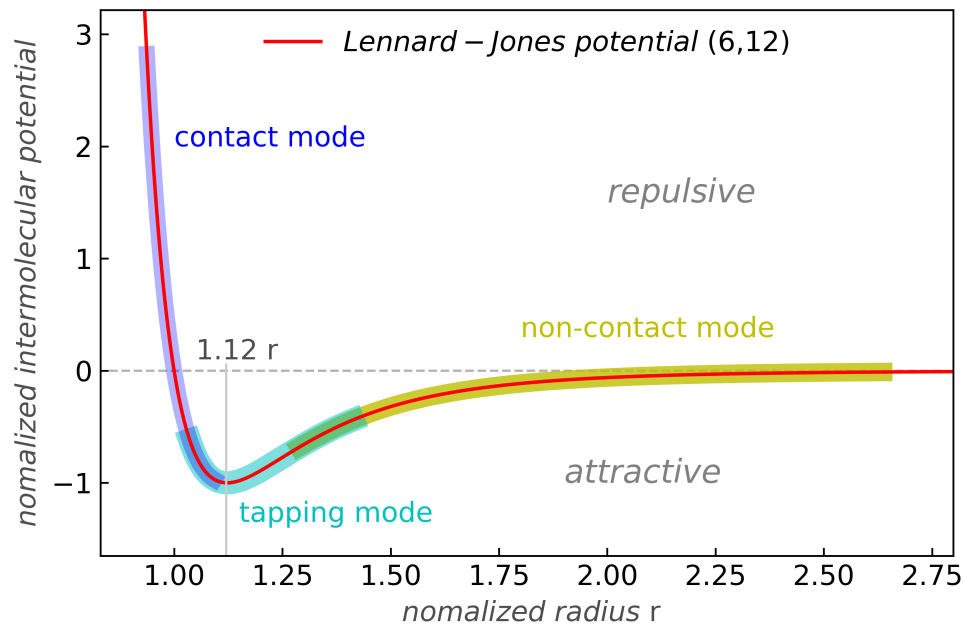


Figure 3.17: Lennard-Jones (pair) potential with tip-sample interaction regions of different AFM operating modes.

the permanent *dipole-dipole* force (*Keesom* interaction, *orientation* [146], [147]), and the *dipole-induced dipole* force (*Debye* interaction, *induction* [148], [147]) are summarized and denoted as the *van-der-Waals* force [149]. The *van-der-Waals* force of two identical materials (also in a fluid) is always attractive [150]. The reciprocal distance to the power of six of the attractive part in the LJP is backed up by the scaling of the individual forces. This scaling is valid for mid range distances, because all multipole interactions are neglected. A thoughtful treatment of those e.g. quadrupole interactions is not within the scope of this thesis, relevant information can be found in [151]. A good overview of this topic can be found in [152], [147]. The *London dispersion force* is universal and always present because all atoms and molecules are polarizable. For two interacting bodies (here sphere and half-space) in vacuum or air the *London dispersion force* is always attractive and through the expression from *Hamaker* [150]

and ([147] *Ch13*) it is given by

$$F_{LondonS}(r) = \frac{2H_{12}r_s^3}{3r^2(r+2r_s)^2}, \quad (58)$$

with r as the distance between the sphere (tip) and flat surface (sample) and r_s the sphere radius. For $r \ll r_s$ this simplifies to $F_{LondonS}(r) = \frac{H_{12}r_s}{6r^2}$. A selection of expressions for different geometries such as an interaction of a cylinder body with a half-space is listed in [147]. For a cylindrical tip to a half space the interaction force given by $F_{LondonC}(r) = \frac{H_{12}\sqrt{r_s}}{8\sqrt{2}r^{5/2}}$ with r_c as the cylinder radius [147]. The *Hamaker constant* H between both materials is given by the number density of each interacting material (both) and a so-called *London coefficient* (integration of forces over both bodies). The real value has many influence factors and is also challenging to estimate by experiment [153]. Adding a third dielectric material in between the two interacting surfaces leads to a change of the *Hamaker constant* [152]. The resulting *van-der-Waals* force can be repulsive or attractive, but it is always attractive between bodies of the same material [150]. Typical values for H are $7 \cdot 10^{-20}$ J. For a silicon-silicon in air it is given by about $18.7 \cdot 10^{-20}$ J and for silica to silica in air $6.5 \cdot 10^{-20}$ J (values can differ dependent on the source) [152]. Simplified, this means the *London dispersion* interaction force is an integration over all inter-molecular interactions and depends on the geometry of the interacting bodies and distribution of the material. Consequently, the origin of this force is not due to the interaction of two surfaces only.

For sufficiently large distances the *London dispersion force* decays with $1/r^3$ [154] and is strongly influenced by the surface roughness. This means, the attractive interaction force component is relevant up to about 100 nm making this a long range force. It is worth mentioning, that the retardation effect of dispersion force is small for conventional AFM probes and usually can be neglected, because in AFM measurements the tip is interacting at very close distances with the sample surface.

In our application of the AFM (in this thesis), only small induced dipole interactions by e.g. polarized surfaces and no measurement environment with ionic liquids is expected, consequently no *Debye* interaction and no *Keesom* interaction is considered here, and was also not observed. Based on their physics, both forces tend to be larger than the *London dispersion force*. Another simplification concerns the impact of the hydration layer on the *van-der-Waals* force. It is also not covered here and usually investigated with molecular dynamics simulations [155]. Thus, the *London dispersion force* represents here the *van-der-Waals* force. To get a feeling for the forces acting on the cantilever tip apex during measurement the *van-der-Waals* interaction forces based on the *Hamaker constant* of silicon are calculated. **Figure 3.18** depicts this significant force over the tip radius at a tip-sample distance of 1 nm.

The depicted force curves are all attractive and pull the probe's elastically suspended tip closer to the sample surface. A force of about 2 nN for a 60 nm tip radius was calculated. At close distances this interaction force and the capillary force are dominating, where the attractive part of the *van-der-Waals* forces act over a long range (see 58), the capillary force acts strongly only with forming of the meniscus of the liquid (usually adsorbed water). Under normal lab conditions (around 50%rh), the adsorbed water layer on a silicon surface is about four water-molecule layers thick, which is about 1 nm. Within three water-molecule layers the adsorbed water on a silicon surface forms an ice-like conformation on the surface

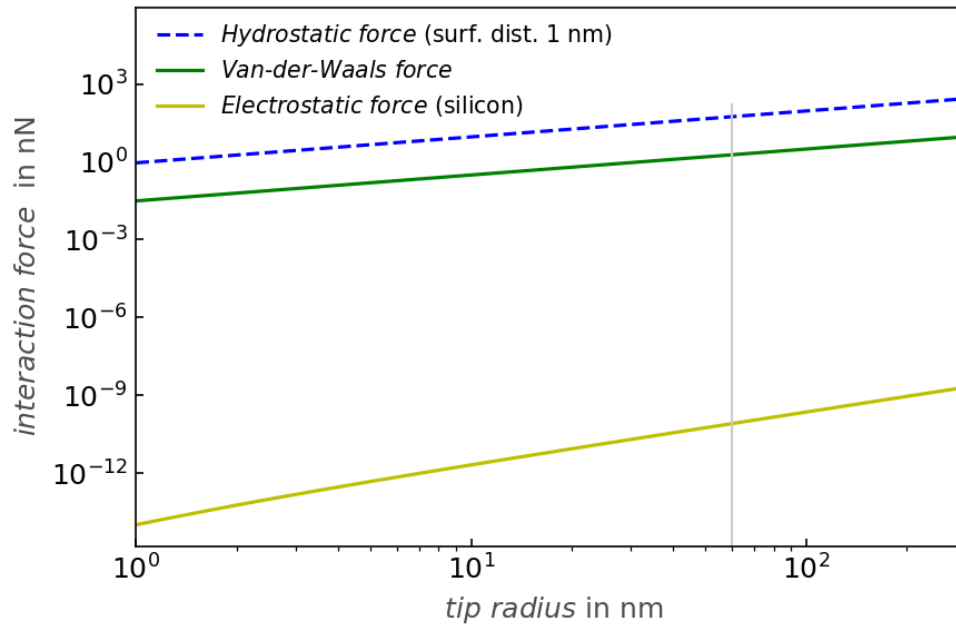


Figure 3.18: Relevant surface forces of a silicon-silicon tip-sample interaction at 1 nm distance.

and contributes to the surface interaction [157], [156]. The meniscus is not instantly formed and the water layer adds a viscoelastic behavior to the tip-sample interaction [157]. The usual time for an interaction of two surfaces with water depends on the tip shape, size and interaction medium and is in the order of μs [157]. For other hydrophilic surfaces this water layer can consist of up to several 10 nm. Consequently, the graph of the hydrostatic force in **Figure 3.18** is the force after the tip has come into contact. A pull-off force of about 55 nN for a 60 nm tip radius is to be expected for the hydrostatic force. Neglecting ambient rel. humidity and using the *Derjaguin* approximation [162], it can be simplified and is expressed by

$$F_{hydroS}(r_s) \approx 4\pi r_s \gamma_{H_2O}, \quad (59)$$

with the surface tension γ_{H_2O} of water of about 0.073 N/m. It represents the main component of the pull-off force. Taking into account the ice-ice layers, the tip-sample interaction force for a pull-off increases drastically [157]. From the pull-off force [157] is assumed to change to about 195 nN with $\gamma_{ice} = 0.103 \text{ N/m}$ (Note: Those large values were not observed in this work, possibly due to solvation or surface roughness).

Another interaction force is the electrical force [154]. It can be split into the well known coulomb interaction and interaction forces induced by image charges of conducting surfaces [158],[159]. The electrical force can be attractive or repulsive and can be considered as a small force (**Figure 3.18**) and is neglected in the following [147]. A surface charge of silicon [111] of $5 \cdot 10^{10} \text{ cm}^{-2}$ was used [166]. Other dissipative or conservative surfaces forces and their interaction with each other such as π -interactions (orbitals), effects of squeeze film damping, Laplace pressure, Casimir force, magnetic forces, solvation forces, electrostatic double layer

forces or tribological systems are also not considered here, because these topics cannot be handled adequately within the scope of this thesis and are not necessary to understand the main topic of this work [160], [147], [165], [170].

Applied to the SPM instruments, the surface forces are used to describe and explain the tip-sample interactions (e.g. instabilities or bistable behavior) shown in experiments.

There are many models to describe tip-sample interactions depending on the used sample, medium and probe, and measurement mode (see section 3.5). In the following, four of the frequently used models which are relevant for dimensional AFM measurements and used to describe the contact mechanics are mentioned and the basic models are briefly described.

The *Hertz* model describes the interaction of two bodies touching at single point under the assumption of smooth curved surfaces. This simple model treats only elastic deformation without attractive or repulsive surface interaction forces. Generally used for macroscopic bodies, the *Hertzian* theory makes two additional assumptions: the contact area is small compared to the body size, and only normal forces are allowed because the surface is assumed to be friction-less. The model exists in various modified versions which are used for elastic and also visco-elastic description of sample properties (e.g. [161]). The simplified classical *Hertz* model for a sphere and a half-space of identical materials is given by

$$d_{Hertz} = \left(\left(\frac{3F}{4E^*} \right)^2 r_s - 1 \right)^{1/3}, \quad (60)$$

with contact force F , Poisson's ratio μ_p , $1/E^* = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}$ and Young's modulus E of the material 1 and 2 [169]. Using a silicon probe tip with 60 nm radius and 35 nN of interaction force on a flat silicon sample ($\mu_1=\mu_2=\mu_p=0.278$, $E=165$ GPa), the expected elastic deformation is below 0.1 nm. This offset is significant but is neglected in the following as it is not within the scope of this work to compensate the impact of the interaction force on the measured geometry. As it can be seen from the equation, the strong hygroscopic interaction force and *van-der-Waals* force is not represented. This is taken into account by the well known DMT and JKS models for tip-sample interaction.

The JKS model combines the viscoelastic behavior of the water adhesion layer with the *Hertz* model and can be found in [168], [169]. The DMT model combines the attractive *van-der-Waals* forces of the contact region with the *Hertz* model, reduces the repulsive forces on the tip and enlarges the contact area [163]. A few decades ago, the Maugis model was developed which combines the JKS and DMT model [164]. A review of interaction models can for instance be found in [167].

Ultimately, also indirectly represented in several interaction models, the probe stiffness has an impact on quality of the measurement. For instance, when the tip-sample interaction force gradient becomes larger than the spring constant of the free elastic cantilever probe, it is pulled towards the surface; a so-called snap-in will occur. Typically, the probe is pulled towards the surface for probe stiffness of less than 1 N/m (using a regular tip) [171]. This limits applicability because the tip will approach the surface uncontrolled. The small stiffness might also lead to a large deflection due to the water adhesion force (thin water layer) when pulled off the surface, which can be difficult to handle in narrow trenches.

As a result, the novel probe, which is to be developed in this work, should have a stiffness of more than 1 N/m to prevent a large snap-in for controlled probing and should withstand tip-sample interactions of a few 100 nN (e.g. due to the pull-off force). To prevent surface damage a stiffness of less than 10 N/m is required [114]. Thus, in the following a total stiffness of about 2 N/m is used as a design goal for the novel probe.

3.5. Measurement or operating modes

There are multiple measurement modes and methods for AFMs developed over the decades. They can be separated into dynamic modes and static modes [66]. In the following, only a brief overview over the most common ones such as the (static) *contact mode*, (dynamic) *intermittent mode* and *non-contact mode* are given [66] and in addition those measurement modes which are directly related or used in this work such as the *vector approach probing* (VAP) mode [172], [173]. The achievable resolution of each mode depends on the sample, tip apex of the probe and experimental (e.g. environmental) conditions, but all of them are capable of achieving atomic resolution.

The ***contact mode*** is the oldest (original) measurement mode and possibly the simplest [2]. It has been used since the beginning of the development of SPM instruments up today. As the designation of the mode indicates, the tip of the probe is in direct contact with the sample. The non-oscillating (static) probe is pressed onto the sample surface and the repulsive tip-sample interaction forces deflect the probe, which is registered by the AFM detection system. The close ranging repulsive interaction forces allow to detect the sample surface as described in the **Figure 3.17** by the interaction potential. Typical interaction forces range from well below 1 nN to several 10 nN. The probes' stiffnesses range from 0.01 N/m to 2 N/m. Due to strong adhesion forces and lateral (friction) forces the tip apex of the probe is most susceptible to tip abrasion [97]. To improve wear resistances of the tips, these contact mode probes are oftentimes coated with a wear resistant material such as diamond-like-carbon (DLC). The forces during scan can also lead to tip breakage, depending on the sample surface, tip geometry, and mechanical behavior of the probe [97]. Probes with first resonance frequencies of about 10 kHz are used, to reduce acoustic coupling and improve measurement speed.

The stiffness matrix is used to describe the probes in contact mode. The soft spring constants of the cantilever (stiffness) allows to investigate soft and delicate samples e.g. biological tissue. Today, the contact mode is often used in high-speed application, because of the immediate interaction with the sample surface.

Generally, there are two operating modes denoted as *constant height* and *constant deflection (force)* mode. In constant height mode the probe is dragged in contact horizontally over the sample surface and the probe's deflection is registered without changes of the scanner's vertical displacement. Because of the limited vertical range the constant height mode is only used for relatively flat, hard and even samples for high resolution images. In *constant deflection (force)* the probe's deflection is controlled during the scan and kept constant. The scanner adjusts the vertical height during the horizontal scan. Thus, the scanner traces the surface profile and generates the topography image via calibrated internal position sensors (of the scanner). The combination of both is denoted as the *contact error* mode. It uses the sudden changes of the probe deflections arising from the bandwidth limited control loop of the constant deflection mode during the scan of topography height changes. These error signal are added to the topography improving image quality.

In ***non-contact mode*** the probe's tip oscillates (dynamically) in close proximity to the sample surface but never touches. The oscillation of a cantilever probe is described in [216],[217].

The probes excitation usually originates from a shaker piezo-actuator but can be manifold e.g. radiation pressure, built in piezoelectric actuators or bi-metal heaters, magnetic induction, and photo-thermal actuation [174], [175]. The tip interacts with the attractive (or in rare cases repulsive) parts of the interaction potential and kinetic energy of the probe is dissipated, caused by the rapidly fluctuating tip–surface interaction [176]. This dissipation changes the amplitude and phase of the oscillating probe, and is consequently a value to control the tip-sample distance. In addition, the cantilever body is tensioned under the attractive force and slightly changes its resonant frequency, resulting in an change of the amplitude. Either the phase or the amplitude can be used to control the tip-sample distance and trace the topography of the sample. A lateral friction force is non-existent during the scan. The small vertical oscillation which changes the effective tip shape has little effect on the resolution of commercial AFM. In CD metrology a horizontal oscillation has to be taken into account, because it broadens the effective tip width [177].

On average, first resonance frequencies of a few 100 kHz and probes stiffness of a few 10 N/m are used. To mechanically describe the probe for the non-contact mode the compliance matrix can be used because only force fields are interacting (no contact). The *non-contact mode* is used for a great variety of samples which are usually relatively even or delicate. Given by a small oscillation amplitude of a few nanometers, under atmosphere the tip acts within the adhesive water layer (meniscus) of tip and sample. The mode can be considered to work best under vacuum conditions.

The *intermittent mode* or also denoted as intermittent-contact mode or dynamic contact mode or tapping mode and is a combination of the *contact* and the *non-contact mode* [178] [179]. This mode operates at a tip-sample distance between contact and non-contact mode (**Figure 3.17**). The cantilever probe is vertically oscillated near (or at) it's resonant frequency with driving amplitude ranges from 10 nm to about 100 nm. Typically, first resonance frequencies of a few 100 kHz and probe stiffnesses in the range from 2 N/m to 50 N/m are used. The kinetic energy of the oscillating cantilever probe must be higher than the surface interaction potential, to be not adhered to the sample surface (e.g. by the water layer). This means the probe has to be stiff or the probe has to be excited with a large amplitude. The dissipation of the oscillation energy originates from the nonlinear tip-sample interaction. For weak interaction, or set-points with larger tip-sample distances, the mode remains rather independent of the material properties [180]. Consequently, this mode is appropriate to measure soft samples or samples with weakly attached particles without damage and reduced tip wear. Hence, this mode is often used for biological samples and delicate unknown topographies. The phase changes during interaction (damping) give additional information e.g. contamination of sample surface, which might not be visible in the topography image derived by the amplitude. When the tip is brought closer to the surface the amplitude is restricted (smaller set-point amplitude) and the elastic and viscoelastic properties of the sample can be measured, which is used e.g. for contact resonance measurements and forms the basis for various additional modes [181]. For samples with steep sidewalls interaction become non-trivial as the oscillation changes from a normal impact to a grazing (zero velocity) impact oscillator [182]. In addition, in CD metrology the large lateral (horizontal) oscillation has to be taken into account, because it broadens the effective tip width and averages tip-sample interaction regions, which has a direct influence on the measured structure by (morphological) dilation

[177]. For large driving amplitudes and small set-points the delicate tip apex is hammered onto the sample surface reaching a few GPa contact pressure and the tip will experience damage during measurement [180]. Compared to the contact mode lateral forces are reduced but can be of the same order depending to the tip geometry [97].

The ***vector approach probing*** VAP mode is not clearly a mode, it is more comparable to a probing strategy or method and can be used in combination with the upper three main modes [172], [173]. The essence of this mode is a controlled approach of the sample surface enhancing a previously developed mode [183],[184] for careful sample inspection by two degrees of freedom. This mode facilitates to probe with the SPM in any spatial direction. The VAP method is applied in a metrological AFM at PTB for CD measurements with great success [173], [185], [186]. The measurement for 3D probing in VAP mode is performed in two steps. At first, a probing scan similar to the so-called *step-in mode* [184] is performed. Based on this scan, the surface normal directions are calculated and probing directions and number of probing locations (points) are determined. This pre-calculated pattern is used to probe the sample geometry in 3D [172], [173]. The probing directions are in normal direction to the apparent sample surface. Probing in normal direction to the sample surface offers the largest sensitivity due to the strongest (and most stable) tip-sample interactions. During the individual probing events, the tip-sample interaction of the probe is not used in a closed-loop control (no feedback loop). The approach of the tip onto the sample is continued until a predefined status is reached [172],[173]. In our setup (section 5.4), respectively in this work, this status is a predefined deflection of the probe. In this work, the VAP mode is used in contact mode. Subsequently, the probe is retracted and steps to the next probing location. The surface point is calculated via the registered tip-sample interaction, the probing curve (distance-deflection curve). The intersection point of a linear fit of the zero deflection with a linear fit of the interaction region of the probing curve marks the quasi force-less point on the surface, thus the surface location. The zero deflection of the probe is used to compensate for drift of the detection system. This VAP method drastically reduces the tip wear because the relative abrasive motion between the tip apex and sample surface is minimized and it incorporates great flexibility in defining measurement points [173]. A drawback of this method is, it is time consuming (a few 10 points/sec) [173].

3.6. The Focused Ion Beam (FIB) for rapid prototyping

The focused ion beam (FIB) milling belongs to the ion beam etching (IBE) processes and is used for fine structuring of solids from the micrometer down to the nanometer level. A comprehensive overview of the FIB is given in [187], [188], [189], [190]. With a precisely focused ion beam, material can be deposited or removed with the energy of accelerated ions under vacuum. To remove material the ion beam is focused, scans over the sample and sputters material with the impacting ions from the surface. This sputtering process is frequently referred to as milling process. The process time and intensity of this ablation process is dependent on the ion current, the sample material and the accelerating voltage, typical values are 5 kV to 30 kV. A liquid metal ion source (LIMS) with Gallium ions (Ga^+), which was first developed in 1978 for the use in a FIB setup, is now used most often. The Gallium in LIMS is heated and wets a sharp tungsten tip. A so-called Taylor cone is formed on the sharp tip by applying an electric field on the liquid Gallium and Gallium is extracted from a small (usually about 5 nm) dome shaped region of the wet tip, which defines the ion beam quality. The large electric field ionizes the Gallium atoms. Apertures within the ion source are used to influence the amount of extracted ions. The ion beam is shaped by electrostatic lenses, accelerated in the ion column and focused on the sample with beam diameters down to about 10 nm. The beam diameter depends on the beam current, for larger currents the beam diameter and beam divergence increases. Because the focus region is so small, the ion beam can ablate/sputter regions down to a few 5 nm. Typical ion currents are 6 pA/cm² to 3-15 A/cm² [187]. In some cases Ar^+ , He^+ and even Xe^+ are used as ions as they do not dope the sample material. The FIB can also be used for imaging, however even at smallest ion current levels ions sputter the sample surface and induce permanent damage. To improve sample inspection and reduce surface damage the FIB is usually combined with a SEM, forming a dual beam FIB/SEM as depicted in **Figure 3.19**. For delicate surfaces with fine structures (e.g. cantilever tip) the SEM is used for imaging.

Milling narrow trenches can take a very long time, because the material which has been sputtered from the surface is adsorbed close to the milling site causing redepositions, as described in [188]. Those redepositions depend on the material, geometry, and process parameters and are usually visible by a V-shape of the milled groove or hole tapering to the bottom [188]. To add material, surface-adsorbed gas molecules are decomposed by electron or ion irradiation and the reaction products are deposited on the sample surface in cycles. The gases are injected via needles near (a few 100 μm) to the sample surface. Adding material with this process is very costly, because it takes about 100 times longer than milling. The FIB/SEM is used in semiconductor industry for mask repair, reverse engineering, rapid prototyping, ion implantation or local doping, TEM-lamella preparation and material analysis of e.g. grain and composition.

In this work, the FIB milling process is used to structure the new AFM probe.

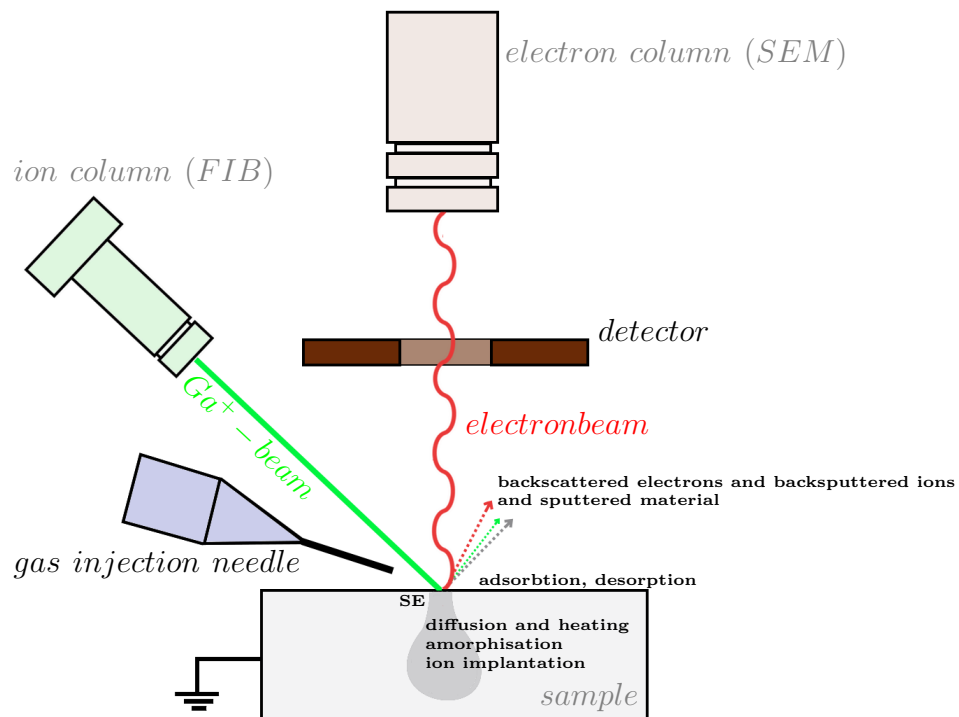


Figure 3.19: Dual beam FIB/ SEM sketch with influence of the Ga^+ -ions on the sample (adapted from [187] and [190]).

4. The 3D-Nanoprobe

In this section the requirements for the 3D-sensor are defined. Derived from this, a probe design is proposed, the so-called 3D-Nanoprobe. A mechanical model is derived from the designed structure and verified by finite element mechanical (FEM) analysis. Based on an analytical model and FEM analysis, the structural parameters of the probe are optimized to meet the requirements. Afterwards, the 3D-Nanoprobe is manufactured with focused ion beam (FIB) process.

4.1. Requirements, design and analytical description of the novel probe

The main requirements of the novel probe are listed below. The three most important requirements are highlighted in following. First and foremost, the 3D-Nanoprobe is designed to overcome the limitations of the classical cantilever design. As previously explained, the cantilever and tip are deflected by interaction forces and the tip contacts the surface (in contact mode) during probing. The direction of this free deflection is determined by the compliance matrix of the cantilever probe and the direction of the tip-sample interaction force. Immediately after the tip apex contacts the surface a force is applied on the tip which is determined by the interaction forces (described in section 3.4) and the probing motion (tip-sample distance) of the cantilever. This interaction can be described by the stiffness matrix and the probing vector. Because the commercial cantilever shows as an anisotropic stiffness ratio between the x-, y-, and z- direction, the tip experiences a bias force tangential to the sample surface, causing the tip to slip uncontrollably and leads to unstable probing conditions, as explained in section 3.2.3 and 3.5. A quasi isotropic stiffness in combination with 3D probing normal to the sample surface (VAP mode) avoids tip slipping in contact mode by reduced bias forces due to the probe's mechanics, as described in sections 3.2.1, 3.2.2, 3.5.

Secondly, as already described in 3.2.1, the compliance and consequently also the stiffness matrix of a cantilever shaped probe shows a crosstalk, which should be optimized to zero. This crosstalk also applies for most of the common 1D detection system for probe displacement measurements, such as the optical lever or simple interferometers (section 3.3). Buckling of the cantilever remains undetected and leads to tip breakage of the delicate tip apex. Consequently, even the simple combination of detection systems (which work for isotropic probes) cannot unambiguously detect the true tip motion of the cantilever probe, because the tip displacement/forces directions cannot be cleanly separated in y- and z-directions. A detection of the 3D tip interaction can be reached by careful adjustment of multiple detection systems on the probe as shown in [85],[86], [87] and [56]. Consequently, the new 3D-Nanoprobe should be structured with specific areas for detection systems for simple integration e.g. into detection systems with large spot diameters.

Thirdly, for slender, compliant and delicate tips such as CD-tips, the detectable signal gets small, because only the cantilever body motion can be detected, not the displacement of the tip apex. The 3D-Nanoprobe aims to compensate for this issue and balances the stiffness of the probes body to the stiffness of the tip to increase sensitivity by more than order of magnitude for each spatial direction to a sufficient level. To reach this required small compliance, the 3D-Nanoprobe is structured with flexure hinges.

Overall, the categorized **requirements** for the novel so-called 3D-Nanoprobe are listed in the following.

Must have (mandatory):

- The novel probe must show a quasi **isotropic compliance** $c_{xx} \approx c_{yy} \approx c_{zz}$
- The novel probe must have a **minimal crosstalk** of the probe's tip apex displacement. This can be achieved minimizing the compliance matrix coefficient $c_{ij}, i \neq j$
- The novel probe must show a quasi **isotropic stiffness** $k_{xx} \approx k_{yy} \approx k_{zz}$ to reduce tip-slipping (specific requirement for contact mode).
- The novel probe's stiffness design value is about 2 N/m (deduced from the surface forces).
- The mechanical properties of the developed probe have to be adapted to the slender, compliant and delicate CD-tip.
- The **sensitivity** in x-, y-, and z-direction should be **balanced and enhanced** compared to the commercial cantilever with a CD-tip.
- The first resonant frequency must be above 10 kHz to facilitate fast and dynamic probing trajectories without large settling times (anticipated q-factor about 200) of mechanical excitation.
- The design has to be scalable and simple to be able to be miniaturized.
- The needed physical dimensions of the design must not exceed the ones of commercial cantilever probes to facilitate a broad application.
- The tip apex diameter of the probe must be smaller than 200 nm with a minimal aspect ratio of the tip length to diameter of at least 5:1 to enable measurements in deep trenches and of large sidewalls, and to evaluate probing capabilities in a first test.

Should have:

- The 3D-Nanoprobe prototype should be manufactureable using focused ion beam (FIB) milling process.
- Design should include the possibility to change the properties, e.g. enhance the sensitivity, of the probe by optimization.
- The probe's design should allow batch process manufacturing with minor changes of the overall structure in the future.
- The probe should be robust and tolerant to probing errors.
- The probe should be usable with more than one detection principle to ensure flexibility in detection and broaden usability.
- The probe's tip apex motion should be detectable by a combination of optical sensors for inclination angles or displacements.

- The **first resonant frequency** of the probe should be **above 50 kHz** with separated higher order resonant frequencies for a stable dynamic behavior.
- The tip apex diameter of the probe should be smaller than 100 nm.
- The developed sensor should be applied for typical metrology tasks in 3D-Nanometrology such as CD, pitch and LWR measurements.

Nice to have:

- The developed sensor could later be used as a transducer (forces).
- The sensor can either be applied for contact mode or non-contact mode measurements.
- In order to avoid complex and expensive CD-tip manufacturing, the CDR120 and CDR70 can be used as suitable cantilever probes.

The novel probe will not be sensitive to measure the torsional momenta on the tip apex around vertical z-direction.

The requirements for the true 3D-AFM head detection system, that have a small effect on the design of the probe but should be considered, are listed below:

- The sensor system must include a microscope objective lens for appropriate sample investigation
- The planned detection principle is selective for 3D and forms with the developed probe a sensor which is selective for 3D
- For 3D-axis control a calibration matrix of the 3D-Nanoprobe needs to be implemented in the controller of the measurement device, thus a mechanical description is required
- The developed 3D-AFM must have a probing repeatability below 1 nm x 1 nm x 1 nm standard deviation (SD) in x-, y-, z-axis direction, respectively

Based on the compliance matrix of a cantilever probe, the aforementioned requirements cannot be fulfilled with a simple cantilever design. However, a combination of at least two cantilevers will achieve it and the mentioned crosstalk between the y- and z-direction can be mitigated and compensated by optimization. The new approach uses two cantilevers consisting of two stiff head section (HS) and two compliant sections realized with flexure hinges (FH). The HS and FH are oriented in a folding arrangement and connected to each other. **Figure 4.1** shows a sketch of the new design with all variables necessary for modeling and later manufacturing. The probe is denoted as the 3D-Nanoprobe.

The effective length of the cantilever body is denoted as L_{eff} , the effective tip length as L_{tip} and the length of flexure hinge 1 (FH1) as L_1 . L_{k1} denotes the length of the head section 1 (HS1) including L_2 , the length of the flexure hinge 2 (FH2). The sum of the length of FH2 and L_{k2} , the effective length of the head section 2 (HS2), is denoted as L_3 . The effective CD-tip length is described by L_s . All width parameters are represented with a w , such as the cantilever width w , the width of FH1 w_1 and the width of HS2 as w_k . The overall width of FH2 is denoted as w_4 . It includes two cuts of 300 nm (width) to separate the surrounding

outer structure with the width of w_1 from FH2 from the inner structure w_2 of FH2. The thickness of the cantilever body is denoted as t . The thickness of FH1 and FH2 are denoted as t_1 and t_2 , respectively. The length of L_{tip} can be shortened by shifting the neutral fiber of the cantilever structure closer to the tip apex. This can be achieved by shifting FH1 and FH2 in z-direction closer to the bottom edge of the cantilever body, because the flexure hinges dominate the overall compliance. In the model, the position of the neutral fiber in z-direction is set to about $1.0\text{ }\mu\text{m}$ from the bottom edge of the cantilever body and is denoted as L_{tip1} (not shown in the drawing).

The proposed design is to our knowledge the simplest structure to fulfill the requirements. The opposite orientation of the FH1 and FH2 relative to the tip location induces a negative sign for the crosstalk. The mandatory requirements such as the quasi isotropic stiffness (reduced crosstalk) and enhancement of the sensitivity can be achieved by a thorough optimization process of the developed mechanical model of the 3D-Nanoprobe. The mechanical model is presented in detail, explained and derived in A.1.

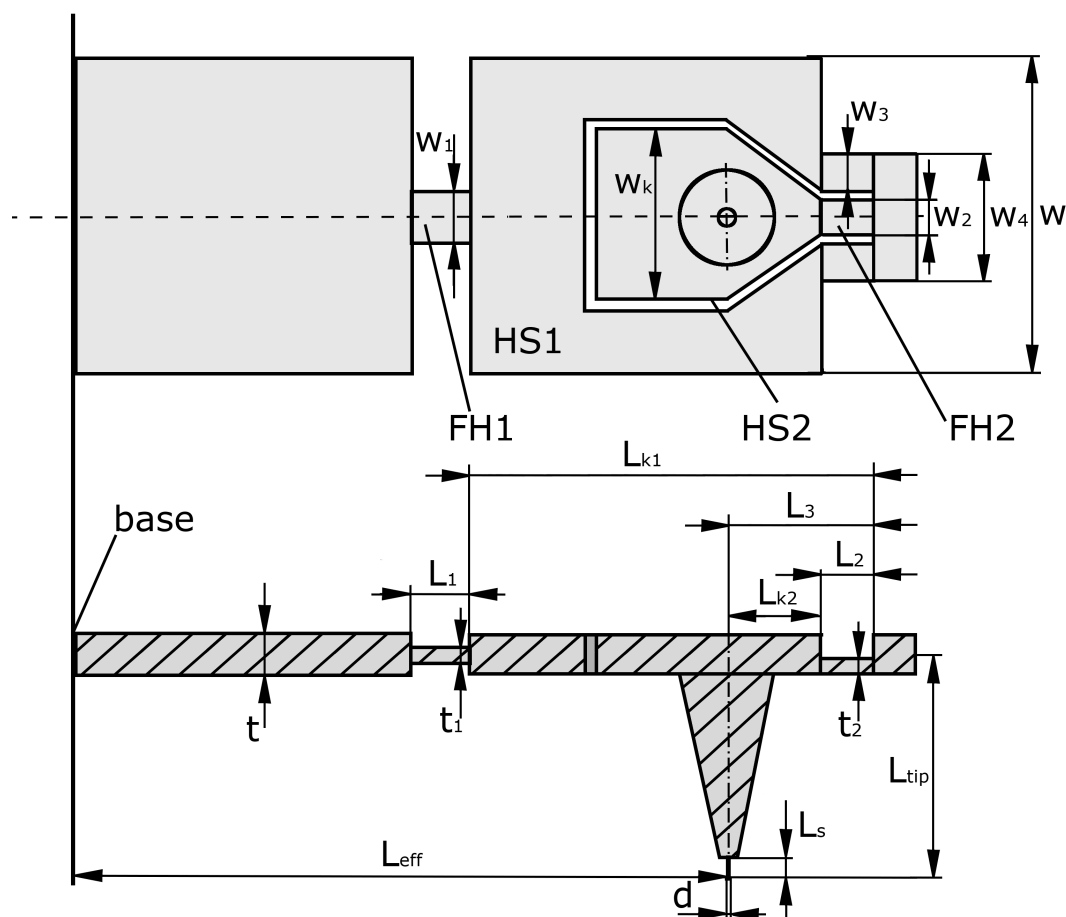


Figure 4.1: The 3D-Nanoprobe drawing with variables used for the mechanical model and manufacturing (own image adapted from [72])

As a result, the compliance matrix of the 3D-Nanoprobe, owing to the cantilever based design, is similar to the general Cantilever probe:

$$\mathbf{C}_{3D} = \begin{pmatrix} c_{xx} & 0 & 0 \\ 0 & c_{yy} & c_{yz} \\ 0 & c_{zy} & c_{zz} \end{pmatrix} \quad (61)$$

with $c_{yz} = c_{zy}$. The large differences are, that the overall compliance in z-direction c_{zz} (104) can be adjusted by the flexure hinges to the compliance of the CD-tip c_s , as requested. The compliance c_{xx} and c_{yy} can be adapted to c_{zz} by optimizing the geometries of FH1 and FH2 for $c_{xx} \stackrel{!}{=} c_{zz}$ and $c_{yy} \stackrel{!}{=} c_{zz}$. The contribution of the tip displacement in y-direction of the in-plane bending in x-direction can be reduced by the position of FH1 and FH2 in (122), because HS2 has the opposite sign for force induced bending. This also allows to reduce the crosstalk c_{yz} to a minimum by optimization (section 4.2), as it was published in for the 3D-Nanoprobe in [72]. Consequently, the compliance matrix can be inverted to receive the stiffness matrix by simply taking the reciprocal. In practice, this results in a smooth transition of from non-contact to contact tip sample interaction and is one of the key characteristics of the 3D-Nanoprobe. Another characteristic is presence of two large areas HS1 and HS2 to detect the motion of the CD-tip apex. Both areas show displacements and changes in inclination angles, that combined, are distinctive for the actual CD-tip position, after calibration. The matrices of the inclination angles of HS1 and HS2 are

$$\begin{pmatrix} \alpha_1 \\ \beta_1 \\ \gamma_1 \end{pmatrix} = \begin{pmatrix} 0 & a_{\alpha 1y} & a_{\alpha 1z} \\ a_{\beta 1x} & 0 & 0 \\ a_{\gamma 1x} & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \quad (62)$$

and

$$\begin{pmatrix} \alpha_2 \\ \beta_2 \\ \gamma_2 \end{pmatrix} = \begin{pmatrix} 0 & a_{\alpha 2y} & a_{\alpha 2z} \\ a_{\beta 2x} & 0 & 0 \\ a_{\gamma 2x} & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}, \quad (63)$$

respectively.

4.2. Optimization of the 3D-Nanoprobe

The semi-analytical model of the previous section which describes the static mechanical behavior of the novel 3D-Nanoprobe is used to optimize the structure and properties by hand for:

- $\alpha_2 = 0$ for displacements z-direction (in the 3D-Nanoprobe's coordinate system) at an incident angle of 0° and
- $c_{zy} = 0$ and $c_{yz} = 0$, (zero crosstalk)
- quasi isotropic stiffness, $c_{xx} \approx c_{yy} \approx c_{zz}$,
- adapted compliance of the probe's structure to the horizontal compliance of the tip (e.g. CD-tip about 8.6 N/m using a CDR120 tip cantilever (*Fa. Team Nanotec*) as basis,
- nominal stiffness about 2 N/m to avoid large uncontrolled snap-in (see section 3.4).
- The detectable bending angles should show balanced sensitivity coefficients (specifically $a_{\beta 2x}$ and $a_{\alpha 2y}$, similar values).

In the model a Young's modulus of $E_{110}=0.169$ GPa and a shear modulus $G_{110}=79.6$ GPa was used for the probes material, silicon [110]. The CD-tip was modeled in silicon [100] with and $E_{100}=130$ GPa and a Poisson's ratio of 0.28.

A CDR120 (*Fa. Team Nanotec*) is used as a cantilever probe base geometry. The geometry was measured via SEM imaging and is given by the length from the base to the tip of $L_{eff}=110.1 \mu\text{m}$, width $w=36.3 \mu\text{m}$, thickness $t=3.99 \mu\text{m}$ and tip length $L_{tip}=16.61 \mu\text{m}$, as an example with typical values. The tip set back should be larger than $11 \mu\text{m}$, apart from that, it will be difficult to optimize the structure with the soft CD-tip. The cylindrical CD-tip on the very end is not imaged closely because of carbon deposition during imaging, which might affect the tip-sample interaction during experiment. A nominal length and diameter of $L_s=0.600 \mu\text{m}$ and $d_s=0.100 \mu\text{m}$ is chosen, respectively. Using the analytical stiffness matrix description of a cantilever probe of section 3.2.2, the nominal compliance of this base cantilever in vertical z-direction is given by $c_{bzz}=0.0142 \text{ m/N}$ (about 70.6 N/m) including the CD-tip. The horizontal compliance including the CD-tip in x- and y-direction is given by $c_{bxx}=0.13 \text{ m/N}$ (about 7.8 N/m) and $c_{byy}=0.13 \text{ m/N}$ (about 7.8 N/m). The corresponding angle matrix coefficients of this basic cantilever are given by $a_{b\beta x}=0.038 \mu\text{rad/nN}$, $a_{b\alpha y}=0.058 \mu\text{rad/nN}$, $a_{b\alpha z}=0.19 \mu\text{rad/nN}$, indicating a stiff cantilever body.

Without CD-tip the compliance in vertical z-direction is given by $c_{bczz}=0.0137 \text{ m/N}$ (about 72.3 N/m) and the compliance in x- and y-direction is given by $c_{bxx}=0.81 \text{ mm/N}$ (about 1.2 kN/m) and $c_{byy}=0.98 \text{ mm/N}$ (about 1.0 kN/m), while the crosstalk is given by $c_{byz}=c_{bzy}=0.0032 \text{ m/N}$ (about 0.32 kN/m). This means, with and without CD-tip the probe shows strong anisotropy.

Comparing the horizontal compliance including, and without CD-tip shows the large impact of the soft CD-tip on the total compliance. As mentioned in sections 3.2.1 and 3.2.3, this has a direct impact on the sensitivity of the probe. The sensitivity S of the basic cantilever

probe of a tip apex displacement in x-, y-, z-direction is given by comparison of the inclination angle matrix coefficients with the corresponding total compliance matrix coefficients by $S_{\beta x}=0.30 \mu\text{rad/nm}$, $S_{\alpha y}=0.46 \mu\text{rad/nm}$, $S_{\alpha z}=13.1 \mu\text{rad/nm}$. The value of $S_{\alpha z}$ can be considered as a normal value for an AFM cantilever probe. The ratio of the sensitivities $S_{\beta x}$ and $S_{\alpha y}$ normalized to $S_{\alpha z}$ is given by 0.023 and 0.035, indicating a small useable signal.

The structure of the novel 3D-Nanoprobe should be manufactured by FIB milling, thus to save manufacturing time only material is removed from the base cantilever body geometry. Because each base cantilever structure is different the optimization process will be performed individually for each single 3D-Nanoprobe (at this stage of development). For better compatibility with several detection principles, the area of HS2 should be at least $8 \mu\text{m} \times 8 \mu\text{m}$, while HS1 (e.g. $20 \mu\text{m} \times 20 \mu\text{m}$) should be larger than HS2. Cuts between w_3 and w_2 are assumed to be 300 nm. Thicknesses, widths or structure lengths below 500 nm are considered as unfeasible because of large manufacturing uncertainties. Structures length (FH1 and FH2) above $4 \mu\text{m}$ are also excluded, because a large amount of material has to be removed, which increases manufacturing time of the prototype 3D-Nanoprobes. During optimization, the most sensitive parameters such as t_2 , L_2 , w_2 , t_1 and L_1 are graphically visualized and the slope of each curve is minimized to lower the impact of manufacturing deviations of a single parameter on the properties of the probe, improving overall specifications. Most important in the optimization process is to achieve a minimal c_{zy} , and minimal α_{z2} for forces in z-direction, to ensure functionality of the probe. The 3D-Nanoprobe is optimized also for quasi isotropic compliance in x-, y-, and z-direction. Limitations given by the base structure geometry do not allow a quasi isotropic stiffness (as presented in [72]) of the 3D-Nanoprobe in this example. In addition, it is optimized for balanced ratio of the force dependent inclination angles and a nominal stiffness of about 2 N/m. **Figure 4.2** shows a selection of these graphs. **Figure 4.2 A, B and C** shows the modeled compliance of a 3D-Nanoprobe over L_{eff} , L_1 and L_2 . It shows that the compliance is mostly dominated by the FH1 and FH2, the probe's effective length has only a small impact. Moreover, it depicts that L_1 and L_2 are antagonists. A balanced ratio of their length and position results in a minimal crosstalk and minimal inclination angle coefficient (minimal α_{z2}). In general, the graphs only give hints for an optimization direction as the parameters are coupled with each other. Other parameters are given in appendix **Figure E.1**.

FH1 can be shifted in z-direction by L_{tip1} to enlarge the impact of a force in x-, and y-direction on the inclination angle of HS1, here $L_{tip1} = L_{tip} + 1 \mu\text{m}$ is used. This is most useful, if L_{tip} is not large enough. The smallest increment to adjust optimization parameters is set to 10 nm, a smaller value is not sensible for manufacturing.

In the following, the CDR120 cantilever probe is used as a basis for an optimization of a novel 3D-Nanoprobe. The hand optimization process is done in several interactions, evaluating the stiffness value and isotropy. Most important during optimization is to achieve minimal (zero) crosstalk and a minimal inclination angle coefficient $\alpha_{\alpha 2z}$ of HS2. This is mandatory for a working 3D-Nanoprobe. A typical optimization takes about 15 min.

As a result, the 3D-Nanoprobe's optimized structure and flexure hinge geometries are given by: $L_{k2}=5.8 \mu\text{m}$, $L_2=2.0 \mu\text{m}$, $L_{eff1}=L_{eff}+L_2+L_{k2}$, $L_1=2.3 \mu\text{m}$, $L_k=12 \mu\text{m}$, $L_{k1}=38 \mu\text{m} + L_{k2}+L_2$, $w_1=2.2 \mu\text{m}$, $w_2=0.9 \mu\text{m}$, $w_3=1.5 \mu\text{m}$, $w_k=15 \mu\text{m}$, $t_1=0.78 \mu\text{m}$ and $t_2=t_3=0.60 \mu\text{m}$.

Comparing the new 3D-Nanoprobe parameter with the classical CDR120 cantilever probe

shows a large improvement regarding 3D-probing capabilities. The optimized 3D-Nanoprobe shows a quasi isotropic ratio of the compliance of (1.4/1.5/1.0), which is a nine-fold improvement compared to the CDR120 cantilever probe with a ratio of compliance of (0.11/0.11/1) in x-, y-, z-direction, respectively. This ratio is not ideal but proved to be sufficient for probing in 3D. This probe optimization was chosen on purpose, because it shows the inherent ranking of each optimization task and the boundaries of an optimization process due to geometrical restrictions and manufactureability. An example of a nearly ideal isotropic compliance of a 3D-Nanoprobe optimization is published in [72] and [106]. The compliance in vertical z-direction was increased (decreased stiffness) by a factor of 25 to $c_{zz}=0.352\text{ m/N}$ (about 2.84 N/m). Excluding the CD-tip, the compliance of the probe in horizontal x- and y-direction were increased by a factor of 467 and 409 to $c_{bxx}=0.38\text{ m/N}$ and $c_{byy}=0.40\text{ m/N}$, respectively. The compliance of the 3D-Nanoprobe in vertical z-direction including the CD-tip remained the same. The total compliance of the 3D-Nanoprobe is given by $c_{xx}=0.51\text{ m/N}$ and $c_{yy}=0.53\text{ m/N}$, which is sufficient for stable probing (small snap-in, section 3.4).

The optimized compliance $c_{zy} = -0.0011\text{ m/N}$, which is responsible for crosstalk cannot be directly compared to the cantilever probe, because it is a different structure with different compliance value. The improvement of the optimization is shown by comparing the ratios of the 3D-Nanoprobe with $c_{zy}/c_{zz} \approx -0.0032$ and the commercial cantilever with $c_{byz}/c_{bzz} \approx 0.224$ with each other. Consequently, the crosstalk was reduced by a factor of 71 compared to the commercial cantilever probe giving a possible smooth and excellent transition between non-contact and contact tip-sample interaction. Compared with the CDR120 cantilever probe, the inclination angle coefficients of the optimized 3D-Nanoprobe were significantly improved as well. The new inclination angle coefficients are given by: $a_{\beta 1x}=1.68\text{ }\mu\text{rad/nN}$, $a_{\beta 2x}=18.1\text{ }\mu\text{rad/nN}$, $a_{\alpha 1y}=3.50\text{ }\mu\text{rad/nN}$, $a_{\alpha 2y}=22.7\text{ }\mu\text{rad/nN}$, $a_{\alpha 1z}=7.30\text{ }\mu\text{rad/nN}$, $a_{\alpha 2z}=-0.033\text{ }\mu\text{rad/nN}$, $a_{\gamma 1x}=1.75\text{ }\mu\text{rad/nN}$, $a_{\gamma 2x}=-4.59\text{ }\mu\text{rad/nN}$.

Because the 3D-Nanoprobe is optimized for a small inclination angle of HS2 for a displacement or force in z-direction, one can only directly compare $a_{\beta 2x}$ and $a_{\alpha 2y}$ and $a_{\alpha 1z}=7.30\text{ }\mu\text{rad/nN}$ with $a_{b\beta x}$, $a_{b\alpha y}$ and $a_{b\alpha z}$, of the classical cantilever probe, respectively. The new 3D-Nanoprobe shows improved (increase) sensitivity to tip-sample interaction forces of a factor of (476 /391 /38) in x-, y-, and z-direction, respectively.

Finally, the sensitivity coefficients of the 3D-Nanoprobe of $S_{\alpha 2z} = -0.095\text{ }\mu\text{rad/nm}$, $S_{\alpha 1z}=20.7\text{ }\mu\text{rad/nm}$, $S_{\alpha 2y}=43.1\text{ }\mu\text{rad/nm}$, $S_{\alpha 1y}=6.65\text{ }\mu\text{rad/nm}$, $S_{\beta 2x}=35.6\text{ }\mu\text{rad/nm}$ and $S_{\beta 1x}=3.32\text{ }\mu\text{rad/nm}$ are compared with the classical CDR120 cantilever probe. The improvement in sensitivity is given by the ratios of $S_{\beta 2x}/S_{\beta x} \approx 119$, $S_{\alpha 2y}/S_{\alpha y} \approx 94$, and $S_{\alpha 1z}/S_{\alpha z} \approx 1.6$ of both probes in x-, y-, and z-direction, respectively.

The small ratio of $S_{\alpha z}/S_{\alpha 2z} \approx 138$ shows the improvement in selectivity for the explicit z-direction later in the detection system and calibration of the 3D-Nanoprobe.

Despite the complexity of the model the compliance matrix coefficients and inclination angle matrix coefficients show good agreement with the FEM simulation of section 4.3, as depicted in **Figure 4.2**. This verifies the semi-analytical model on a theoretical basis. Consequently, the structure of the 3D-Nanoprobe can be optimized based on this mechanical description. Furthermore, the semi-analytical model can be used in the description of the detection system later on.

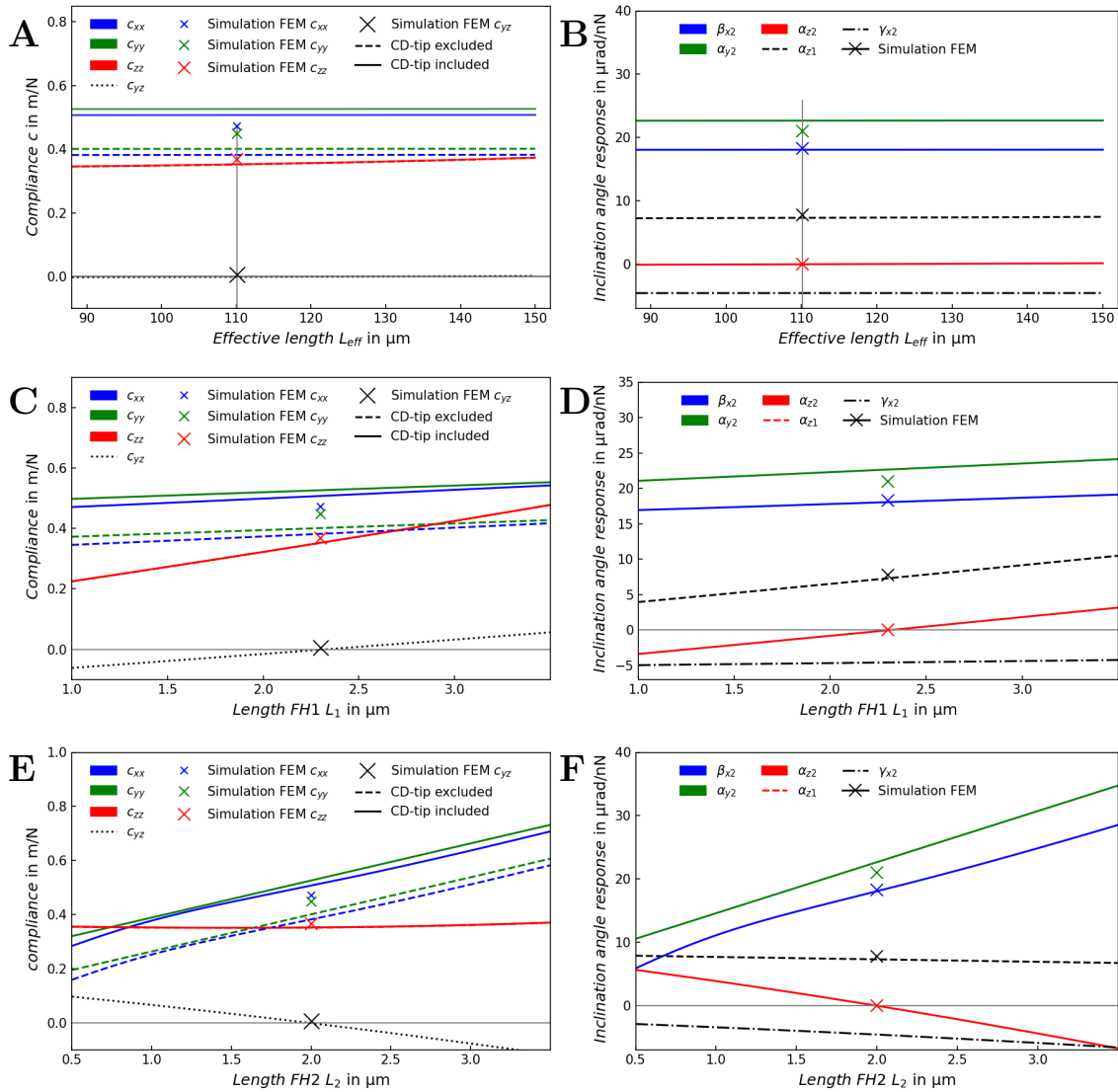


Figure 4.2: Optimization of force dependent inclination angles and compliance of a 3D-Nanoprobe. A, C and E show compliance dependence of the effective cantilever length L_{eff} , length of flexure hinge 1 (FH1) L_1 and length of FH2 L_2 . B, D and F show the corresponding force dependent inclination angles. The FEM simulation results of the following section 4.3 are already included in the graphs.

4.3. Simulation of the 3D-Nanoprobe

After the analytically based optimization, the 3D-Nanoprobe is modeled in CAD to verify its compliance and to optimize the resonance frequencies of the new structure. **Figure 4.3** shows the first optimized eight resonance frequencies. Owing to the mass distribution of the base cantilever probe and shape of HS1 and HS2 the resonance frequencies can be shifted. The resonance frequencies are separated from each other to avoid crosstalk in between them (e.g. transition of kinetic energy) and to prevent chaotic behavior. In general, it is sufficient to reduce or elongate L_k , the length of HS2. A change in width of HS2 is used to impact the torsional resonance modes. The mechanical and modal finite element method (FEM) simulations were conducted with the software *Ansys R19.2*. No analytical model is used, since it does not represent the details of the 3D-Nanoprobe design and would lead to large deviations of the properties for the final manufactured geometry.

The first resonance mode of 112.8 kHz is depicted in **Figure 4.3** and shows the bending

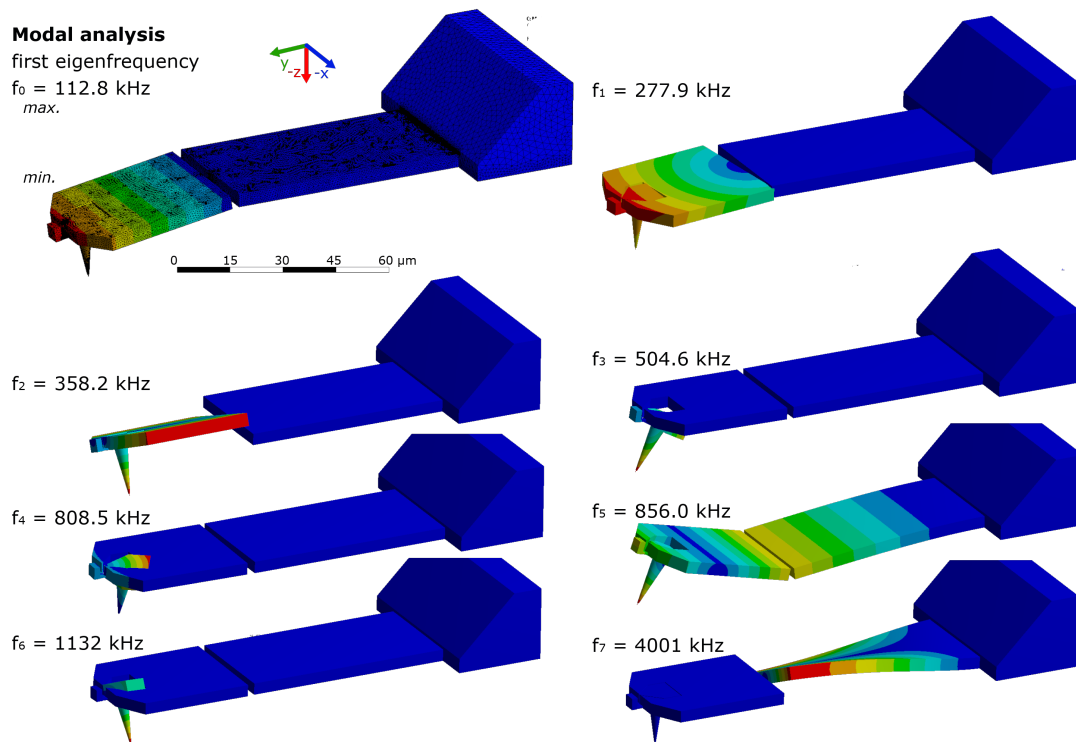


Figure 4.3: Relevant simulated resonant frequencies of a 3D-Nanoprobe of a FEM modal analysis. f_0 denotes the first eigenfrequency.

mode of HS1 in z-direction. The second resonance mode at 277.8 kHz is the (horizontal) in-plane bending motion of HS1, while the third resonance mode at 358.2 kHz is the torsional oscillation of HS1. The next two resonance are the bending mode of HS2 in z-direction and the in-plane bending oscillation at 504.6 kHz and 808.5 kHz, respectively. The sixth resonance is the 2nd order bending oscillation of the HS1 structure. The torsional oscillation for a tip displacement in x-direction of HS2 is at 1.13 MHz. The last depicted resonance frequency is

the eigenmode of the cantilever base of about 4 MHz. Consequently, all optimized eigenmodes are cleanly separable.

In addition, a mechanical simulation was conducted with the same modeled geometry. A static mechanical FEM analysis was used to receive the structural displacements. To analyze the compliance in x, y, z-direction a load 1 nN in F_i ($i = x, y, z$) is applied to the CD-tip apex. The results are shown in the **Figure 4.4**. The tip apex displacement relative to the base of the simulated geometry was used to give an estimate of the probes compliance in x-, y-, and z-direction. The compliance is given by $c_{xxsim}=0.472$ m/N, $c_{yy sim}=0.448$ m/N, $c_{zzsim}=0.367$ m/N, $c_{zysim}=0.00627$ m/N. This shows good agreement with the semi-analytical model, as depicted in **Figure 4.2 and E.1**.

Derived from the bending strength of silicon (300 to 1000 MPa) the developed 3D-Nanoprobe can withstand tip-sample interaction forces of more than 200 nN without damage.³

The bending, torsion and in-plane bending of HS1 and HS2 are used to calculate the

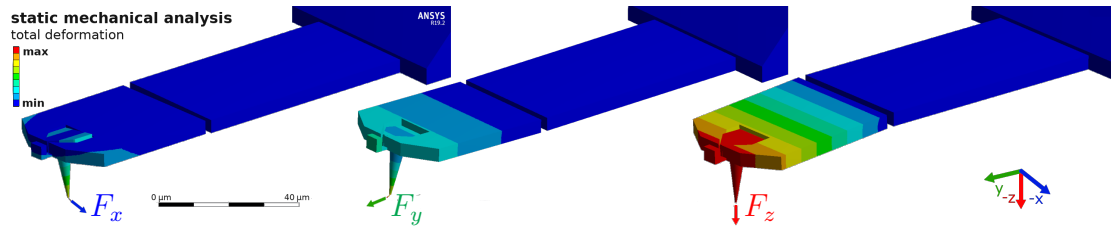


Figure 4.4: Static mechanical FEM analysis of the 3D-Nanoprobe to receive the relevant displacements of the tip apex and structure (inclination angles).

changes of the inclination angle coefficients from FEM analysis and give an estimate of the sensitivity to tip-sample interaction forces. They are given by $a_{\beta 1 xsim}=2.01$ μ rad/nN, $a_{\beta 2 xsim}=18.3$ μ rad/nN, $a_{\alpha 1 ysim}=3.10$ μ rad/nN, $a_{\alpha 2 ysim}=20.9$ μ rad/nN, $a_{\alpha 1 zsim}=7.76$ μ rad/nN, $a_{\alpha 2 zsim}=-0.0033$ μ rad/nN, $a_{\gamma 1 xsim}=1.12$ μ rad/nN, $a_{\gamma 2 xsim}=-1.97$ μ rad/nN. The determined inclination angles coefficient values and the compliance values are in good agreement with semi-analytical model, thus the semi-analytical model is verified.

In the following, the optimized 3D-Nanoprobe is manufactured.

³During experiment the 3D-Nanoprobe was displaced by up to 1 μ m in z-direction without measurable damage.

4.4. Manufacturing of the 3D-Nanoprobe

The 3D-Nanoprobes are manufactured by focused ion beam (FIB) milling. As described in section 3.6, the FIB uses accelerated Gallium-Ions (Ga^+) to erode material from the sample in the selected area. The amount of Gallium-Ions is defined by the beam-current of the emitter. Small current values facilitate to a narrow beam, which is also less divergent and leads to more accurate manufacturing. The downside of a smaller beam-current is longer manufacturing time. For larger beam-currents the beam is more divergent and manufacturing is usually less accurate but faster. Therefore, the prototypes of the 3D-Nanoprobes are manufactured as rough as possible and as fine as needed, in two steps: The first step (currents: $>1 \text{ nA}$) is for roughing-out material, which needs to be removed for the next finishing steps with currents $<0.5 \text{ nA}$. The finishing step defines the geometry of the flexure hinges. The ion energy is set by the accelerating voltage, here 30 kV is used.

Before the FIB manufacturing, the geometry of the CD-tip cantilever, which the 3D-Nanoprobe will be based on, is measured by a scanning electron microscope (SEM). Three SEM-images view the CD-tip cantilever from the side **Figure 4.5**, the free end in detail from the side **Figure 4.6**, and from the top **Figure 4.7**. Measurements are taken from the image by multiplying the counted pixels with the scale factor per pixel of the image. Based on the CD-tip cantilever geometries the 3D-Nanoprobe is optimized (see section 4.2). Based on the geometry, the CD-tip cantilever can have significant different properties, thus each individual 3D-Nanoprobe has their own set of parameters. The CD-tip cantilever is mounted on a self-built sample holder for two samples (CD-tip cantilevers) with a pre-tilt of 38° for manufacturing and imaging purpose. With this pre-tilt a manufacturing from two orthogonal sides is possible, because the ion column is mounted under an angle of 52° relative to the electron column. The CD-tip cantilever is mounted with the CD-tip facing downwards to protect the CD-tip from stray ions. The CD-tip cantilever can have a mounting error angle of $\pm 2^\circ$ in tilt and rotation. In the following the manufacturing process of a 3D-Nanoprobe based on a CD-tip cantilever CDR120 (CD-tip diameter of nominal 120 nm) is shown. During the manufacturing process the CD-tip should never be imaged by the ion-beam, because the delicate CD-tip will be damaged immediately. In general the ion beam damages the surface of the sample in the process of aligning with the selected areas during manufacturing, according to the optimized geometry of the 3D-Nanoprobe. To reduce the damage the current is set to 1 pA to view the sample before the next manufacturing step. After the current is changed to the manufacturing higher current, a snapshot is taken because the selected areas (rectangles and polygons) are usually offset and have to be repositioned, to ensure accurate manufacturing. The total progress can be checked with the SEM between the manufacturing steps. The commercial CD-tip cantilever body oftentimes has a thickened edge with a tub like structure, which has to be taken into account during manufacturing. The total manufacturing time for one 3D-Nanoprobe takes about 3 h to 4 h , with careful manufacturing. The parameters used for manufacturing are given for each manufacturing step in B. First, the absolute stage position for tilt and rotation in degree is listed. Second, the type and size of the selected area for manufacturing, the ion beam current and the beam time used for manufacturing is shown. The size of the selected rectangle pattern in x and y is given, as well as the milling depth z in μm . For the varying shape of polygon pattern only the milling depth is needed.

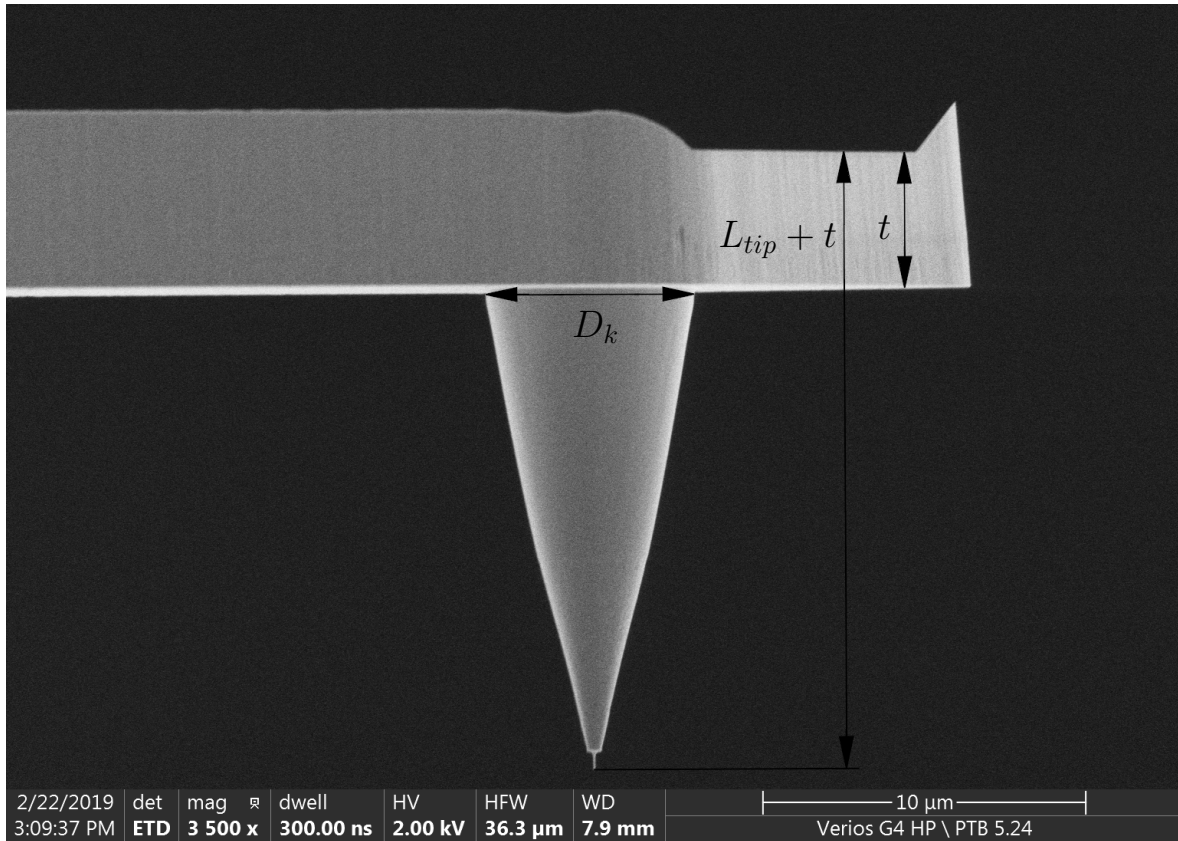


Figure 4.5: SEM image side view of the CD-tip cantilever free end with the measured geometries used for optimization, thickness t , length of the Cantilever tip L_{tip} and cone diameter at the bottom side of the cantilever body D_k .

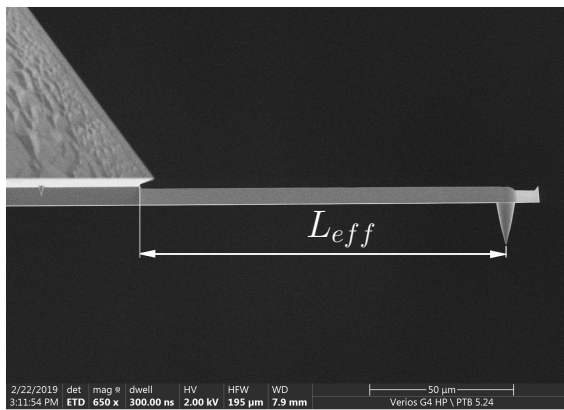


Figure 4.6: SEM image side view of the CD-tip cantilever with the effective length from the base to the tip L_{eff}

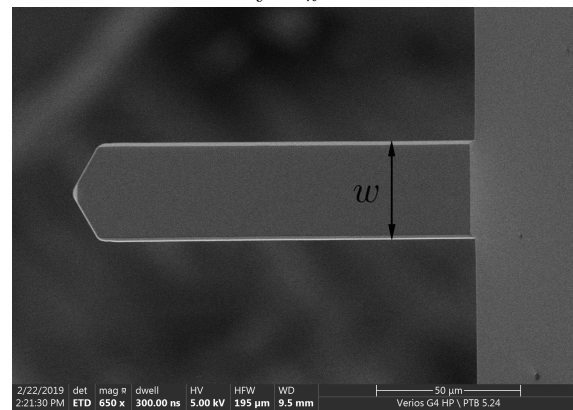


Figure 4.7: SEM image top view of the CD-tip cantilever with the width of the cantilever body w

Figure 4.8 and **Figure 4.9** show the 3D-Nanoprobe from the side and top, respectively. One can clearly see the structure with the head section and flexure hinges and see the difference compared to the CD-tip cantilever shown in **Figure 4.6** and **Figure 4.7**.

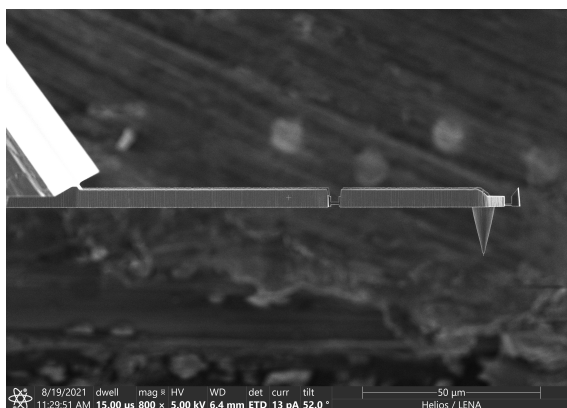


Figure 4.8: Manufactured 3D-Nanoprobe from the side.

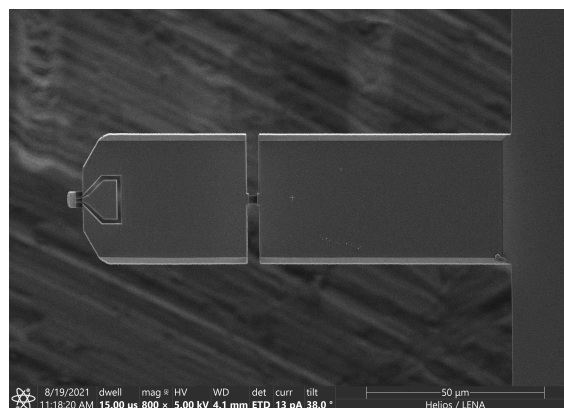


Figure 4.9: Manufactured 3D-Nanoprobe from the top.

5. The true 3D-AFM head detection system

The detection system of the true 3D-AFM head is described in this chapter. First, two detection principles are proposed, which can be used to detect the displacements of the tip apex of the 3D-Nanoprobe in 3D. In the following both detection principles are mathematically applied on a 3D-Nanoprobe in sections 5.1.1 and 5.1.2. The calculated coefficients from a sensitivity matrix can be used as start values for calibration of 3D-Nanoprobes. One detection principle is selected as detection system and implemented in a true 3D-AFM head. In section 5.2 the true 3D-AFM head design is described in detail and the construction is shown in section 5.4. The detection system components are built-up, tested and evaluated in section 5.4.1 and 5.4.2. After the true 3D-AFM head is tested, it is implemented into the test setup, shown in chapter 6.

5.1. 3D-detection principles of the 3D-Nanoprobe

The 3D-Nanoprobe is optimized to work with inclination angle detection or displacement detection of the head sections. In this work optical detection principles are used as described in section 3.3. Two functional principles for optical detection of the 3D-Nanoprobe's motion are shown as a scheme in **Figure 5.1**.

The first detection principle is a hybrid combination of an interferometer and a dual optical lever and will be introduced in the following. The free end of an optimized 3D-Nanoprobe is shown at the top of **Figure 5.1** with tip-sample interaction forces $\mathbf{F}$, which displaces the tip apex in x-, y-, and z-direction. The tip apex displacement is shown qualitatively over time t . The interferometer beam is focused on *HS1* and detects the average displacement of *HS1* in z-direction z_{HS1} . A second interferometer beam is focused on the *base* of the 3D-Nanoprobe and detects the z-displacement of the base z_{base} to reduce drift and environmental influences. The optical microscope image on the right shows both spots in red. The differential signal $z_{int} = z_{HS1} - z_{base}$ is the actual displacement of *HS1*. From **Figure 5.1 A** one can see that the interferometer is mainly sensitive for a displacement of the tip apex in z-direction, but also detects a z-displacement of *HS1* under a tip apex displacement in y-direction. A crosstalk in z-direction from a tip apex displacement in x-direction is considered in section 5.1.2. For the developed 3D-Nanoprobe, it has a negligible effect on the z-interferometer signal. The interferometer beam can also be focused on *HS2*. The dual optical lever is focused on *HS2* and is sensitive for the bending inclination angle α_2 and torsion inclination angle β_2 of *HS2*. A tip apex displacement in x-direction will proportionally twist the 3D-Nanoprobe and torsion inclination angle β_2 is detected. The inclination angle α_2 only changes for a tip apex displacement in y-direction, because the 3D-Nanoprobe *HS2* is optimized not to change the inclination angles of *HS2* for a tip displacement in z-direction. Consequently, the combination of the interferometer and dual optical lever is sensitive for tip apex displacements in 3D.

The detection principle B detection principle is based on two dual optical levers. The optical beams are focused on the head section *HS1* and *HS2* and are denoted in the details as *laser spot 1* and *laser spot 2*, respectively. The first dual optical lever, detects the bending inclination angle α_1 and torsion inclination angle β_1 of *HS1*. As indicated, a tip displacement in z-direction leads to a large change in inclination α_1 compared to a tip displacement in y-direction. A tip displacement in x-direction leads to a change in the second detectable

inclination angle β_1 . The second dual optical lever is focused on *HS2* and detects α_2 and β_2 , which are constant for a tip displacement in z-direction as already described above, using the optimization of the 3D-Nanoprobe. The combination of both dual optical levers is also sensitive for tip apex displacements in 3D and is described in section 5.1.1.

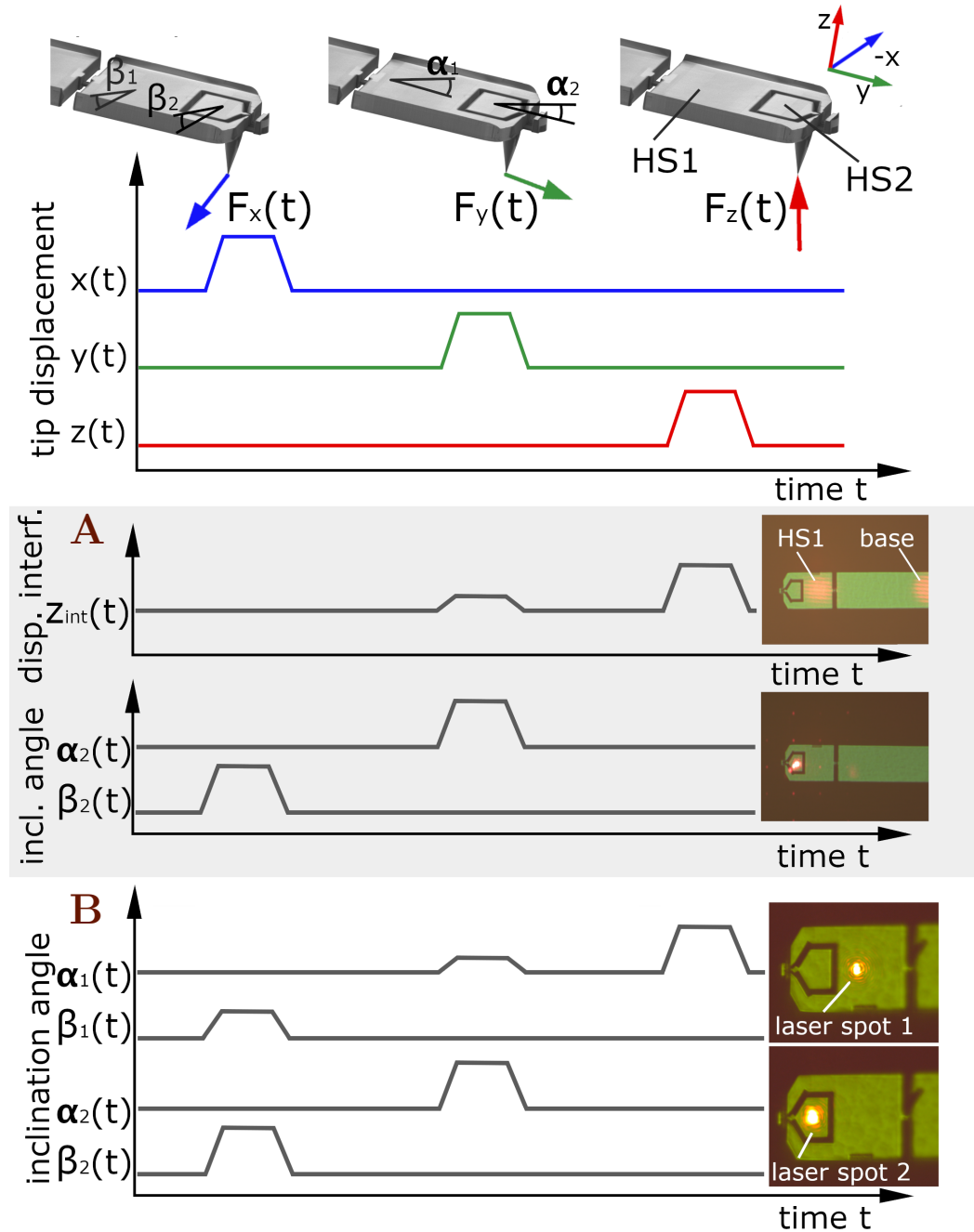


Figure 5.1: Scheme of the functional principle of detection principle A and B applied to the 3D-Nanoprobe. The detection principle A (marked in grey) uses an interferometer and a dual optical lever. The dual optical lever detects the bending inclination angle α and torsion inclination angle β . The spots in red are visible in the optical microscope image (right). The detection principle B uses two (double) dual optical lever (adapted own image [72], [106]).

5.1.1. The double dual optical lever detection principle for the 3D-Nanoprobe

The two dual optical levers were applied on the HS1 and the HS2 of the 3D-Nanoprobe. From the matrices of the inclination angles in (62) and (63) the detectable inclination angles are α_1 and β_1 of HS1 for dual optical lever 1 and α_2 and β_2 for HS2 for dual optical lever 2.

$$\begin{pmatrix} \Delta\alpha_i \\ \Delta\beta_i \\ \Delta\gamma_i \end{pmatrix} = \begin{bmatrix} \alpha_{xi} & \alpha_{yi} & \alpha_{zi} \\ \beta_{xi} & \beta_{yi} & \beta_{zi} \\ \gamma_{xi} & \gamma_{yi} & \gamma_{zi} \end{bmatrix} \cdot \begin{pmatrix} \Delta F_x \\ \Delta F_y \\ \Delta F_z \end{pmatrix}, \quad i = 1, 2. \quad (64)$$

To ensure enough safety distance with the support chip from the sample surface, the cantilever based 3D-Nanoprobes is tilted. This commonly used incident angle ϕ rotates the 3D-Nanoprobe's coordinate system in relation to the machine coordinate system. During the probing, the mechanical tip-sample interaction with the probe changes. If the tip apex can move freely during non-contact, force fields (e.g. tip-sample interaction, force vector $\vec{F}$) are acting on the tip and the compliance matrix $\mathbf{C}$ can be used to describe the mechanical properties. When the tip apex is in contact with the sample during probing, the tip apex is displaced by

$$\vec{s} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \quad (65)$$

consequently the stiffness matrix $\mathbf{C}^{-1} = \mathbf{K}$ is used to describe the mechanics by $\mathbf{K} \cdot \vec{s} = \vec{F}$. Since the 3D-Nanoprobe will be applied in contact measurements, the stiffness matrix is given by

$$\begin{bmatrix} \frac{1}{c_{xx}} & 0 & 0 \\ 0 & \frac{c_{zy}\sin(\phi)+c_{zz}\cos(\phi)}{c_{det}} & \frac{c_{yy}\sin(\phi)+c_{yz}\cos(\phi)}{c_{det}} \\ 0 & \frac{c_{zy}\cos(\phi)-c_{zz}\sin(\phi)}{c_{det}} & \frac{c_{yy}\cos(\phi)-c_{yz}\sin(\phi)}{c_{det}} \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \quad (66)$$

with $c_{det} = (c_{yy}\cos(\phi) - c_{yz}\sin(\phi)) \cdot (c_{zy}\sin(\phi) - c_{zz}\cos(\phi)) - (c_{yy}\sin(\phi) - c_{yz}\cos(\phi)) \cdot (c_{zy}\cos(\phi) - c_{zz}\sin(\phi))$

Implementing (66) into (64) by replacing $\vec{F}$ leads to an angle sensitivity matrix, which depends on the tip apex displacement of the 3D-Nanoprobe, by dividing the angle coefficients by the compliance:

$$\begin{pmatrix} \alpha_i \\ \beta_i \\ \gamma_i \end{pmatrix} = \begin{bmatrix} 0 & \alpha_{yi}k_{yy} + \alpha_{zi}k_{zy} & \alpha_{yi}k_{yz} + \alpha_{zi}k_{zz} \\ \beta_{xi}k_{xx} & 0 & 0 \\ \gamma_{xi}k_{xx} & 0 & 0 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix}, \quad (67)$$

with $k_{yy} = \frac{c_{zy}\sin(\phi)+c_{zz}\cos(\phi)}{c_{det}}$, $k_{zy} = \frac{c_{yy}\sin(\phi)+c_{yz}\cos(\phi)}{c_{det}}$, $k_{yz} = \frac{c_{zy}\cos(\phi)-c_{zz}\sin(\phi)}{c_{det}}$, $k_{zz} = \frac{c_{yy}\cos(\phi)-c_{yz}\sin(\phi)}{c_{det}}$ and $k_{xx} = \frac{1}{c_{xx}}$.

The dual optical lever 2 is used to detect the tip displacement of the tip-sample interaction force F_x in x-direction, because the angle matrix coefficient β_{x2} is larger than β_{x1} . In practice both signals can be used in parallel. Consequently, the relevant detectable angles are given by

$$\begin{pmatrix} \beta_2 \\ \alpha_1 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} \beta_{x2} & 0 & 0 \\ 0 & \alpha_{y1} & \alpha_{z1} \\ 0 & \alpha_{y2} & \alpha_{z2} \end{pmatrix} \cdot \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}. \quad (68)$$

The rotation of the 3D-Nanoprobe around the x-axis by ϕ leads to force dependent inclination angles of

$$\begin{pmatrix} \beta_2 \\ \alpha_1 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} \beta_{x2} & 0 & 0 \\ 0 & \alpha_{y1}\cos(\phi) - \alpha_{z1}\sin(\phi) & \alpha_{z1}\cos(\phi) + \alpha_{y1}\sin(\phi) \\ 0 & \alpha_{y2}\cos(\phi) - \alpha_{z2}\sin(\phi) & \alpha_{z2}\cos(\phi) + \alpha_{y2}\sin(\phi) \end{pmatrix} \cdot \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}. \quad (69)$$

For a specific small ϕ tilt, $\alpha_{z2}\cos(\phi)$ is compensated by $-\alpha_{y2}\sin(\phi)$, which results in an unambiguous detection of the tip sample interaction forces. The inclination angle coefficient is already optimized for $\alpha_{z2} = 0$ at the incident angle $\phi = 0$ for a vertical z-force. For small optimization and manufacturing deviations from zero, α_{z2} can be corrected with a specific small $\pm\phi_{adjust}$ tilt of the probing vector. Consequently, the fixed build-in incident angle $\phi_{incident}$ of the 3D-Nanoprobe in the detection system can be changed to $\phi = \phi_{incident} + \phi_{adjust}$. This probing vector defines the z-coordinate of the 3D-Nanoprobe. As a result, the inclination angle coefficient of the in-plane y-direction of α_2 can be separated from the z-direction. The coordinate system of the probe and the sensitivity for each direction is therefore well defined, resulting in a selectivity for three dimensions (3D).

Based on design and compliance of the 3D-Nanoprobe, the positioning of the focused beams of the dual optical levers on the head section areas show a negligible impact on the inclination angle coefficients. The signals of a tip apex displacement in x-, y-, and z-direction of the two dual optical levers are given by β_2 , α_1 and α_2 , respectively. Using the expression (50), (54) and (55) of the optical lever simulation with $f=4\text{mm}$ and implementing (66), the relevant detectable signals on the QPD 1 and QPD2 of the orthogonal tip apex displacements Δx_{tip} , Δy_{tip} and Δz_{tip} in x-, y-, and z-direction are given by

$$S_{QPD2x} = V_{SUM} \cdot 1.28 \cdot 10^{-6} \frac{1}{nm} \cdot 2 \cdot f \cdot \frac{\beta_{x2}}{c_{xx}} \Delta x_{tip} = V_{SUM} 10.24 \cdot \frac{\beta_{x2}}{c_{xx}} \Delta x_{tip} \quad (70)$$

$$S_{QPD2y} = V_{SUM} * 10.24 * \alpha_{y2} \frac{c_{zy}\sin(\phi) + c_{zz}\cos(\phi)}{c_{det}} + \alpha_{z2} \frac{c_{zy}\cos(\phi) - c_{zz}\sin(\phi)}{c_{det}} \Delta y_{tip} \quad (71)$$

$$S_{QPD1y} = V_{SUM} * 10.24 * \left[\left(\alpha_{y1} \frac{c_{zy}\sin(\phi) + c_{zz}\cos(\phi)}{c_{det}} + \alpha_{z1} \frac{c_{zy}\cos(\phi) - c_{zz}\sin(\phi)}{c_{det}} \right) \Delta y_{tip} + \left(\alpha_{y1} \frac{c_{yy}\sin(\phi) + c_{yz}\cos(\phi)}{c_{det}} + \alpha_{z1} \frac{c_{yy}\cos(\phi) - c_{yz}\sin(\phi)}{c_{det}} \right) \Delta z_{tip} \right], \quad (72)$$

respectively.

Rearrangement and implementation of a calibration factors $\Phi_{calibration}$, to adjust for eventual deviations, leads to:

$$\Delta x_{tip} = \frac{S_{QPD2x}}{V_{SUM} 10.24 * \frac{\beta_{x2}}{c_{xx}}} \Phi_{calibration_x} \quad (73)$$

$$\Delta y_{tip} = \frac{S_{QPD2y}}{V_{SUM} * 10.24 * (\alpha_{y2} \frac{c_{zy} \sin(\phi) + c_{zz} \cos(\phi)}{c_{det}} + \alpha_{z2} \frac{c_{zy} \cos(\phi) - c_{zz} \sin(\phi)}{c_{det}})} \Phi_{calibration_y} \quad (74)$$

$$\Delta z_{tip} = \frac{\frac{S_{QPD1y}}{V_{SUM} * 10.24} - \left(\alpha_{y1} \frac{c_{zy} \sin(\phi) + c_{zz} \cos(\phi)}{c_{det}} + \alpha_{z1} \frac{c_{zy} \cos(\phi) - c_{zz} \sin(\phi)}{c_{det}} \right) \Delta y_{tip}}{\left(\alpha_{y1} \frac{c_{yy} \sin(\phi) + c_{yz} \cos(\phi)}{c_{det}} + \alpha_{z1} \frac{c_{yy} \cos(\phi) - c_{yz} \sin(\phi)}{c_{det}} \right)} \Phi_{calibration_z} \quad (75)$$

which can be used to control the tip-sample interaction in 3D during measurement of the device after calibration. The start values of the calibration factors are $\Phi_{calibration_x} = 1$, $\Phi_{calibration_y} = 1$ and $\Phi_{calibration_z} = 1$ in the x-, y-, and z-direction, respectively.

5.1.2. The hybrid combination of a dual optical lever and interferometer detection principle for the 3D-Nanoprobe

The alternative detection principle is a hybrid combination of a dual optical lever and an interferometer. The expressions and description for the dual optical lever to measure the x and y tip displacement Δx_{tip} and Δy_{tip} can be used from (73) and (74). Only the tip displacement Δz_{tip} of the 3D-Nanoprobe is required to be measured with this interferometer. The interferometer can be applied on HS1 or HS2. The measured displacement signal of HS2 in z-direction is about 2 times larger than that of HS1. Using HS2 also has the advantage in measuring the tip displacement directly, because the 3D-Nanoprobe is optimized and calibrated to keep the inclination angle of HS2 constant for displacements in z-direction, it denotes the z-direction. Just small compression of the CD-tip and sample would affect the measured displacement. The contribution of this deformation between the tip and sample is calibrated and therefore negligible for the description of this detection system. This small contribution of the tip-sample interaction is dominated by the manufacturing uncertainties, which makes calibration necessary.

The second measurement beam location spot is on HS1. The larger area of HS1 is very useful when adjusting the spots and also has the advantage in allowing a larger laser spot being focused, but HS1 shows a crosstalk in bending motions for tip apex displacements in x- and y- direction. This crosstalk is common for all cantilever based designs and, is only eliminated for HS2. The influence or contribution of Δy_{tip} and Δx_{tip} on the measured z-displacement of HS1 z_{int1} can be compensated by using the signals of the optical lever aimed on HS2, as shown in **Figure 5.1**.

In the following, the model of the hybrid detection system with an interferometer beam centered on HS1 is described, which was already published in [106]. The model does not consider the small contributions to the z-displacement of the elastic elongation or compression of the 3D-Nanoprobe under a force F_y . The measurable displacement consists of two components. The first component, is the vertical z-displacement of the HS1 z_1 considering F_y and F_z forces. The second component constitutes the crosstalk from the horizontal x-displacement of the tip apex, which induces an in-plane bending (horizontal) x-displacement x_1 and torsion. For small torsion angles β_1 can be multiplied by the x-displacement and the contribution to detectable HS1 z-displacement z_{int1} is given by:

$$z_{int1} = z_1 + \beta_1 * x_1 \quad (76)$$

By applying the incident angle rotation of the probe on the compliance matrix expression (7) for HS1, the relevant measurable force-dependent displacements are given in detail by

$$\begin{pmatrix} x_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} c_{1xx} & 0 & 0 \\ 0 & c_{1zy}\cos(\phi) - c_{1zz}\sin(\phi) & c_{1zz}\cos(\phi) + c_{1zy}\sin(\phi) \end{pmatrix} \cdot \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}. \quad (77)$$

The compliance matrix coefficients $c_{1zz} = \Delta z_1/F_z$ and $c_{1yz} = \Delta z_{1y}/F_y$ of HS1 are derived from (104), (107) and (113). The displacements are adapted according to the tip apex position and boundary conditions, the 3D-Nanoprobe structures FH2 and HS2 are treated as rigid and do not contribute to the compliance. The displacements of HS1 relative to the tip apex displacements are

$$\begin{aligned} \Delta z_1 = & \frac{F_z}{E} \left(\frac{L_{eff1}^3}{3J_z} - \frac{(L_{k1} + L_1)^3}{3J_z} + \frac{(L_{k1} + L_1)^3}{3J_{1z}} - \frac{L_{k1}^3}{3J_{1z}} + \frac{L_{k1}^3}{3J_z} - \frac{(L_k + L_2)^2}{3J_z} \right) \\ & + \frac{6B_{v1}(L_{k1} + L_1)^2}{Ew_1t_1^2} + \frac{6B_{v1}L_{k1}^2}{Ew_1t_1^2} + \frac{L_1(2 + 2\nu_{110})}{E\kappa w_1t_1} \\ & - \frac{L_3F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} \right) \\ & - \frac{\alpha_{1z}}{F_z} \left(\frac{L_{k1} - L_k}{2} + L_k \right) \end{aligned} \quad (78)$$

and

$$\begin{aligned} \Delta z_{1y} = & \frac{L_{tip}F_y}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2L_{tip1}}{2J_{1z}L_{tip}} - \frac{L_{k1}^2L_{tip1}}{2J_{1z}L_{tip}} + \frac{B_{v1}6(L_{k1} + L_1)L_{tip1}}{w_1t_1^2L_{tip1}} \right) \\ & + \frac{B_{v1}6L_{k1}L_{tip1}}{w_1t_1^2L_{tip}} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} \\ & - \frac{L_3L_{tip}F_y}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)L_{tip1}}{J_{1z}L_{tip}} - \frac{L_{k1}L_{tip1}}{J_{1z}L_{tip}} + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} \right) \\ & + \frac{(L_k + L_2)}{J_{zu}} + \frac{2B_{v1}6L_{tip1}}{w_1t_1^2L_{tip}} \Big) - F_y \frac{\alpha_{1z}}{F_z} \left(\frac{L_{k1} - L_k}{2} + L_k \right) \end{aligned} \quad (79)$$

with the description of the interferometer beam position on HS1 at $((L_{k1} - L_k)/2 + L_k)$, respectively. Both expression are adapted for the laser spot location/position close to the center of HS1. L_k is the length of HS2. In general, the sensitivity of the measured interferometers displacement is influenced by the laser spot location on the head section and averaged by the area determined by the spot diameter. The *Timoschenko* beam coefficient [195] of $K = 0.84$ was chosen and the Poisson's ratio of silicon (material of the 3D-Nanoprobe) considering the crystal orientation is given by $\nu_{110} = 0.064$. The compliance matrix coefficient $c_{xx1} = \Delta x_1/\Delta F_x$ can be extracted from (122) and corrected for the tip location by (121). The tip apex displacement is given by

$$\begin{aligned}\Delta x_{1xx} = & \frac{\Delta F_x}{E} \left(\frac{L_{eff1}^3}{3J_x} - \frac{(L_{k1} + L_1)^3}{3J_x} + \frac{(L_{k1} + L_1)^3}{3J_{x1}} - \frac{L_{k1}^3}{3J_{x1}} + \frac{6B_{h1}(L_{k1} + L_1)^2}{w_1^2 t_1} + \frac{6B_{h1}L_{k1}^2}{w_1^2 t_1} \right) \\ & - \frac{2L_3 \Delta F_x}{E} \left(\frac{L_{eff1}^2}{2J_x} - \frac{(L_{k1} + L_1)^2}{2J_x} + \frac{(L_{k1} + L_1)^2}{2J_{x1}} - \frac{L_{k1}^2}{2J_{x1}} + \frac{L_{k1}^2}{2J_x} \right) \\ & + \frac{L_3^2 \Delta F_x}{E} \left(\frac{L_{eff1}}{J_x} - \frac{L_{k1} + L_1}{J_x} + \frac{L_{k1} + L_1}{J_{x1}} - \frac{L_{k1}}{J_{x1}} + \frac{L_{k1}}{J_x} \right)\end{aligned}\quad (80)$$

The matrix of the inclination angles (62) and (77) of HS1 can not be inverted. Consequently, the components are treated individually. Rearrangement and coefficient comparison leads to:

$$\begin{aligned}F_x &= \frac{\beta_1}{a_{\beta 1x}} \text{ and } F_x = \frac{\gamma_1}{a_{\gamma 1x}} \\ F_y &= \frac{\alpha_{1y}}{a_{\alpha 1y}} \\ F_z &= \frac{\alpha_{1z}}{a_{\alpha 1z}}\end{aligned}\quad (81)$$

where α_{1y} and α_{1z} are the detectable bending angles of HS1 for forces in y-and z-direction respectively. The expressions of the detectable bending inclination angles α_{1z} and α_{1y} of HS1 are shown in (129) and (111) and are adapted for the center laser spot location. The torsion angle of HS1 is given by expression (124). The influence of the in plane bending angle γ_1 is negligible. The expression of the forces in (81) are implemented in the matrix (77) and changes the relevant measurable force-dependent displacements to inclination angle dependent displacements to

$$\begin{pmatrix} x_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} c_{1xx} \frac{\beta_1}{a_{\beta 1x}} & 0 & 0 \\ 0 & (c_{1zy} \cos(\phi) - c_{1zz} \sin(\phi)) \frac{\alpha_{1y}}{a_{\alpha 1y}} & (c_{1zz} \cos(\phi) + c_{1zy} \sin(\phi)) \frac{\alpha_{1z}}{a_{\alpha 1z}} \end{pmatrix}. \quad (82)$$

The individual inclination angles of HS1 are proportional to the individual inclination angles of HS2, because the force in (81) is the tip-sample interaction force and the components in (82) are rewritten regarding the tip position of the 3D-Nanoprobe. This means, the lateral displacement of HS1, which is proportional to torsion inclination β_1 , is proportional to the detectable torsion inclination β_2 . Hence, the ratio of the inclination angles has the same value as the ratio of the angle coefficients $\frac{\beta_1}{\beta_2} = \frac{a_{\beta 1x}}{a_{\beta 2x}}$. The lateral displacement of HS1 is therefore expressed as

$$x_1 = c_{1xx} \frac{\beta_1}{a_{\beta 1x}} = c_{1xx} \frac{a_{\beta 1x}}{a_{\beta 2x}} \frac{\beta_2}{a_{\beta 1x}} = c_{1xx} \frac{\beta_2}{a_{\beta 2x}}. \quad (83)$$

The matrix (82) shows, that the linear contribution of HS1 to a virtual tip apex displacement

in the explicit z-direction of the 3D-Nanoprobe is given by

$$z_{1ztip} = (c_{1zz}\cos(\phi) + c_{1zy}\sin(\phi))\frac{\alpha_{1z}}{a_{\alpha 1z}}. \quad (84)$$

Consequently the total z-displacement of HS1 is given by

$$z_1 = z_{1ztip} + (c_{1zy}\cos(\phi) - c_{1zz}\sin(\phi))\frac{\alpha_{1y}}{a_{\alpha 1y}}. \quad (85)$$

Using (76), (84) and the equation above results in the detectable z-displacement of the tip apex from the interferometer of

$$z_{1ztip} = z_{int1} - (c_{1zy}\cos(\phi) - c_{1zz}\sin(\phi))\frac{\alpha_{1y}}{a_{\alpha 1y}} - c_{1xx}\frac{\beta_2}{a_{\beta 2x}}\frac{\beta_2 a_{\beta 1x}}{a_{\beta 2x}}. \quad (86)$$

The inclination angle α_{1y} is not detectable by the optical lever on HS2. With optimization and calibration of the 3D-Nanoprobe for $\alpha_{2z} = 0$ and identical tip-sample interaction force acting on HS1 and HS2, the α_{1y} is proportional to α_{2y} . The general expression $\frac{\alpha_1}{\alpha_2} = \frac{\alpha_{1y} + \alpha_{1z}}{\alpha_{2y} + \alpha_{2z}}$ of the summation of the inclination angles from tip sample interaction in y- and z-direction, changes to $\frac{\alpha_1}{\alpha_2} = \frac{\alpha_{1y}}{\alpha_{2y}}$ in the calibrated explicit y-direction. Hence, the crosstalk in y-direction on the detectable z-displacement of HS1 can be measured and corrected by $\frac{\alpha_{1y}}{\alpha_{2y}} = \frac{a_{\alpha 1y}}{a_{\alpha 2y}}$. This leads to:

$$z_{1ztip} = z_{int1} - (c_{1zy}\cos(\phi) - c_{1zz}\sin(\phi))\frac{\alpha_{2y}}{a_{\alpha 2y}} - (c_{1xx}\frac{\beta_2}{a_{\beta 2x}} \pm x_{offset})\frac{\beta_2 a_{\beta 1x}}{a_{\beta 2x}}. \quad (87)$$

In addition, the variable $\pm x_{offset}$ is implemented to compensate for a not perfectly centered interferometer beam in the lateral x-direction on HS1. Because the compliance coefficients of HS1 were calculated regarding the tip location of HS2, the contribution to total tip displacement of the 3D-Nanoprobe in z-direction is given by using the ratio of the compliance to $z_{tip} = z_{1ztip}\frac{c_{zz}}{c_{1zz}}$. Implementing this into (88) the detected z-displacement of HS1 by the interferometer of the 3D-Nanoprobe changes to

$$z_{tip} = z_{int1}\frac{c_{zz}}{c_{1zz}} - (c_{1zy}\cos(\phi) - c_{1zz}\sin(\phi))\frac{\alpha_{2y}}{a_{\alpha 2y}}\frac{c_{zz}}{c_{1zz}} - (c_{1xx}\frac{\beta_2}{a_{\beta 2x}} \pm x_{offset})\frac{\beta_2 a_{\beta 1x}}{a_{\beta 2x}}\frac{c_{zz}}{c_{1zz}}. \quad (88)$$

The conversion of the measured displacement interferometer signal to the DA-Converter is given by $\xi_{int} = 10 \text{ nm/V}$ (S_{INTz} in Volt) and is implemented with $S_{INT} = \xi_{int}z_{int1}$ into (88)

and results in

$$\begin{pmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \end{pmatrix} = \begin{pmatrix} \frac{1}{V_{SUM} 10.24 \frac{\beta_{x2}}{c_{xx}}} & 0 & 0 \\ 0 & \frac{1}{V_{SUM} * 10.24 * (\alpha_{y2} \frac{c_{zy} \sin(\phi) + c_{zz} \cos(\phi)}{c_{det}} + \alpha_{z2} \frac{c_{zy} \cos(\phi) - c_{zz} \sin(\phi)}{c_{det}})} & 0 \\ \frac{\pm x_{offset} \frac{a_{\beta 1x}}{V_{SUM} 10.24} \frac{c_{zz}}{a_{\beta 2x} c_{1zz}}}{\frac{c_{1xy} \cos(\phi) - c_{1zz} \sin(\phi)}{a_{\alpha 2y} V_{SUM} 10.24} \frac{c_{zz}}{c_{1zz}}} & \xi_{int} \frac{c_{zz}}{c_{1zz}} \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x} \\ S_{QPD2y} \\ S_{INT} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \frac{c_{1xx}}{V_{SUM}^2 10.24^2 a_{\beta 2x}} \frac{a_{\beta 1x}}{a_{\beta 2x} c_{1zz}} & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x}^2 \\ S_{QPD2y}^2 \\ S_{INT}^2 \end{pmatrix} \quad (89)$$

For controlling the tip-sample interaction the stage controller uses the tip displacement. The coordinate system of the measured tip displacement is rotated backwards by the incident angle ϕ into the machine coordinate system denoted as *stage*, to obtain the tip displacement (thus the displacements for the controller).

$$\begin{pmatrix} x_{stage} \\ y_{stage} \\ z_{stage} \end{pmatrix} = \begin{pmatrix} x_{tip} & 0 & 0 \\ 0 & y_{tip} \cos(\phi) & -z_{tip} \sin(\phi) \\ 0 & y_{tip} \sin(\phi) & z_{tip} \cos(\phi) \end{pmatrix} \quad (90)$$

The calculated values of the matrix from the model are adapted during calibration and are used as start parameters for calibration, because the displacement of the stage is assumed to be equal to the calibrated displacement of the tip apex. They can be calculated directly from the design values of the 3D-Nanoprobe and setup parameters.

For sake of completeness, the model of the alternative interferometer spot location on HS2 is calculated. With coefficient comparison from (88) the tip z-displacement of HS2, measured with an interferometer, can be expressed as

$$z_{tip} = z_{int2} - (c_{zy} \cos(\phi) - c_{zz} \sin(\phi)) \frac{\alpha_{2y}}{a_{\alpha 2y}} - (c_{xxbend} \frac{\beta_2}{a_{\beta 2x}} \pm x_{offset}) \beta_2, \quad (91)$$

using the in-plane bending compliance c_{xxbend} from (118) of the 3D-Nanoprobe. All other matrix components remain unchanged.

Start values of calibration coefficients for the hybrid detection system with the interferometer beam focused on HS1 using a CD-tip cantilever *CDR120* are taken from [106] and are given by:

$$\begin{pmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \end{pmatrix} = \begin{pmatrix} 0.277 \pm 0.024 & 0.0 & 0.0 \\ 0.0 & 0.213 \pm 0.015 & 0.0 \\ 0.001 \pm 0.001 & -0.082 \pm 0.017 & 0.021 \pm 0.001 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x} \\ S_{QPD2y} \\ S_{INT} \end{pmatrix} + \begin{pmatrix} 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.00006 \pm 0.00003 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x}^2 \\ S_{QPD2y}^2 \\ S_{INT}^2 \end{pmatrix} \quad (92)$$

To simulate a lateral (horizontal) offset of the interferometer beam location on HS1 $x_{offset} =$

$\pm 3 \mu m$ was used. Start values of calibration coefficients for the hybrid detection system using HS1 of a CD-tip cantilever *CDR70* with a nominal 70 nm tip widths are given by:

$$\begin{pmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \end{pmatrix} = \begin{pmatrix} 0.326 \pm 0.044 & 0.0 & 0.0 \\ 0.0 & 0.241 \pm 0.031 & 0.0 \\ 0.001 \pm 0.001 & -0.165 \pm 0.033 & 0.025 \pm 0.001 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x} \\ S_{QPD2y} \\ S_{INT} \end{pmatrix} \quad (93)$$

$$+ \begin{pmatrix} 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 \\ 0.00011 \pm 0.00004 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x}^2 \\ S_{QPD2y}^2 \\ S_{INT}^2 \end{pmatrix}$$

Despite the optimization of the 3D-Nanoprobe's structure, the larger calibration coefficients show the impact the softer CD-tip.

The small calibration coefficient for higher orders from small torsional motion of HS1 is neglected in the following. The calculated calibration factor matrix of the previously optimized 3D-Nanoprobe is given by:

$$\begin{pmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \end{pmatrix} = \begin{pmatrix} 0.271 \pm 0.021 & 0.0 & 0.0 \\ 0 & 0.215 \pm 0.014 & 0 \\ 0.001 \pm 0.001 & -0.085 \pm 0.018 & 0.023 \pm 0.001 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x} \\ S_{QPD2y} \\ S_{INT} \end{pmatrix} \quad (94)$$

Figure 5.2 shows the simulated tip displacement depending on the probing direction signal with $S_{QPD2x} = 1$ mV, $S_{QPD2y} = 0$ mV and $S_{INT} = 1$ V as dummy signals. The probing direction here is denoted as the incident angle from -90° to -90° in the zy-plane. Tip displacement in y- and z-direction is represented by two sinusoidal curves which are phase shifted to each other by about $\pi/2$. As expected the tip displacement in x-direction x_{tip} is unaffected. The coordinate system of the 3D-Nanoprobe is marked by an incident angle of 0° and the machine coordinate system is rotated by an incident angle of nominal -8° . The intersection of the tip y-displacement y_{tip} at an inclination angle of 0° with dashed line (zero) is to be calibrated. A S_{QPD2y} signal leads to a shift of the sinusoidal curves. Consequently, this detection principle is sensitive for 3D-tip-sample displacements.

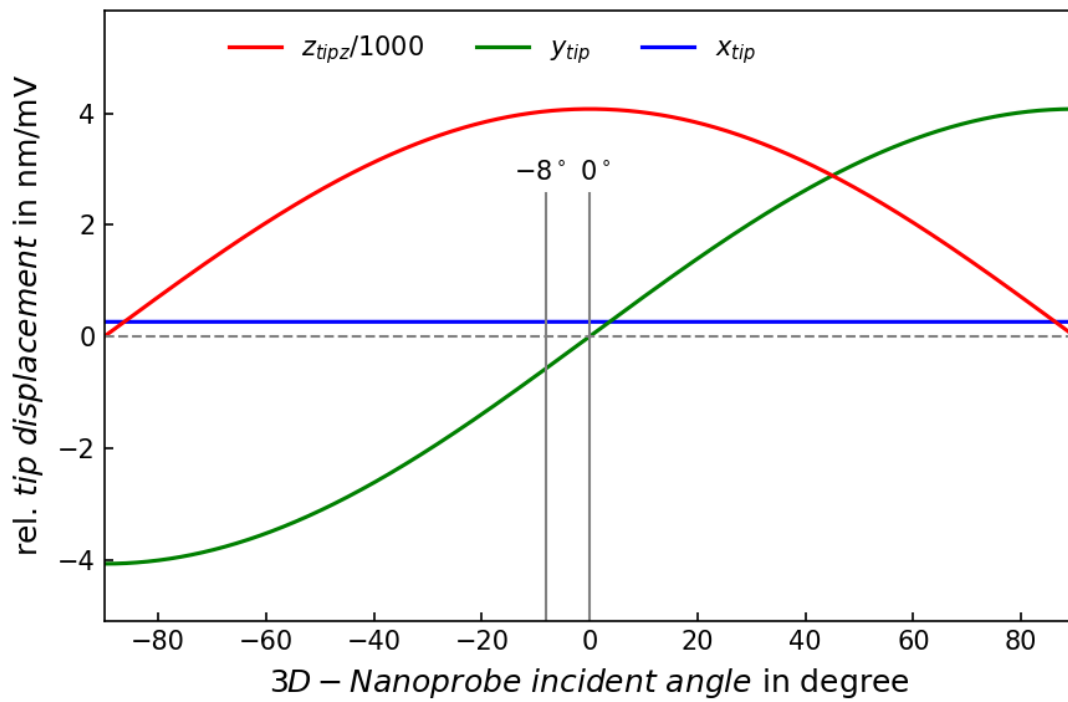


Figure 5.2: Semi-analytical modeled tip displacement of the 3D-Nanoprobe's detection system over the incident angle (probing vector orientation) using a probing signal of $S_{QPD2x} = 1 \text{ mV}$, $S_{QPD2y} = 0 \text{ mV}$ and $S_{INT} = 1 \text{ V}$. The incident angle at 0° marks the coordinate system of the 3D-Nanoprobe. A tilt of -8° marks the machine coordinate system (stage coordinate system relative to the probe).

5.2. Design of the detection system for the 3D-Nanoprobe

Based on its structure, the 3D-Nanoprobe is designed to operate with multiple detection systems. In this design, the detection system should detect the changes of the displacements or the inclination angles of the head sections of the 3D-Nanoprobe. A first attempt to detect the tip displacement of the 3D-Nanoprobe was made with a double dual optical lever (own research work [72]). This AFM-head build was abandoned, because of laser instabilities due to optical feedback inside one of the used pig-tailed laser diodes. The laser diodes were driven by a self-build ultra low noise diode laser driver. The laser driver design was inspired by the *Libbrecht-Hall* current driver. A second drawback of this AFM-head build was a ghost image of a cube-beamsplitter, forming an etalon with the cantilever reflection, which affected the signal of the position sensitive diode (while used with a low noise laser with long coherence wavelength). This artifact could also not be prevented in a simulation (with *Zemax*) or experiments by tilting the segmented photo diode or beamsplitter. Consequently, the probe's detected inclination angles appeared unstable with this previous AFM-head. The improved second AFM-head with a hybrid detection system is explained in detail in this chapter. General requirements for the true 3D-AFM head detection system are:

- To achieve proper sample investigation, the new sensor system is equipped with a microscope objective lens.
- For uncomplicated implementation into test setups, the detection system should provide a voltage signal.
- To achieve 3D-axis control, first values of the calibration matrix of the 3D-Nanoprobe (see section 5.1) of the detection system should be modelled.
- To be applicable for true 3D-Nanometrology, the developed 3D-AFM head must have a probing repeatability below 1 nm x 1 nm x 1 nm standard deviation (SD) in the orthogonal x-, y-, z-axis, respectively.

Figure 5.3 shows a sketched scheme of this AFM-head detection principle.

As already mentioned in section 5.1.2, the two orthogonal inclination angles of HS2 are detected with a dual optical lever. The beam is reflected from the reflective-coated top side of HS2 of the 3D-Nanoprobe and intensities are detected on the *QPD*. The principle of the optical lever is described in detail above in section 3.3.3. Using this kind of detection system allows compatibility for a great variety of commercial cantilevers and probes to be applied in this new AFM-head, e.g. from large and soft probes used in contact measurement mode to small cantilevers used for high-speed measurements. This angle detection system is combined with a differentially working displacement detection, here an interferometer. A description of the interferometers working principle, is given in section 3.3.2. As already mentioned, the interferometer detects the relative displacements between the base of the 3D-Nanoprobe and HS1 via $\Delta z = \Delta r_{base} - \Delta r_{HS1}$. The vertical displacement of HS1 is detected in differential mode with minimal environmental influences by using nearly the same optical path of the reference arm as for the measurement beam. Both beams are reflected from the reflective coated top of the 3D-Nanoprobe and the interference is detected, symbolized by the photodetector *PD*. The vertical displacement of HS1 is used to detect the tip displacement, because

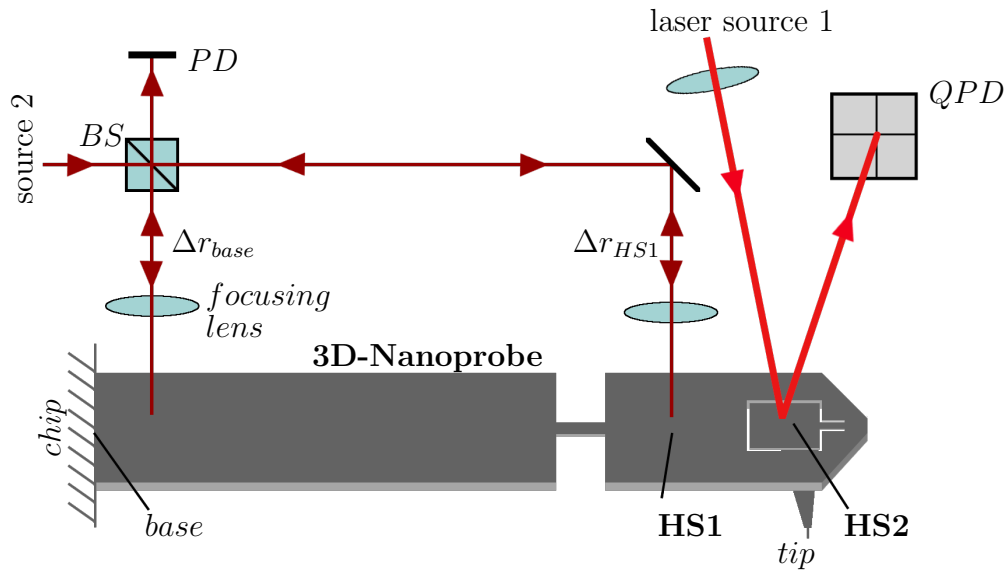


Figure 5.3: The detection principle is based on a combination of a **differential working** interferometer and a dual optical lever, where HS1 = head section 1, HS2 = head section 2, Δr_{base} = length of the reference arm, Δr_{HS1} = length of the measurement arm, PD = detector (photodetector). The dual optical lever laser source is denoted as (laser source 1) and the sectioned photodiode as QPD, (own image, reused from [106]).

the spot size of the interferometer is too large for HS2 (calculated and verified by experiment). A schematic drawing of the new 3D-AFM head setup is shown in **Figure 5.4**. Core of the setup is a microscope objective lens (*M Plan Apo NIR 50x, Fa. Mitutoyo*) used as the focusing lens for all optical beams. All optical beams can be adjusted in the focal plane of the microscope objective lens. The 3D-Nanoprobe is mounted in the focal plane of the microscope objective lens. The detection unit is tilt-able around the focal point (center of rotation) of the microscope objective lens for fine adjustment.

The infinity corrected microscope objective lens *M Plan Apo NIR 50x, Mitutoyo* has a long working distance of about 17 mm, a numerical aperture of 0.42, a par-focal distance of 95 mm and a focal length of 4 mm. The infinity correction from 480 nm to 1800 nm (wavelength) allows for a simple integration of collimated optical beams of the *detection unit* into the optical axis of the microscope objective lens. The optical path of the AFM head setup is divided by a long-path filter *LPF no. #69-879 (Fa. edmund optics)* with a cut-on wavelength of 600 nm and 1.05 mm substrate thickness into two parts. The first part is denoted as the optical path of the *detection unit* marked in gray in **Figure 5.4**. It contains two fiber coupled commercial interferometer heads (*SmarAct PICOSCALE, C01*) with *Michelson* interferometer type layout with internal reference mirrors, and the optical lever detection system with the QPD circuit. By that means, the detection system is realized by two interferometer heads working in differential mode and a dual optical lever. The 14 mm long *C01* cylindrical interferometer

heads are mounted next to one another with 2.8 mm radial offset to each other. Both heads are individually adjustable mounted at an angle to each other to separate the focused spots of the two beams in the focal plane of the microscope objective lens as shown in **Figure 5.5 A**. The collimated beams with about 1550 nm wavelength are focused by the microscope objective lens to a minimum diameter of 19 μm . The beams are reflected back into the fiber coupled *CO1* heads.

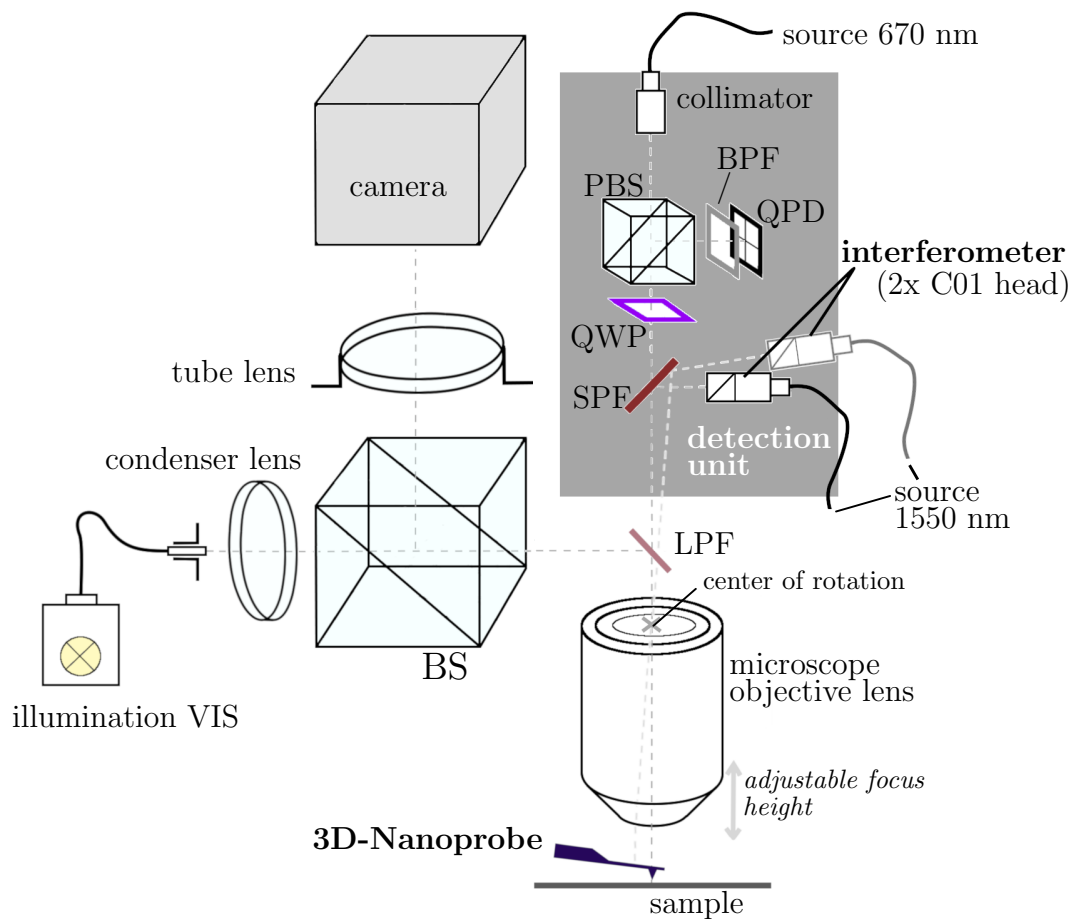


Figure 5.4: Drawing of the 3D-AFM head: The setup consists of an optical microscope and the detection unit (*marked in gray*) with two interferometer C01 heads, a polarising beam splitter (PBS), an optional bandpass filter (BPF), a segmented photodiode detector (QPD), a quarter-wave plate (QWP), a short-pass filter (SPF). The optical microscope consists of a microscope objective lens, a beam splitter (BS), an illumination system in the visible frequency range (VIS), a condenser lens, a tube lens and a RGB camera. Both optical beam paths are separated by the long-pass filter LPF, (own image, reused from [106]).

The separation distance from the base of the 3D-Nanoprobe to the middle of HS1 can be assumed to be within $90\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$, depending on the used probe. A beam separation angle of about 23 mrad is needed to separate the two interferometer beams in the focal plane of the microscope objective lens with a focus length of $f = 4\text{ mm}$ by about $95\text{ }\mu\text{m}$. The minimum distance for both beams at the *CO1* heads is given by 2.8 mm , considering a collimated beam diameter of 0.4 mm and a *CO1* head diameter of about 4 mm . With the given beam separation angle the first interferometer head is mounted at $117.9 \pm 0.5\text{ mm}$ distance from the back focal plane of the microscope objective lens inside a sleeve made of low expansion material alloy (e.g. invar). The second head is mounted closely behind (offset $15 \pm 0.5\text{ mm}$). The sleeve is depicted in **Figure 5.11**. A sectional view is shown in **Figure 5.5 B**. The short pass filter *SPF* couples the interferometer beams to the optical axis of the microscope objective lens (objective not shown here). A M10 thread combines the *sleeve housing tube* with the frame, here denoted as *housing SPF* which is part of the detection unit's frame. The *invar sleeve*'s position can be adjusted inside the *sleeve housing tube* by six M2 screws.

Both interferometer signals are digitally subtracted, working as one differential interferome-

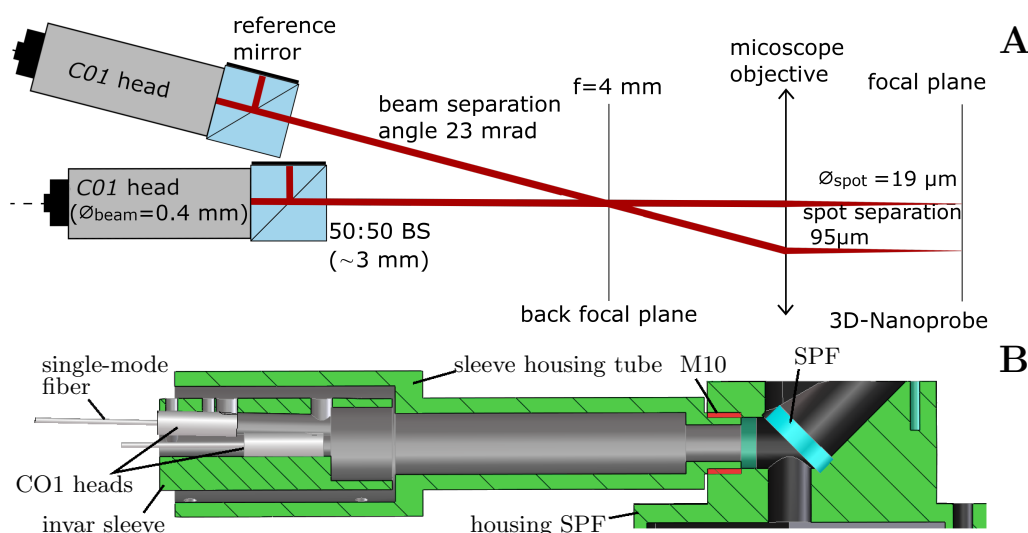


Figure 5.5: Interferometer beam separation in the AFM head. **A** shows a sketch of the collimated beams which are focused by the microscope objective lens to a minimum diameter of $19\text{ }\mu\text{m}$. Both beams have a separation angle of 23 mrad . The beams intersect at the focal plane of the microscopic objective lens and are reflected back into the fiber coupled *CO1* heads (own image, reused from [106]). **B** shows a sectional view of the CAD drawing of the 3D-AFM head's interferometer detection system, with short pass filter *SPF*, *sleeve housing tube* and *housing SPF*. The interferometer *CO1* heads are mounted in the *invar sleeve*.

ter. This was mandatory, because the interferometer used in this work, is a type of scanning wavelength interferometer, which principle is described in detail in section 3.3.2 and equation (41). Those type of interferometer requires a certain dead path to work, because the laser diode's tuning range is limited to a few 100 pm . The required dead path of the *SmarAct*

PICOSCALE device is denoted as working distance. The device in combination with the *CO1* head can work from minimal 13 mm distance to a maximum distance to a flat mirror of 5 m. Especially for long optical paths (counted here as dead paths) it is most useful to mathematically subtract two interferometer channels, because the device uses the same laser source and induced phase noise of the laser, fluctuations, environmental influences on the refractive index and wavelength drift are correlated and most of the noise can be subtracted from another. For similar optical paths, influences such as thermal expansion of the setup and overall environmental influences (e.g. acoustic) are reduced to a minimum because the dead path is shortened by simple subtraction. A disadvantage in using fiber coupled interferometers can be that thermal, mechanical induced stress and vibration, which induce intensity fluctuations, polarization changes and phase shifts, lead to measurement artifacts. By using two separated fibers in a differential working interferometer those influences might also superimpose, doubling the noise (constructive).

Both interferometer beams with a center wavelength of about 1550 nm are coupled into the optical path via a short pass filter *SPF* type *DMSP950T*, *thorlabs* with a cut-off wavelength of 950 nm at an angle of incidence (AOI) of 45°. The 3 mm thick substrate prevents the influence of back reflections and ghost images of the narrow optical beams of the interferometer and reduces stray light coupling back into the optical single-mode fiber. The reflected optical beams of the interferometers are coupled back into the single mode fibers of the *CO1* heads and the interfering beams of the reflected light of the internal reference mirrors and 3D-Nanoprobe is analyzed in the interferometer device, distant from the AFM-head to reduce possible heat-up of the setup.

The collimated light of the optical lever detection system passes the *SPF*. A polarization maintaining fiber (*P3-630PM-FC-2 - PM, FC/APC, thorlabs*) is used to couple the superluminescent laser diode (SLED) light with about 670 nm center wavelength into the triplet lens collimator (*TC12APC-633, thorlabs*) with about 2.24 mm beam waist diameter. A SLED from type *SLD-261-HP2-DBUT-PM-PD-FC/APC, SUPERLUM* with a spectral line width of about 9 nm at full width at half maximum (FWHM) is used as a source. The SLED shows good stability and is a compromise between low intensity noise and reduced coherence length. Consequently, it shows negligible influence of unwanted interference for the optical lever detection. The diode is driven by a commercial laser driver *CTL101-1, Koheron*. The collimator is adjusted for minimum intensity for the off-axis beam of the polarizing beam splitter *PBS*, maximizing the optical input power of the optical lever, to achieve a large summation signal. The collimated beam passes the polarizing beam splitter *PBS* and gets linearly polarized. The collimated beam gets circularly polarized by passing the zero order quarter wave plate *QWP* type *WPQ05M-633, Fa. thorlabs*. The *QWP*'s fast axis is rotated at 45° to the orientation of polarization. The beam passes the *SPF*, the *LPF*, and the microscope objective lens. The microscope objective lens acts as a high quality focusing lens and focuses the collimated beam on HS2. The 3D-Nanoprobe is mounted in the optical focus plane of the microscope objective lens. The reflected light is collimated by the microscope objective lens, passes the filters and gets perpendicularly linear polarized by being retarded a second time by the *QWP*. The *PBS* couples the beam out onto the quadratic photo diode (*QPD*) and displacement of the beam position is detected.

The second part and components are assigned to the *microscope objective lens*.

The second part of the optical path and remaining components are common for optical mi-

croscope in the visual range *VIS*. The *illumination* of the optical microscope is coupled with a multi-mode fiber via an SMA connector into the 3D-AFM head, to reduce heat-up of the system from the light source. A condenser lens ($f=100\text{ mm}$) is used to focus the light to the back focal plane of the microscope objective lens in the so called *center of rotation* and illuminates the sample and the 3D-Nanoprobe. Reflected light from the sample and probe with a wavelength of $<600\text{ nm}$ gets reflected from the *LPF* and passes the optical beamsplitter *BS* and the *tube lens*. The tube lens *MT-1*, *Fa. Mitutoyo* has a focal length of 200 mm . The $50\times$ magnified image is collected by the color camera sensor. A *UI-3070 cp Rev. 2* from (*Fa. IDS*) with $2056\text{ pixel} \times 1542\text{ pixel}$, a sensor size of $7.093\text{ mm} \times 5.320\text{ mm}$, and USB-3 interface was used for imaging. A color camera image is used because the *LPF* is imperfect and about 2% of the transmitted light is reflected to the camera. A fraction of reflected collimated red light of the optical lever and pilot laser of the interferometer with about 635 nm are focused by the *tube lens* on the camera sensor and is used for adjustment. The three red appearing laser spots are clearly visible on the 3D-Nanoprobe during the alignment process and are distinguishable from each other in the greenish appearing camera image. During pre-adjustment, the beams are shifted in the focus plane by rotating them around the so-called *center of rotation*, which is located on the back focal plane and in the center of the aperture of the microscope objective lens.

Preliminary tests during the construction of the AFM head showed that only a fraction of the optical input power reaches the QPD. The optical power reaching the QPD was measured to be $14\text{ }\mu\text{W}$ with a laser power-meter *Fieldmate*, *Fa. Coherent*, which is far below the expected $374\text{ }\mu\text{W}$, assuming a perfect mirror (reflectance of 100%). **Figure 5.6** shows the result of the optical power measurements in the AFM-head. The 3D-AFM head is a compact construction, consequently the optical power of the laser beam could not be measured on every location before and after each individual optical component.

The AFM-head was investigated for polarization and transmittance of the light beams. The collimated beam of the optical lever enters the setup with 1.15 mW optical power. Assuming equal front and back propagation of the light, the transmittance was estimated and the expected optical power at the QPD with a perfect mirror is calculated to be about $429\text{ }\mu\text{W}$. In reality, optical mirrors are oftentimes far from perfect. The used protected silver mirror has a nominal reflectance below 96% . It revealed, that the *LPF* has an impact on the dual optical lever detection system. The *LPF* acts as a quarter wave plate for light in the 670 nm region. The reflected beam is retarded a second time and is not coupled out to the QPD by the *PBS*. Consequently, the design of the AFM head was changed. The *QWP* was removed and the *PBS* was rotated by 45° around the optical axis by adapting the upper part of the detection unit, which contained the dual optical lever detection system, because the *LPF* position could not be changed. This rotation required also a rotation of the QPD circuit by 45° . After optimization of the 3D-AFM head's design an optical power of $367\text{ }\mu\text{W}$ is measured at the QPD, which is sufficient for our detection system. A bandpass filter *BPF* can be placed in front of the QPD if straylight, e.g. from the *illumination*, affects the signal. The interferometer does not affect the QPD because the silicon quadratic photo diode is not sensitive for eventual stray-light of infrared radiation (e.g. wavelength of the interferometer, about 1550 nm). In our setup, during measurement, the apparent displacements of HS1 and HS2 of a few 10 nm are small compared to the focal length of 4 mm and depth of focus of about $1.6\text{ }\mu\text{m}$

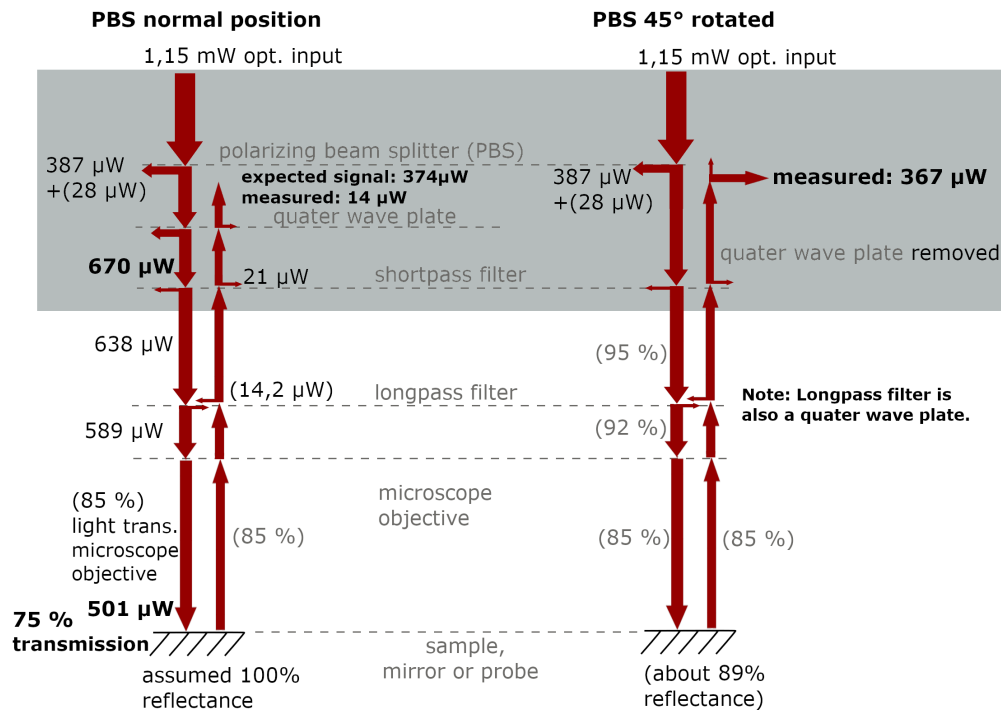


Figure 5.6: Transmission of the AFM head for visible light in the 670 nm wavelength region. To improve the transmission of light, the setup was changed by rotating the *PBS* and removing the quarter wave plate *QWP*. Calculated and deduced values are in parentheses.

of the microscope objective lens. Small changes of diverging and converging beams of the collimated reflected beams do not have a significant impact on the signal of the QPD. The optical lever will mainly be sensitive for the rotation of the diverging beam around the focus point on the 3D-Nanoprobe, detecting the off-axis displacements of the collimated beam, as intended. Because the microscope objective lens is a high quality lens, a spherical wave-front can be assumed for the far field of the diverging reflected light of the probe (*Hygens-Fresnel principle*).

The interferometer beams use only part of the microscope objective lens and converge with an F-number of about 10. Consequently the beam waist diameter is about $19.7 \mu\text{m}$ with a *Rayleigh* length of about $197 \mu\text{m}$. This implies, that the changes of the wave-front error of the interferometer during the probing is negligible. The collimated interferometer beams are refocused back into a single mode fiber. A calibration of the 3D-Nanoprobe's measured displacements reduces eventual linear errors.

The main part of the 3D-AFM head's computer-aided design (CAD) model is depicted in **Figure 5.7** in a sectional view. As already mentioned, the center part of this construction and design is the *microscope objective lens*. It is connected to the *main frame* via the housing of the *LPF*, which separates the optical light microscope and detection unit, here denoted as *mount LPF*. The *mount LPF* is rigidly connected with four M3 screws to the *main frame* and

has a M26 x 36 TPI thread to mount the *microscopic objective*. The main frame's upper part (manufactured as a mono-block) has a flexure hinge structure, which allows a tilt of the upper part around two horizontal orthogonal axes. The axes' positions intersect with the optical axis of the built and with the the back-focal plane of the *microscope objective lens*, to allow a fine adjustment (shift) of the aligned spots of the detection unit in the focus plane of the *microscope objective lens*. This flexure design can be used to realize an automatic adjustment with e.g. two piezoelectric micrometer screws. The *main frame*'s lower part has a rectangular shape with a bore of 36 mm in diameter for the *microscope objective lens* and incorporates functional surfaces and threads to mount components, such as the frame of the optical microscope and the mechanical stage with the *platform* for x-, y-, z-positioning to adjust the probe in the focal plane, here denoted as *frame optical microscope* and *adjustable mount for probe holder*, respectively. The *main frame* also includes the mounting area to connect the complete 3D-AFM head built to a measurement setup. The 3D-AFM head is designed with the option to be mounted from two sides by four M4 screws to an external frame, from the right side or from the backside with an L-shaped mount, which is not depicted here, but shown in **Figure 5.11** as *L-mount*. The *frame optical microscope* is rigidly connected to the *main frame* by four M3 screws and incorporates the *BS*, the *tube lens*, and (not shown here) the illumination system with the condenser lens. The *tube lens* is covered by the *housing tube lens*. The housing has a c-mount thread for mounting an extension tube with a camera.

The mechanical stage uses micrometer screws with 6.5 mm travel *148-205ST*, *thorlabs* and the *adjustable mount for probe holder* has travel range of about 1 mm x 1 mm x 1 mm in x-, y-, z-direction. Each direction applies two micrometer screws working in opposite direction. The elastic deformation of the carriers inside the stage to transfer the micrometer screws displacement facilitate an adjustable position with a resolution below micrometer. The stage structure is symmetrical (thermo-symmetrical design) to avoid temperature drift of the mounted probe and drift of the aligned laser positions relative to the probe's position. The first test with the developed AFM-head was done with a preliminary and rudimentary adjustment unit for the 3D-Nanoprobe and QPD-circuit, depicted in **Figure H.1** in the *appendix*.

The magnetic probe holder, shown as a schematic drawing and image in **Figure 5.14**, is from previous developments at PTB and has an incident angle of 8° . Three magnets attract the magnetic probe to the probe holder mount. The position is defined by three grooves in the probe holder, which interlock with three spheres on the holder mount. The magnetic probe holder has a modified alignment chip and a mechanical brass spring to mount the probe. The mounted probe can be mechanically actuated by two parallel oriented piezo crystals. For compatibility these probe holders will be used. The incident angle of 8° is too large to image the 3D-Nanoprobe in the focal plane of the microscope. Consequently, the base of the probe holder was tilted backwards to rotate the 3D-Nanoprobe parallel to the image plane and into the focus of all detection beams. To realize a sufficient incident angle for a cantilever shaped probe the 3D-AFM head is designed to be tilted forwards by 8° . The frame of the *detection unit* is mounted on the flexure mechanism of the *main frame* and consists of two parts. The first part is designed to implement the two interferometer beams into the optical path of the microscope objective lens via the *SPF*, location here denoted as *housing SPF*. The sleeve housing tube (**Figure 5.5**) of the *invar sleeve* is not depicted here. To facilitate a mounting of the 3D-AFM head from the right side the *SPF* and *invar sleeve* is rotated by 45° around the optical axis of the microscope objective lens. The second part at the top of the *detection*

unit is dedicated to the dual optical lever. The frame *housing PBS* belongs to the detection unit and carries the *PBS* and holds the collimator. The position adjustment of the QPD with front end circuit (not depicted here) is mounted to this frame, complementing the detection unit. The front end circuit is developed in section 5.3.

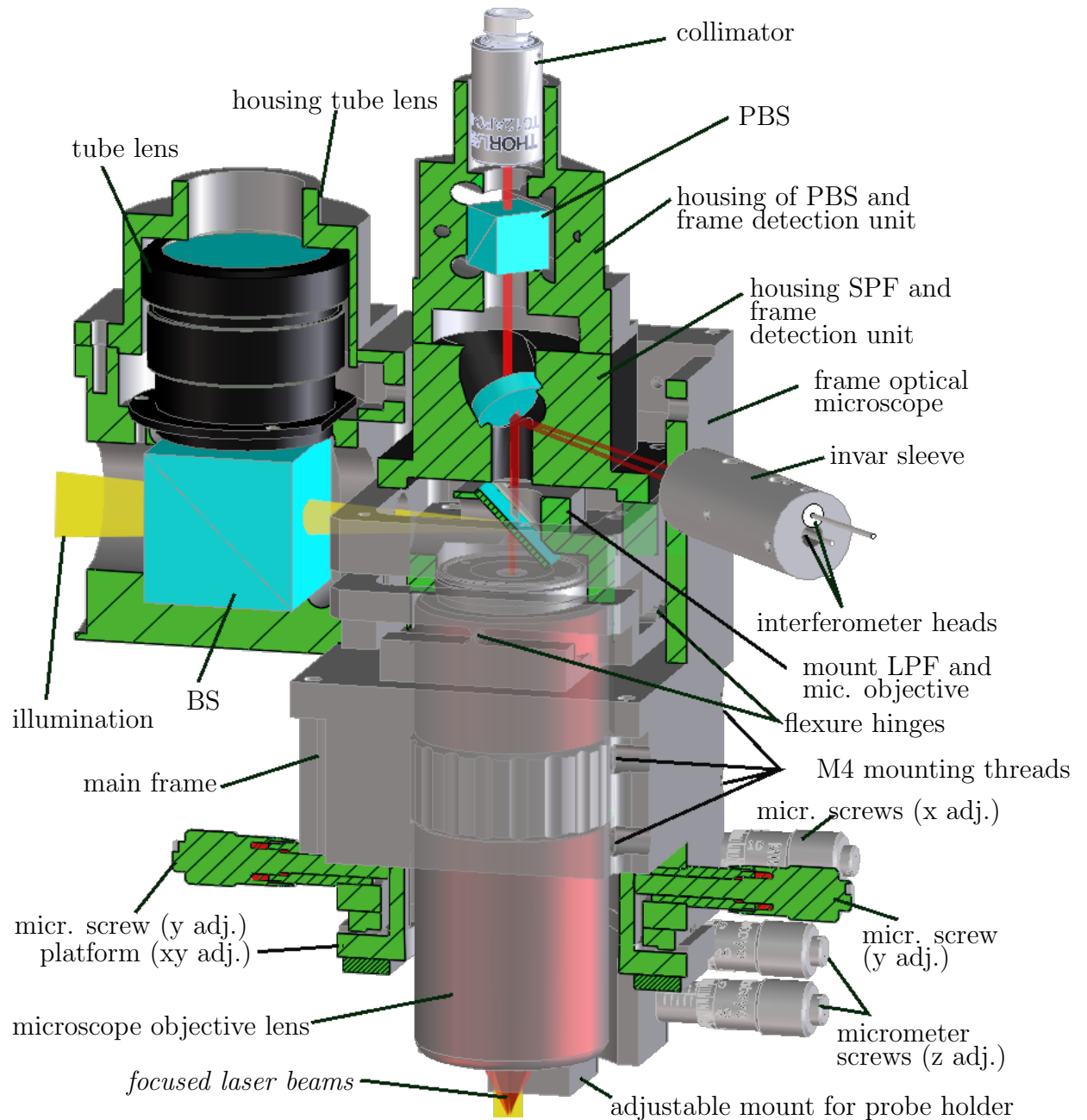


Figure 5.7: CAD model of the 3D-AFM head main part in sectional view with semitransparent parts and collimated laser beams (red). The 3D-Nanoprobe and probe holder is not shown here.

5.3. Development and test of the dual optical lever front-end photo diode circuit

The optical lever is designed to have a large optical (quasi noise free) amplification, but should also have a small spot that fits on the HS2 area (section 3.3.3). A optical lever setup used for SPM mainly consists of a collimator, a focusing lens and a position sensing unit, here a QPD with front-end circuit (section 3.2). The microscope objective lens was pre-selected because of a large working distance, reasonable imaging area and good imaging properties. The microscope objective lens has a focal length of 4 mm. Section 3.3.3 describes the optical lever in theory. From this description one can deduce that optical beam parameter, the optical detection unit and the amplification can be optimized.

To achieve a large signal amplification and easier adjustment, visible light was chosen for the light source of the optical lever. An SLED with about 670 nm center wavelength and relatively large spectral bandwidth of 9 nm was used to avoid interference pattern on the QPD surface. With the high-quality triplet collimator (*TC12APC-633*, *thorlabs*) a reasonable small spot size diameter of less than 4 μm was achieved and enables possible miniaturization of the HS2 and usage of small and narrow high-speed cantilevers in the future. This leaves only the electrical amplification to be optimized, because the optical transmission was already improved (see above). An improved reflected optical power of 367 μW was measured at the QPD position, using a flat mirror surface with high reflective-coating (**Figure 5.6**). The reflectance of a probe is expected to be less than 70 % of the reflectance of the flat mirror. The photo-sensitivity of the silicon-based QPD is assumed with 0.47 A/W for the SLED wavelength [199]. Consequently, the total collected photo-current from the radiant power is expected to be less than 121 μA . The photo-current is electrically amplified and converted to a voltage signal by a current-to-voltage converter or trans-impedance amplifier (TIA) circuit. For lowest noise and large signal to noise ratio the first amplification stage is very important and should have ultra-low noise, high bandwidth and low thermally induced drift. The second amplification stage generates the differential signals and the summation signal of all four amplified diode currents of the QPD and has lower requirements. The detected differential signals are proportional to the summation signal.

The new circuit and PCB is developed, to achieve lowest noise in the low frequency range up to about 50 kHz specifically for contact mode measurements and VAP technique. The circuit should have a relatively high bandwidth of >700 kHz (-3 dB) to be applicable in combination with tapping or intermittent mode, and to enable using this head for other commercial probes. To reduce thermal drift, passive parts were selected whose design value changes only within ± 25 ppm/K. For the first amplification stage metal foil resistors with ± 10 ppm/K and capacitors with *C0G* electrolyte were used. All devices are hand soldered.

The setup's electronics have an analog input range of ± 10 V from DC up to 200 Sa/s, with 16 bit resolution [200]. To utilize the available dynamic range an amplification factor of the circuit of 100 k is needed. The maximal expected voltage signal is therefore about 12 V, which slightly exceeds the analog input range on purpose, because those high-voltage signals can only occur during the manual adjustment. The summation signal is divided by four, to keep the summation signal within the analog input range. The analog range of the differential signals is sufficient, because the differential LR and TB signals are adjusted to be within ± 10 % (about ± 1 V) of the summation signal during the measurement, to stay in the linear region of the optical lever detection system. Each of the TIA should generate a maximum

voltage signal of about 3 V, if the radiant power is equally spread on the QPD segments. To reduce thermal heat generation of the circuit the lowest useful supply voltage of ± 12 V was chosen, enabled by the use of rail-to-rail output amplifier. During the measurements the amplifier will not be driven near the rail.

The operational amplifier (OPA) type for the QPD circuit is selected for:

- a low 1/f-noise corner frequency of below 50 Hz,
- a peak to peak noise of smaller than 250 nV in the low bandwidths range of 0.1 Hz to 10 Hz,
- a low voltage noise density below $6 \text{ nV}/\sqrt{\text{Hz}}$ and
- a low current noise density well below $0.4 \text{ pA}/\sqrt{\text{Hz}}$,
- a small input offset voltage (precision OPA) and a low input offset voltage drift below $\pm 0.5 \mu\text{V}/\text{K}$,
- a gain bandwidth product of more than 8 MHz,
- a slew rate of more than $4 \text{ V}/\mu\text{s}$,
- a small total harmonic distortion (THD) of below $1 \cdot 10^{-5}$,
- high input impedance for low dark currents to achieve low offset voltages.
- low input capacitance below 12 pF and
- capacitance driving capabilities (about 1 nF).

Moreover the devices should be commercially available, in production and manufactured in a hand-solder-able package size such as small outline integrated circuit (SOIC), preferably SOIC-14 or SOIC-8, which is also important for sufficient heat dissipation. The *AD8672 (analog devices)* was selected as the differential amplifier for the second stage of the circuit to generate the LR, TB, and SUM signals [201]. It shows no phase reversal, has a low power consumption, can drive relatively large capacitance and is unity gain stable. The *ADA4075-2 (analog devices)* can also be recommended as an alternative device for the *AD8672 (analog devices)* as the differential amplifier [202].

The circuit is shown in **Figure B.23**. As already mentioned, the first stage is a trans-impedance amplifier (TIA), the second stage an operational amplifier (OPA) configured as a differential or summation amplifier circuit. A feedback capacitance for the TIA of more than 2.3 pF should be used for the QPD which is a *surface mountable, segmented type Si photo diode S5980 (Hamamatsu)* with common cathode.

The QPD circuit can be configured in photo-voltaic or photo-conductive mode by connecting the cathode to GND or to a bias voltage (marked as *alternative* in **Figure B.23**). A bias voltage of about 3 V is used to lower the junction capacitance of the diodes for a higher bandwidth of the circuit. The bias current is driven by the second operational amplifier AD8672 (*U3B*). The bias voltage reduces the junction capacitance of the diode to a terminal capacitance of the *S5980* device from about 40 pF to about 15 pF. Despite a sufficient channel separation of

the *AD8672*, the second *AD8672* device with relatively stable SUM signal channel was chosen for the bias voltage.

Feedback resistors of 100 k Ω (metal film, selection $\pm 0.1\%$) and feedback capacitance of 3 pF (selection $\pm 10\%$) were selected, for sufficient amplification and bandwidth enhancement. The *OPA4140* (Texas Instruments) or the *AD867x* with four channels in a SOIC-14 foot print denoted as *U1A*, *U1B*, *U1C* and *U1D* is selected for the TIA stage and they will be compared to each other in the following regarding noise, especially for the important low frequency region from 0.1 Hz to about 50 kHz [203].

A simulation with *LTspice*, (*Linear Technology*) of the QPD circuit with an additional photo diode equivalent circuit was carried out to identify the noise contributions and help to select the TIA device. A shunt resistance of 1 G Ω and a capacitance value of 30 pF was used per diode quadrant, taken from the low reverse voltage region of the segmented photo-diode data sheet *S5980* (Hamamatsu), and from a QPD circuit approximation. The simulation of the TIA with a 3 pF feedback capacitance and 100 k Ω feedback resistor showed a -3 dB bandwidth of about 721 kHz for the *OPA4140* and 727 kHz for the *AD867x* with minor peaking. This cutoff frequencies are used in the noise calculation.

The calculated theoretical noise of the TIA for the important LR signal and TB signal of the QPD circuit is given by D in *appendix*. The total RMS voltage noise of the TIA using the *AD8674* device is given by 60.1 μ V, with a voltage noise density of 63.8 nV/ $\sqrt{\text{Hz}}$ over the full noise bandwidth of the device assuming a flat and even spectrum. The calculation included thermal, current and voltage noise sources, as shown in the **Table 5.1**. The calculated noise using the same circuit with the *OPA4140* device, gives a larger total RMS voltage noise of 83.0 μ V, with a voltage noise density of 88.5 nV/ $\sqrt{\text{Hz}}$ over the similar full noise bandwidth assuming a flat and even spectrum.

To compare this theoretical total noise density with the measured noise voltage values for the noise density, the higher frequency components need to be excluded, because the measurements could only cover the low frequencies (up to 50.17 kHz) dominated by flicker noise (1/f-noise contribution) and white noise [204]. This leads to a calculated voltage noise density contribution of the TIA to the QPD signal of 50.6 nV/ $\sqrt{\text{Hz}}$ and 41.0 nV/ $\sqrt{\text{Hz}}$ for the *AD8674* and the *OPA4140* device, respectively. The contributing noise of the following second stage is the noise of a differential amplifier (D). The calculated voltage noise density using the *ADA867x* is given by 27.3 nV/ $\sqrt{\text{Hz}}$ with 10 k Ω feedback resistor and 12 pF feedback capacitor to enhance stability (*C6-C10*). The calculated total noise density of the circuit for the differential LR and TB signals is given by summing the noise power of four TIA and the differential amplifier noise by 101.9 nV/ $\sqrt{\text{Hz}}$ and 87.2 nV/ $\sqrt{\text{Hz}}$ for the *AD8674* and the *OPA4140*, respectively. The *OPA4140* in comparison to the *AD8674* device shows a smaller noise density value considering a bandwidth of about 50 kHz and voltage noise sources of only white noise and 1/f-noise, which are the main present noise contributions in this bandwidth. Considering the total RMS noise over the full bandwidths, the TIA *OPA4140* shows larger noise values than the TIA *AD867x* device. Consequently, choosing the of OPA is not a trivial task. In this work, the lower frequency bandwidths are more important and despite the low 1/f corner frequency of the *AD8674* device, the *OPA4140* was selected as the TIA for experiment.

The leakage current of the input stage of the *AD8674* amplifier is not an issue because differential signals are measured and the current appears only as a small offset to the SUM

Table 5.1: Noise contributions to the QPD circuit dependent from the operational amplifier (OPA). The *AD867x* is a precision ultra low-noise OPV and the *OPAx140* is JFET input precision OPV. The first stage is a trans-impedance amplifier (TIA) with 100 k Ω feedback resistor. The voltage noise density (VND) values are calculated for the position signals (denoted as LR signal and TB signal in the document) from the root mean square (RMS) noise. The RMS noise is denoted here as noise. The devices are compared at different bandwidths (BW).

Device	thermal noise in μV	current noise in μV	voltage noise in μV	total noise in μV	total* TIA in $\frac{\text{nV}}{\sqrt{\text{Hz}}}$ over full BW	total* TIA in up to 50.18 kHz $\frac{\text{nV}}{\sqrt{\text{Hz}}}$
AD8674**	38.3	28.3	36.7	60.1	63.8	50.6
OPA4140	38.2	0.28	74.7	83.0	88.5	41.0

* noise density

Voltage noise density contribution of TIA feedback resistor: $40.7 \frac{\text{nV}}{\sqrt{\text{Hz}}}$

** as device *AD8672* also used as differential OPA: Calculated noise density for SUM signal is $11.3 \frac{\text{nV}}{\sqrt{\text{Hz}}}$ ($V_{\text{rmsDiff}}=32.8 \mu\text{V}$) and with 10 k Ω resistors for LR signal and TB signal $27.3 \frac{\text{nV}}{\sqrt{\text{Hz}}}$ ($V_{\text{rmsDiff}}=39.3 \mu\text{V}$), from D.

signal. In the PCB circuit 10 k Ω resistor arrays *RN1*, *RN2* and *RN3* are used to realize the differential and summing circuits. Two *very-low noise* operational amplifiers *AD8672 ARZ* were selected to generate the summation (SUM) signal and position signals left-right (LR) and top-bottom (TB) signals. The relative high resistor values were chosen for the second stage because of limited driving capabilities of the first amplification stage and possible heat generation. The contribution to the total noise of the second amplification stage is small and allows the use of those relatively large resistor values. To reduce high frequency noise in the power supply 100 nF decoupling capacitors were placed close to each active device. The PCB is made of FR4. All devices are hand-soldered. The PCB was designed with four copper layers, as shown in detail in **Figure B.23** denoted as *Top*, *center mid (CM) 1*, *CM 2*, and *Bottom layer* with a standard thickness of 35 μm . The TIA devices were placed on the *Bottom layer* side, close to the QPD, to reduce stray capacitance. Similar short track lengths were used for the feedback loop of the TIA and the edges of the footprints in the signal paths were rounded. The PCB was produced with tinned pads. Large resistors of 600 Ω protect the circuit from short cuts and reduce the influence of line impedance.

The QPD circuit's signals are fed into a simple clipping circuit to protect the input of the used Lock-in amplifier (input max. $\pm 3.3 \text{ V}$). The LR, TB and SUM signals are accessible at the SMA connectors of the clipping circuit. The soldered PCB is shown in **Figure 5.8**.

The soldered PCB front and back side is depicted on the left side in the figure. The PCB is mounted with two *M2 screws* to the 3D-AFM head. The fastening points are placed close to the QPD, to reduce the influence of thermal expansion of the PCB material on the position of the QPD. A support structure is glued to the PCB, to define the orientation of the PCB during the position adjustment when applied to the 3D-AFM head.

The soldered PCB circuit was investigated for dark noise. A spectrum of the LR signal and

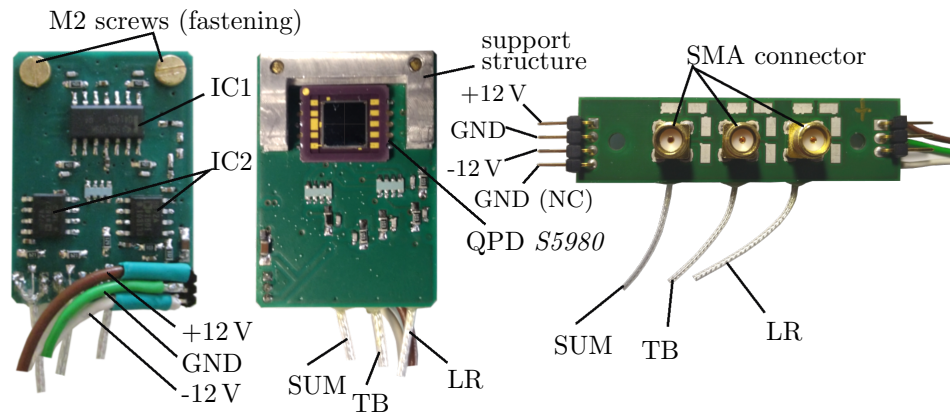


Figure 5.8: The QPD Printed Circuit Board (PCB) is depicted on the *left* from the front side and back side with the quadratic photo diode (QPD) *S5980*, *Hamamatsu*. The clipping circuit with three SMA connectors for the three signals denoted as SUM, LR, TB is shown on the *right*.

background noise is shown in **Figure 5.9**. The measured spectrum was dominated by white noise with a visible slight blue noise contribution. The additional noise might come from gain peaking at higher frequencies. The spectrum also shows noticeable peaks. While most of the peaks coincide with the background noise spectrum, the peaks at 331 Hz and 1264 Hz do not overlap. The true origin of these peaks could not be estimated, but the connected impedance seems to have an influence on it's position. The peaks appear on a different position, if another channel of the data acquisition card is used, and might originate from the data acquisition card itself [204]. This artifact has negligible contribution to the measured noise value. Considering this, a flat and even noise spectrum was achieved with a low 1/f corner frequency in the 10 Hz region.

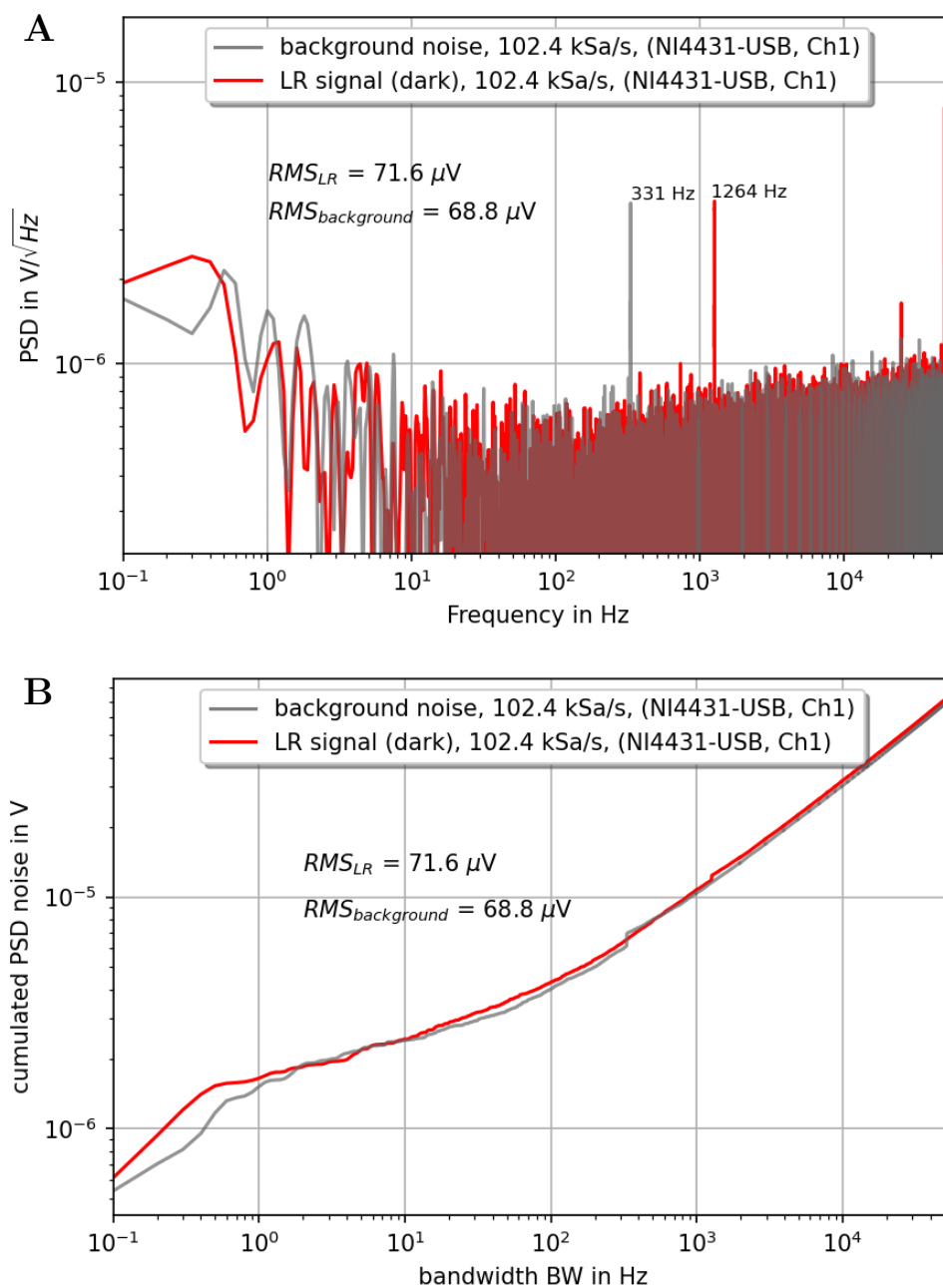


Figure 5.9: Power spectral density (PSD) of QPD Printed Circuit Board (PCB) of the differential LR and background signal. The distinct peaks in (A) are from environmental noise. The peaks at 331 Hz and 1264 Hz were investigated and seem to originate from the input stage of the data acquisition card (*NI4431-USB, Fa. National instruments*). The position depends on the output impedance of the measured source. The cumulative PSD is shown in (B).

The measured background RMS noise of the channel 1 of the data acquisition card [204], is given by $(68.66 \pm 0.50) \mu\text{V}$ ($k=2$). The measured noise value of channel 1 does not consider the device accuracy or systematic errors. The data acquisition card input channels have an input impedance of $200 \text{ k}\Omega$. The QPD circuit was supplied with a voltage of $\pm 12 \text{ V}$ by a self-build power supply (not shown here) using *LM337T*, *Texas Instruments* and *LM317 HVT*, *Texas Instruments*, which regulation response was tailored to the supply current of the connected QPD circuit. The QPD circuit bandwidth was briefly investigated showing a -3 dB bandwidth at about 700 kHz.

The RMS noise of the differential LR and TB signal with standard error of the mean was measured to be $(71.68 \pm 0.48) \mu\text{V}$ ($k=2$) and $(71.90 \pm 0.46) \mu\text{V}$ ($k=2$), respectively. The RMS noise of the SUM signal was measured to be $(69.28 \pm 0.44) \mu\text{V}$ ($k=2$). All the measured values include the background noise of the data acquisition card and gain error of $\pm 0.025 \text{ dB}$, which contribution is removed in the following. Consequently, the measured LR, TB and SUM signals of the QPD circuit are $(20.59 \pm 0.70) \mu\text{V}$ ($k=2$), $(21.34 \pm 0.68) \mu\text{V}$ ($k=2$) and $(9.29 \pm 0.67) \mu\text{V}$ ($k=2$), respectively. Assuming white noise and a bandwidth of 50.176 kHz (*NI4431-USB device*), the noise levels of the measured LR, TB and SUM signals are given by $91.9 \pm 3.2 \frac{\text{nV}}{\sqrt{\text{Hz}}}$, $95.3 \pm 3.1 \frac{\text{nV}}{\sqrt{\text{Hz}}}$ and $41.5 \pm 3.0 \frac{\text{nV}}{\sqrt{\text{Hz}}}$, respectively. The theoretical voltage noise density of the important LR and TB signals of $87.2 \frac{\text{nV}}{\sqrt{\text{Hz}}}$ show slightly lower noise values than measured. This was expected, because the depicted spectrum shows a positive slope (blue noise contribution), and in the theoretical noise value for low frequencies the gain noise peaking was neglected as well as other noise sources such as shot-noise from the photo diode and the noise of the bias voltage of the photo diode. The SUM signal is still within the determined standard error of the mean, but also shows higher values than predicted with $42.6 \frac{\text{nV}}{\sqrt{\text{Hz}}}$.

The illumination has a large impact on the noise. The expected theoretical noise induced by a current of $30 \mu\text{A}$ per diode originating from illumination increases the total RMS noise of the TIA (*OPA4140*) to $419.5 \mu\text{V}$ (noise density $447.3 \frac{\text{nV}}{\sqrt{\text{Hz}}}$).

The QPD circuit was optimized for the needed spectral range, shows very low noise and is ready for integration into the 3D-AFM head as part of the dual optical lever detection system.

5.4. Construction and test of the 3D-AFM head in the measurement setup

The 3D-AFM head is depicted in **Figure 5.10**. The complete structure of the AFM-head is made from duraluminium with high thermal conductance for fast thermal equilibration. The compact detection system with the interferometer and optical lever only takes little space in the 3D-AFM head design. To a great extent the outer dimensions of the 3D-AFM head are determined by the parts of the integrated optical microscope, for instance by a tube lens with 200 mm focal length or the microscope objective lens itself.

The design of the 3D-AFM head is shown in **Figure 5.7** in sectional view. The designed *flexure hinges* of the *main frame* were not activated (not fully manufactured), because this additional adjustment to align the beams of the detection system on a mounted probe was not needed. The *micrometer screws* to shift the mount of the *probe holder* to position the probes in the center of the camera image and in the focal plane of the *microscope objective lens* were sufficient and convenient. In the following, the assembly of the 3D-AFM head is described. First of all, the optical filters and lenses are mounted in the housings. The *LPF* and *SPF* were glued in place with a slow curing epoxy resin. After curing, the *mount LPF* is fixed to the *main frame* by tightening four M3 screws. The microscope objective lens is screwed into place and fixed to the *mount LPF*. The *sleeve housing tube* and the *housing SPF* from the frame of the detection unit are screwed together. The six M2 screws denoted as *adjustment screws* to adjust the position of the *invar sleeve* are screwed to contact the *sleeve housing tube*. The *housing SPF* is pre-assembled to the *main frame*. The *collimator* and *PBS* are mounted inside the *housing of PBS*. The *PBS* is clamped with two poly-amid screws to the *housing of PBS*. The polarization maintaining *fiber from the SLED* is connected with the *collimator*. An aperture of 2.5 mm is placed in front of the *collimator* to block the low intensity regions of the beams (Gaussian) and avoid stray-light artifacts. The effects of the aperture on the beam quality are visible and are taken into account in the simulation of section 3.3.4. The *collimator* is rotated to maximize transmitted intensity after the *PBS*. The *housing of PBS* is assembled to the *housing SPF* after checking the beam alignment. The *position adjustment of the QPD* is assembled with the soldered and tested low noise *QPD PCB* and they are mounted to the *housing of PBS*. The *QPD PCB* is positioned by the *position adjustment of the QPD* at about 5° tilt to the axis of the incoming collimated SLED beam to reduce reflected stray light of the silicon surface of the QPD reentering into the optical path of the detection system. The *QPD PCB* position can be adjusted in three directions. The relative beam position is adjusted in two directions with the adjustment screws denoted as *adj. LR* and *adj. TB* to achieve minimal differential LR and TB voltage signals. The SUM signal value should remain relatively constant during this adjustment process. The adjustment screws are oriented in a push pull configuration to use elastic deformations of the mechanics for fine adjustments. The remaining third direction is a rotation of the positioned *QPD PCB*. The rotation is used to compensate a misalignment of the probe orientation or misalignment in the 3D-AFM head of frames and housings, which leads to a cross-talk between the LR and TB signals. The *QPD signals* are passed out via three coaxial cables.

The manual adjustment stage is mounted to the *main frame* to adjust the position of the probe holder. As already mentioned, the six *micrometer screws* facilitate to adjust the mounted 3D-Nanoprobe in three orthogonal (x-, y-, and z,-) directions.

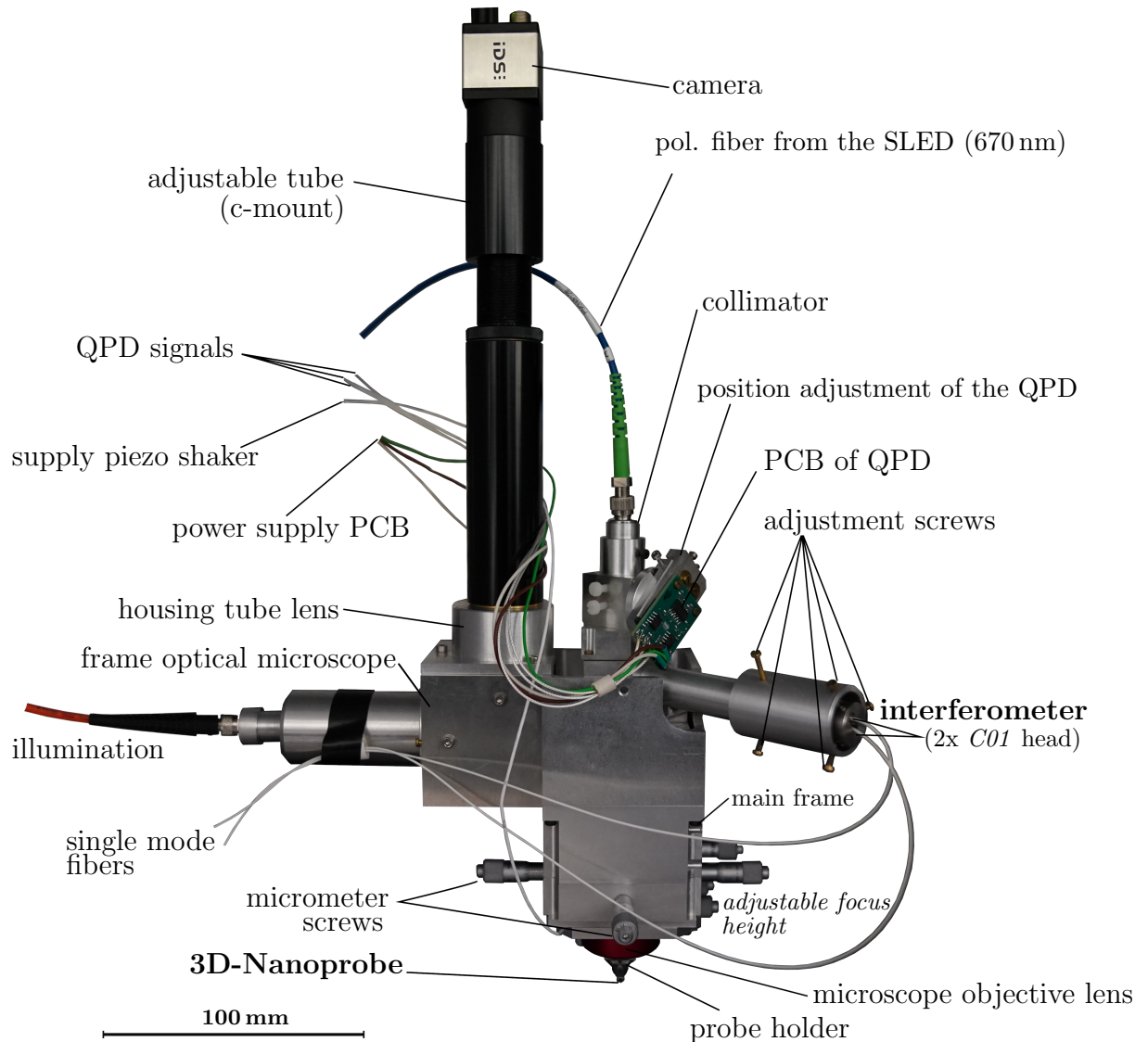


Figure 5.10: The 3D-AFM head consists of the optical microscope with the microscope objective lens, camera, tube lens, and illumination, and the detection system. The detection system is realized by two interferometer heads working in differential mode and a dual optical lever detection unit with a QPD. The 3D-Nanoprobe is adjusted in the focal plane of the microscope objective lens by six micrometer screws.

The *BS* is clamped onto the *frame optical microscope* and the tube containing the *condenser lens* of the illumination is set up (see **Figure 5.4**) and is also fixed to the *frame optical microscope*. The multi-mode fiber is connected and the illuminating light is focused in the back focal plane of the *microscope objective lens* by shifting the position of the fiber end relative to the *condenser lens*, (not shown in detail here). The *tube lens* and *tube lens housing* are mounted to the *frame optical microscope*. The *tube lens housing* connects the *adjustable tube* of the *camera* with the frame structure, using a *c-mount* thread. The frame structure reduces mechanical stress on optical components (e.g. *tube lens*). The *camera* is mounted on top of the 3D-AFM head on the *adjustable tube*. The *camera* position is adjusted to the focal plane of the *tube lens* to acquire a high quality image and to examine the focal plane of the infinity corrected *microscope objective lens*. Two *C01 interferometer heads* are clamped inside the *invar sleeve* and are adjusted to intersect at a distance of about 117.8 mm with a focusing screen (not shown here). The distance is measured from the position of the first interferometer head. Alternatively an intersecting angle of about 23 mrad can be used, as depicted in **Figure 5.5**. Finally, the *invar sleeve* is placed in the *sleeve housing tube* and adjusted for maximum signal intensity with the six *adjustment screws* using the reflected light of a mounted probe. The 1.5 m long, delicate, single-mode optical fiber cable of the interferometer heads are routed in soft bends to the left side of the head. The position of the *BS* can be modified to accomplish a high quality camera image, showing all focus points of the detection unit in the field of view together with the probe. The characteristics of the optical microscope part of the 3D-AFM head is tested. The 3D-AFM head is ready for integration into a test measurement setup.

Figure 5.11 shows the complete 3D-AFM head mounted in the test setup for characterization measurements. The test setup is part of the measurement setup in the laboratory depicted in **Figure 6.1**. The test setup is used to test the 3D-AFM head's detection units in the measurement environment regarding noise, stability and signal delay.

A pre-tilt angle of 8° is incorporated in the L-mount that connects the *main frame* of the 3D-AFM head with the *coarse z-stage HUMES 60-12* from *OWIS GmbH*, which is used for the coarse step-wise approach onto the sample surface. To keep the measurement loop small the *main frame* is directly connected to the *L-mount*. The denoted *coarse z-stage* is combined with a goniometer stage to rotate other connected AFM-heads. The goniometer stage is not used in this thesis (disabled) and is therefore not of any interest. The *coarse z-stage* is fixed to a *portal frame* made of solid duraluminium beams with 100 mm x 100 mm profile. The *portal frame* is connected to an aluminium *base plate*, forming the stiff mechanical frame of the setup. The *base plate* is placed on a *vibration isolation table* with active air bearings for damping and leveling. The *vibration isolation table* decouples the setup from ground vibrations. A *coarse xy-stage KT305-EDLM* from *Steinmeyer Mechatronik GmbH* is mounted in the center of the setup for coarse positioning of the *6-axis piezo stage* over a travel range of 210 mm x 210 mm with a repeatability of about 1 μm . An adapter plate is screwed to the moving platform of the *6-axis piezo stage* to carry various mounted *samples*. The scan range of the special built (*Physik Instrumente GmbH*) low noise *6-axis piezo stage* is 12 μm x 12 μm x 10 μm in x-, y-, z-direction, respectively. During measurement, this sample scanning AFM setup controls the *6-axis piezo stage's* displacement, whereas the *coarse xy-stage* is disabled and the *coarse z-stage* is not used.

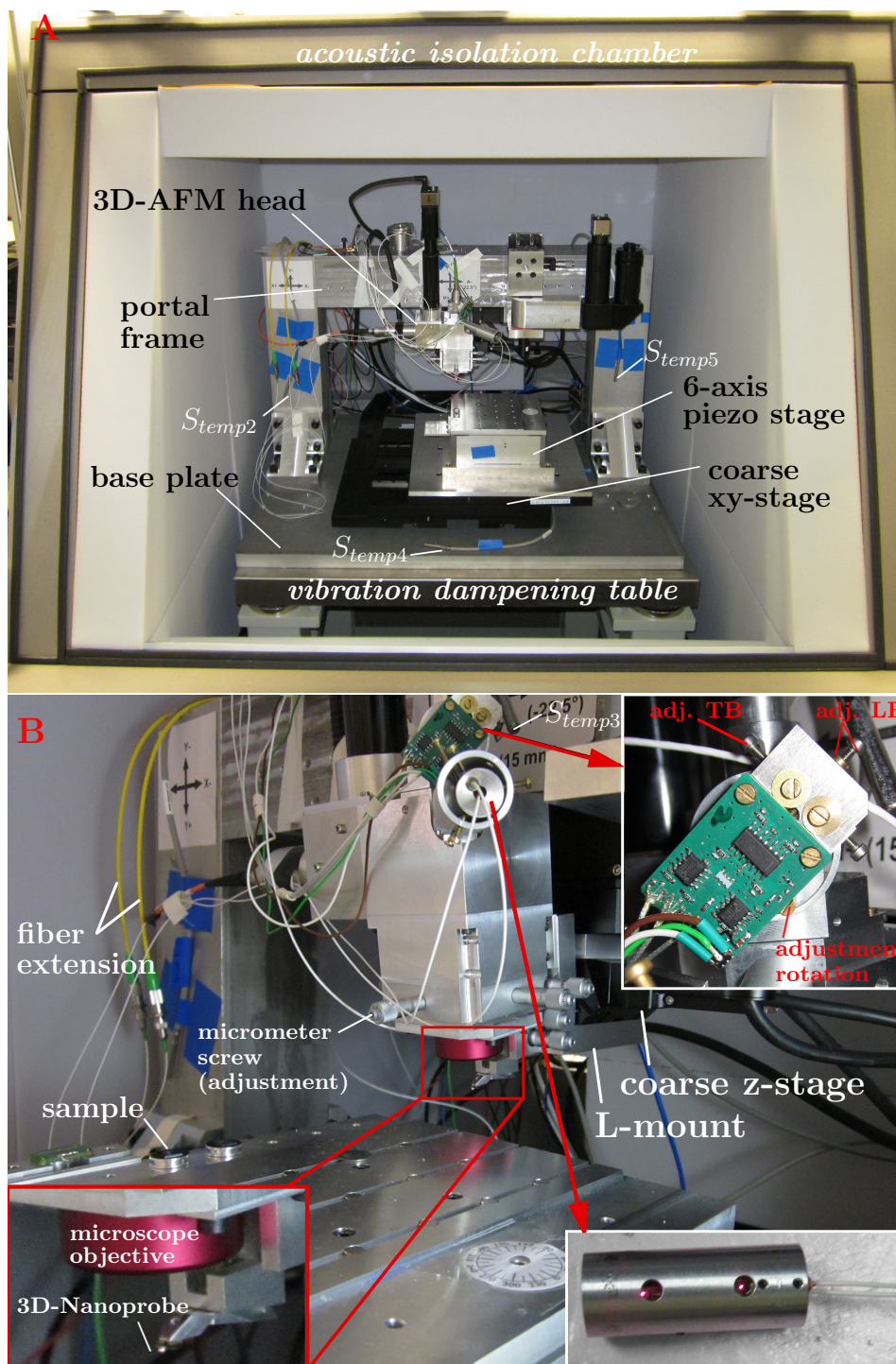


Figure 5.11: The measurement setup with the developed 3D-AFM head inside the acoustic isolation chamber with acoustic damping foam (A). (B) shows the developed 3D-AFM head from the side. In the *upper right* the QPD-circuit is shown in detail with the adjustment mechanism and four temperature sensors S_{temp_i} ($i=2,3,4,5$). The *lower right* detail shows the invar sleeve with the mounted angled interferometer heads. The *lower left* inset image shows the mounted 3D-Nanoprobe below the microscope objective lens (red) in detail.

The complete AFM measurement setup with the mounted 3D-AFM head is placed inside an *acoustic isolation chamber* to dampen/reduce acoustic influences, to thermally isolate the setup from sudden environmental changes in the laboratory, reduce air convection and protect the measurement environment from dust, dirt, particles and humans. The *acoustic isolation chamber* is not air tight, which signifies that ambient air pressure changes of the laboratory acting on the measurement setup are not inhibited. The temperature is measured at four positions with four temperature PT100 sensors by the *PicoLog PT-104-4* from *Pico Technology Ltd.*. Temperature sensor S_{temp4} is placed on the *base plate* to measure the equilibrated temperature in the middle height of the chamber. S_{temp2} and S_{temp5} are fixed to the left and the right column of the *portal frame* to measure the temperature of the *portal frame*. The remaining temperature sensor S_{temp3} is placed above the 3D-AFM head nearest to the detection unit to measure the temperature changes from the 3D-AFM head. To avoid an influence on the position of the 3D-AFM head by the stiff temperature sensor cable only the air temperature is measured. In general, mechanical coupling to the 3D-AFM head is reduced by using bendable signal cables soft power supply cables and flexible optical cables. All cables are connected to the portal frame and are extended to reach out of the *acoustic isolation chamber* with extension cables. The optical fiber cables of the interferometer heads were extended by 5 m to reach the interferometer *SmarAct PICOSCALE* device outside of the acoustic chamber of the measurement setup. The optical fiber cables of the illumination and the fiber cable of the optical lever are not extended. The extension cable length for the coaxial signal cables and power supply of the QPD circuit is about 3 m.

In the following, the optical lever signals and interferometer detection unit of the 3D-AFM head are tested individually.

5.4.1. Test of the optical lever detection system

To test the optical lever principle and verify the focal length $f = 4 \text{ mm}$ of the microscope objective lens a tilt-able flat mirror (protected silver coating, flatness $\lambda/10$ at 633 nm) was mounted in the focal plane of the microscope objective lens. A test wavelength of about 635 nm was used. As it was designed, the collimated light is focused by the microscope objective lens, is reflected by the flat mirror and collected on the QPD. The QPD is replaced by a camera *µeye UI-3580CP-C-HQ*, (*IDS Imaging Development Systems GmbH*). By changing the tilting angle of the flat mirror the imaged beam position on the camera shifts. The beam center position in pixel of the reflected collimated beam was determined with a simple canny edge detector and Hough circle transformation in *python*. The beam's center displacements are received via the camera sensor's pixel size of $2.20 \mu\text{m}$.

For each incident angle the mirror was adjusted in the focus plane of the microscope objective lens using the camera of the optical microscope of the 3D-AFM head. The smallest appearing spot diameter indicates the focus plane. **Figure 5.13** shows the spot of the optical lever. The brightest spot in the camera image of the 3D-AFM head marks the actual spot location. **Figure 5.12** shows the shift of the beam center over the tilting angle. This simple test shows that the slope of the measured beam center displacement over the incident angle of the probe (mirror) corresponds to a lens with a focal length lens of 4 mm up to about 8° . The visible offset to the ideal curve can be explained by a shift of the zero angle of the used flat mirror in the experiment. Above 8° the reflected collimated beam is cut by the aperture of the microscope objective lens showing a smaller beam center displacement, which was expected by geometric optics. With this chosen collimated beam diameter, it is the limiting incident angle or inclination angle of the probe for the optical lever. This test validates the optical lever detection unit and optical amplification for static beam displacements.

All other spots in the camera image of the optical microscope of the 3D-AFM in **Figure 5.13** are presumably reflections from the optical filter of the camera and possibly the *BS* of the setup. The camera sensor acts as a 2D grating with a pitch determined by the pixel size of $d_{cam} = 3.45 \mu\text{m}$. The spot positions can be calculated by the simple equation for grating maxima, given by the well known formula $\sin(\theta) = \frac{m\lambda}{d_{cam}}$, with the wavelength λ and diffraction angles θ for specific diffraction orders m . The first order denoted as *1st* ($m=1$) is calculated to appear at about 11.2° . One can assume the diffracted beams are reflected back onto the sensor, because the diffraction pattern is imaged. A commercial cantilever *PPP-NCLR*, (*Fa. NANOSENSORS™*) was mounted in the image plane to show that the pattern does not originate from a reflective surface. The first order beams are imaged at a distance of $1107 \mu\text{m}$. This implies, that the reflective surface is at a distance of 2.3 mm in front of the sensor. The only optical interface at this distance is the infrared cutoff filter of the camera, which reflects the focused red light of the optical lever beam. Consequently, the imaged pattern artifact does not originate from the detection system or 3D-AFM head. So far, it cannot be prevented with this camera, but the appearance can be reduced by shortening the exposure time.

The commercial cantilever *PPP-NCLR*, (*Fa. NANOSENSORS™*) shown in **Figure 5.13** was used to test the optical lever dynamically. The cantilever was excited near its first resonance frequency. 200 mV was used to drive the small piezo-actuators from the cantilever holder for excitation of the cantilever. The piezo actuators denoted as *shaker piezos* in the following and the *probe holder* are shown in **Figure 5.14**. The QPD circuit was rotated slightly so the main

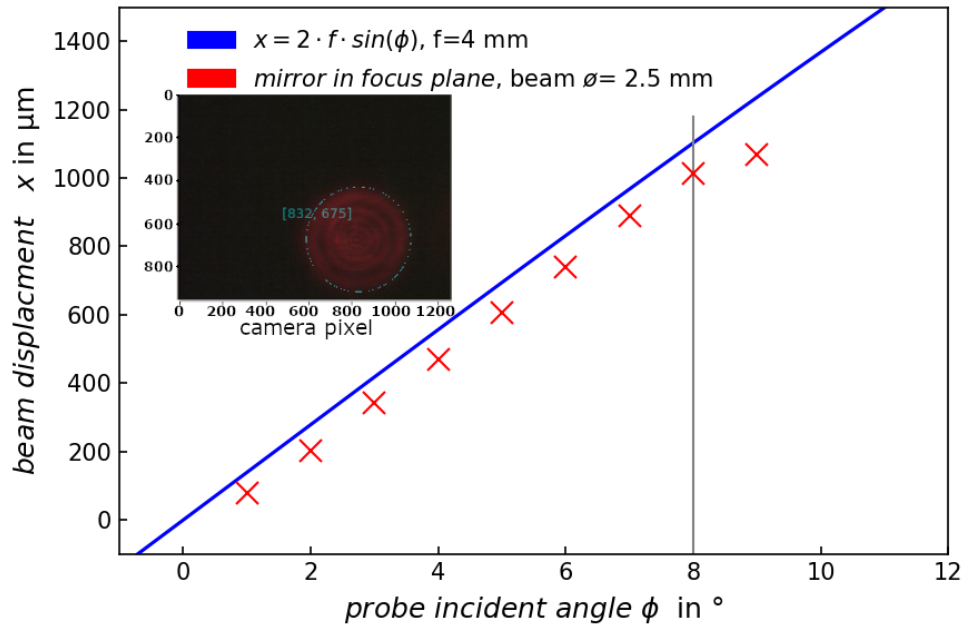


Figure 5.12: Beam displacement of an optical lever using the microscope objective lens with $f=4 \text{ mm}$ (Mitutoyo, long working distance 50x). The displacement of the reflected beam is measured by a camera placed in the position of the QPD. The camera image is shown in detail with the pixel number (location) marking the center of the collimated beam. Above 8° the beam is cut by the aperture of the microscope objective lens.

bending signal and a small torsion signal are measured simultaneously. Both show expected clean sine-waves of about 150 kHz with a significant phase delay of about $\pi/2$ to the piezo driving signal originating from the resonating cantilever. The noise was tested previously during the development of the QPD circuit (section 5.3). The developed optical lever is ready to be applied for measurements of the 3D-AFM head properties, such as the influence of temperature changes on the QPD signals are tested in the following, to evaluate the thermal stability of the detection unit.

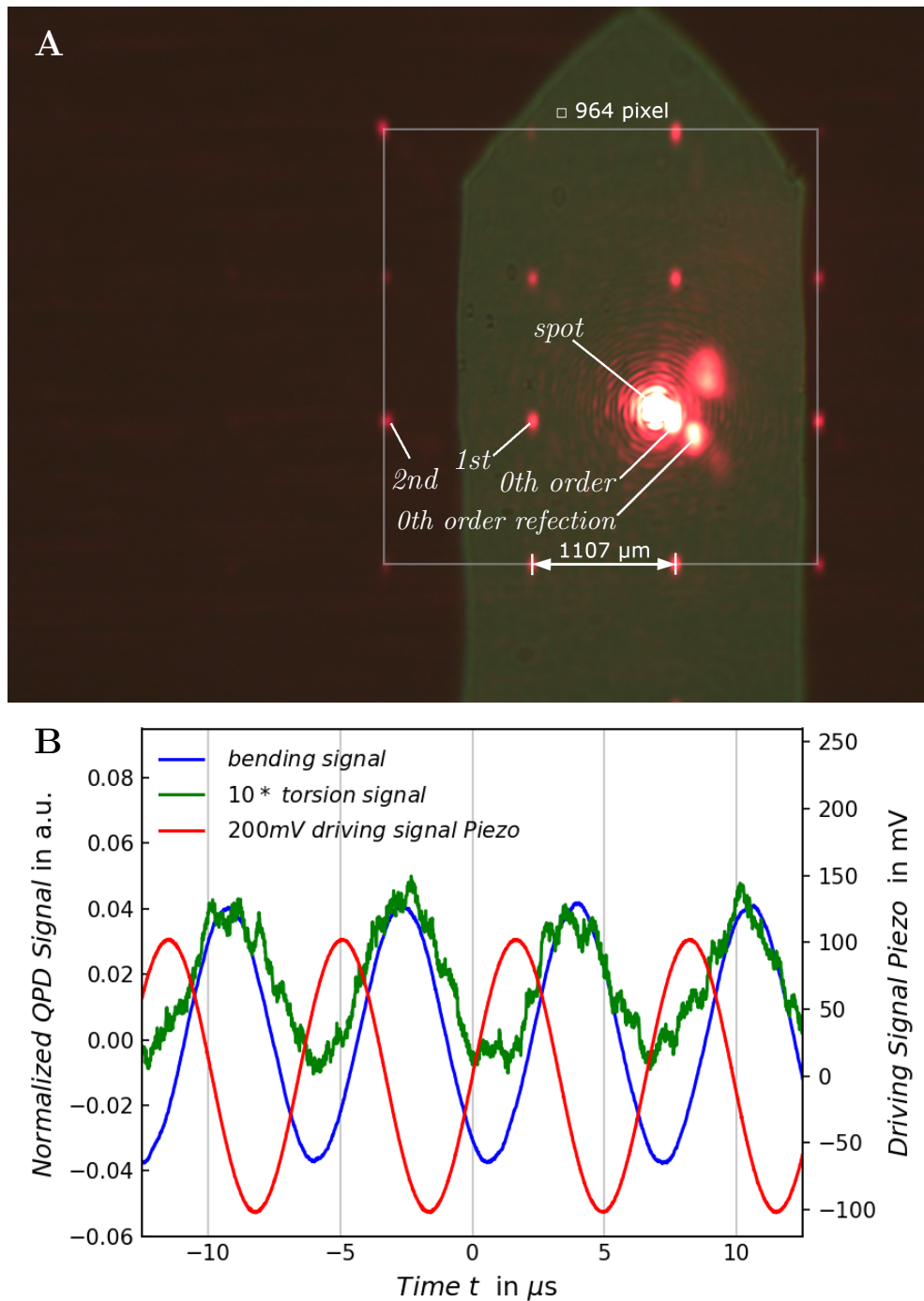


Figure 5.13: Optical lever spot and raw oscillating signal: A shows the optical microscope image with a mounted *PPP-NCLR*, (*Fa. NANOSENSORS™*) cantilever probe. (B) shows the signal of the exited cantilever probe, measured by the optical lever.

5.4.2. Test of the differential interferometer detection system component

After the invar sleeve with the C01 heads is placed in the 3D-AFM head, it adjusted according to the probe beam spot positions on 3D-Nanoprobe and signal quality with the six *adjustment screws*. The arrangement of the *adjustment screws* allows a positioning of the invar sleeve in 6 degrees of freedom. The position of the 3D-Nanoprobe is determined by the spot of the optical lever. The 3D-Nanoprobe can be positioned in x-, y-, and z-directions over the full field of view with the six micrometer screws, in case a new mounted probe is adjusted to the already aligned optical beams. This is in contrast to the general procedure, where a new probe requires a new alignment of the optical beam of the detection system.

The digital distance filter value of the interferometer device (*SmarAct Picoscale*, see *appendix*) is set 15 mm to 20 mm before and after the absolute measured optical distances of the two channels of the interferometer device, depending on the signal quality. The signal quality can be seen by the shape of the depicted Lissajous figures of the channels in the user interface of the device. A star-shaped Lissajous figure indicates multiple reflections causing higher order non-linearity. The used microscope objective lens with multiple optical interfaces (lenses) is causing such higher order non-linearity, despite being optimized for infrared. With careful adjustment those disturbing interference can be reduced, but cannot be avoided, and the overall signal is optimized. A signal intensity of more than 50 digits in signal value of the device per channel is recommended. The value is indicated by the device during the adjustment process, to achieve a sufficient signal for the measurement. After the manual adjustment process, the device will perform an automatic correction of the lower order quadrature errors. Typical optical dead-path values of channel 1 and channel 2 (spots at the base and HS1) are about 225.0 mm and 239.8 mm. As designed, these two interferometer with long dead-paths are used as one differential interferometer to reduce environmental influences on the measured distance. The typical remaining dead-path is now reduced from about 225 mm by a factor of 15 to about 14.8 mm. This facilitates that the 3D-AFM head can be used under normal lab conditions.

The interferometer detection system needs to be tested before it is applied on probes. **Figure 5.14** shows the sketched test setup. The *probe* is mounted on the *probe holder* by clamping it with a *spring* to the *alignment chip*. The *alignment chip* and *probe* can be exited by the two parallel oriented *shaker piezos*. The *probe holder* has three magnet and three alignment grooves which interact with three spheres on the *holder mount* to fix it. The magnet pull the three spheres into the alignment grooves to statically determine the orientation after a *probe holder* was changed. The *holder mount* has four mechanical spring contacts which connect to the *probe holder* contacts. The four contacts are denoted by the appearance of the connection cable of the *holder mount* as *electrical contact red, green, black and white*. One *shaker piezo* is connected to the *electrical contact red, green* the other *shaker piezo* is connected to the *electrical contact black, white*. As a result both *shaker piezos* can be exited individually for bending and torsional modes of the mounted probe, as described for instance in [13]. An image from the bottom side of the *probe holder* is shown in **Figure 5.14 B**. To test both interferometer channels a 3D-Nanoprobe is mounted and the laser spots are focused with the help of a so-called probe beam (red) to the *base (Channel2)* and *HS1 (Channel1)* region. The mounted 3D-Nanoprobe is depicted in detail in **Figure 5.14 D**.

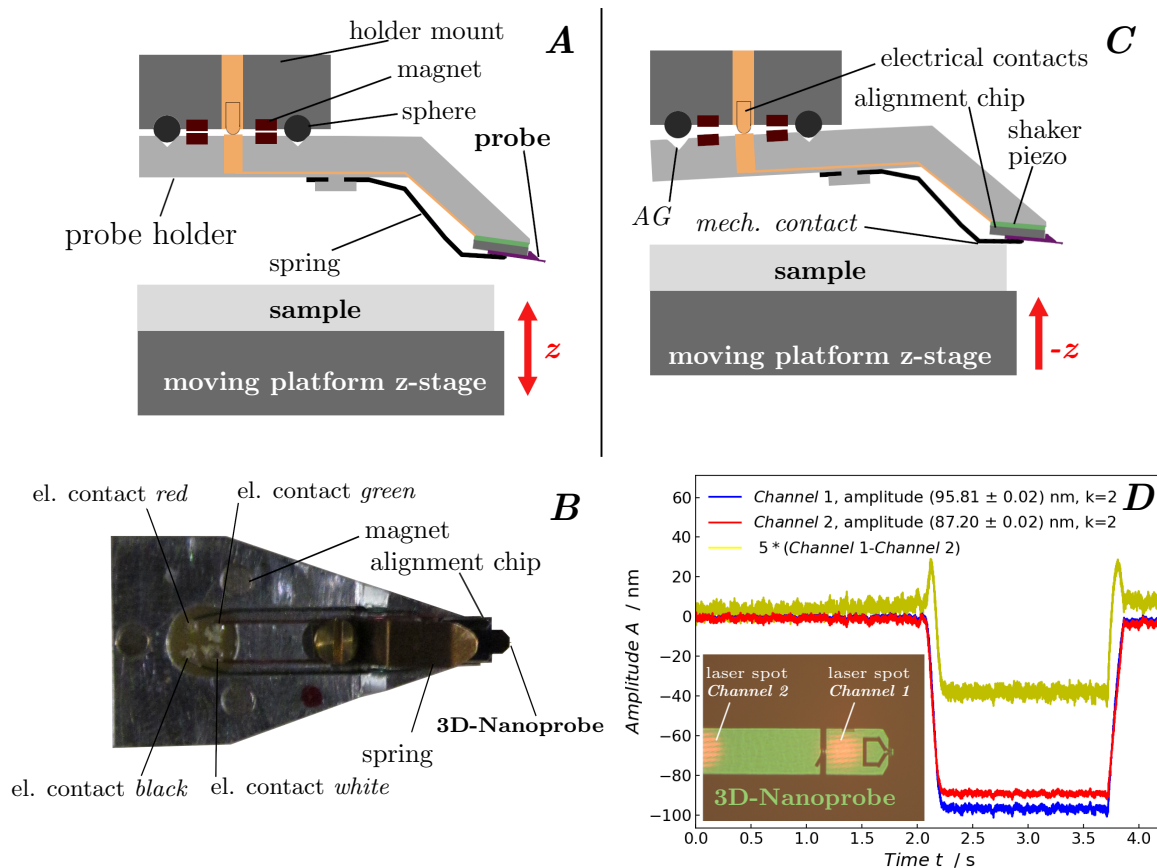


Figure 5.14: Passive safety mechanism test for fatal probing error and signal test of adjusted interferometers by displacing a probe with the *probe holder*. The simplified shematic drawing in **A** shows a side view of the *probe holder*, which is fixed by magnetic forces and positioned with three *spheres* and *alignment grooves (AG)* on the *probe holder mount*. **B** depicts the *probe holder* from the bottom side. Sketch **C** show the displaced *probe holder* with mechanical contact in side view. The interferometer signals of *Channel 1* and *Channel 2* are shown in the graph **D**. The differential signal (*Channel 1-Channel 2*) is here small because the probe is displaced, not just the probes tip region. The detail in **D** shows the optical microscope camera image of a mounted *3D-Nanoprobe* with laser spots of the probe beams.

An indirect approach is performed as a first test, because a 3D-Nanoprobe is delicate. In addition both channels need to be tested, consequently the complete probe needs to be displaced. An analog signal conversion factor of 10 nm/V for the 16-bit DAC (data rate max. 100 kHz) of the available digital IO of the breakout box (interferometer device) was used. An internal 20 kHz band pass filter and a 9.77 kHz sampling rate was used for the measurement. The *spring* clamps the *probe* on the *alignment chip*. This magnetic probe holder was used in previous builds and is included in the device for compatibility with other AFM-heads at PTB. The *probe holder* breaks free (as indicated in the sketch **C**, side view), if a large force of about a Newton is applied in the region of the *alignment chip*. This reduces a hard or forceful contact between the AFM-head (*probe holder*) and *sample surface*, thus avoids damage of the instrument setup e.g. *z-stage*. This built-in passive safety mechanism of the *probe holder* is used, which allows a tilt of *probe holder* to avoid a hard and forceful contact applied to the end of the *alignment chip* region, during a malfunction. A fine positioning *z-stage* is used to displace the complete probe holder by gently pushing onto the soft *spring*, as depicted in **Figure 5.14 C**. The measured displacements of the *base* and *HS1* are depicted in **Figure 5.14 D**. As expected, the *base* shows a smaller displacement than the free end *HS1* of the 3D-Nanoprobe. The *probe holder* was tilted only about 0.08 mrad and shows a small drift, without the risk of damaging the 3D-Nanoprobe in a first test. The drift can be explained because the measurement was performed with an open *acoustic isolation chamber*. The differential signal is smaller than the individual displacements of the channels. To conclude, the principle of differential interferometer detection system was tested successfully and is applied for probing in the next test.

Probing with the differential interferometer detection system

A 3D-Nanoprobe was mounted in the 3D-AFM head to test probing in contact mode with the differential interferometer detection system. **Figure 5.15** shows the interferometer displacement raw signal over time during the probing of a flat silicon sample surface in vertical *z*-direction. The optical beams of *Channel 1* and *Channel 2* are focused on HS1 and on the base of the 3D-Nanoprobe, respectively. The tip apex of the 3D-Nanoprobe approaches the silicon sample surface, showing zero deflection until 0.18 s, because the tip-sample distance is too large for a detectable interaction of the surface potentials. Both signal channels are affected by noise originating predominately from fluctuation of the refractive index of the dead path due to environmental changes. The differential signal shows the position signal without correlated noise. The visible small jump shortly after 0.18 s can be identified as the *snap-in* (the tip jumps into contact with the sample). The sample approach continues, the tip of the 3D-Nanoprobe stays in contact with the sample surface and the 3D-Nanoprobe is continuously deflected. Comparing the displacement signals of *Channel 1* and *Channel 2* one can see that only *Channel 1* shows a significant and proportional displacement, whereas *Channel 2* shows no significant changes. The HS1 region is displaced, due to the compliance of the applied 3D-Nanoprobe. The stiff base of the probe shows no changes, as expected. Thus, the differential signal *Channel 1* - *Channel 2* can be used to detect the deflection in *z*-direction of the probe. The maximum deflection of about 16 nm is reached at the *setpoint*. This measured value differs from the actual *setpoint* of 30 nm, because HS1 is connected via HS2 and FH2 with the tip. The 3D-Nanoprobe model predicts a ratio of the detected displacement to the actual tip displacement of about 1/2, which supports the model. Subsequently, the sample

is retracted and the 3D-Nanoprobe shows an elastic deflection due to tip-sample adhesion forces. The tip sample adhesion force deflects the probe about 5 nm from zero deflection. The 3D-Nanoprobe is pulled off the sample at about 0.23 s and returns to the former condition. The sample is withdrawn. This implies that the 3D-AFM head's differential interferometer detection system is sufficiently stable to work for single probing. This experiment also shows, that the 3D-Nanoprobe can be applied in the 3D-AFM head and the differential interferometer detection system can be used to detect the displacement of HS1. The probing test was successful.

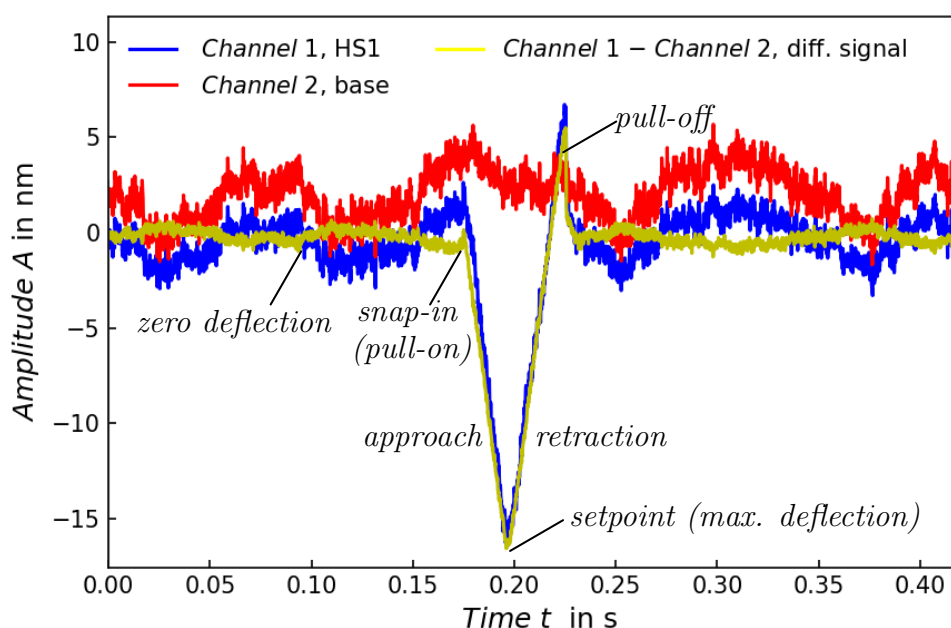


Figure 5.15: Probing curve of the differential interferometer using a 3D-Nanoprobe. *Channel 1* is focused on HS1 and *Channel 2* is focused on the base. *Channel A* is displaced by a 2 nm offset for better visibility. The subtracted signal is used to measure the HS1 z-displacement of the 3D-Nanoprobe.

Noise of the differential working interferometer and higher order non-linearity

A 3D-Nanoprobe is mounted and adjusted in the 3D-AFM head, to test the noise reduction of the differential working interferometer compared to the the raw signals of the individual Channels. **Figure 5.16** shows the measured position signals of the 3D-AFM head in the time and in the frequency domain. The measurements were conducted with an equilibrated experimental setup. Measurement frequencies of 1.22 kHz, 9.77 kHz and 625 kHz were chosen for time intervals of 100 s, 1.5 s and 0.2 s, respectively. The interferometer device was used to save the collected data. As mentioned before, *Channel 2* is focused on the base of the 3D-Nanoprobe and *Channel 1* is focused on the HS1 of the 3D-Nanoprobe. The differential interferometer signal in **Figure 5.16 A** denoted as *Channel 1-Channel 2* shows a drift of about 2 nm and a standard deviation without linear detrending of 0.62 nm with a reduced position noise amplitude compared to the single *Channel 1* and *Channel 2* with 1.90 nm and 2.40 nm, respectively. The root-mean-square (RMS) noise value using linear detrending of *Channel 1* and *Channel 2* is given by 0.96 nm and 1.20 nm, respectively. The smaller RMS noise of the differential signal is given by 0.44 nm. The 100 s time interval seems to have an effect on the noise, by that means the differential signal does not seem to be stable to the nanometer. At about 40 s some periodic fluctuation are visible, which are discussed later in detail. The corresponding Fast Fourier transform (FFT) in **Figure 5.16 B** shows a drift with increasing amplitudes towards low frequencies. In the low frequency region the position noise amplitude of the differential position is reduced compared to the single channels. The 10 Hz region shows a contribution to the overall noise power indicated by the cumulative power spectral density (PSD) (here the ASD is shown), due to environmental influences. Above 2 Hz the noise power of the differential signal is reduced compared the noise power of the single channels. In the region between 0.1 Hz and 1 Hz, the aforementioned fluctuation are only reduced slightly. Ultimately, using the differential signal at this sampling rate is beneficial to reduce the position noise.

A sampling rate of 9.77 kHz is used to measure the differential position during probing with the developed 3D-AFM head.

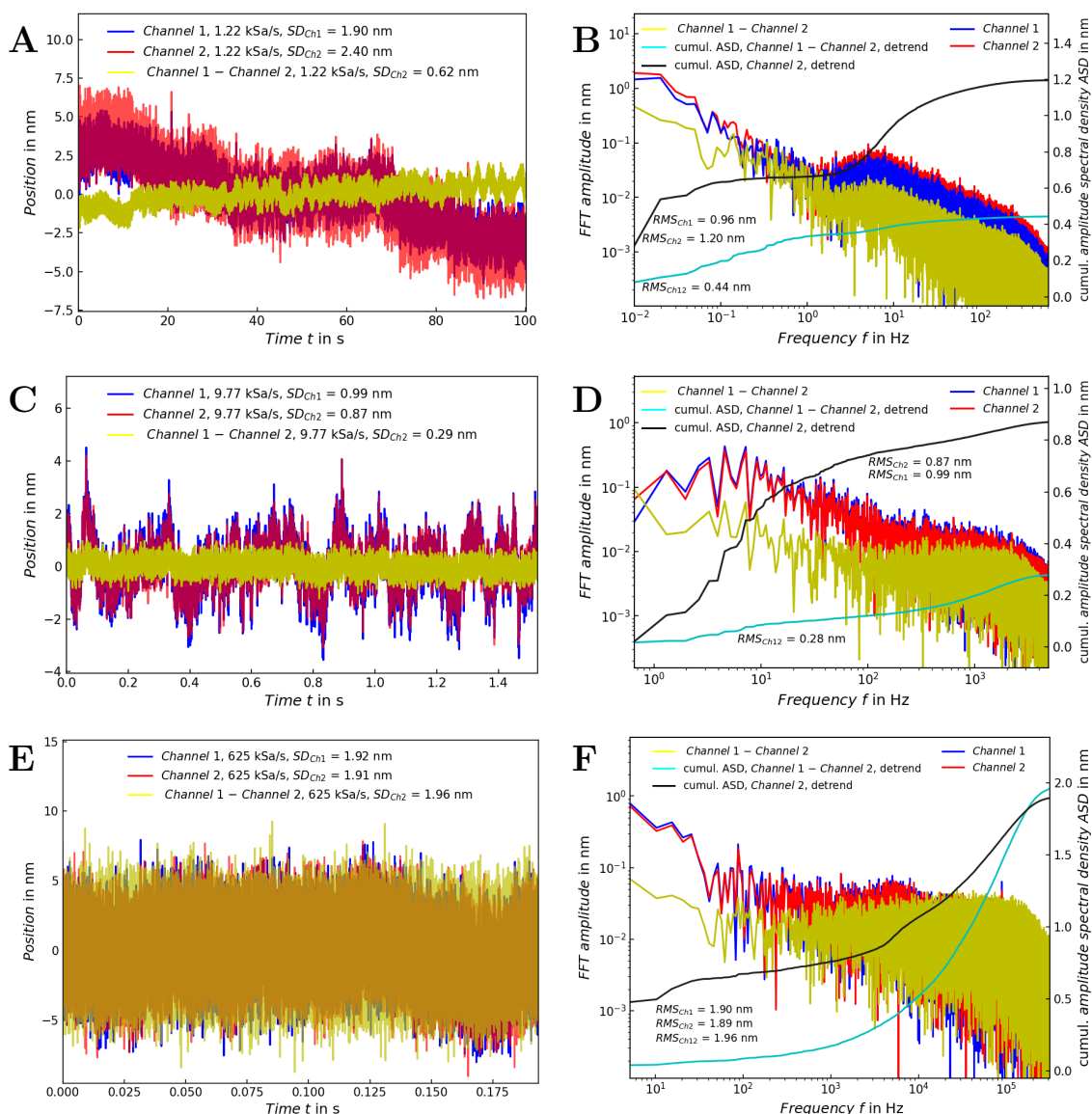


Figure 5.16: Position noise of the interferometer detection system with two commercial *C01* interferometer heads aligned on a 3D-Nanoprobe. **A**, **C** and **E** shows the position signal at different selected sampling rates and bandwidths. **B**, **D** and **F** show the corresponding amplitude spectrum (FFT) and ASD of the noise. The noise was measured after applying the internal correction algorithm of the interferometer device.

Figure 5.16 C shows the noise measurement of the differential signal at this rate (9.77 kHz) with a standard deviation of 0.29 nm, which is significantly smaller than the *Channel 1* and *Channel 2* with 0.99 nm and 0.87 nm, respectively. At this time interval of 1.5 s drift is negligible. The position signal fluctuation, presumably originating from environmental influences on the dead-path of the two channels correlate with each other. The FFTs of the three position signals are shown in **Figure 5.16 D** with no distinct peaks. As indicated already in **Figure 5.16 B** the region around 10 Hz contributes significantly to the overall noise. The position signal fluctuations of both channels presumably from environmental influences are the prevalent noise sources in the frequency range between 1 Hz and about 100 Hz, which is visible in the ASD with maximum noise amplitudes at about 7 Hz. The differential position shows reduced fluctuations over a wide spectral density range. The RMS noises (with linear detrend) of *Channel 1* and *Channel 2* are given by 0.99 nm and 0.87 nm, respectively, which is significantly larger than the RMS noise of their difference with 0.28 nm. Above 3 kHz, the influence of the selected limited bandwidth of the interferometer device is shown, indicated by reduced position noise amplitudes in the FFT.

The position noise at a sampling rate of 625 kHz is also investigated, because the interferometer should also be capable of measuring fast displacement changes. At this rate, the standard deviations of the channels with 1.92 nm and 1.91 nm are similar to the standard deviation of the differential signal with 1.96 nm. The total noise power with RMS_{Ch12} of the differential signal is slightly reduced compared to *Channel 1* and *Channel 2* with 1.90 nm and 1.89 nm, respectively. The corresponding cumulative ASD shows a reduction in noise power in the differential signal up to a frequency of about 180 kHz. Above about 180 kHz noise is added, which might come from phase noise of the interferometer device, fast fluctuations of the refractive index in the long dead path that appears uncorrelated in the individual channels, or non-simultaneous sampling. The distinct small peak at about 100 kHz seems to be an artifact as it is not shown in the differential signal. The artifact might originate from acoustic coupling, but this could not be proven by experiment. A thermal excitation of the probe cannot be detected due to the noise level. The selected bandwidth limit of the interferometer device is shown by a decrease of the position noise amplitudes above about 200 kHz. Overall, using the differential signal at this sampling rate and given time interval would lead to a larger position noise value compared to the single channels. However, the differential signal is used, because the signal has to be stable over a long time.

The differential signal of the noise measurement with 1.22 kHz sampling rate is investigated further, because the region for an ideal probing time can be deducted from this measurement. **Figure 5.17** shows the overlapping Allan-deviation from this 100 s noise measurement. Two distinct broad peaks can be identified for the 0.05 s and 0.8 s period regions, which presumably come from environmental influences and already mentioned periodic fluctuations of the position signal, respectively. The arrow marks a dip in the shown deviation over an averaged period of about 0.15 s. A reasonable duration for the probing can be identified in the region around 0.1 s to 0.2 s, because for each probing cycle the zero deflection of the probe is taken as a new reference. For shorter periods, there are simply not enough data points to generate a useful probing curve. As a result, a probing rate of about 3 Hz to 5 Hz should provide the best probing repeatability for this interferometer detection unit and will be used in the following experiments.

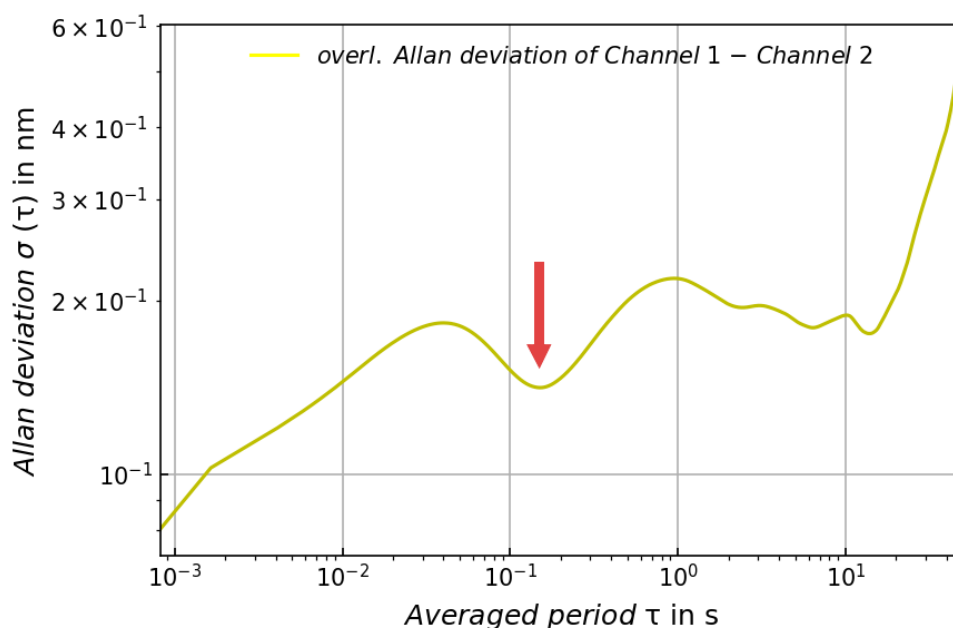


Figure 5.17: Overlapping Allan-deviation of the interferometer noise at a sampling frequency of 1.22 kHz over 100 s (shown in Figure 5.16 A). The (red) arrow marks where the Allan-deviation shows a local minimum. It is the region of the most useable probing frequency.

As mentioned before, periodic fluctuations are visible in **Figure 5.16 A** at around 40 s in the measurement. Those are investigated in detail in the depicted measurement in **Figure 5.18**. The depicted non-linearity in **Figure 5.18 A** of the *Channel 1* and the *Channel 2* show similar amplitude and shape, but are phase shifted to each other by about π . Based on the interferometer principle, described in the theory, nonlinearities can appear in the measured position signal because of the sinusoidal wavelength modulation. The differential signal shows clean nonlinear fluctuations with about 5.5 nm amplitude. The non-linearity of this interferometer device is also shown in [205],[206]. Assuming a sinusoidal periodicity, the non-linearity of the 4th order is predominant. This higher order is not corrected by the device and can also not be corrected in a post process because the phase between the channels shifts slowly over time with arbitrary sign. **Figure 5.18 B** shows the differential interferometer signal with 5 Sa/s over about 6.5 h. At about 1 h the fluctuations are in phase and are subtracted from each other. After 6 h the fluctuations show an amplitude of about 3 nm. During the measurement the atmospheric pressure was changing relatively fast and relatively linear by about 4 hPa, which might explain the constant increase in fluctuation amplitude. The experimental setup is located in a humidity and temperature controlled laboratory environment. The experimental setup is not pressure controlled. The Allan deviation shows a large dominating broad peak of 1.1 nm for a measurement time of about 5 s at 3 h, already known from previous measurements. Those fluctuations increase with a weak signal and are also predominantly enlarged by including the microscope objective lens. It seems that the microscope objective lens

has parasitic reflexes which overlap with the measurement beam. Both beams may interfere and cause the disturbances and fluctuations of the differential position signal. Unfortunately, the commercial device itself does not allow a profound investigation. The internal, automatic correction of the device is applied on the adjusted 3D-AFM head, after the optical distance range is set by hand. The internal calibration factors are fixed. The parasitic beam may cause a phase offset and consequently lead to outdated correction factors over time, which also explains the large low frequency oscillation of the interferometer signal with zero and first order nonlinearities of up to 40 nm in **Figure 5.18 A** and sinusoidal drift in **Figure 5.18 B** over five hours. The influence on the measured position signal of a 3D-Nanoprobe can be mitigated by careful optimization of the measurement mode and monitoring of the signals. The fluctuations can be mitigated further by applying an additional correction cycle or resetting the interferometer device shortly before the measurement.

During the measurement with the 3D-AFM head the differential interferometer signal is constantly evaluated and the measurement is aborted if the amplitude fluctuation approaches 2.0 nm to reduce the influence of the nonlinearities. This limits the gradient of the short term fluctuations with usually 0.5 Hz to less than ± 6 nm/s.

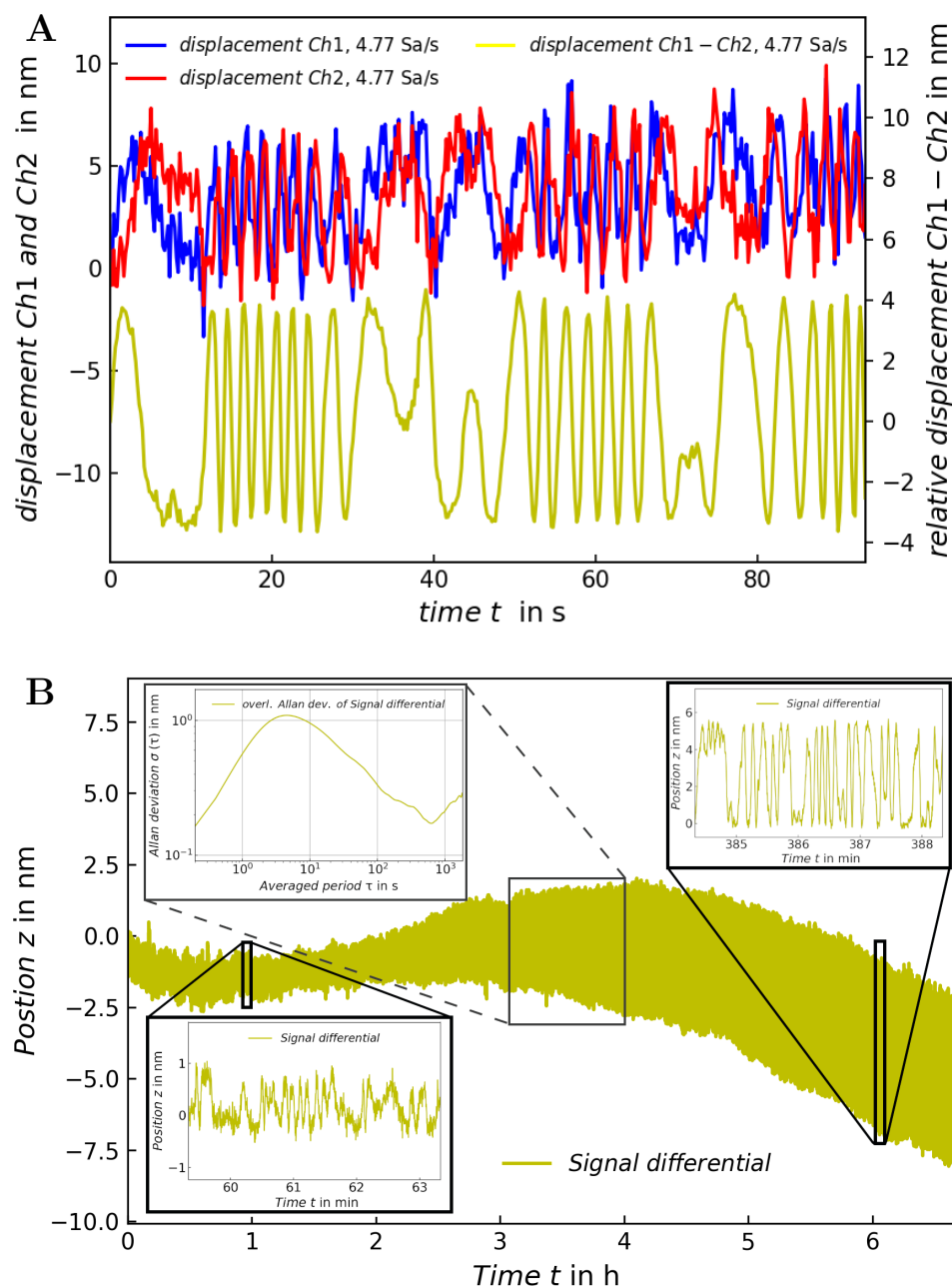


Figure 5.18: Nonlinearities of the interferometer about 24 h after powering up of the setup. **A** shows the displacement signal of channel 1 (Ch1), channel2 (Ch2) and the differential signal of both channels (*Channel 1 -Channel 2*) of the interferometer detection system. The signals show slow periodic fluctuations of several nanometer over a displayed time interval of 100 s. **B** shows changes of the periodic fluctuations of the differential signal (Ch1-Ch2) of the interferometer detection system over about 7 h.

Raw probing signals of a 3D-Nanoprobe and signal delay between the detection system components

The raw signals of a 3D-Nanoprobe probing curve are evaluated for apparent delays. This signal delay between the high bandwidth dual optical lever detection system signal and the position signal of the differential working interferometer detection system should be as small as possible to ensure stable controlling. The maximum time delay should at least be smaller than the time to exchange data of the FGPA with the internal digital signal processor (DSP), which is smaller than 0.4 ms. **Figure 5.19 A** shows the raw signal of a 3D-Nanoprobe probing in z-direction and the z-position signal of the used piezo stage. An oscilloscope *Yokogawa 100 MHz, 10 bit* is used to measure the signal delay time with 12.5 MSa/s. All signals are smoothed with a moving average filter ($n=21$), because the small signals appear too noisy for clear identification, as shown in **Figure 5.19 B**. The piezo stage scanning platform is displaced in approaching direction until the *setpoint* is reached at 80 ms. After that, the scanning platform with the sample is retracted. The *snap-in*, maximum probe displacement (*setpoint*) and *pull-off* are visible in the interferometer signal, as previously described in **Figure 5.15**. The bending and torsion signal show very small changes and shallow slopes during the probing in z-direction, as expected. Small spikes in the bending and torsion signal are visible during *snap-in*, as the tip jumps in contact, and throughout the *pull-off* of the 3D-Nanoprobe. The moment of the *pull-off* is used, because of the sudden changes in signal values, to test the signal delay between the detection system components. **Figure 5.19 C** shows the 3D-Nanoprobes *pull-off* at about 80.267 ms in detail. After the tip detached from the sample surface, a free oscillation of about 85 kHz is shown in the bending signal. It corresponds to the first Eigenmode of the used 3D-Nanoprobe. The oscillation slowly decays due to damping in the ambient environment (e.g. air, squeeze film damping). The interferometer device with a 9.77 kHz data rate shows this tip-sample detachment with about 0.29 ms delay by coming back to zero deflection. The average signal with about 10 kHz (9.77 kHz) band width of the interferometer device does not show the free oscillation of the 3D-Nanoprobe. The measured delay is considerable large but still meets the specification. The time can be reduced slightly by using a higher data rate of the interferometer device and higher filter bandwidth. The delay originates from calculating the position signals, subtract the channels from each other and update the digital-to-analog converter for signal output. In contrary, a smaller time delay, would add more noise to the interferometer signal because the data is collected with 5 kHz rate by the DSP of the measurement setup as the signals averaging time would be reduced per data point. The experimental setup at PTB is described in the following section 6.1 .

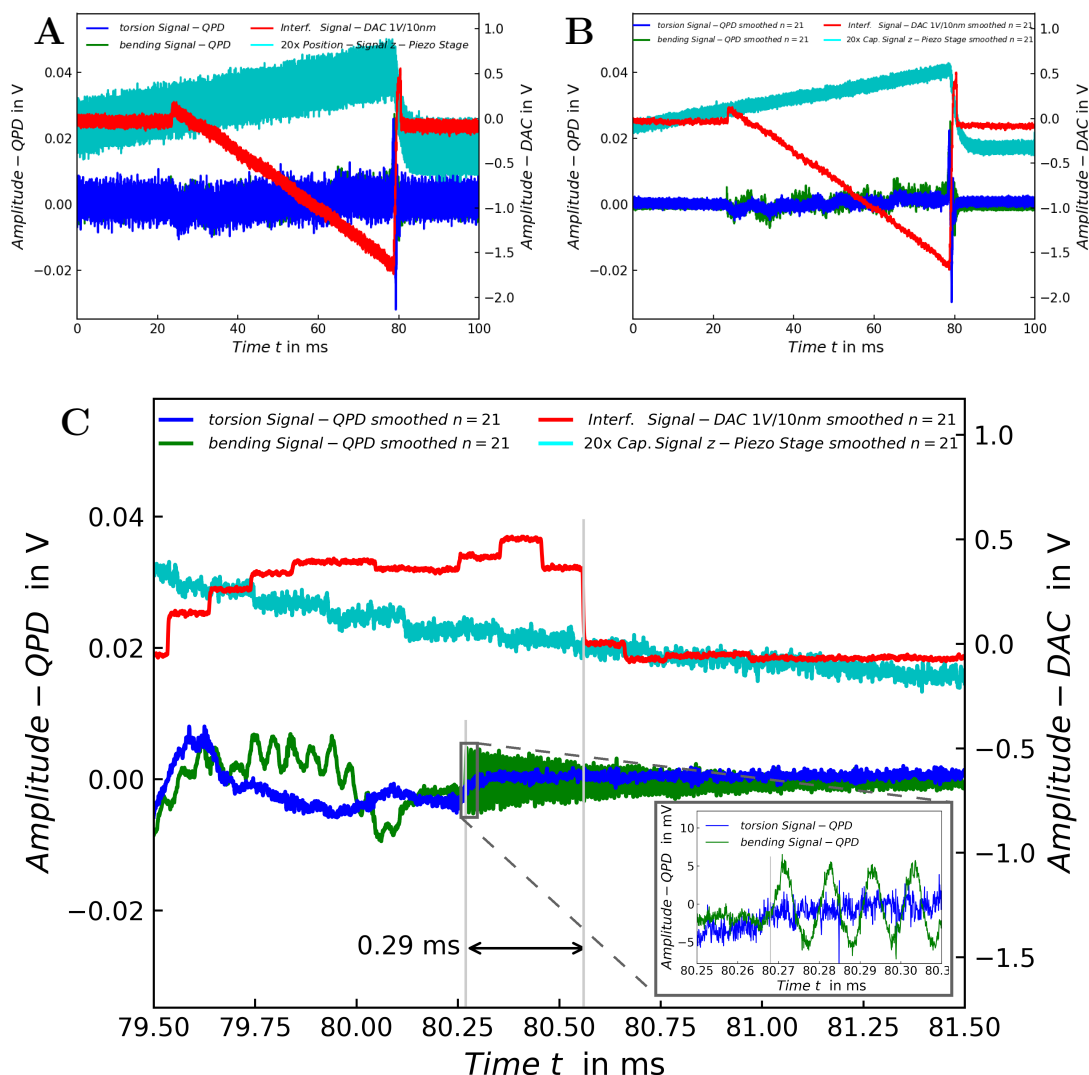


Figure 5.19: Probing curve of a 3D-Nanoprobe on a flat silicon sample surface depicted with an oscilloscope with 12.5 MSa/s. Graph **A** shows the raw signal of the detection system (bending and torsion signal of the optical lever and interferometer displacement signal). The curves of the probing show a *snap-in* at about 23.3 ms and a *pull-off* at about 80.27 ms. **B** shows the raw signals with a moving average filter applied ($n=21$). **C** shows the signals during *pull-off* in detail and smoothed with a moving average filter ($n=21$ samples) for better visibility. The signal delay time between the analog QPD signal and interferometer DAC signal of the device breakout box is indicated with about 0.29 ms. The DAC position signal of the piezo stage can be converted with 500 nm/V. The detail in **C** shows free bending oscillation mode of the 3D-Nanoprobe after *pull-off*.

5.4.3. Drift of the 3D-AFM head signals in the measurement setup

The temperature drift is tested by warming-up the 3D-AFM head in the measurement setup. To test the influence of dissipated thermal energy of components on the 3D-AFM head, internal components of the setup are used as a heat source. The 3D-AFM head's camera (USB camera, *IDS*) is used as one heat source. The camera is operated with fixed setting and dissipates about 1 W. The 3D-Nanoprobe is mounted in the holder and suspended in free air, without tip-sample interactions.

At the beginning of the experiment, the measured optical path length (dead paths) for the interferometers inside the 3D-AFM head were 240.893 mm for *Channel 1* and 222.442 mm for *Channel 2*, while *Channel 3* of the interferometer device remains unused. The detection unit is powered up a least 3 days before the measurement. **Figure 5.20 A** shows *Channel 1* and *Channel 2* of the interferometer device with removed offset denoted as *Ch1* and *Ch2*, respectively. The differential signal *Ch1-Ch2* shows the used signal and relative drift of both channels to one another. **Figure 5.20 A** shows an improved drift reduction by a factor of about 170 to about 50 nm compared to the single channel (total drift of *Ch1* 8524 nm) by using the *invar sleeve*⁴. The heads are mounted about 15 mm behind each other, the ferule of the interferometer heads are clamped at the same distance from the internal reference mirror to reduce the influence of the ferule material expansion on the thermal drift. The obvious nonlinearities of the differential signal (*CH1-Ch2* in **Figure 5.20 A**) will be discussed later. Both channels show very a similar progression of the displacement changes over time. The drift is fitted by exponential functions to characterize the drift of interferometer detection inside the 3D-AFM head regarding temperature changes. A superposition of two exponential functions was chosen to extract the time constants for temperature equilibration of the 3D-AFM heads detection system, and volume of the acoustic isolation chamber including the measurement setup. Both channels show first time constants of about 3456 s. The second time constants denoted as τ_2 , τ_4 are 58386 s and 60480 s for (about 16.5 h) *Ch1* and *CH2*, respectively. The ratio of the influence of the time constants is given by about $6839/3066=2.23$ and $6803/3109=2.19$ for *Ch1* and *CH2*, respectively. This means that the interferometer drift is dominated by the shorter time constant. The deviation between both fits is depicted as the fit $f_{Ch1} - f_{Ch2}$. The fit shows a maximum of about 50 nm relative displacement after 10 h and slowly decays by about 10 nm reaching 24 h. The same fitting function is used to fit the measured temperature drift of the Pt100 temperature sensors *sensor 3* and *sensor 4* (location is shown in section 5.4). Temperature *sensor 3* represents the temperature of the detection system while *sensor 4* measures the temperature of the measurement setup. **Figure 5.11** shows the positions of the temperature sensors. A temperature measurement unit *PicoLog PT-104-4* (*Pico Technology Ltd.*) with four channels, 1 mK resolution and 10 mK (+0.01 % of the value) accuracy is used, connected via USB port.

The temperature sensor *sensor 3* measures a total temperature drift of about 1.2 K. The fitted time constants of 3784 s and 41931 s are similar to the determined time constants of the drift curves of the interferometer displacements of both channels, which means the position drift seems to be correlated to the measured temperature. The ambient temperature of the measurement setup is measured by the other temperature sensors, denoted as *sensor*

⁴Drift and long-term stability of the 3D-AFM head interferometer signals were not sufficiently stable with a sleeve made of aluminium. The material of the sleeve was changed to low expansion material (invar).

2, *sensor 4*, *sensor 5*. Only one sensor is fitted, as is placed near center of the setup and because they show very similar behavior. The larger time constant of 50781 s dominates the fit $f_{\text{sensor4}}(t)$. Consequently, this large time constant represents the ambient temperature in the chamber and frame of the measurement setup. The smaller time constant of about 1 h can be addressed to the 3D-AFM head.

Based on the measured temperature difference during the 24 h measurement, the measured drift seems to be slightly larger than the estimated one, which is investigated by an estimate in the following.

The geometrical length from the position of the interferometer heads inside the *invar sleeve* to the cantilever can be estimated by adding the design value of the position of the first interferometer head to the back focal plane of the microscope objective lens with the par-focal distance of the microscope objective lens. Thus, the geometrical length is given by 117.9 mm + 95 mm = 212.9 mm. Both interferometer heads are treated as one unit inside the invar sleeve. The material is assumed to be homogeneous, since the 3D-AFM head parts are made from aluminium and are mounted to each other. During AFM measurements no temperature sensor should be mechanically connected to the 3D-AFM head to reduce the tip-sample position noise induced by mechanical tension of the cables. The contribution to the drift by the thermal expansion of the 3D-AFM head's material and geometry is given by 5.37 μm (5365 nm) using the linear expansion coefficient of aluminium of $21 \cdot 10^{-6} \text{ 1/K}$ and the temperature change of 1.2 K of *sensor 3* given by **Figure 5.20 B**. This geometry expansion is less than the measured total drift. The environmental influences on the refractive index of air inside the acoustic isolation chamber for a wavelength of 1550 nm are extrapolated from *Ciddor* formula, and are given for temperature $-0.94 \cdot 10^{-6} \text{ 1/K}$ (at 22°C), pressure $0.26 \cdot 10^{-6} \text{ 1/hPa}$ (at 1013.25 hPa), relative humidity $-9.8 \cdot 10^{-9} \text{ 1/\% rel. hum.}$ (at 50 % rel. hum.), CO_2 level $0.14 \cdot 10^{-9} \text{ 1/ppm}$ (at 450 ppm), respectively [126]. The length of the optical path of the microscope objective lens is consequently given by 222.442 mm - 117.9 mm $\approx$ 104.5 mm (par-focal length of the microscope objective lens 95 mm). Excluding the microscope objective lens, the theoretical drift of the refractive index from the temperature change of 1.2 K of the optical path length with 117.9 mm is given by about -133 nm, assuming predominantly air and neglecting the unknown properties of the lenses and gas inside the microscope objective lens. The optical path of the working distance of 17 mm is mainly influenced by the environmental conditions of the chamber. Using a temperature difference of the setup of about 0.4 K (**Figure 5.20 B**), the drift of the displacement measurements of both channels is estimated to be influenced by about -7 nm, which is negligible compared to the total drift.

Consequently, there is a large unknown influence on both measured optical paths contributing with about 3.30 μm (or relative $1.4 \cdot 10^{-5}$ to the dead path of *Ch1*).

The mounting of the interferometer heads contributes to the differential signal drift with 22 nm, assuming a linear expansion coefficient of the invar sleeve of $1.2 \cdot 10^{-6} \text{ 1/K}$, a temperature difference of the detection unit of 1.2 K after the warm-up and a relative distance of both heads to one another of 15 mm. The remaining drift of the differential signal originates from the difference in optical paths lengths and guidance of the beams. Assuming constant pressure, humidity and CO_2 level over time and relative measured optical distance of both heads to one another of 18.45 mm, the optical path difference should be reduced by 21 nm. Consequently, the invar sleeve expansion and the changes of the optical path difference should compensate each other, if equilibrated completely. The slow decay over time with

rising temperature might show a hint to this designed property but neither the position of the temperature sensors nor the large geometry of the sensors itself allow an elevation. Thus, it is not visible in the differential drift signal. Slow pressure changes during the measurement and different optical paths of the two channels give a reasonable explanation for about 40 nm drift of the differential signal within 24 h. Assuming a change of environmental conditions on the air medium (e.g. influence by a pressure change) on the dead-path of *Channel 1* results in a possible drift of $240.893 \text{ mm} / 18.45 \text{ mm} \cdot 40 \text{ nm} = 522 \text{ nm}$. This drift contribution is subtracted from the total drift. The remaining $2.8 \mu\text{m}$ seems to be the influence of the microscope objective lens or the drift of the *invar sleeve* inside the aluminium tube or a measurement error due to an insufficient amount of temperature sensors. The apparent jump in the differential signal at about 12.5 h is a lab activity induced by pressure changes in the lab (door opening) due to the climate control in the laboratory and building. Sudden temperature changes can be excluded due to the thermal isolation of the acoustic isolation chamber, which acts as a low pass filter for external temperature changes on the measurement setup.

Overall, the induced drift on the 3D-AFM head of a constant heat source with about 1 W is significant. During the warm-up, temperature gradients are prevalent, which would require multiple measurement positions for an accurate determination of the underlying influence sources inside the 3D-AFM head. For instance, the holder of the 3D-Nanoprobe could warm up unevenly, which is unlikely but would lead to a change in inclination angle of the 3D-Nanoprobe and to a change of the differential drift.

The determined time constants show a short term equilibration of the 3D-AFM head near the region of the detection system and a long equilibration time (time constant) of the complete measurement setup. The time duration of five time constants is used to equilibrate the measurement setup in practice. As a result, the measurement setup is sufficiently equilibrated after 3.5 days from initial warm-up (cold start). The 3D-AFM head can be used after 5 hours, to achieve good measurement conditions. Thereof heat sources, e.g. the camera and piezo stages, are always switched on and are idling to keep the influence constant.

In addition, the temperature distribution of the measurement setup is influenced by thermal conduction and convection, which would require a separate consideration. This cannot be provided, since it is not the scope of this work and requires a thorough understanding of all components of the measurement system under various applications. Consequently, an accurate online temperature measurement with a theoretical model for direct compensation of the 3D-AFM head's drift cannot be applied during probing and should also be not the goal of further improvement steps, because the nonlinearities with about 20 nm amplitude of the interferometer show a significantly larger influence than the smooth fit of the relative displacement drift curve.

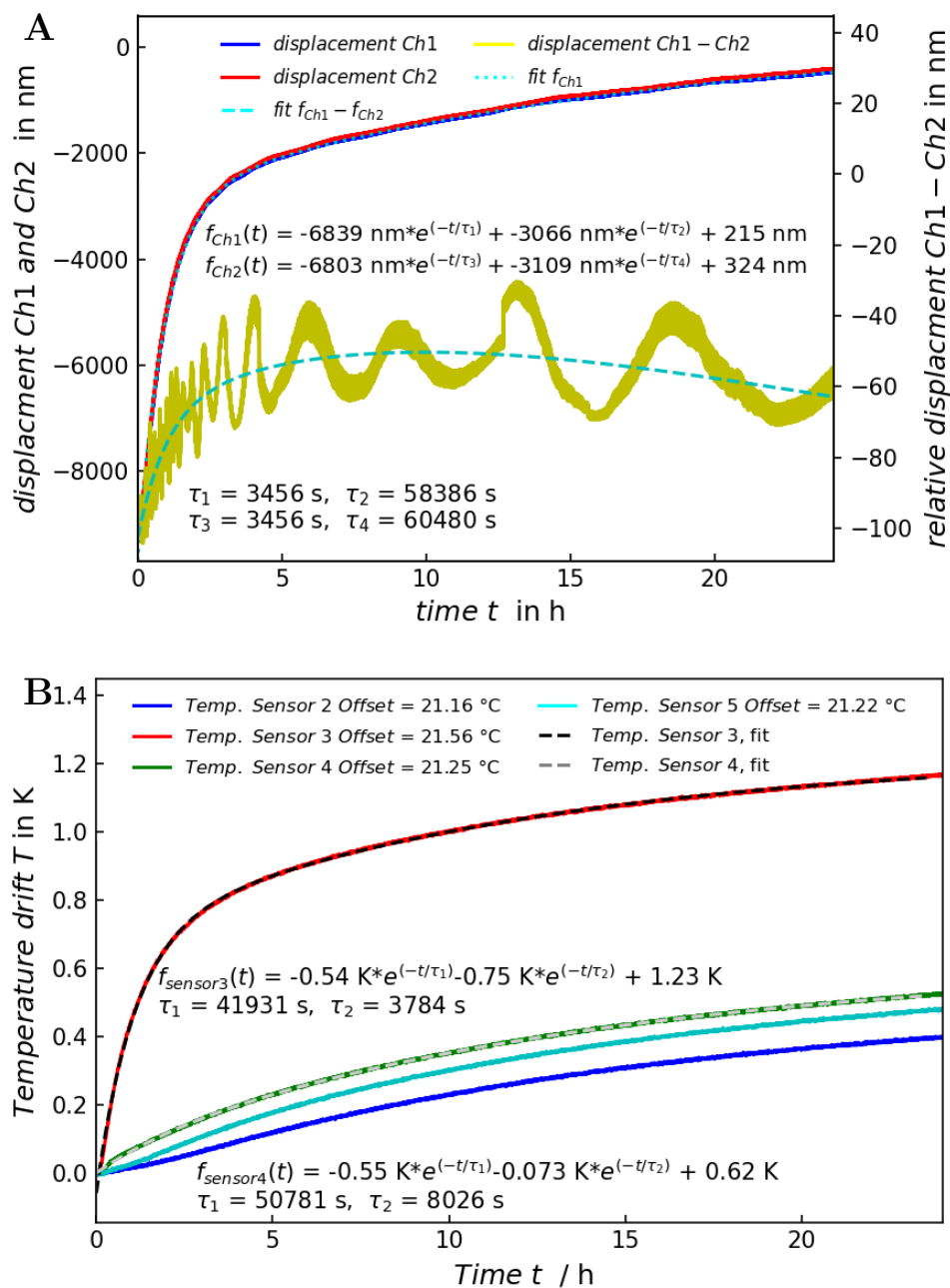


Figure 5.20: Drift of the interferometer (A) during warm-up from powering up the camera of the optical microscope with temperature change (B). The camera dissipates about 1 W.

The residue of the differential signal fit is depicted in **Figure 5.21** with an RMS value of 8.7 nm over the total drift of *Channel 1* normalized to center wavelengths of the interferometer of about 1532 nm (nominal 1550 nm). Predominately the first order non-linearity is shown. The zero order non-linearity seems to be corrected during initialization of the device. The maximum slope of the depicted residuum of the differential drift signal is 0.2, inflicted by the nonlinearities. This has a direct contribution on the calibration curves of the 3D-Nanoprobe. If the 3D-Nanoprobe is used as transducer, it would require short term calibration on an even and rigid surface of a sample. If the 3D-Nanoprobe is used as a null sensor this long term drift is less important, because the change in slope has only minor impact on the intersection point of the zero deflection and displacement curve. In general, the measured non-linearities are quite large and encourage the use of a different interferometer device (e.g. Figure 8.1). However, during that time another interferometer was not available for the experiments.

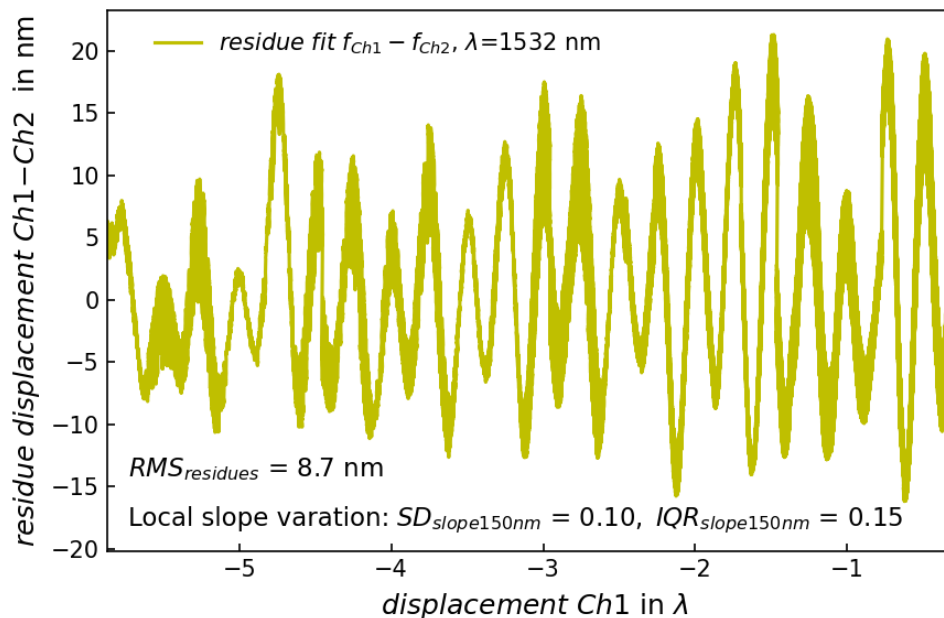


Figure 5.21: Residue of the drift fit of the differential signal of the interferometer during warm-up from powering up the heat source (camera of the optical microscope), as shown in figure 5.20. The maximum slope of the depicted residuum (nonlinearities) is 0.2, the standard deviation (SD) is 0.10 and the inter-quartile range (IQR) is 0.15.

Drift of the raw signals of the AFM-head

Next, the impact of the warm-up of the dual lever detection unit on the interferometer detection module and the measurement setup is investigated. **Figure 5.22 A** shows the bending, torsion and summation signals of the dual optical lever detection system and the differential signal of the interferometer after powering up the detection system, including the SLED driver. The interferometer signal shows fluctuations of 65 nm over 24 h. After about 10 h the signals seem to have settled and the interferometer fluctuation are in the range of 30 nm (peak to peak), but with drift rates of about 10 nm/h. Maximum drift values were about 26 mV, 46 mV and 117 mV for the bending, torsion and summation signal, respectively. The time constant of the raw signal drift for the bending, torsion and summation signals are 2554 s, 4473 s and 3982 s, respectively. **Figure 5.22 B** shows the corresponding temperature drift. For better visibility the temperature drift is only shown for the first 13 h. Temperature sensor *Sensor 3* is again placed nearest to the detection unit and is fitted with a superposition of two exponential functions. The fitted time constants are 30520 s and 2551 s. The short time constants have larger impact on the temperature signal drift curve (ratio of the influence factors of the time constants about $0.34/0.18=1.9$), similar to the previously described warm-up by the camera. *Sensor 2* and *Sensor 5* are fixed to the portal frame. *Sensor 4* is mounted about 50 cm over 3D-AFM head close to the roof of the acoustic isolation chamber and shows the air temperature inside of the measurement setup. The dominating time constant of this temperature induced drift is given by 54010 s. The time constants are very similar to the previous experiment, depicted in **Figure 5.20** with the camera as a heat source. Also the time constants of the raw signal drift are close to the time constant of the interferometer channels with 3456 s (from **Figure 5.20 A**). This indicates that there are indeed two thermally coupled systems, the 3D-AFM head with the short time constant of about 1 h and the measurement setup (portal frame, stages, table, acoustic isolation chamber) itself with a large time constant of about 15 h. The total temperature difference is 0.53 K, originating from the PCB circuit of the dual optical lever, which draws about 0.5 W. The maximum drift values of the raw signals were about 26 mV, 46 mV and 117 mV for the bending, torsion and summation signal, respectively. The slow changes in the bending and torsion signals after the 10 h can be explained by intensity fluctuation of the laser diode. This is visible in the summation signal. The sign of these small changes depends on the sign of the signal offset.

The cumulative Allan deviation is used, to estimate the stability of the raw signals over various integration times. **Figure 5.23** shows the Allan deviation of the drift of the raw signals, of the AFM-head over 12 h after a warm up of 12 h. **Figure 5.22** shows the time dependent signals. The torsion and bending signals of the dual optical lever show very good long-term stability with a standard deviation below 0.4 mV over a time period of 3000 s and less than 2 mV (SD) over half a day. The interferometer signal is considered to be stable over a period of about 100 s. It shows a deviation below 0.5 nm, allowing normal scans and trajectories of the 3D-Nanoprobe, when applied for probing in 3D.

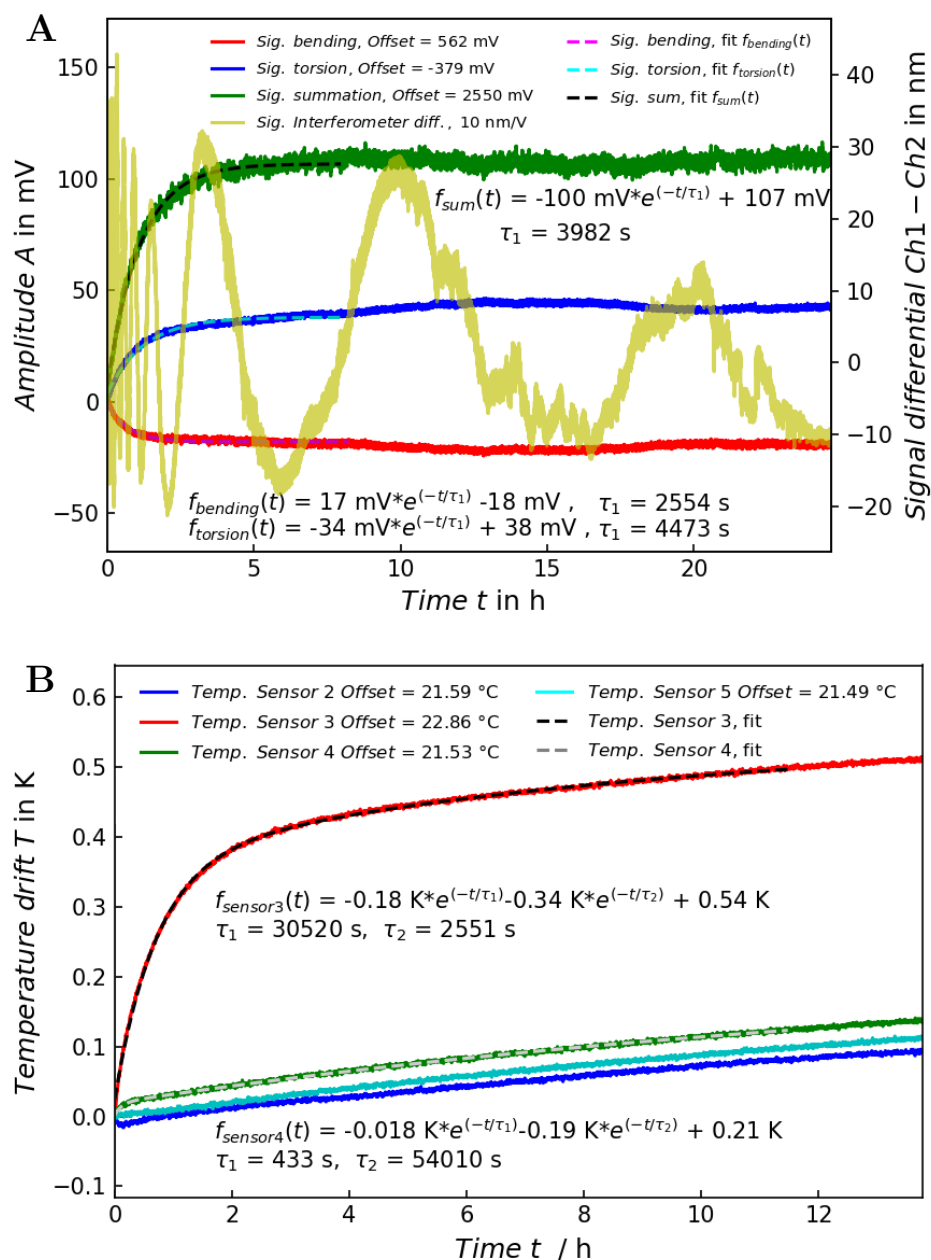


Figure 5.22: Drift of the raw signals of the AFM-head over one day of the measurement setup, powering up in the acoustic isolation chamber of the experimental setup in the laboratory. **A** shows the signal drift after power up of the detection system (including the SLED). **B** shows the temperature drift of the setup during the power up. Temperature Sensor 2 and Sensor 5 are mounted on the bridge frame of the setup. Sensor 3 is mounted nearest (adjoining) to the 3D-AFM head. Sensor 4 is mounted about 50 cm above the 3D-AFM head close to the top of the acoustic isolation chamber (housing).

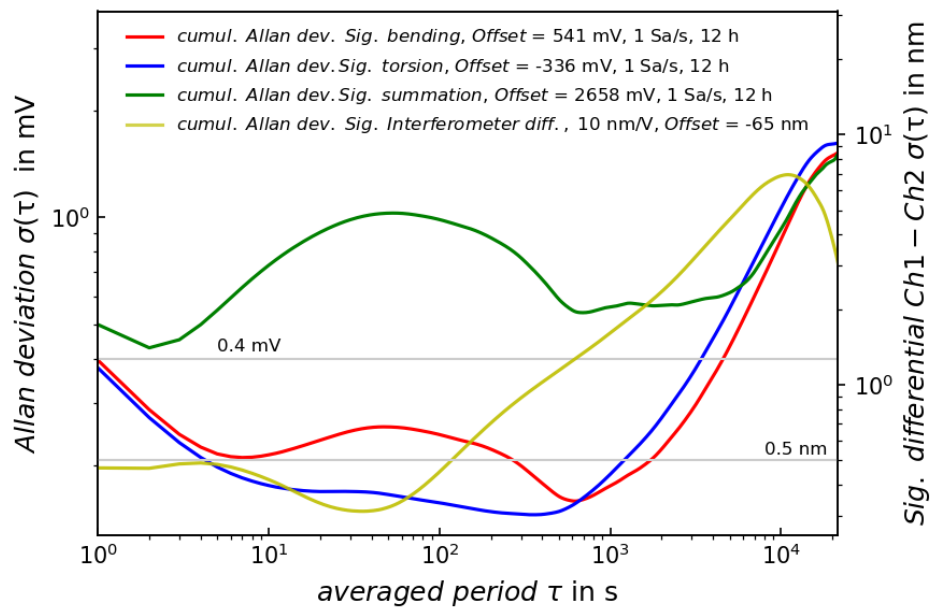


Figure 5.23: Allan deviation of the drift of the raw signals of the AFM-head over 12h after a warm up of 12h. The time dependent signal is shown in figure 5.22. The torsion and bending signals of the dual optical lever shows very good long-term stability with a standard deviation below 0.4mV over a time period of 3000s. The interferometer signal is considered to be stable over a period of about 100s. It shows a deviation below 0.5 nm, allowing normal scans and trajectories in 3D-probing.

6. True 3D-AFM measurements

In this chapter, the 3D-Nanoprobe is applied for true 3D measurements on reference structures. At first, the laboratory setup is described in which the measurement setup is located. After the signal acquisition is investigated, the calibration procedure of the 3D-Nanoprobe is explained. The sensitivity of the 3D-Nanoprobe and detection system is calibrated in 6.2.1 and compared with the semi-analytical model-based sensitivity of the optimized 3D-Nanoprobe (section 4.2 and 4.3). The dynamic behavior is evaluated by a frequency sweep and the resonance modes are identified and evaluated. The mechanical properties of 3D-Nanoprobes are tested via a reference spring and compared with the modeled compliance in 6.2.2.

After those first tests, the 3D-Nanoprobe is applied for various typical measurement tasks in 3D-Nanometrology such as CD, side-wall angle, line edge roughness (LER), line-width roughness (LWR) and pitch measurements in x-, and y- direction in one orientation. The CD-measurement is explained in detail and is used to investigate repeatability and stability. The determined properties of the true 3D-AFM regarding CD-measurements are already described in [106] and will only be mentioned here shortly.

6.1. The laboratory setup at PTB

After the true 3D-AFM head signals were tested, the 3D-AFM head was implemented into the measurement setup, that was shown in **Figure 5.11**. The measurement setup described in 5.4 is enclosed in the *acoustic isolation chamber*, which is part of the laboratory setup at PTB (*Ohm-Bau 025, Braunschweig*). **Figure 6.1 A** shows the laboratory setup with the graphical user interface (GUI) in detail in **Figure 6.1 D**. In general, a description of the relevant used devices can be found in appendix C.

Most of the components are mounted in the *server rack*, which is placed next to the *acoustic isolation chamber*. All connectors and cables are routed to and through the back side of the *acoustic isolation chamber* and are fixed and sealed to it with polymer foam. The *power supplies*, electrical ground (GND) and distribution of the mains via a power strip are located at the bottom of the *server rack*. The *Lock-in amplifier HF2LI*, is mounted on the first shelf level of the *server rack* and is described in C. On top of the *Lock-in amplifier*, the self-built *digital signal processor*, (*DSP*) unit is placed. It collects all signals from the 3D-AFM head, *Lock-in amplifier*, and customized xyz-piezo stage (described in C) on its front panel. The *DSP* controls the position of the xyz-piezo stage moving platform and x-, y-, z-probing. It is connected to the host PC via a USB port to exchange position data. The host PC, denoted as *PC* in the image, is described in C as *Industrial computer*. The graphical user interface (GUI) is shown in **Figure 6.1 D**. The GUI consists of two screens. On the over-head screen, the mounted 3D-Nanoprobe is displayed in the camera image of the optical microscope of the 3D-AFM head. On the bottom screen, the GUI of the 3D-AFM head is shown. It is a modified software version of the developed LN-AFM and CD-AFM [207]. The general use of this software will not be described in detail here, because it is not within the scope of this work. The *SmarAct interferometer* is placed on the second shelf level of the *server rack* and the corresponding so-called *breakout box* is placed on top of the device. The *breakout box* distributes the analog and digital signals passively to the interferometer device denoted as *SmarAct interferometer* and *DSP* unit. The properties of the *SmarAct interferometer* are listed

in C. The front panel is depicted in **Figure 6.1 B**, with 5 m extension single mode optical fibers for *Channel 1 (Ch1)* and *Channel 2 (Ch2)*. The digital differential interferometer signal of *Ch1* and *Ch2* is converted to an analog voltage signal as described before and distributed to the *DSP* unit, to measure the relative main z-displacement of the probe.

On the third shelf level, the *E-712 piezo controller, (PI)*, is fixed to the *server rack*. The *E-712 piezo controller* is optimized to work with the customized *xyz-piezo stage*. The properties are listed in C. The *industrial computer* and additional illumination sources are arranged on the fourth shelf level of the *server rack*. Above that, the controller of the *coarse xy-stage* is located and denoted in **Figure 6.1 A** as (1). Details to this controller and stage are also listed in C. On the top shelf, the *oscilloscope* is set up. It images the present raw signals of the z-stage, the dual optical lever (bending and torsion) signals and the differential interferometer analog signal, distributed by the *breakout box* (usually 0.1 V/nm). All analog signals are transferred with 50 Ω coaxial cables with Bayonet Neill Concelman (BNC) connectors. The *temperature sensor module* is placed on top of the *acoustic isolation chamber* and is connected via USB with a temperature monitor PC denoted as (5) for temperature data collection. The monitor PC is fold-able into *server rack* below the *industrial computer*.

Figure 6.1 C shows the self-built *laser unit* of the dual optical lever in detail. The butterfly SLED diode (*Fa. SUPERLUM*, specification in C) is driven by a *Koheron CTL101-1* laser driver. The single mode fiber coupled SLED diode is connected to a fiber port *PAF2-11B*, (*Thorlabs*). The free-space beam passes through an optical isolator and is coupled into the PM optical fiber via a second fiber port *PAF2-11B*, (*Thorlabs*). The polarization maintaining optical fiber is connected with the AFM-head via angled physical contact connectors *pol. FC/APC*.

As mentioned in the beginning, the 3D-AFM head was built up to be compatible with the current self-built AFMs at PTB.

In the following, pre-adjustments of the 3D-Nanoprobe for the calibration process are explained. The 3D-Nanoprobe is mounted on the probe holder and is adjusted by the six *micrometer screws* in the field of view of the *camera* and focus plane of the *microscope objective lens*. As already mentioned, the adjustment is designed to work for all types of commercial probes by being able to shift the probe holder up to 1 mm in three spatial directions. Usually, the aligned optical detection system does not need any further correction, because the probe is shifted into the optical axis and is adjusted to the focal plane. The optical detection system only needs readjustment if the probe was mounted at large rotation angle around the vertical z-axis or if the geometry of the probe changes significantly.

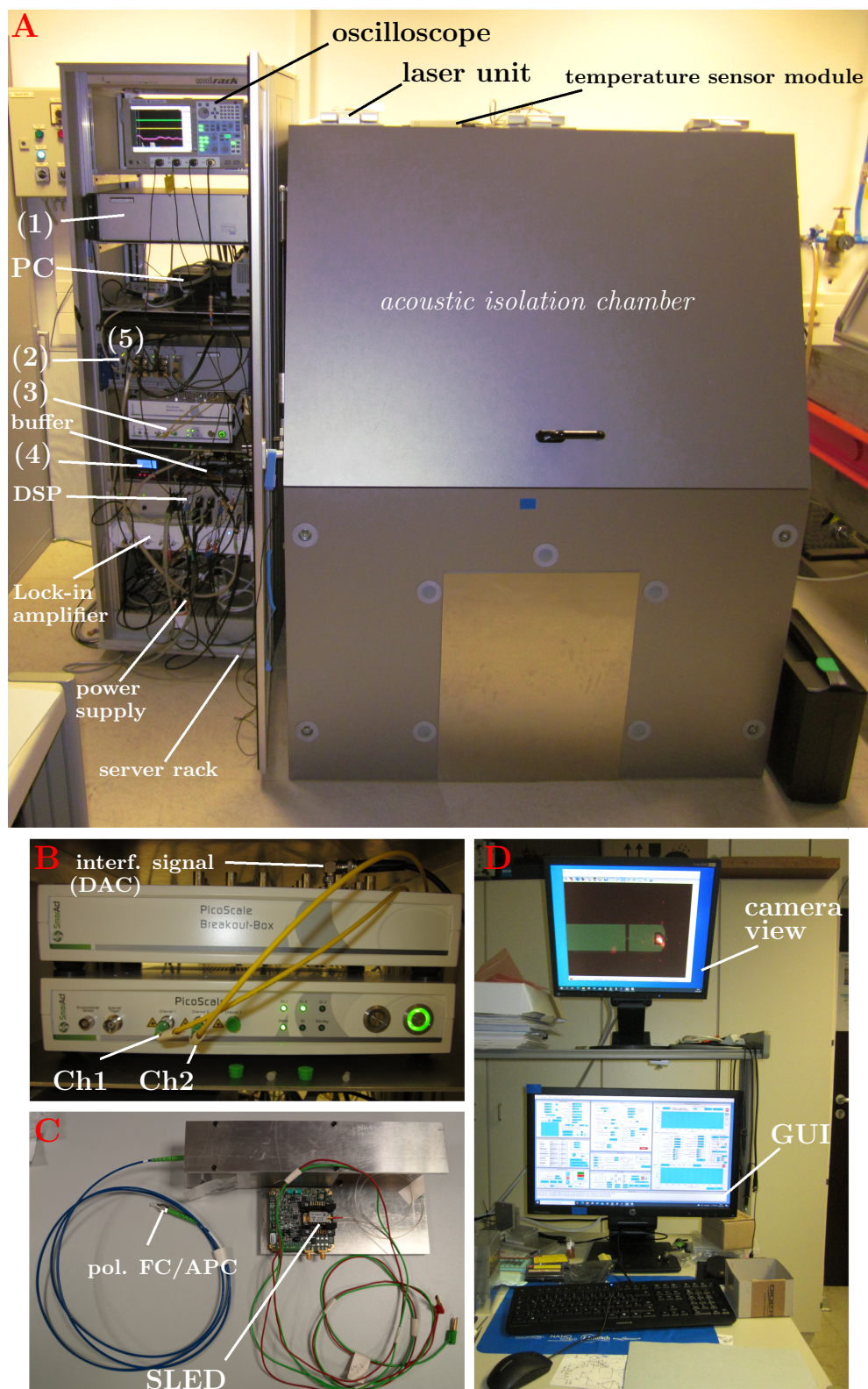


Figure 6.1: The laboratory setup is shown in A with the graphical user interface (GUI) in detail in D. The interferometer unit of the 3D-AFM head and laser unit of the dual optical lever are shown in detail in B and C, respectively.

An additional gain-stage with about $2.2\,\Omega$ output impedance and gain of two is used as an impedance converter (*OPA601*, *Texas Instruments*) to drive a high current signal into the used *DSP* input *sb-RIO9627* (card from *National Instruments*). The impedance converter is used because the *sb-RIO9627* card has a multiplexer which shows typical voltage spikes that might affect the signal of the following channel. These sharp spikes originate from the not negligible input capacitance of the multiplexer's switch. By switching from one channel to the next channel with different potential an additional charge is loaded into the input capacitance of the neighboring signal channel, which might cause a small bias, if the signal input has a high impedance. **Figure 6.2** shows the voltage of one input channel of the *sb-RIO9627*. The open channel shows a large amplitude of typically more than $0.15\,\text{V}$. By connecting the developed QPD circuit, the amplitude is reduced below $0.05\,\text{V}$ and the potential seems to settle within the acquisition time. For large potential difference between the channels, the settling is not sufficient, because of the relatively large output impedance of about $600\,\Omega$ of the QPD circuit. By using the low impedance gain stage, the voltage spikes are reduced to a negligible level. The impedance converter shows negligible noise contribution on the *DSP* inputs.

In the following section 6.2, the 3D-Nanoprobe is applied in the true 3D-AFM head to determine the stiffness and calibrate the sensitivity coefficients.

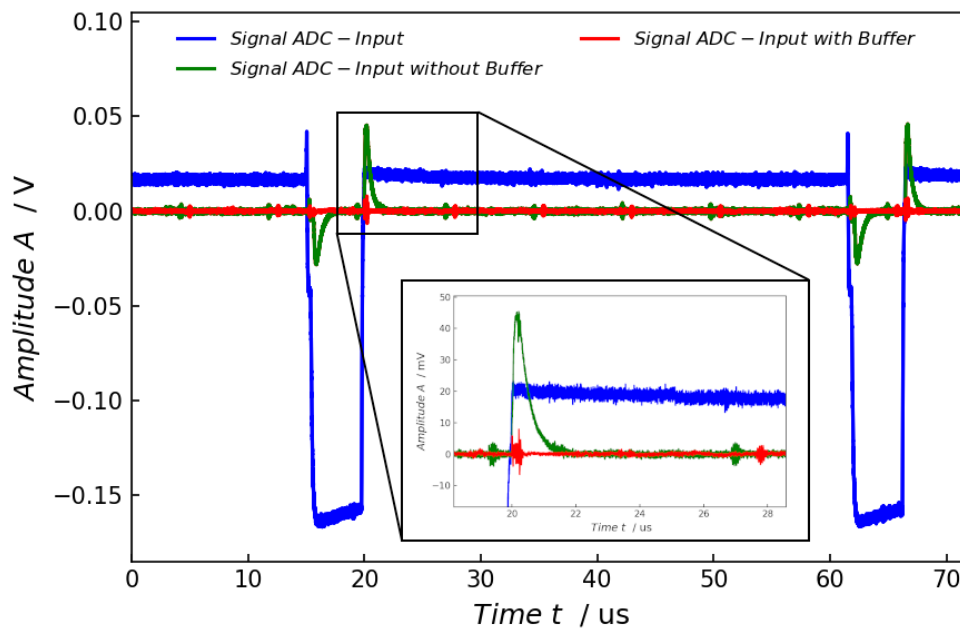


Figure 6.2: Influence of a buffer amplifier on the Multiplexer (MUX) input of the *National Instruments sbRIO* board.

6.2. Calibration of the 3D-Nanoprobe

Manufacturing uncertainties and the detection principle in combination with the mounting position of the 3D-Nanoprobe inside the 3D-AFM head makes a calibration necessary. In the following the calibration procedure is explained. The sensitivity coefficients and resonant frequencies are determined for one 3D-Nanoprobe, as an example. The experimental sensitivity coefficients are compared with the theory to verify the detection model of the true 3D-AFM head. By comparing the slopes of the probing curves of the calibration, the selectivity for 3D-probing can be approximated. In addition, the stiffness of the 3D-Nanoprobe is calibrated. The model based stiffness is compared with the experiment, to verify the optimization procedure and overall manufacturing. The stiffness calibration method used in this work is a contact measurement, consequently the 3D-Nanoprobes functionality is investigated in advance briefly regarding resonant frequencies and noise.

After the 3D-Nanoprobe is mounted in the 3D-AFM head, the signals of the detection system are adjusted to a minimal offset. A bending and torsion signal offset of up to 10% of the summation signal can be used according to theory, so between about $\pm 1.2\text{ V}$. The recommended offset is below $\pm 600\text{ mV}$. The differential signal of the interferometer is reset to zero before calibration, to keep it within the dynamic range of the ADC output ($\pm 10\text{ V}$) and dynamic range of the *DSP* input. As mentioned, a distance to voltage conversion factor of $\xi_{int} = 10\text{ nm/V}$ is used for the DAC in the interferometer device. According to the time constants of the measured thermal drift, the experimental setup should be warmed up for 3 days from a cold start. An equilibration time of one day is sufficient after changing of the 3D-Nanoprobe, or for a large distance travel or long-time travel of the coarse XY-stage, or for readjustments of the 3D-AFM head signals, which includes opening the acoustic isolation chamber. For short travels of the coarse XY-stage of a few millimeters, an equilibration time of more than 3 h is needed, because of the induced heat of the linear actuators and magnetic brakes, which leads to a drift between tip and sample. During all measurements, the brakes are activated (passive) and the linear actuators and the stepper motors are switched off, to induce less heat.

To safely test the probe's dynamic behavior and signals, the 3D-Nanoprobe is mechanically excited by the shaker piezos of the probe holder. The shaker piezos are driven by the output channels of the *Lock-in amplifier* (see **Figure 6.1**). A simple buffer circuit with an *OPA2227*, *Texas Instruments* (not shown here) is used to drive both shaker piezos of the probe holder via 4 cables synchronously (bending excitation) and out of phase (torsion excitation). An amplitude spectrum from a frequency sweep of the previously optimized and manufactured 3D-Nanoprobe is depicted in **Figure 6.3**. It shows the free bending and torsional oscillation amplitudes of HS2 at about 30 mV excitation amplitude. The first bending resonance is shown at 107.0 kHz and can be attributed to the bending mode of HS1 in z-direction, according to the simulated first resonance of this one probe in **Figure 4.3**. The lower value compared to the simulated 112.8 kHz indicates a smaller stiffness of FH1 as expected, which might originate from a minimal too thinly manufactured thickness t_1 or width w_1 . This first resonance amplitude is used to mechanically compensate a slightly rotated 3D-Nanoprobe by rotating the QPD-circuit, to minimize the eventual crosstalk of the bending signal on the torsional signal. Thus, the detail in **Figure 6.3** shows no visible peak in the torsional signal at this frequency.

The second measured resonance at 265.2 kHz is also below the simulated 277.8 kHz, indicating also a smaller stiffness of FH1 than expected. It belongs to the in-plane bending motion of HS1 and shows a small contribution of bending motion due to the mass distribution, as also shown in **Figure 4.3**. The third resonance mode at 350.0 kHz is the torsional oscillation of HS1 (simulation 358.2 kHz), showing a small resonance amplitude due to the small driving voltage of the shaker piezos. The next two resonance, are the bending mode of HS2 in z-direction and its in-plane bending oscillation at 513.4 kHz and 713.0 kHz, respectively. The bending mode of HS2 in z-direction is slightly higher than expected with 504.6 kHz, whereas the resonance frequency of the in-plane bending of HS2 is lower than the simulated 808.5 kHz. It might originate from a narrower manufactured width w_2 than intended. The sixth resonance is the 2nd order bending oscillation of HS1 and FH1, which is visible in the torsion and bending signal. A non-symmetrical location of FH1 might show two resonances modes of HS1 because of an additional momentum. The last shown resonance peaks represent the torsional oscillation of HS2 at 1.255 MHz, which fits to the simulated value. Based on these resonances, one can identify a functional 3D-Nanoprobe. It also shows a clean separation between each bending and torsion amplitude of HS1 and HS2, which was also shown for other 3D-Nanoprobes in [72], via separated frequency sweeps for HS1 and HS2.

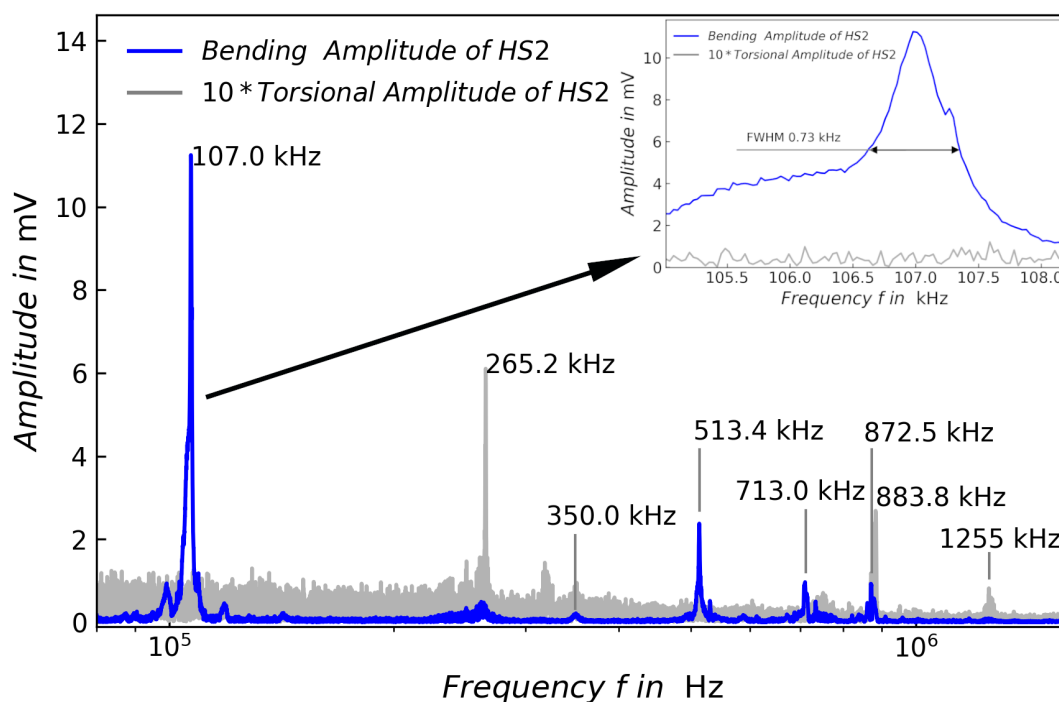


Figure 6.3: Frequency sweep of a 3D-Nanoprobe of the dual beam optical lever after adjustment. The detail shows, the torsion amplitude of the first eigenfrequency (bending motion of HS1). It is adjusted to a minimum by rotating the PCB circuit in a pre-calibration process.

To calibrate the 3D-Nanoprobe for the usage in contact mode, the mechanical excitation (shaker piezo) is switched off and the position noise in no-contact is measured and evaluated. **Figure 6.4** shows the three raw signals of the 3D-AFM head inside the measurement setup at 5 kSa/s. The dual optical lever torsion signal and the dual optical lever bending signal are mainly attributed to the x-signal and y-signal, respectively. The interferometer is attributed to the depicted z-signal. The optical lever signals indicate similar RMS values of 0.35 mV and 0.37 mV for torsion and bending, respectively. Both signals show the quantisation of 0.305 mV of the used ADC of the *DSP*. The higher total noise power of the bending signal originates mainly from two noise frequency contributions at 625 Hz and 2.190 kHz. The torsion signal shows a small noise peak at frequency of 170 Hz. **Figure 6.5** depicts the signals in an amplitude spectral density plot. The true origin of these distinct frequency noise contributions could not be found, since they do not seem to be constant over time and seem to change with the mounted probe. The interferometer shows a higher RMS value of 7.37 mV which obviously depends on the used conversion factor of the differential interferometer signal. The large signal fluctuation of the interferometer signal is simply not present because of the short time period of the measurement and because measurement was taken at quasi ideal conditions regarding stability of the interferometer. Under normal conditions the interferometer measures a considerably higher RMS noise value of about 20 mV to 40 mV, due to the already described signal fluctuations. All signals are mainly dominated by white (frequency) noise and quantization noise as indicated by the slopes close to -0.5 in the Allan-deviation plot of **Figure 6.5**. The x-, and y-signal shows a small waviness due to sinusoidal noise contributions. The z-signal indicate correlated noise contributions around 0.03 s and at 0.3 s. All signals show a local minimum at about 0.1 s.

As a result, the 3D-Nanoprobe shows sufficient RMS noise values with minor interference frequencies and can be used for probing.

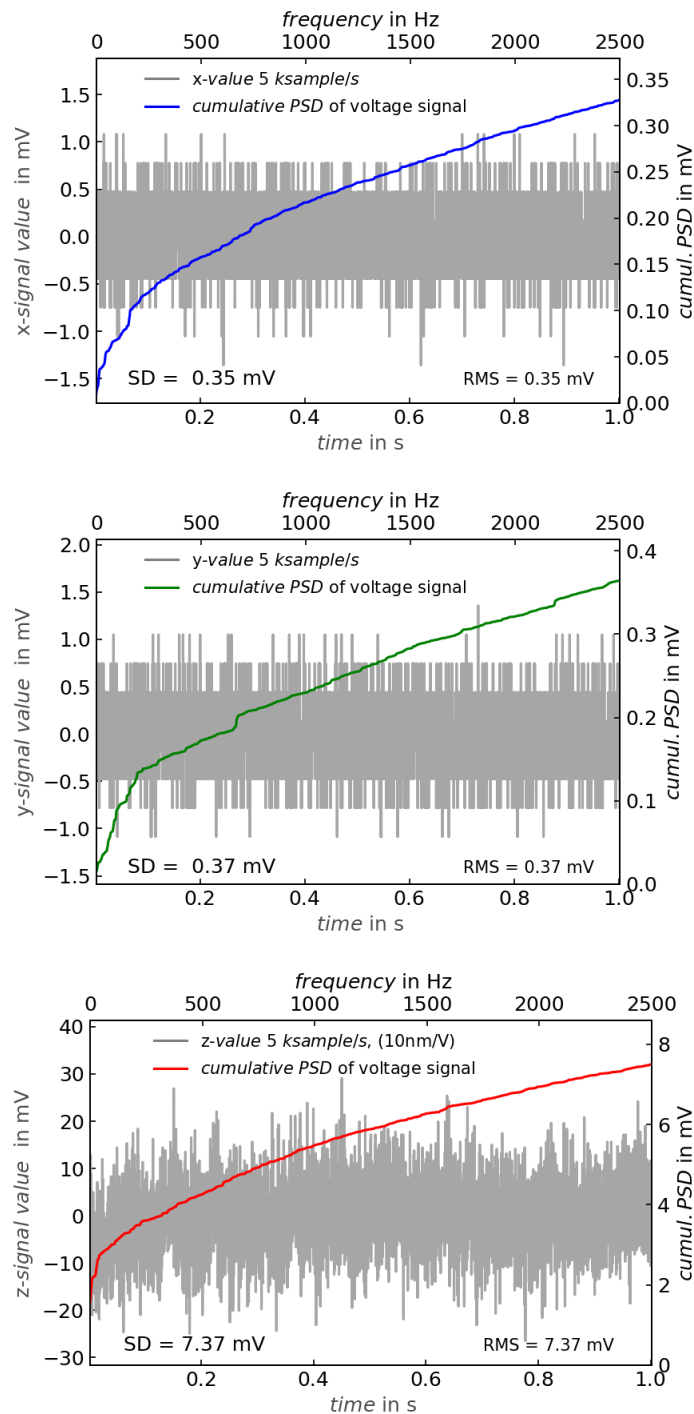


Figure 6.4: Noise of the bending, torsion and interferometer raw signals on the 16-bit ADC Multiplexer (MUX) input measured with the *National Instruments sbRIO* board.

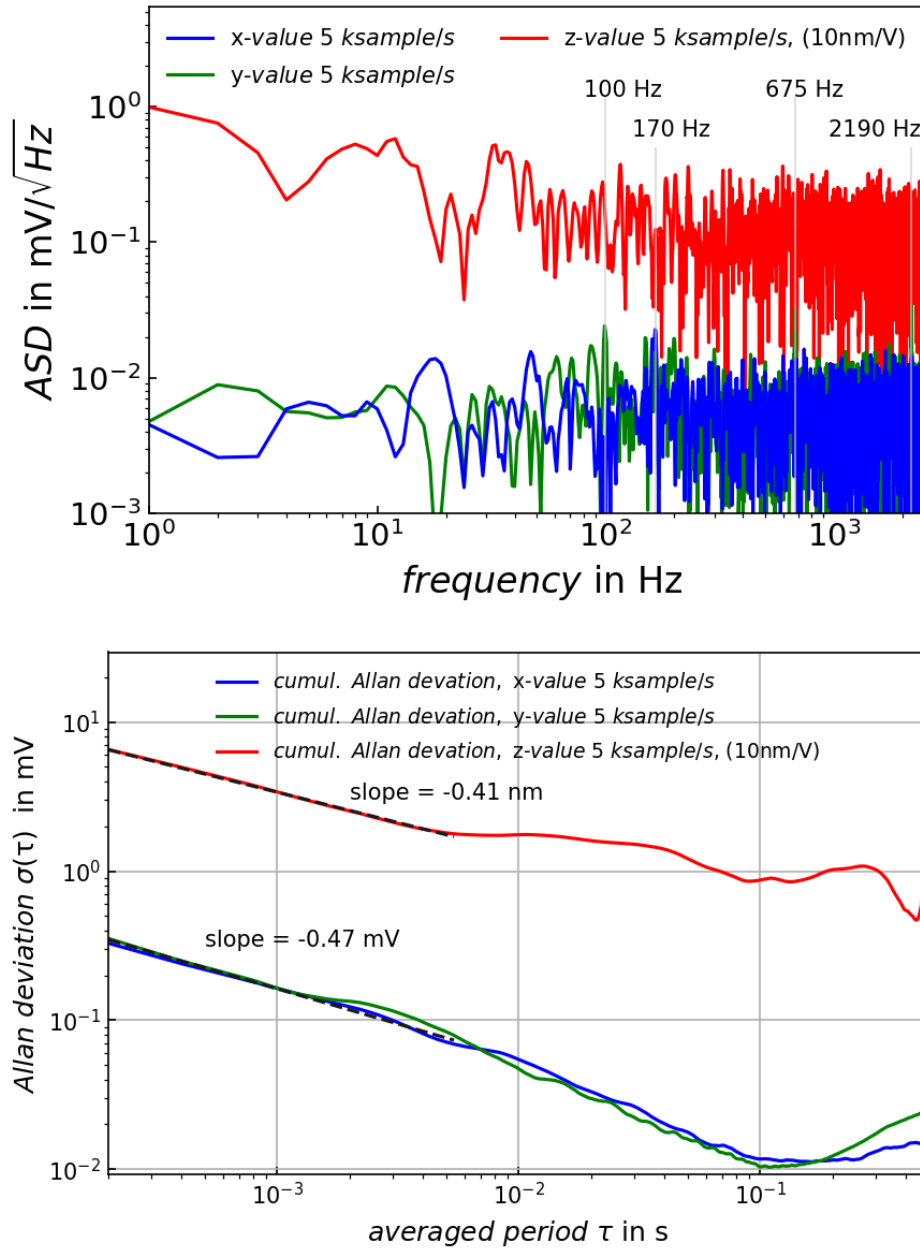


Figure 6.5: Amplitude spectral density (ASD) and Allan deviation noise of the bending, torsion and interferometer raw signals measured with the 16-bit ADC Multiplexer (MUX) of the *National Instruments sbRIO* board.

6.2.1. Calibration of the sensitivity coefficients of a 3D-Nanoprobe

After evaluation of the raw signal noise, and resonant frequencies of the 3D-Nanoprobe, the 3D-Nanoprobe is ready for calibration. **Figure 6.6 and 6.8** show the calibration setup with two mounted so-called IVPS100-PTB reference structures (*from team-nanotec*), (shown in **Figure 6.17**) [208]. In the following, the IVPS100-PTB no.0301 and no.0205 are denoted as IVPS0301 and IVPS0205, respectively. These reference structures are made of single crystal silicon whose surface is oriented in $[110]$ direction and has very smooth, vertical, and parallel sidewalls. They are frequently used to calibrate the tip of AFM probes. The upper corner rounding of these line structures is smaller than 7 nm [209]. The IVPS chip is 6 mm x 6 mm and has 4 quadrants with 25 individually numbered structures. Each structure consists of five line structures denoted as S1, S2, S3, S4 and S5 with nominal line width of 50 nm, 70 nm, 90 nm, 110 nm and 130 nm, respectively. The pitch is about 500 nm. The structures M35 are used in the experiments. The IVPS0301 is mounted with the line structure aligning with the y-axis, as depicted in the sketch in **Figure 6.6**. The IVPS0205 is mounted orthogonal to the IVPS0301 with the line structure parallel to the x-axis direction. As already mentioned, a first preliminary set of calibration coefficients can be received from the design data of the 3D-Nanoprobe in combination with the model of the 3D-AFM head detection system. They are given by the matrix of the sensitivity coefficients in (89). **Figure 6.6** shows the ordinary calibration procedure with the calibration steps from (I) to (IV). The calibration starts with (I) by defining the vertical z-direction of the 3D-Nanoprobe's coordinate system. The probing direction is slightly varied in the zy-plane until the changes in the raw signal of the the optical lever bending signal are minimal, because the manufacturing deviations have an influence on the functional properties. The pre-tilt of 8° given by the 3D-Nanoprobe incident angle is used as start value for the probing vector. As mentioned before, a constant inclination angle of HS2, defines the z-direction of the probe. Typical deviations from the nominal incident angle are within $\pm 2^\circ$. The 3D-Nanoprobe specifically described in this work shows minimal changes of the optical lever raw signals for a (x, y, z) probing vector in $(0, 30 \text{ nm}, 200 \text{ nm})$ direction, which corresponds to a rotation of 8.5° of the probes coordinate system relative to the machine (stage) coordinate system. The z-displacement of the CD-tip apex is calibrated via the travel of the stages probing vector in yz-direction. The probing curves are analyzed and the slope of the interferometer or z-displacement signal of the probe is set to 1 via the calibration coefficients of the matrix. All other registered tip apex displacements in x- and y-direction are optimized to zero via the upper diagonal elements of the calibration matrix. On the smooth surface of the IVPS0301 or IVS0205 sample the probing direction can be varied up to about $\pm 30^\circ$ without tip slipping, due to the compliant 3D-Nanoprobe and surface adhesion forces. This can be used for a careful first estimation of the main sensitivity coefficients of the matrix in x- and y-direction, since the probing is safely performed on an even surface on top of the structures. This can also be used to check for re-calibration (e.g. z-direction).

After the initial step, the calibration structure of the IVPS0205 sample is searched by the VAP method (section 3.5), probing exceptionally in z-direction. The triangular alignment structures of the IVPS100-PTB sample are used to find the middle of the M35 structure and orientation. The orientation of the sample is measured and compensated. A so-called cut-off-plane is set at 100 nm below the upper surface of the sample, because the sample is

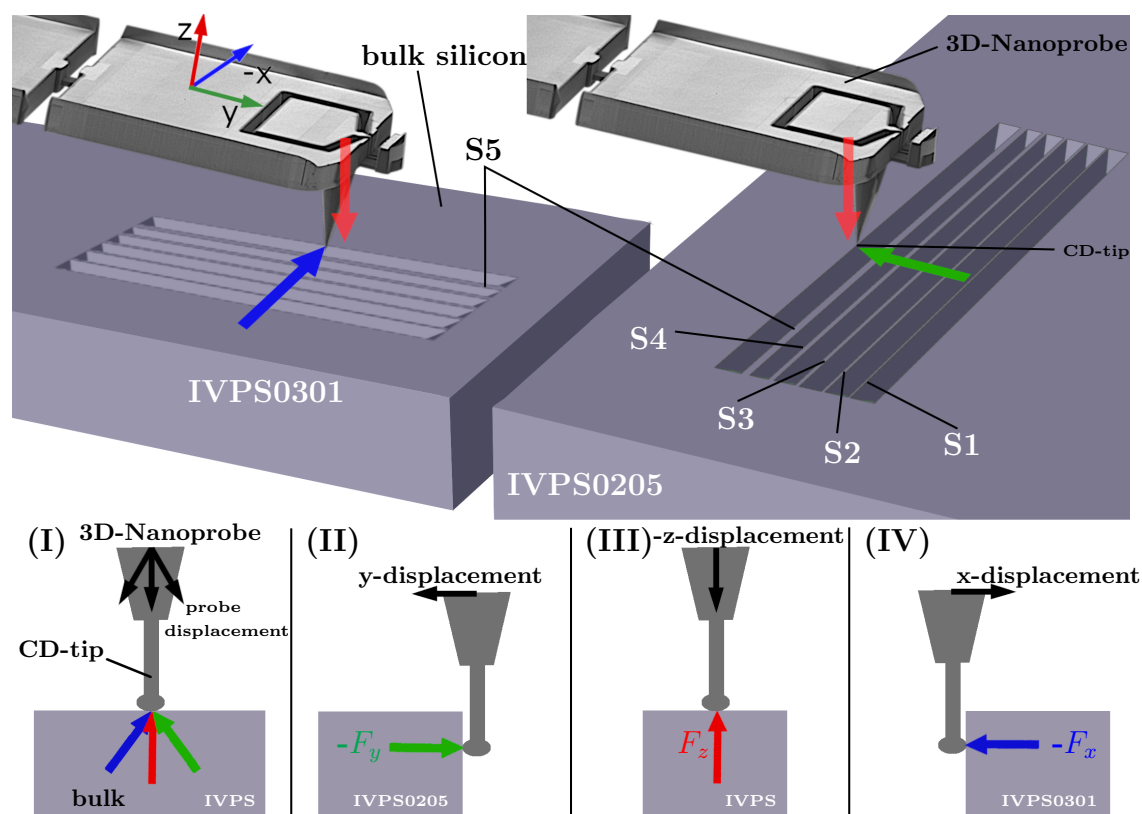


Figure 6.6: Calibration procedure sketch of the 3D-Nanoprobe in x-, y-, and z-direction (*top*) using two orthogonal oriented IVPS100-PTB denoted as IVPS0301 and IVPS0205. The calibration steps are marked from the initial step (I), to the steps for calibration of the x-, y-, z-directions given by (IV), (II), (II), respectively. The 3D-Nanoprobe and IVPS100-PTB are not to scale. During probing, the tip-sample interaction forces F_x , F_y , F_z deflects the flared CD-tip due to the relative displacement between tip and sample.

structured deeper (about 900 nm) than the length of the used CD-tip (about 600 nm). This cut-of-plane sets a limit for the probing depth to avoid tip collision under unstable probing conditions. In a second calibration step, the coefficients of the y-direction are determined. The procedure is depicted in (II). The bulk sidewall of the IVPS0205 sample is used as a rigid surface to calibrate the tip displacement in y-direction without bias of the lateral stiffness of the narrow IVPS100-PTB line structures. The tip apex of the 3D-Nanoprobe is positioned inside the trench between the bulk and the S5 line structure of the IVPS0205 at a probing depth of about 70 nm from the upper (top) surface of the sample. The CD-tip apex displacement in y-direction is calibrated via the slope of the registered tip-sample interaction curve. As previously described for the z-direction, the slope of the CD-tip apex displacement in y-direction is optimized to 1 (see **Figure 6.7 (e)**). Other CD-tip apex displacements are optimized to zero. A set of calibration curves of the y-direction are displayed in **Figure 6.7 (b), (e), (h)**.

In a third step (III), the z-direction is re-calibrated, because of eventual drift. The calibration steps of the y- and z-direction, described in (II) and (III) are usually repeated 2 times, because they can influence each other (see calibration matrix). A set of calibration curves of the z-direction are displayed in **Figure 6.7 (c), (f), (i)**.

In the final step (IV), the tip-sample interaction in x-direction is calibrated. The 3D-

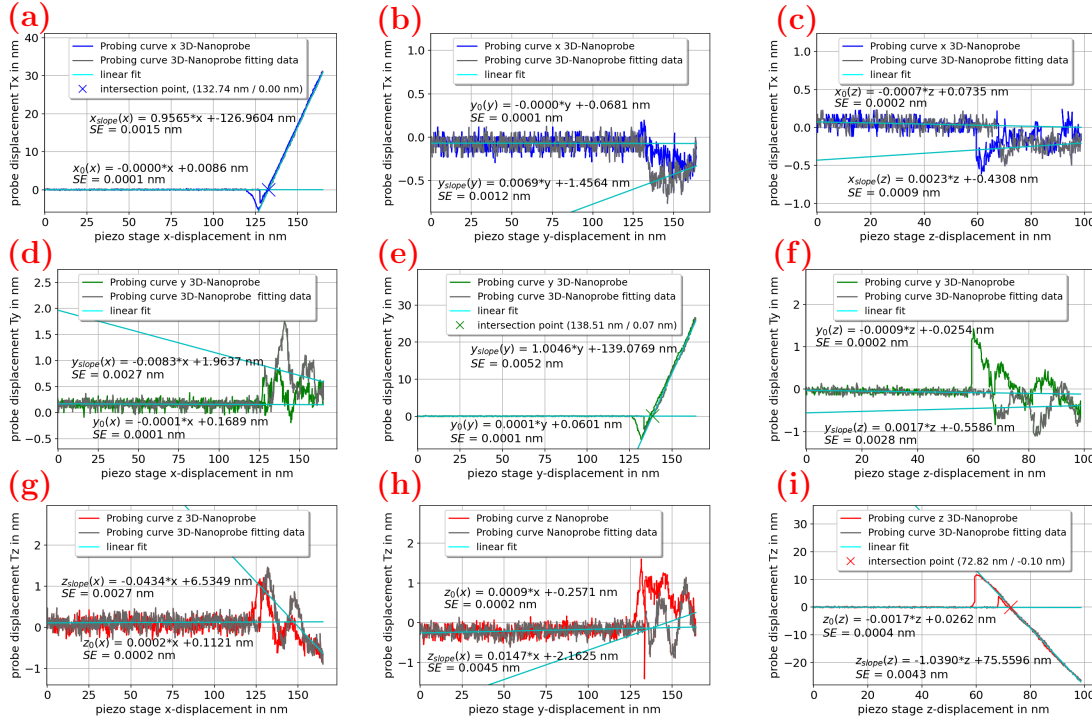


Figure 6.7: Full set of calibration curves of the 3D-Nanoprobe in x-, y-, and z-direction with standard error (SE) of the linear fit.

Nanoprobe is moved to the second sample, the IVPS0301. As already described in (II) the CD-tip apex is positioned at a probing depth of 70 nm inside the trench between the S5 line structure and the bulk material and the rigid bulk sidewall is probed. The slope of the CD-tip apex displacement is optimized to 1, whereas the registered y- and z-displacement directions are optimized to zero. A set of calibration curves of the x-direction are displayed in **Figure 6.7 (a), (d), (g)**.

As a result, the calibrated sensitivity matrix for the 3D-Nanoprobe no. 2F1 based on a CDR-120 cantilever is given as an example by:

$$\begin{pmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \end{pmatrix} = \begin{pmatrix} 0.5200 & -0.0150 & 0.000 \\ 0.0330 & 0.3900 & 0.0007 \\ -0.020 & -0.1550 & 0.0190 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x} \\ S_{QPD2y} \\ S_{INT} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x}^2 \\ S_{QPD2y}^2 \\ S_{INT}^2 \end{pmatrix}, \quad (95)$$

with the dual optical lever signals $S_{QPD2x} = V_{LR} * 1000/V_{SUM}$, $S_{QPD2y} = V_{TB} * 1000/V_{SUM}$ and the interferometer signal S_{INT} . V_{LR} , V_{TB} , V_{SUM} and S_{INT} are given in Volt.

After calibration, the 3D-Nanoprobe's coordinate system is rotated backwards by expression(90) into the machine (piezo stage) coordinate system. As mentioned before, the rotating angle was determined during the optimization of the 3D-Nanoprobe and is given by the approaching vector in the yz-plane for $S_{QPD2y} = 0$ (*or const.*) and the incident angle of the probe of about 8° . As already indicated, for this 3D-Nanoprobe it is given by 8.5° .

By comparing the slopes of the probing curves, the hand-calibration process revealed an average selectivity ratio of the tested 3D-Nanoprobes of about 50:1 for probing in the orthogonal the x-, y-, and z-directions [106].

The used 3D-Nanoprobe (above) was remounted after 4 months and the calibration of the sensitivity matrix was repeated. The sensitivity matrix of the second calibration is given by:

$$\begin{pmatrix} x_{tip} \\ y_{tip} \\ z_{tip} \end{pmatrix} = \begin{pmatrix} 0.4800 & \textcolor{red}{0.5170} & 0.0260 & 0.0002 \\ -0.040 & 0.3920 & 0.000 & \\ -0.041 & -0.1600 & 0.0195 & \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x} \\ S_{QPD2y} \\ S_{INT} \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} S_{QPD2x}^2 \\ S_{QPD2y}^2 \\ S_{INT}^2 \end{pmatrix} \quad (96)$$

The new calibration coefficients show different values, which might originate from remounting and usage of the 3D-Nanoprobe (e.g. tip abrasion). The calibration coefficient of the interferometer depends on the position of the beam spot on the 3D-Nanoprobe, as indicated by the analytical description of the hybrid detection system. In addition, the relatively large sinusoidal non-linearities of the interferometer, which are shown in **Figure 6.7** during the tip sample interaction, might also affect the coefficients of the z- and y-axis. Despite the small overall deviations of the y- and z-axis of the first set of calibration factors in (95) compared to a second set of calibration factors in (96) one can identify a slight, but noticeable larger deviation for the x-direction of about 8%. This deviation can be attributed to a human error, because the calibration is done via the slope of the individual calibration curves by hand. The slope was not estimated correctly. By comparing the probing curves of the x-direction in a post-process, the compensated calibration coefficients can be estimated relative to the first set (estimated slope difference 7.7%). This post-process coefficient is marked in red in (96) and shows small deviation compared to the first set. The minor diagonal elements show a small rotation in the horizontal (lateral) plane because the 3D-Nanoprobe's support chip has no alignment grooves, consequently the mounting angles can deviate. Rotation angles of a few degrees for cantilever probes without physical alignment features can be considered as normal. The calibration compensates this mounting error.

As a result, the calibration of the 3D-Nanoprobe seems to be repeatable within about 3% of the main diagonal elements and the 3D-Nanoprobe's properties are stable over at least 4 months. This can be seen as a first (careful) estimation of the stability of the calibration. In general, one can assume a bias from tip-sample interaction of a few percent to the slopes of the probing curves and thus to the calibration coefficients. Because the calibration was done with the same samples in the same probing directions under similar conditions, those effects

are reduced. For a thorough understanding, more measurements have to be performed. By comparing both calibrations with the theoretically modeled values, one can see that the coefficients for the z-direction are close to the expected value, deviating by about 1.2:1 from each other, whereas the coefficients for the x-direction and y-direction deviate by 1:1.9 and 1:1.8, respectively. The deviation in z-direction can easily be explained by a shift of the focused beam position on HS1 to free end by a few micrometer, because the base cantilever of this 3D-Nanoprobe was about $10\text{ }\mu\text{m}$ shorter than other base cantilever probes, which shifts the HS1 spot closer to HS2 and increases sensitivity. In addition, the frequency sweep indicates a possibly more compliantly manufactured FH1 which also increases sensitivity (due to the presence of FH2). The deviation of the sensitivity in x-direction and y-direction is also present in other 3D-Nanoprobes with this tip geometry. The larger coefficient indicates a more compliant CD-tip than expected, because the frequency sweep of the 3D-Nanoprobe shows relatively good agreement with the simulation, which can be attributed to a relatively accurately manufactured structure. Thus, a slightly more compliant tip is very likely, because the stiffness $c_{sxx} = c_{syy}$ of this small CD-tip is highly influenced by its geometry with $c_{sxx} \sim L_s^3$ and $c_{sxx} \sim d_s^{-4}$. This shows the importance of a high-quality and stable manufacturing process. The assumption of a softer tip is also supported by slightly lower stiffness values in x- and y-direction (see following 6.2.2). The lower stiffness did not affect the usage and functionality of the investigated 3D-Nanoprobe and was therefore chosen here as an example to demonstrate the robustness of this design. Other 3D-Nanoprobes are shown in [106].

6.2.2. Calibration of the stiffness of a 3D-Nanoprobe

The stiffness of the 3D-Nanoprobe is determined via a reference spring method using as *MEMS device* [211], inspired by ISO 11775:2015 [210]. The *MEMS device* itself is glued to a *PCB* and the *PCB* is mounted to a *support structure* to improve handling and stability [211],[212]. **Figure 6.8** shows images of the setup for calibrating the 3D-Nanoprobe's stiffness in x-, y-, z-direction. The moving platform of the *xyz-piezo stage* is enhanced by the so called *extended platform* to place the *support structure* with the reference spring.

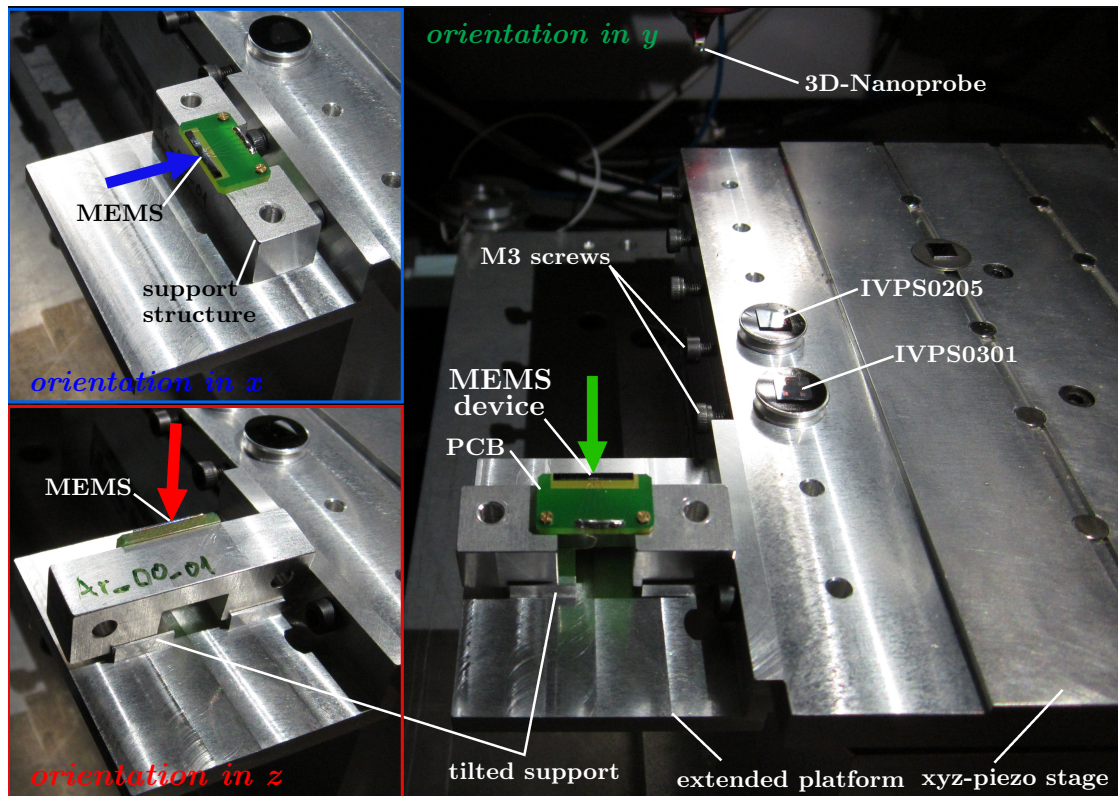


Figure 6.8: Setup for stiffness calibration of the 3D-Nanoprobe with oriented micro electro-mechanical system (MEMS) device in x-, y-, and z-direction. The MEMS device incorporates the reference spring for calibration. The main image shows the MEMS device oriented for measuring in y-axis direction. The orientation of the MEMS in x- and z-axis direction of the 3D-Nanoprobe is shown in image details. The (*blue, green and red*) arrows mark the coarse probing direction.

Figure 6.9 shows a photo-montage of the calibration procedure in x-, y-, and z- direction. The micro electro-mechanical system (MEMS) device is oriented according to the coordinate system of the 3D-Nanoprobe and re-positioned for each spatial direction. This implies tilting of the MEMS device according to the incident angle of the probe by about 8° relative to the machine coordinate system with the *tilted support* for the stiffness calibration measurements in y- and z-axis direction. The small cosine error between the fixed incident angle and calibrated incident angle of the 3D-Nanoprobe's coordinate system is smaller than 1° and

can thus be neglected. The depicted 3D-Nanoprobe and MEMS device are not to scale. The complete MEMS device is monolithic and is made of silicon [211],[212]. It consists of a bulk part of the silicon support chip surrounding the delicate reference springs and comb structure for electro-mechanical actuation [212]. The electro-mechanical actuation is not used and is therefore shortened during the calibration process of the 3D-Nanoprobe via electrical contacts (see **Figure 6.9**) to avoid bias of electrical surface charges.

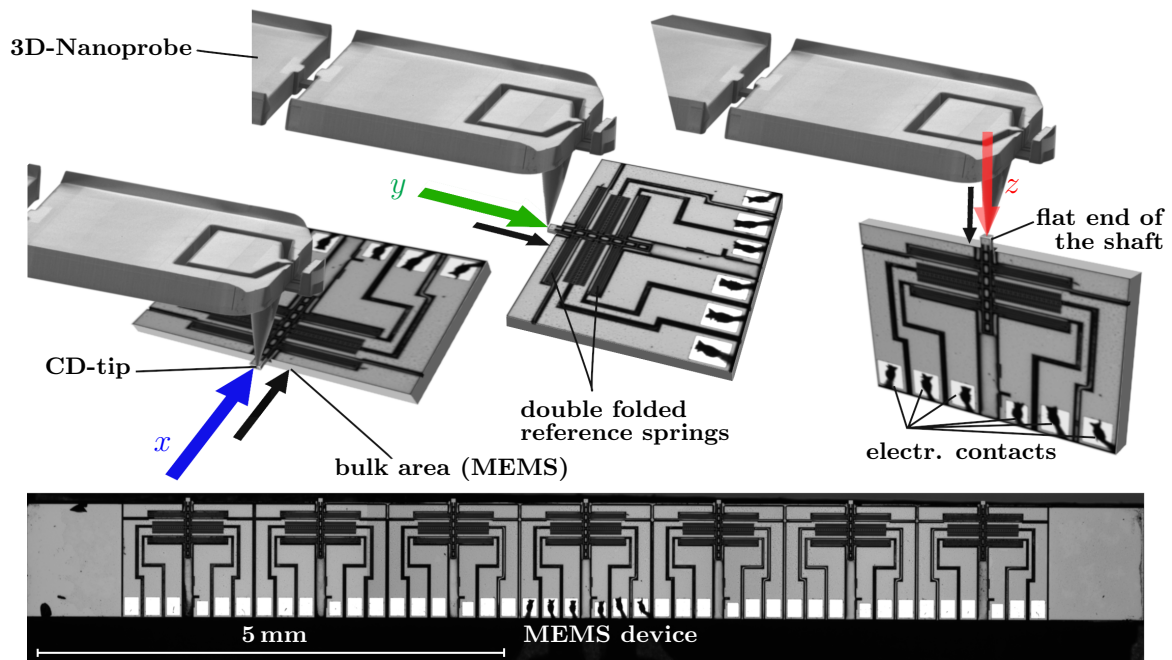


Figure 6.9: Stiffness calibration image montage of the 3D-Nanoprobe with re-oriented micro electro-mechanical system (MEMS) device in x-, y-, and z-direction. The MEMS device incorporates the reference spring for calibration. The 3D-Nanoprobe is not to scale with the MEMS device. The *black*, *blue*, *green* and *red* arrows mark the probing region. At the *bottom*, the MEMS device is shown in a overview from the top. The contacted structure in the middle was used as a reference spring.

The parallel, double folded reference springs of the MEMS device are connected to the shaft and mechanically guide the shaft for displacements in one direction [212]. The combined stiffness of each individual folded reference spring of the MEMS structure form the nominal reference spring value of the flat end of the shaft. The flat end of the shaft is used as the interface for probing, actuating the reference spring. The calibrated reference spring value of $k_{ref}=2.571(2) \text{ N/m}$ is compared to the stiffness of the 3D-Nanoprobe in two measurements by dividing the probing curve's slopes of the stiff bulk area m_{bulk} and of the compliant reference spring m_{spring} [106]. This implies, that the compliance of the shaft of the reference spring is compared with the stiff bulk area to compensate for the instrument compliance and eventual compliant elastic mount of the MEMS device. However, the contact stiffness is not taken into account here, because it is considered to be negligible in this comparison measurement

method (for the same probing conditions it is compensated). The flat end of the shaft, and the used *bulk areas* of the silicon chip of the reference MEMS, were polished in a FIB process to improve surface quality and flatness for accurate probing. The black arrows in **Figure 6.9** mark the polished bulk areas for probing and probing directions in x-, y-, and z-axis of the 3D-Nanoprobe coordinate system. The blue, red and green arrows mark the actuation and probing direction of the oriented MEMS device in the 3D-Nanoprobe's coordinate system. The stiffness of the 3D-Nanoprobe, according to [211], from [106] is given by

$$k_{probe.i} = \left(\frac{m_{bulk.i}}{m_{spring.i}} - 1 \right) k_{ref} \quad (97)$$

with $i = x, y, z$.

Figure 6.10 depicts two probing curves in x-direction with the slopes $m_{bulk.x}$, and $m_{spring.x}$ for the rigid bulk and compliant spring, respectively. The average of five probing curves are taken for each surface and orientation and the slopes are fitted by least square method. An

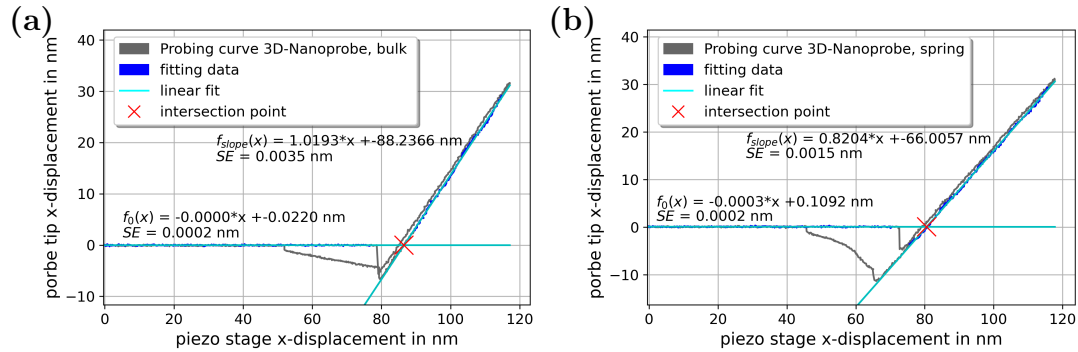


Figure 6.10: Stiffness calibration curves of the 3D-Nanoprobe in x-direction (SE = standard error of the fit).

equilibration time of about 6 hours for each measurements location or orientation is sufficient because the slope of the probing curves of the rigid bulk and compliant spring are compared shortly after each other. The calculated stiffness results $k_{probe.i}$ of three tested 3D-Nanoprobes are compared against their FEM simulation (solving accuracy of 2%). The results of three 3D-Nanoprobes are taken from [106] and listed down below. **Table 6.1** shows the stiffness of three measured 3D-Nanoprobes. 3D-Nanoprobe B was used as an example in this thesis. The quasi isotropic ratio of the measured stiffness is given by 0.87:0.88:1.00 for the x-, y-, and z-direction, respectively [106].

A detailed description of the other 3D-Nanoprobe's stiffness measurement results is given in [106] and is not repeated here. However, the manufactured values are close to the simulated ones and prove that the optimization works correctly and the manufacturing process of the 3D-Nanoprobe is appropriate and functions well. Overall deviation in the stiffness value in the range of about 25% can mainly be addressed to an unknown exact CD-tip geometry in combination with manufacturing uncertainties. It indicates the importance of a thorough optimization process and manufacturing of each individual CDR-cantilever based 3D-Nanoprobe

Table 6.1: Stiffness values k of three manufactured 3D-Nanoprobes obtained by calibration with a reference spring and values from a finite element method (FEM) simulations, (data from [106])

3D-Nanoprobe	Measured stiffness in N/m ($k=2$)	FEM modeled stiffness in N/m
A*	$k_x = 1.722 \pm 0.083$	$k_x = 2.13$
	$k_y = 1.511 \pm 0.034$	$k_y = 1.98$
	$k_z = 1.64 \pm 0.16$	$k_z = 2.45$
B**	$k_x = 2.016 \pm 0.024$	$k_x = 2.11$
	$k_z = 2.036 \pm 0.070$	$k_y = 2.23$
	$k_z = 2.311 \pm 0.089$	$k_z = 2.72$
C***	$k_z = 2.719 \pm 0.067$	$k_x = 2.22$
	$k_y = 2.461 \pm 0.065$	$k_y = 2.42$
	$k_z = 1.198 \pm 0.099$	$k_z = 2.32$

* calibrated incident angle 8.3°

** 3D-Nanoprobe from the example above, with the calibrated incident angle of 8.5°

*** calibrated incident angle 6.8°

setup incident angle 8°

prototype.

This stiffness calibration shows, that the 3D-Nanoprobe might also be used as a force transducer, e.g. to determine tip-sample interaction forces, via a calibrated matrix of sensitivity coefficients.

6.3. The 3D-AFM properties in the measurement setup

After calibration of the 3D-Nanoprobe, the measured 3D-AFM head voltage signals of the detection system are translatable to position signals via the determined calibration matrix. The noise and drift measurements of previous chapters are used to give an estimation for the position noise and stability of the 3D-AFM head. The no-contact position noise signals in x-, y-, and z-direction are presented in the following. The no-contact position drift of the 3D-AFM-head during warm-up is shown in **Figure 6.14**. Finally, the 3D-Nanoprobe is tested for probing repeatability in 3D (x-, y-, and z-direction), which is shown in **Figure 6.16**.

6.3.1. Position noise

The voltage noise signals in **Figure 6.4** and **6.5** are used to calculate the position noise in x-, y-, and z-direction via the determined calibration matrix. **Figure 6.12** and **G.1** show the no-contact position noise signal of a 3D-Nanoprobe in nanometer. The RMS value of the noise is given by 0.053 nm, 0.068 nm and 0.15 nm in x-, y-, and z- direction at bandwidth of 2.5 kHz, respectively. As already mentioned, the relatively small RMS value of the interferometer is only valid for small signal fluctuations. The typical value for the position noise with environmental fluctuations in z- direction is given by about 0.4 nm but can be up to about 0.9 nm, as depicted in **Figure 6.11**. The cumulated PSD and ASD of the y-position signal in **Figure 6.12** and in **Figure G.1** shows significant frequency contributions to the total noise at around 100 Hz, 675 Hz and 2190 Hz, such as the voltage noise signal. The x-position signal shows a noise contribution at 170 Hz. The origin of those noise contributions could not clearly be identified, since they seem to change with the probe, thus it might be an aliasing effect or depends on lab activities. The Allan deviation in **Figure G.1** shows a main slope of -0.47 for the x- and y-position noise which indicate quantization noise and flicker noise. The small undulations can be attributed to the sinusoidal frequency contributions, as indicated in ASD. The y-position is larger than the x-position because of the influence from the interferometer signal. The z-position noise is the largest, it shows correlated noise contributions around a period of 0.06 s and 0.03 s. The slope of -0.41 can also be attributed to flicker noise and quantization noise. A local minimum of the z-position and y-position Allan-deviation curves can be found at around 0.1 s, which can be used as a estimate for an ideal probing frequency.

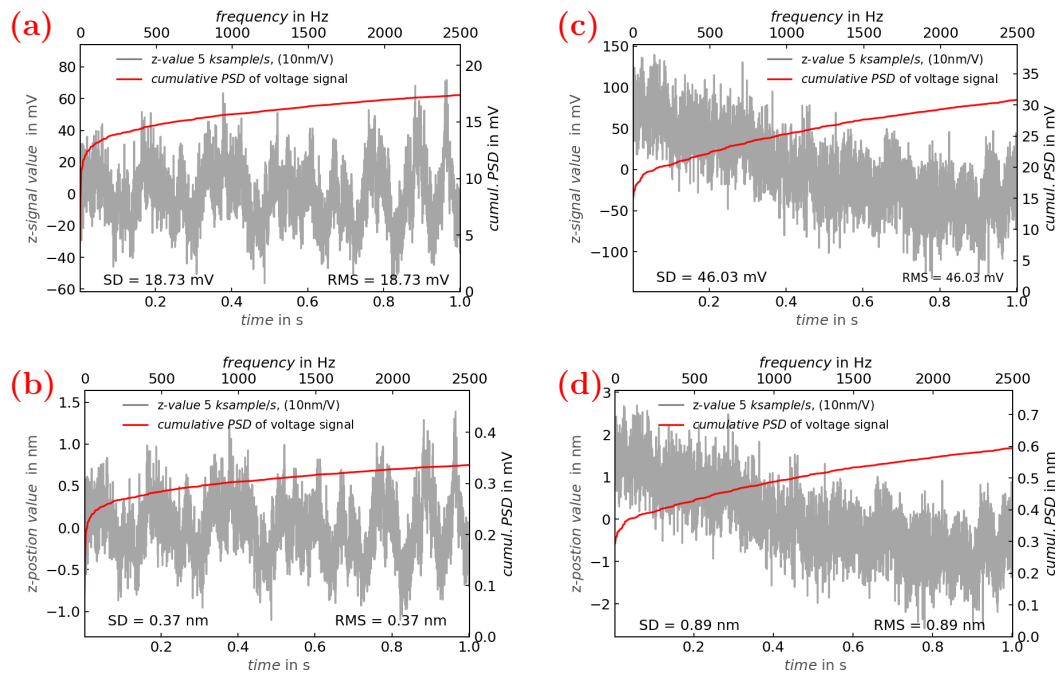


Figure 6.11: Interferometer position noise of the raw interferometer signal of the z-position on the 3D-Nanoprobe. (a) and (b) show the position signal with environmental fluctuations directly after closing the acoustic isolation chamber. (c) and (d) show the signal with typical sinusoidal fluctuations after long switch-on time of the interferometer without additional corrections (standard deviation (SD), root mean square (RMS)).

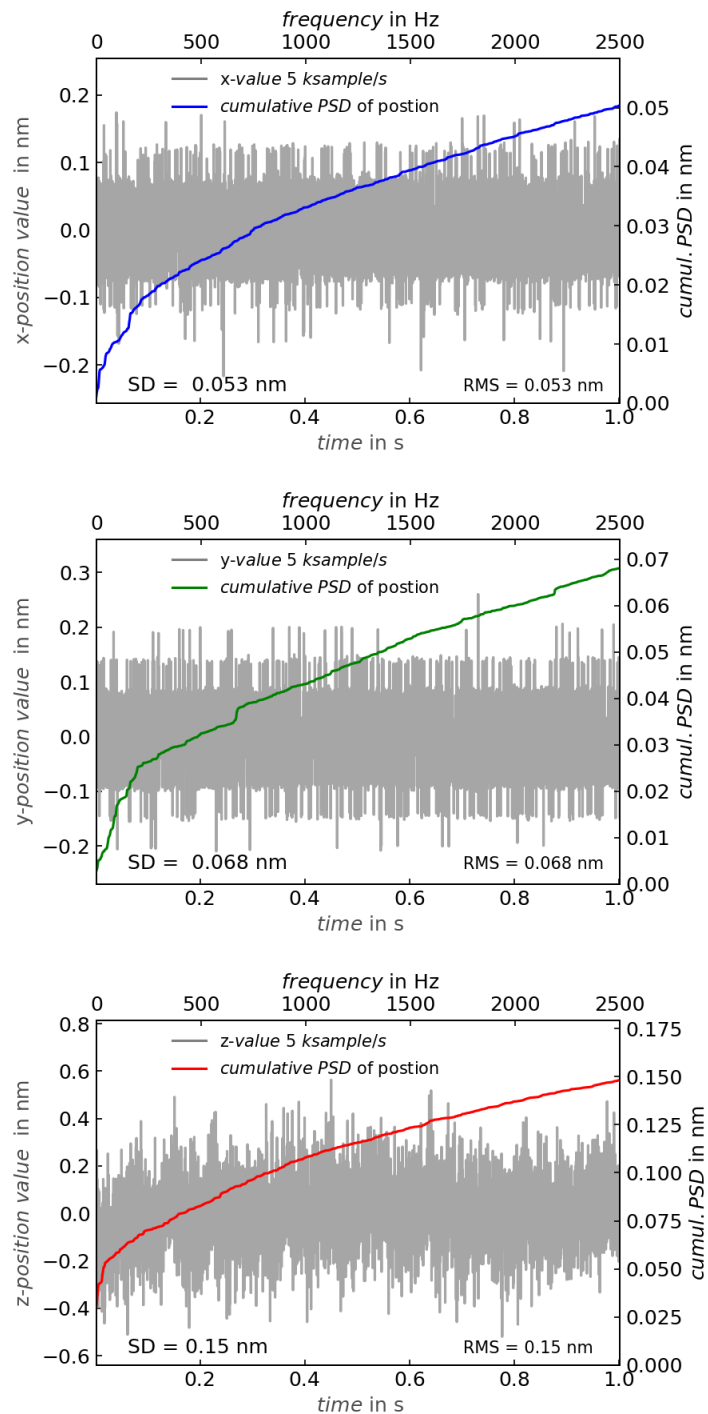


Figure 6.12: Position noise of the bending, torsion and interferometer raw signals measured with the 16-bit ADC of the *National Instruments sbRIO* board.

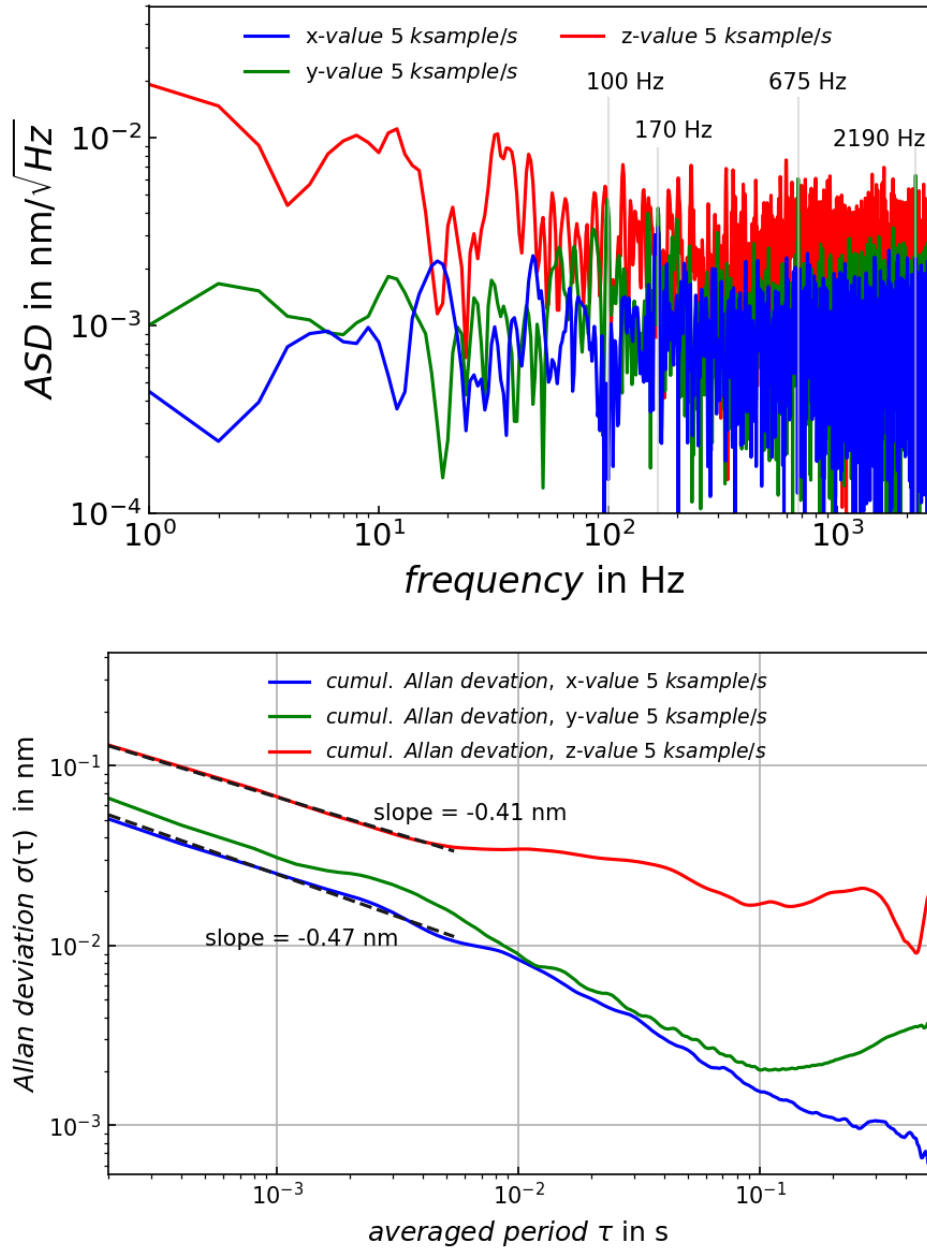


Figure 6.13: Amplitude spectral density (ASD) and Allan deviation noise of the position noise of the bending, torsion and interferometer raw signals measured with the *National Instruments sbRIO* board.

6.3.2. Position drift

Figure 6.14 shows the x-, y-, z-position drift of the 3D-AFM head with a mounted and calibrated 3D-Nanoprobe. The drift is induced by a temperature change of about 1.2 K, from switching on the camera of the setup (for details see **Figure 5.20 B**). The 3D-Nanoprobe is not approached on the sample surface. The position signals experience a drift due to the warm-up of about 8 nm, 11 nm and 40 nm for the x-, y-, and z- direction, respectively, over about 24 h. All position signals show fluctuations induced by the interferometer via the sensitivity matrix, as indicated in **Figure 5.20 A**. It is the dominating influence to the stability. Especially, the z -direction shows fluctuation of up to 35 nm. As already described, these fluctuations cannot be avoided using this kind of interferometer. Based on the calibration matrix of the 3D-Nanoprobe, the interferometer fluctuations are also displayed in the y-position signal. The fluctuation appears with an opposite sign and reduced amplitude below 10 nm. The x-position signal is most stable and shows a fluctuation amplitude below 3 nm. The phase jump after 13 h results from lab activities. The time constants of the exponential fits of the position signals given by τ_{1x}, τ_{1y} and τ_{1z} of about 1 h match the previously estimated time constants of the 3D-AFM head in **Figure 5.20**. Overall, the position drift indicates that the head is sufficiently stable for true 3D-Nanometrology measurement tasks, but could be improved regarding stability of the interferometer signal.

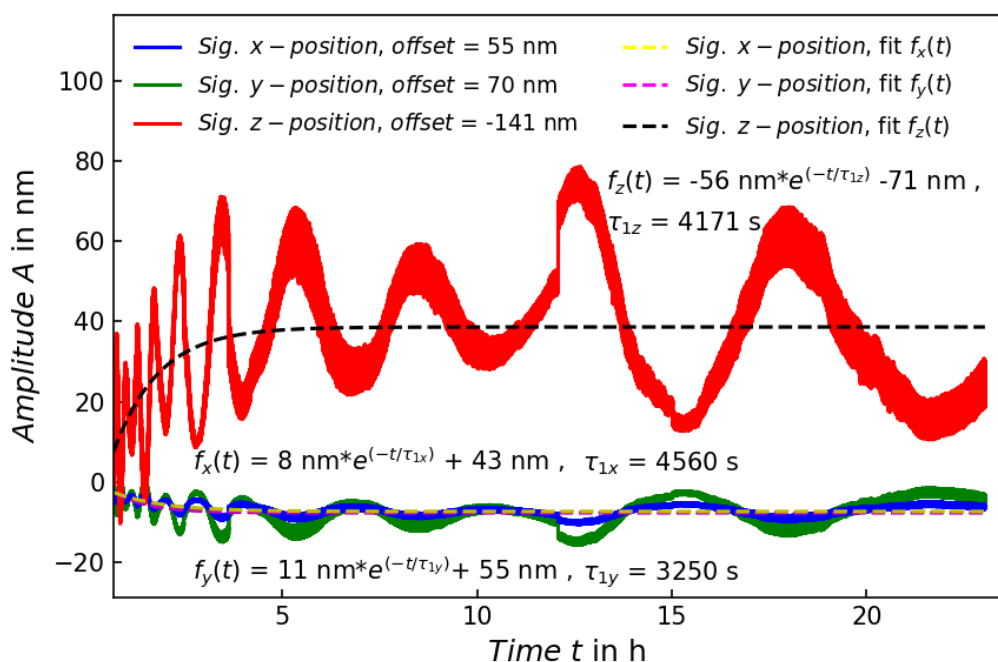


Figure 6.14: Position signal drift of the 3D-AFM head of a mounted 3D-Nanoprobe (for temperature changes and raw interferometer see **Figure 5.20 B**).

6.3.3. Probing repeatability

Figure 6.15 shows the typical probing repeatability (standard deviation) of a 3D-Nanoprobe in x-, y-, and z-direction with about 0.17 nm, 0.31 nm and 0.82 nm, for 100 repetitions, using the described 3D-AFM head with the hybrid detection system, respectively. Certainly, the probing repeatability includes the stages position noise. The setup was equilibrated for at least 5 hours and a probing speed of 1000 nm/s was used (probing frequency about 4 Hz). In general, position noise of the x-, and y- directions are relatively consistent over all of the tested 3D-Nanopores [106]. Significant deviations occur in z-direction.

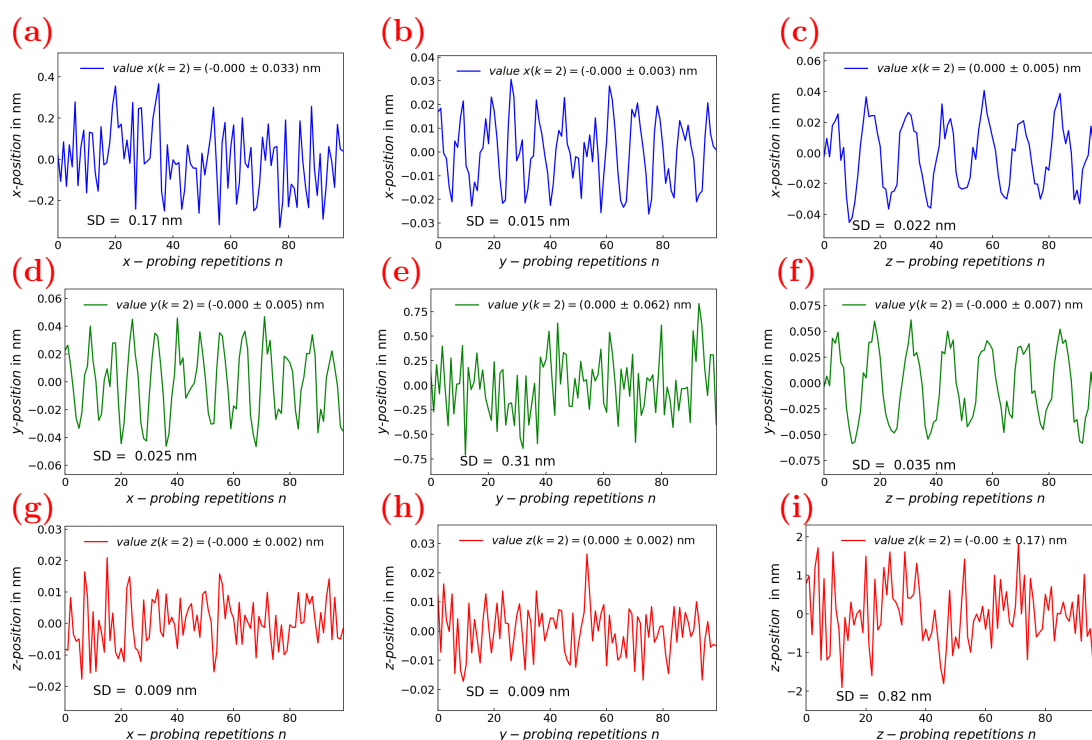


Figure 6.15: Probing repeatability curves of a 3D-Nanoprobe in x-, y-, and z-direction for 100 repetitions at the same location with a probing speed of 1000 nm/s, with typical interferometer non-linearities; standard deviation (SD).

Figure 6.16 (a), (e) and (i) shows the probing repeatability for exceptional small short term signal fluctuations of the used interferometer, and small non-linearities. A standard deviation in z-direction of down to 0.37 nm can be reached, with 0.16 nm and 0.34 nm standard deviation in x- and y-direction, respectively. The x- and y-position signals show noisy sinusoidal fluctuations perpendicular to the main probing directions with amplitudes of up to about 0.05 nm, which is depicted in **Figure 6.16 (c), (d) and Figure 6.15 (b), (c), (d), (f)**. A test revealed, that the oscillating position signals in **Figure 6.15** and **Figure 6.16** with about 0.05 nm amplitude increase in frequency with decreasing probing speed. It might be an aliasing effect of the piezo stage positioning servo-loop time with the probing frequency of the 3D-Nanoprobe. The doubled amplitude matches the positioning resolution increment

of the stage of about 0.1 nm. It could also be a mechanical frequency of the setup that has not been investigated or fluctuations of the interferometer which have a dynamic effect on the stage positioning in 3D, because the fluctuation seem to be more prominent in **Figure 6.15**. Overall, the detection systems shows good performance in 3D-probing and is within the design specification for probing repeatability, of below 1 nm standard deviation in x-, y-, and z- direction. Consequently, a true 3D-AFM head for true 3D-measurements is developed.

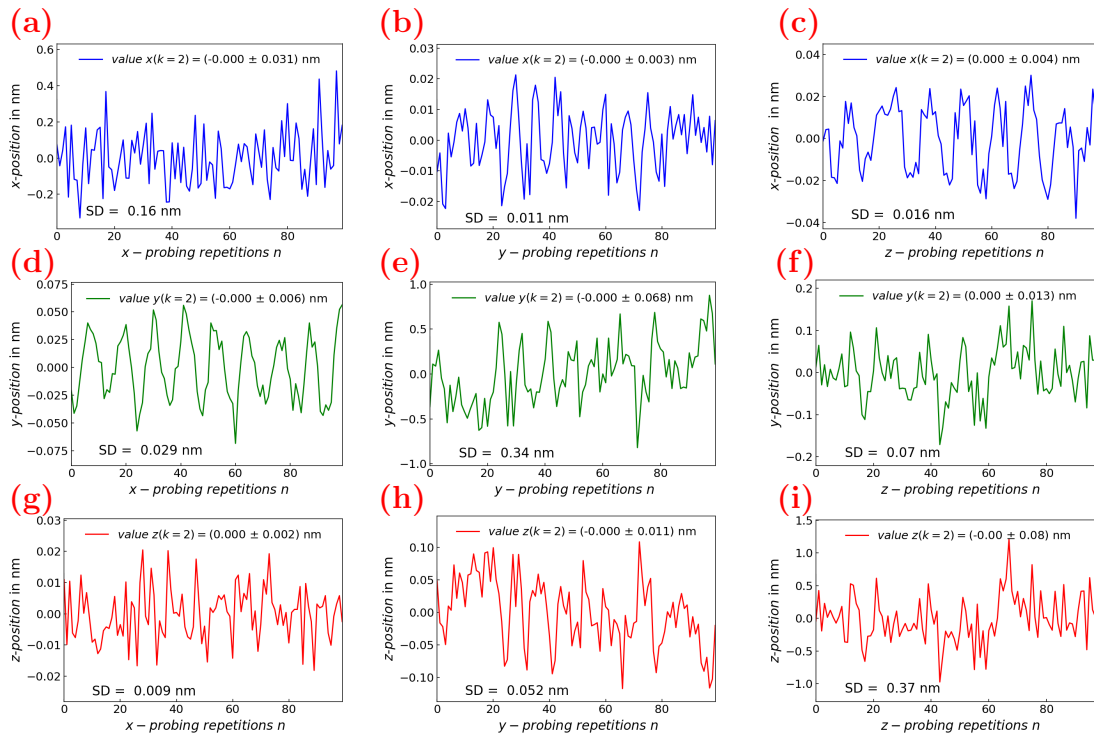


Figure 6.16: Probing repeatability curves of the 3D-Nanoprobe in x-, y-, and z-direction of the 3D-Nanoprobe coordinate system for 100 repetitions at the same location, standard deviation (SD).

6.4. The 3D-Nanoprobe applied for true 3D-measurements of CD structures

The 3D-Nanoprobe is applied for critical dimensional metrology tasks in x- and y- direction. The reference CD-structures M35 of the IVPS0205 and IVPS0301 (IVPS100-PTB), shown in **Figure 6.6** and **6.8**, were used as samples. An IVPS100-PTB structure is depicted in **Figure 6.17**. The widest line structures S5 and S4 of the M35 structure are used to test the probing capabilities of the developed true 3D-AFM. The setup is already described in 6.1. An equilibration time of more than one day was used per sample after coarse positioning. A probing speed of 1000 nm/s is used for all following experiments in contact VAP mode, with a target value for the deflection of the 3D-Nanoprobe of 30 nm.

The 3D-AFM head and 3D-Nanoprobe were tested for repeatability by measuring CD-structures to investigate the change in CD-value and the sidewall angles in x- and y- direction. Also, the stability of the CD-values in x- and y- direction over 125 measurements was investigated. In addition, the pitch between the S4 and S5 line was measured, such as the roughness of the sidewalls.

Because these measurements are explained in detail in [106], only the results are cited in the following. Two typical CD-measurements of the IVPS0205 and IVPS0301 S5 structures are depicted in **Figure 6.18** and described to prove the full 3D-probing capabilities for CD-structures.

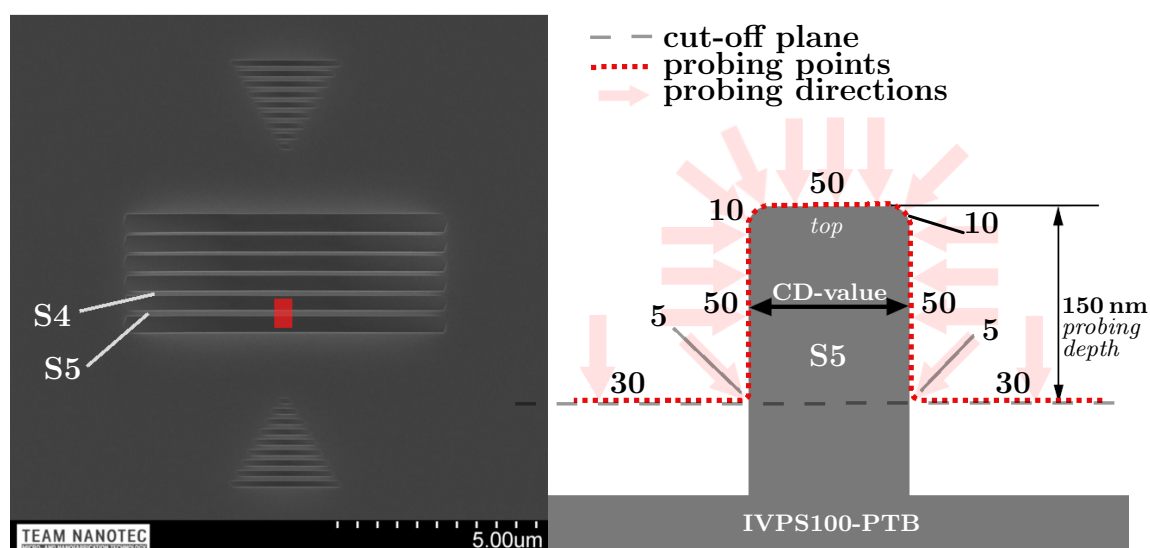


Figure 6.17: IVPS100-PTB sample and CD pattern curve of the VAP measurement for the CD-value measurement of the line structure S5. The *left* side shows an SEM image of the top of IVPS100-PTB sample with the marked S4 and S5 line structures (SEM image reused with permission from *team nanotec*[208]).

6.4.1. Critical dimension (CD) measurements

The Critical dimension (CD) measurement was performed in VAP mode without dithering. A probing vector length of 300 nm was used. The cut-off plane, to limit the probing depth,

was set to -150 nm as indicated in **Figure 6.17**. A total number of 240 probing points for each line was calculated for the S5 line structure from a pre-scan in z-direction (VP-line scan). The pattern is illustrated by the drawing in **Figure 6.17**. The sidewalls are probed with 50 points. An area of 600 nm (fast scan) $\times$ 500 nm (slow scan direction) was measured as indicated in **Figure 6.17** by the *red* area in the SEM image of the IVPS100-PTB sample. The S5 line structure was measured with 20 lines with equal spacing. The total measurement time for 20 lines is given by 18 min 41 s, which results in an average probing rate of about 4.3 Hz. The CD-value is determined at a probing depth of 75 nm from the top of the structure using 20 points of each vertical sidewall iteratively with linear least square fits [106]. The top position was calculated from 20 probing points of the middle of the line structure. **Figure 6.18** shows one measurement of the CD-structure of the IVPS0205 and of the orthogonally oriented IVPS0301. The depicted measurements include the CD-tip width and shape without any correction.

The CD-measurement of the IVPS0301 depicts a very uniform measurement without outliers with nearly vertical sidewalls. The left and right top corners show small dips in the corner rounding, which result from a slightly too narrowly determined pattern of the probing points (**Figure 6.18**). This might be very likely, because the more compliant structure of the 3D-Nanoprobe deflects more easily for a round CD-tip apex scraping along a vertical sidewall, while probing z-direction during VP-line scan, using the VAP-mode. As the small dips on the upper edges seem to be constant, it might also be a CD-tip-shape apex related effect, because the probing vector changes according to the anticipated corner rounding. A definitive explanation of this artifact would require further research. The CD-measurement of the IVPS0205 shows similar results; however, the contour is asymmetric due to the CD-tip dilation [106]. The top at corner shows a slope of about 8° , which is expected and corresponds to the incident angle of the probe, it shows a typical blunt tip. This incident angle also affects the right side of the CD-structure and shows probing artifacts from shaft probing, because the small overhang of the flared CD-tip apex cannot reach the vertical sidewall at increasing probing depths [106]. Thus, an apparent non-vertical sidewall is measured at depth. To test the **repeatability** of the developed true 3D-AFM, 12 single and consecutive measurements, including the VP-line scan and re-calculation of the probing pattern of the CD-structure, are investigated [106]. The x-direction shows a very good repeatability of the 189.339 nm CD-value with a decrease in CD-value of only -6.6 pm per single measurement [106]. The y-direction shows a considerably larger value of 252.396 nm with a decrease of -106 pm per single measurement, which is still usable but shows the impact of shaft probing [106]. The larger determined decrease in y-direction originates from the probing condition of the right sidewall. Tip abrasion processes and presumable large wear of the sharp upper right corner of the IVPS structure result in a decreasing CD-value.

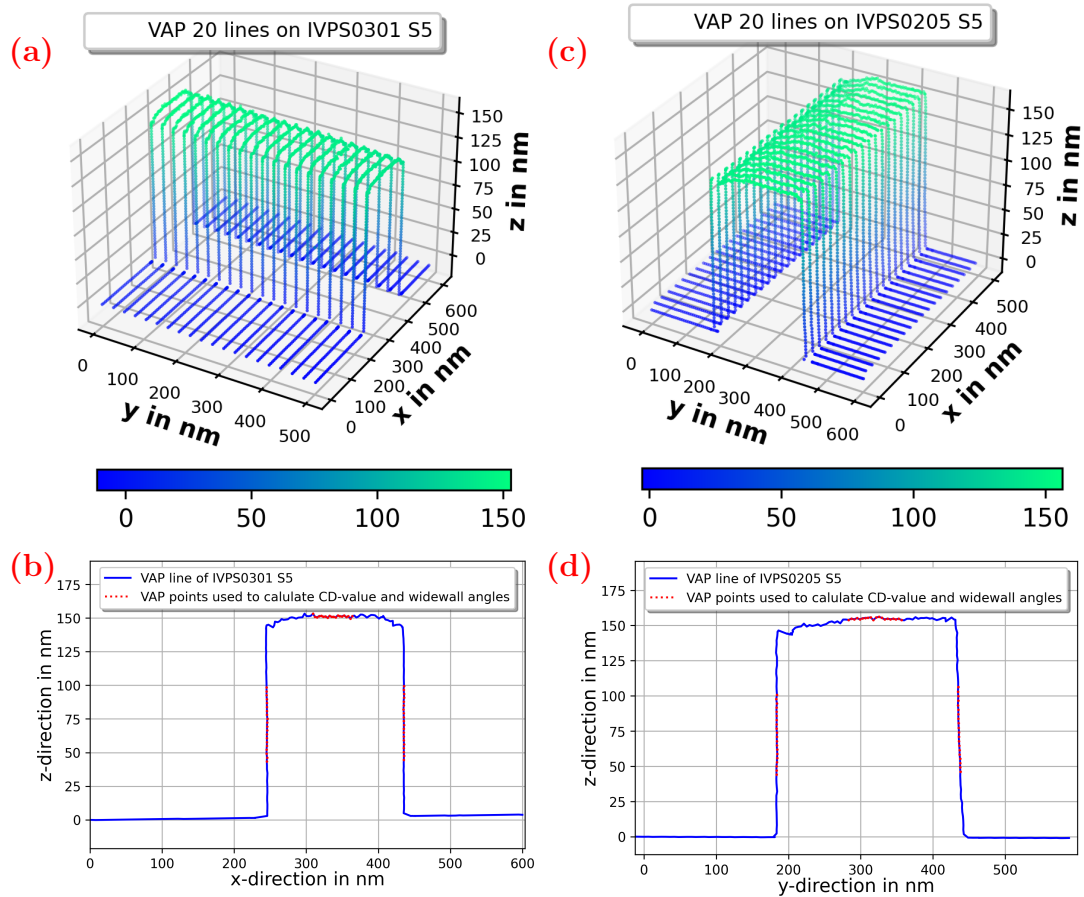


Figure 6.18: Vector approach probing measurements raw data from the line structure IVPS100-PTB no. 0301 (IVPS0301) in (a) and orthogonal mounted IVPS100-PTB no. 0201 (IVPS0205) in (c). One measured line in x- and y-direction of each line structure is shown in (b) and (d) below, respectively.

6.4.2. Stability of CD-measurements and SWA, LER, LWR, pitch measurements

The **sidewall angle** (SWA) measurements of the S5 structure of the IVPS0301 of the left and right sidewalls with 89.5° and 90° , respectively, show very good agreement with the expected nominal value of 90° [106]. The IVPS0205 sidewall angles of the left sidewall with 89.8° show also very good agreement with the nominal value [106]. The measurement of the right sidewall angle of the IVPS0205 shows 87.6° [106]. The deviation to the vertical nominal 90° sidewall angle of about 2.4° is expected, because the incident angle of the 3D-Nanoprobe in combination with a small flare of tip apex leads to shaft probing. This can clearly be seen by a decreasing sidewall angle on the right side of **Figure 6.18 (d)** for increasing probing depth, and can be avoided using cantilevers with a pre-tilted CD-tip or larger flared tip apex, in the future.

The **stability** measurements over more than 38 h for the x-direction shows an excellent stability of the CD-value of -5.5 pm per measurement or 0.26 pm per line (about 0.9 nm/mm), which means a total decrease of 0.7 nm over 125 measurements [106]. The y-direction show a slightly larger total decrease of 1.2 nm with stronger fluctuations, a trend line would show an 4.6 pm increase of the CD-value per repetition of a single measurement [106]. The CD measurements indicate that the level of precision and tip wear of the used true 3D contact mode is similar to the state of the art VAP mode for 1D gratings in [13], and slightly smaller than the values for CD-tip abrasion of silicon tips reported in [99]. Both measurements show less variation per measurement repetition than the repeatability measurement of the CD-values, which means that the VP-line scan for calculating the probing pattern has a strong effect on the abrasion of the CD-tip. During the VP-line scan in z-direction the flared part of the CD-tip scrapes along the sidewall, thus it changes the tip width and the measured CD-value [106].

The **pitch** measurements in x-direction of the IVPS0301 from S4 to S5 structure sample of 499.314 nm shows good agreement with the nominal pitch of 500 nm [106]. Unfortunately, at this stage of development a comprehensive uncertainty evaluation of the complete setup and measurement cannot be given. Consequently, the pitch value remains without uncertainty, to avoid misleading information. The measurements were alternated between the S4 and S5. The center pitch shows a small increase of 6.6 pm per single measurement over 10 repetitions. The IVPS0205 in y-direction shows a center pitch of 503.92 nm with a decreasing value of -0.13 nm per measurement over 10 repetitions [106]. The relatively large decrease per measurement presumably comes from tip abrasion from the alternating VP line scans and from shaft probing for the y-direction [106]. This can be reduced by the use of a more tip abrasion resistant material such as diamond-like carbon or improvement of the probing strategy.

The **line width roughness (LWR)** and **line edge roughness (LER)** measurement were performed over the $2\text{ }\mu\text{m}$ calibrated region of the IVPS structures with 500 points/ μm at a probing depth of 100 nm. The IVPS0301 shows a LER standard deviation S_q value of 0.75 nm with the corresponding LWR S_q of 1.49 nm. The IVPS0205 shows a LER standard deviation S_q value of 0.44 nm with the corresponding LWR S_q of 1.46 nm of the left sidewall. Both measurements in x- and y- direction show very good repeatability [106].

As a result, the developed true 3D-AFM head was successfully tested and can be applied to CD-metrology tasks in x- and y-direction, thus for complex nano-structures in true 3D-nanometrology.

7. Conclusion

Within this work a new true 3D-sensor was analyzed, designed, modeled, optimized, manufactured, tested and validated for true 3D-Nanometrology. The 3D-sensor consist of a novel probe denoted as 3D-Nanoprobe and a detection system denoted as the true 3D-AFM head. The 3D-Nanoprobe is designed to overcome the 3 main drawbacks of state-of-the-art cantilever based probes, which do not allow true 3D-probing at the nanoscale. The first disadvantage is a strong anisotropy of the cantilever probe stiffness in x -, y -, z -direction. To achieve the best signal, the probing direction is in normal direction to the sample surface. In combination with an anisotropic stiffness of the cantilever probe, tip-sample interaction force components are oriented orthogonal to the probing direction. Those forces result in to unstable probing conditions and so-called tip slipping. The second drawback is a mechanical crosstalk of the stiffness and of the detectable inclination angles, which can cause tip breakage during probing, because of indistinguishable tip-sample interaction forces and tip displacements. The third disadvantage concerns the cantilever probes with delicate and slender tips used for CD-metrology. With decreasing size, to get into small and narrow trenches, those tips get more and more compliant, whereas the stiff base cantilever probe remains the same. This leads to a very small sensitivity and consequently detectable signal, because only the deflection of the cantilever is detected. Those special cylindrical tips are so called CD-tips and are flared at the very end to probe sidewalls to measure complex structures and critical dimension (CD). The 3D-Nanoprobe is based on a such a cantilever for CD-metrology and is structured to adapt the overall compliance of the probe to the delicate CD-tip [213],[214]. Flexure hinges were applied to structure the novel probe. However, with decreasing size of the structure, manufacturing gets increasingly demanding. The 3D-Nanoprobe consists of two flexure hinges FH1 and FH2 and two so-called head sections HS1 and HS2, respectively, where FH1 connects the base with HS1. HS2 is serially connected to HS1 via FH2. The head sections are used as interfaces for optical detection. The 3D-Nanoprobe is designed to work with deflection and displacement detection principles. Both principles are described in this work. Moreover, the 3D-Nanoprobe is optimized for quasi isotropic stiffness and is in addition optimized for a balanced sensitivity ratio between the x -, y -, z -direction. The sensitivity to tip-sample interaction forces of the 3D-Nanoprobe compared to the commercial cantilever structure was improved by factors of (476, 391, 38) in x -, y -, and z -direction, respectively. During optimization careful attention was paid to manufacturability. FEM simulations were used to extent and verify the analytical model and optimization. The 3D-Nanoprobe prototype was manufactured by FIB milling process in about 3.5 h. The hybrid detection system consisting of a dual optical lever and a differential working interferometer was used in the developed true 3D-AFM head. The true 3D-AFM-head incorporates a microscope objective lens and optical microscope for sample inspection. The true 3D-AFM-head is primarily made of aluminum, only the interferometer parts are made of low thermal expansion nickel alloy. The differential working interferometer shows long-term fluctuations originating from non-linearities of up to 20 nm amplitude and drift rates of about 10 nm/h. The present short-term fluctuations can compromise the interferometer signal for or long-term scans, but are tolerable up to about 2 nm amplitude due to optimized probing. A careful investigation of the signal revealed that the applied probing strategy allows a use of this commercial interferometer in this 3D-AFM head. However, the interferometer should be improved in the future. The dual optical lever with self-build low

noise QPD circuit shows excellent stability of about 2 mV (SD) over half a day, and a RMS dark noise of only $(71.68 \pm 0.24) \mu\text{V}$ ($k=2$) and $(71.90 \pm 0.17) \mu\text{V}$ ($k=2$) of the differential LR and TB signal (BW 51.2 kHz), respectively.

The true 3D-AFM head is applied in a test setup for true 3D probing. The semi-analytical model of the 3D-Nanoprobe and model of the hybrid detection system are used to generate start values for the calibration process. The calibration was performed by hand on two orthogonally mounted IVPS100-PTB calibration artifacts with very smooth, and vertical side-walls. After calibration, the 3D-Nanoprobe is selective for 3D-tip displacements showing a selectivity ratio of about 50:1 for x-, y-, z-probing, with good repeatability. A stiffness calibration with a reference spring showed a measured quasi isotropic ratio of the stiffness of about 0.87:0.88:1.00 for the x-, y-, and z-direction, respectively, with a nominal stiffness in z-direction of $k_z = 2.719 \pm 0.067 \text{ N/m}$, for the given 3D-Nanoprobe prototype example [106]. The achieved isotropic ratio of the stiffness is well suited for probing in 3D. The calibration process and results verified the semi-analytical models, considering a slightly more compliant CD-tip (which seems very likely).

Typical RMS noise values of the 3D-Nanoprobe's no-contact tip position are given by 0.053 nm, 0.068 nm and 0.4 nm in x-, y-, and z- direction at bandwidth of 2.5 kHz, respectively. The stability of the 3D-Nanoprobe's no-contact tip position is biased by the interferometer fluctuations. Relatively large non-linearities and position noise of the available interferometer device contribute significantly to the RMS noise in z-direction, which should be improved in the future. The developed true 3D-AFM head shows a time constant of about 1 h for an exponentially fitted temperature depended signal drift. During warm-up ($\Delta T \approx 1.2 \text{ K}$) the measured position signal drifts only about 8 nm, 11 nm and 40 nm in x-, y-, and z- direction, respectively. The true 3D-AFM head shows good stability over about 24 h, enabling true 3D measurements of CD structures.

The typical probing repeatability (standard deviation) of the new 3D-Nanoprobe, applied in the developed true 3D-AFM head, shows about 0.17 nm, 0.31 nm and 0.82 nm in x-, y-, and z-direction, respectively, for 100 repetitions. The CD measurements indicate that the level of precision and tip wear of the used true 3D contact mode is similar to the state of the art VAP mode for 1D gratings in [13], because the initial scan, similar to a step-in mode, seems to have an effect on the tip abrasion process. With the new developed capability to detect an additional degree of freedom, probing in real 3D (x-, y-, z-direction) is enabled and enhances the current measurement capabilities in 3D-Nanometrology for SPM at the nanoscale.

Consequently, the developed true 3D-AFM head, which consists of the 3D-Nanoprobe and the hybrid detection system, allows true 3D-measurements of geometries at the nanoscale. In combination with the used test setup, it can be considered as the first (actual) true 3D-AFM.

8. Outlook

First, in a further development step, the tip apex of the developed 3D-Nanoprobe needs a pre-tilt of about 3° to reduce shaft probing for deep trenches for y-scan directions. Semi-finished probes with a pre-tilt of the CD-tip are purchasable, giving no restriction for CD metrology and allow measurements in true 3D for a variety of samples with complex and dense structures. Secondly, with a new interferometer true 3D probing with atomic resolution (smaller than 0.2 nm) will be possible in the future. A suitable interferometer was tested separately. The measured position noise of this interferometer is about 65 pm at 25 kSa/s. **Figure 8.1** shows a relative displacement measurement of this interferometer with $50\text{ }\mu\text{m}$ over a travel of 1 mm in the frequency domain. It shows very small periodic nonlinearities of below 16 pm, which is in agreement with [206]. In addition, it shows very small influence to stray light or double reflections and is directly compatible with used co-called C01 interferometer heads, which make this interferometer ideal to be used in the developed 3D-AFM head with the microscope objective lens or under other difficult measurement conditions. To further improve resolution of our probing more data points of the probing could be analyzed.

Thirdly, the novel developed 3D-Nanoprobe enables the investigation of the 3D tip-sample

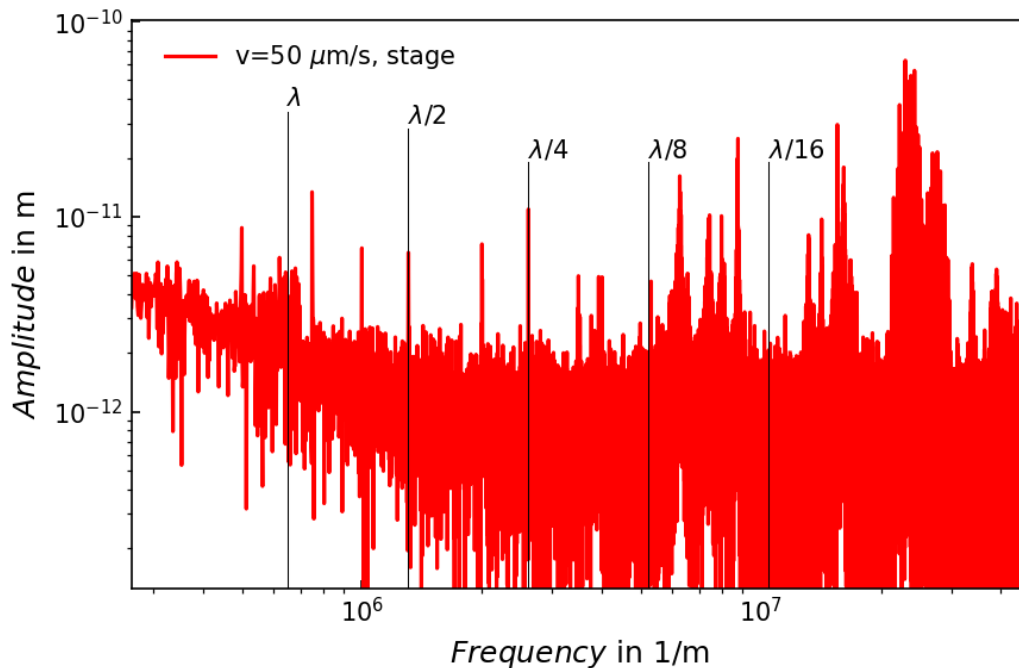


Figure 8.1: Periodic nonlinearities of the novel interferometer at a velocity of $50\text{ }\mu\text{m/s}$ over a travel of 1 mm, with $\lambda = 1535\text{ nm}$.

interaction forces and true tip apex displacements during probing. This can lead to improved understanding of probing conditions under changing environmental conditions, which result in a smaller uncertainty. In addition, the influence of material combinations to probing and for instance an adsorbent water layer at the nanoscale can be quantified. To achieve this,

a new 3D tip characterizing sample should be developed and the currently used 3D-contact VAP mode needs an update to true force-less probing. This true force-less probing in 3D is also necessary for very delicate and compliant sample surfaces or structures, because until now, the snap-in is not taken into account. In the moment of contact, the tip of the probe has jumped to the surface in direction of the largest force gradient. This leads to a small tip displacement offset from the planned trajectory and to a small bias force during probing. **Figure 8.2** shows this effect. The calculated force-less point in z-direction is shown in **Figure 8.2 (c)** by the intersection point. The position (or moment in time) of the intersection is transferred to the x-, and y-directions and intersect with their linear fits of the zero deflection and approaching part of the probing curve (denoted as *slope* in **Figure 8.2**). A snap-in of 0.65 nm and 3.14 nm is shown for x-, and y-direction in this example, respectively. With fast data processing, this sudden jump could be detected and the stage x,- and y-position can be reset for the x- and y displacement at the probing set-point (max deflection). When the probe is retracted, this offset allows the retraction curve to intersect with the zero deflection of the probe. Thus, for a stable signal and stable probing conditions, this allows true force-less probing as indicated by the **Figure 8.2 (a)**. For unstable signal the force can only be reduced as **Figure 8.2 (b)** shows. Another advantage of this probing mode is, the impact of an eventual small tip slide while making contact is reduced, and the impact of the melting ice like-water layer (about 1 nm) is reduced by using the retraction part of the probing curve, allowing a more accurate probing of the actual geometry without feedback. Fourth, the verified semi-analytical model can be used to build a digital twin to thoroughly determine the measurement uncertainty of the developed true 3D-AFM and true 3D-AFM head. Fifth, this probe can also be used as force transducer to investigate mechanical properties of samples such as nanopillars in 3D in the future, without special sample preparation. In general, the developed 3D-Nanoprobe might also be applied as a basis to enhance common SPM modes to true 3D, such as MFM or Kelvin probe force microscope (KPFM) and many more.

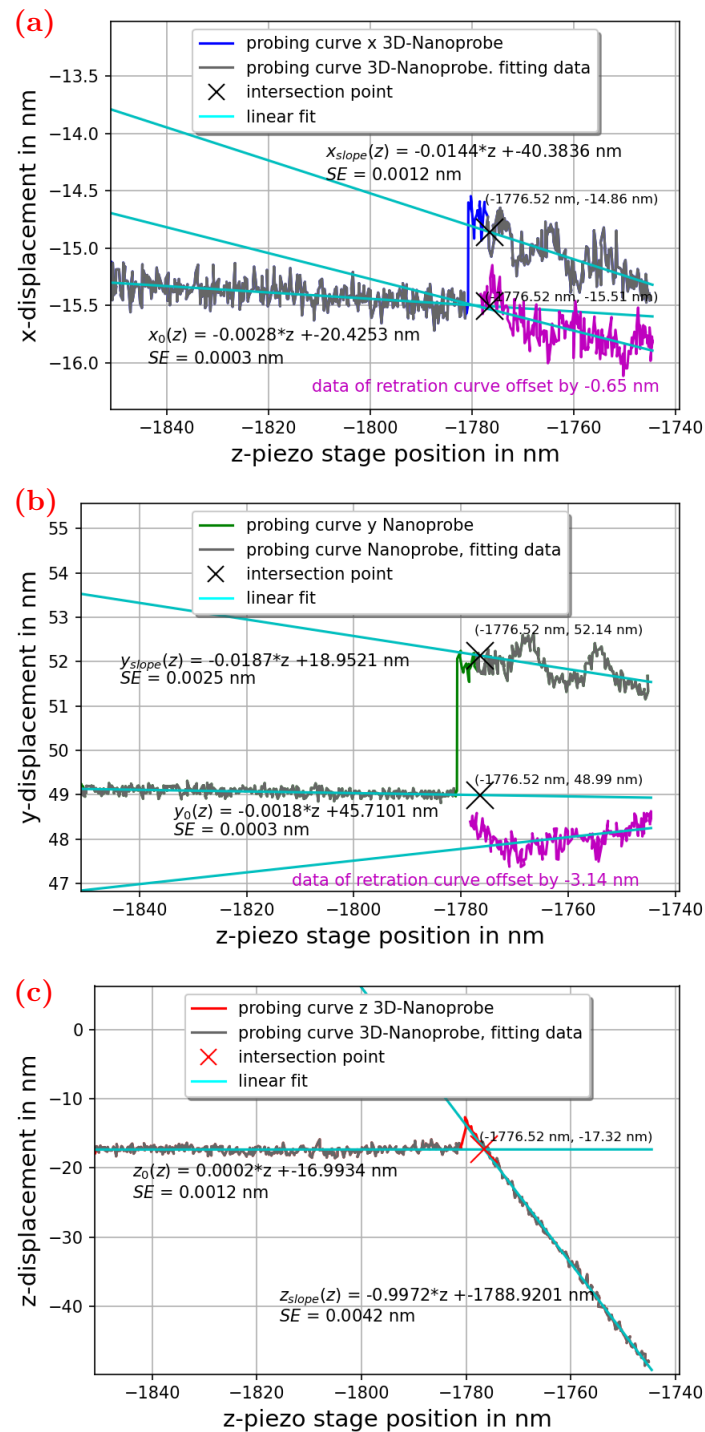


Figure 8.2: Update of 3D-contact VAP mode for true tip-sample interaction force-less probing. All graphs show the raw data and display the probing displacement in x-, y- and z-direction in (a), (b) and (c) over the z-stage position, respectively. The probing vector (x, y, z) was given by (0 nm, 40 nm, 200 nm).

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Appendix

A. Structure parameter η_{rec}

Table A.1: Structure parameter η_{rec} of rectangular cross-section with width w and thickness t ($n, m = 1$ bis 11), from [197].

$\frac{w}{t}$	1	1,2	1,4	1,6	1,8	2	2,5	3	4	7	5	10	14	∞
η_{rec}	0.141	0.166	0.187	0.204	0.217	0.229	0.249	0.263	0.280	0.291	0.297	0.310	0.315	0.333

A.1. Analytical description of the 3D-Nanoprobe

The Euler-Bernoulli beam model and the Saint-Venant torsion [191] is used to find a mechanical description of the 3D-Nanoprobe [72]. The mechanical description of a commercial cantilever with a tip is described in the sections 3.2.2 and 3.2.3. This linear model is later enhanced with higher order terms such as shear (*Timoschenko* beam theory [192]) and coefficients are implemented for the elastic boundary conditions of the compliant sections, the flexure hinges. The coefficients were determined by finite element method (FEM) modeling, making the final model semi-analytic. The 3D-Nanoprobe has a cantilever based structure; therefore, one can use the cantilever compliance matrix in (26). For small angles, the 3D-Nanoprobe can be calculated in sections and the superposition principle can be applied. The model does not include a description of an anisotropic crystalline material [193], [194]. Instead it uses an isotropic material description of the crystalline material silicon in the specific [110] lattice plane orientation, the cantilever's orientation in y -direction. The anisotropic crystalline material matrix is used in FEM simulations to model correction parameters for the compliant geometry parts in the model.

Starting with the tip-sample interaction force F_z , the parameters c_{xz} , c_{zy} of the compliance matrix and the inclination angle matrix coefficients $\alpha_1(F_z)$ and $\alpha_2(F_z)$ of the out-of-plane bending angle of the head section 1 and 2 (HS1 and HS2) are calculated, respectively. **Figure A.1** shows the tip displacements and probe motion. The total tip apex displacement is described by the tip displacements vector $\Delta \vec{s} = (\Delta x \ \Delta y \ \Delta z)^T$. All other components, in z -direction such as a crosstalk in (orthogonal) x -direction c_{xz} , torsion angles $\beta_1(F_z)$ and $\beta_2(F_z)$ or (horizontal) in plane bending angles $\gamma_1(F_z)$ and $\gamma_2(F_z)$ are negligible and consequently set to zero.

From the tip to the support at HS2 of FH2 there are two compliant components, the relative stiff head section HS2 and the delicate flexure hinge FH2. The inclination angle of the

separated head section 2 is therefore given with $L_3 = L_{k2} + L_2$ and $M_z = F_z(-L_3 + y)$ by,

$$\begin{aligned}\alpha_2(F_z)^* &= \frac{du_{2z}^*}{dy} = \frac{du}{dy}\bigg|_{y=L_{k2}} + \frac{du}{dy}\bigg|_{y=L_2} \\ &= \frac{F_z(-L_{k2}y + \frac{1}{2}y^2)}{EJ_{k2z}}\bigg|_{L_{k2}} - \frac{F_z(-L_3y + \frac{1}{2}y^2)}{EJ_{2z}}\bigg|_{L_3} + \frac{F_z(-L_{k2}y + \frac{1}{2}y^2)}{EJ_{2z}}\bigg|_{L_{k2}} \\ &= \frac{F_z}{E} \left(\frac{-L_3^2}{2J_{2z}} - \frac{-L_{k2}^2}{2J_{2z}} + \frac{-L_{k2}^2}{2J_{k2z}} \right),\end{aligned}\quad (98)$$

while all separately treated sections used for calculation of the 3D-Nanoprobe are marked with an *, to keep the nomenclature consistent, because the bending inclination angle of HS2 is given by $\alpha_{2z} = \alpha_{1z}^* + \alpha_{2z}^*$. The moment of inertia for bending in z-direction for the rectangular cross-section of HS2 and FH2 are $J_{k2z} = \frac{w_k t_2^3}{12}$ and $J_{2z} = \frac{w_2 t_2^3}{12}$, respectively. Because L_3 is located further away from the base of the cantilever body than the tip, it has a theoretical maximum length of $\max(L_3) = L_{ges} - L_{eff}$ and the bending inclination angle $\alpha_2(F_z)^*$ is negative. The z-displacement of the HS2 and FH2 component is given by:

$$\begin{aligned}\Delta z_{2z}^* &= u(y)_{2z}^* = \frac{F_z(-3L_3y + y)y^2}{6EJ_{2z}}\bigg|_{L_2}\bigg|_{y=L_3} - \frac{F_z(-3L_{k2}y + y)y^2}{6EJ_{2z}}\bigg|_{L_{k2}}\bigg|_{y=L_{k2}} \\ &\quad + \frac{F_z(-3L_{k2}y + y)y^2}{6EJ_{k2z}}\bigg|_{y=L_{k2}} - \alpha_{1z}^* L_3\end{aligned}\quad (99)$$

The structure is supported at HS1 the inclination angle α_{1z}^* of the boundary condition of FH2 has to be taken into account.

The other compliant components of the 3D-Nanoprobe are summed from the base to the FH2 support at $L_{eff1} = L_{eff} + L_3$. This structure is bent under the tip-sample interaction force F_z and the bending momentum $M_{bz} = -L_3 F_z$ of the HS2 and FH2 structure. The inclination angle is given by:

$$\begin{aligned}\alpha_{1z}^* &= \frac{du_{1z}(F_z)}{dy} + \frac{du_{2z}(M_{bz})}{dy} \\ &= \frac{F_z}{E} \left(\frac{L_{eff1}y - \frac{1}{2}y^2}{J_z}\bigg|_{y=L_{eff1}} - \frac{(L_{k1} + L_1)y - \frac{1}{2}y^2}{J_z}\bigg|_{y=L_{k1}+L_1} + \frac{(L_{k1} + L_1)y - \frac{1}{2}y^2}{J_{1z}}\bigg|_{y=L_{k1}+L_1} \right. \\ &\quad - \frac{L_{k1}y - \frac{1}{2}y^2}{J_{1z}}\bigg|_{y=L_{k1}} + \frac{L_{k1}y - \frac{1}{2}y^2}{J_z}\bigg|_{y=L_{k1}} - \frac{(L_k + L_2)y - \frac{1}{2}y^2}{J_z}\bigg|_{y=L_k+L_2} \\ &\quad + \left. \frac{(L_k + L_2)y - \frac{1}{2}y^2}{J_{zu}}\bigg|_{y=L_k+L_2} - \frac{L_2y - \frac{1}{2}y^2}{J_{zu}}\bigg|_{y=L_2} + \frac{L_2y - \frac{1}{2}y^2}{J_{2zu}}\bigg|_{y=L_2} \right) \\ &\quad - \frac{L_3 F_z}{E} \left(\frac{y}{J_z}\bigg|_{y=L_{eff1}} - \frac{y}{J_z}\bigg|_{y=L_{k1}+L_1} + \frac{y}{J_{1z}}\bigg|_{y=L_{k1}+L_1} - \frac{y}{J_{1z}}\bigg|_{y=L_{k1}} \right. \\ &\quad + \left. \frac{y}{J_z}\bigg|_{y=L_{k1}} - \frac{y}{J_z}\bigg|_{y=L_k+L_2} + \frac{y}{J_{zu}}\bigg|_{y=L_k+L_2} - \frac{y}{J_{zu}}\bigg|_{y=L_2} + \frac{y}{J_{2zu}}\bigg|_{y=L_2} \right),\end{aligned}\quad (100)$$

with moment of inertia of FH1 $J_{1z} = \frac{w_1 t_1^3}{12}$. After integration and with the moments of inertia $J_{zu} = 2 \frac{w-w_k t^3}{12}$ and $J_{z2u} = 2 \frac{w_3 t_3^3}{12}$ of the U-shaped structure surrounding the inner HS2 structure, the matrix coefficient is given by

$$\begin{aligned} \alpha_{1z}^* &= \frac{du_{1z}(F_z)}{dy} + \frac{du_{2z}(M_b z)}{dy} \\ &= \frac{F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} \right. \\ &\quad + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{z2u}} \left. \right) - \frac{L_3 F_z}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)}{J_{1z}} - \frac{L_{k1}}{J_{1z}} \right. \\ &\quad + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} + \frac{(L_k + L_2)}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{z2u}} \left. \right). \end{aligned} \quad (101)$$

The detectable inclination angle α_{1z} , by a focused laser spot of an optical lever or interferometer to register the change of the inclination angle on HS1, is given by

$$\begin{aligned} \alpha_{1z} &= \frac{F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} \right) \\ &\quad - \frac{L_3 F_z}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)}{J_{1z}} - \frac{L_{k1}}{J_{1z}} + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} \right), \end{aligned} \quad (102)$$

excluding the structure surrounding of HS2, because the spot cannot be located at the very end of the 3D-Nanoprobe (area too small).

The integral of (100) gives the z-displacement of the structure, which yields the compliance c_{zz1} . The displacement is expressed by:

$$\begin{aligned} u(y)_{1z}^* &= \frac{F_z}{E} \left(\frac{3L_{eff1}y^2 - y^3}{6J_z} \Big|_{y=L_{eff1}} - \frac{3((L_{k1} + L_1) - y)y^2}{6J_z} \Big|_{y=L_{k1}+L_1} + \frac{3((L_{k1} + L_1) - y)y^2}{6J_{1z}} \Big|_{y=L_{k1}+L_1} \right. \\ &\quad - \frac{3(L_{k1} - y)y^2}{6J_{1z}} \Big|_{y=L_{k1}} + \frac{3(L_{k1} - y)y^2}{6J_z} \Big|_{y=L_{k1}} - \frac{3((L_k + L_2) - y)y^2}{6J_z} \Big|_{y=L_k+L_2} \\ &\quad + \frac{3((L_k + L_2) - y)y^2}{6J_{zu}} \Big|_{y=L_k+L_2} - \frac{3(L_2 - y)y^2}{6J_{zu}} \Big|_{y=L_2} + \frac{3(L_2 - y)y^2}{6J_{z2u}} \Big|_{y=L_2} \left. \right) \\ &\quad - \frac{L_3 F_z}{E} \left(\frac{y^2}{2J_z} \Big|_{y=L_{eff1}} - \frac{y^2}{2J_z} \Big|_{y=L_{k1}+L_1} + \frac{y^2}{2J_{1z}} \Big|_{y=L_{k1}+L_1} - \frac{y^2}{2J_{1z}} \Big|_{y=L_{k1}} \right. \\ &\quad + \frac{y^2}{2J_z} \Big|_{y=L_{k1}} - \frac{y^2}{2J_z} \Big|_{y=L_k+L_2} + \frac{y^2}{2J_{zu}} \Big|_{y=L_k+L_2} - \frac{y^2}{2J_{zu}} \Big|_{y=L_2} + \frac{y^2}{2J_{z2u}} \Big|_{y=L_2} \left. \right). \end{aligned} \quad (103)$$

The expression regarding the relevant displacement of the tip apex has to be extended by the inclination of HS1 by $\Delta z_1 = \Delta z_1^* - \alpha_{1z}^* ((L_{k1} - L_k)/2 + L_k)$, where L_k is the length of HS2.

After substitution it results in

$$\begin{aligned} \Delta z_1 = & \frac{F_z}{E} \left(\frac{L_{eff1}^3}{3J_z} - \frac{(L_{k1} + L_1)^3}{3J_z} + \frac{(L_{k1} + L_1)^3}{3J_1 z} \right. \\ & - \frac{L_{k1}^3}{3J_1 z} + \frac{L_{k1}^3}{3J_z} - \frac{(L_k + L_2)^2}{3J_z} \\ & + \frac{(L_k + L_2)^3}{3J_{zu}} - \frac{L_2^3}{3J_{zu}} + \frac{L_2^3}{3J_{z2u}} \Big) \\ & - \frac{L_3 F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_1 z} - \frac{L_{k1}^2}{2J_1 z} \right. \\ & + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{z2u}} \Big) - \alpha_{1z}^* ((L_{k1} - L_k)/2 + L_k). \end{aligned} \quad (104)$$

With $c_{zz} = \frac{\Delta z}{F_z}$, (104) and (99) the nominal compliance component of the compliance matrix is given by

$$\begin{aligned} c_{zz} = & \frac{F_z}{E} \left(\frac{L_{eff1}^3}{3J_z} - \frac{(L_{k1} + L_1)^3}{6J_z} + \frac{(L_{k1} + L_1)^3}{3J_1 z} \right. \\ & - \frac{L_{k1}^3}{3J_1 z} + \frac{L_{k1}^3}{3J_z} - \frac{(L_k + L_2)^2}{3J_z} \\ & + \frac{(L_k + L_2)^3}{3J_{zu}} - \frac{L_2^3}{3J_{zu}} + \frac{L_2^3}{3J_{z2u}} \Big) \\ & - \frac{L_3 F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_1 z} - \frac{L_{k1}^2}{2J_1 z} \right. \\ & + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{z2u}} \Big) \\ & - \alpha_{1z}^* L_3 + \frac{L_3 F_z}{E} \left(\frac{L_3^2}{2J_{2z}} - \frac{L_{k2}^2}{2J_{2z}} + \frac{L_{k2}^2}{2J_{k2z}} \right) \end{aligned} \quad (105)$$

The bending inclination angle for HS2 is given by adding (98) and (101) to

$$\begin{aligned} \alpha_{2z} = & \frac{F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_1 z} - \frac{L_{k1}^2}{2J_1 z} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} \right. \\ & + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{z2u}} \Big) - \frac{L_3 F_z}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)}{J_1 z} - \frac{L_{k1}}{J_1 z} \right. \\ & + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} + \frac{(L_k + L_2)}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{z2u}} \Big) \\ & - \frac{F_z}{E} \left(\frac{L_3^2}{2J_{2z}} - \frac{L_{k2}^2}{2J_{2z}} + \frac{L_{k2}^2}{2J_{k2z}} \right), \end{aligned} \quad (106)$$

while the components in the matrix of inclination angles are $a_{\alpha 2z} = \frac{\alpha_{2z}}{F_z}$ and $a_{\alpha 1z} = \frac{\alpha_{1z}}{F_z}$. The inclination angle in (106) is used to calculate the possible crosstalk displacement in y-direction. With $c_{yz} = \frac{\Delta y(z)}{F_z}$ and $\Delta y(z) = \alpha_{2z} L_{tip}$ the compliance component is given by

$$c_{yz} = \frac{\alpha_{2z} L_{tip}}{F_z} \quad (107)$$

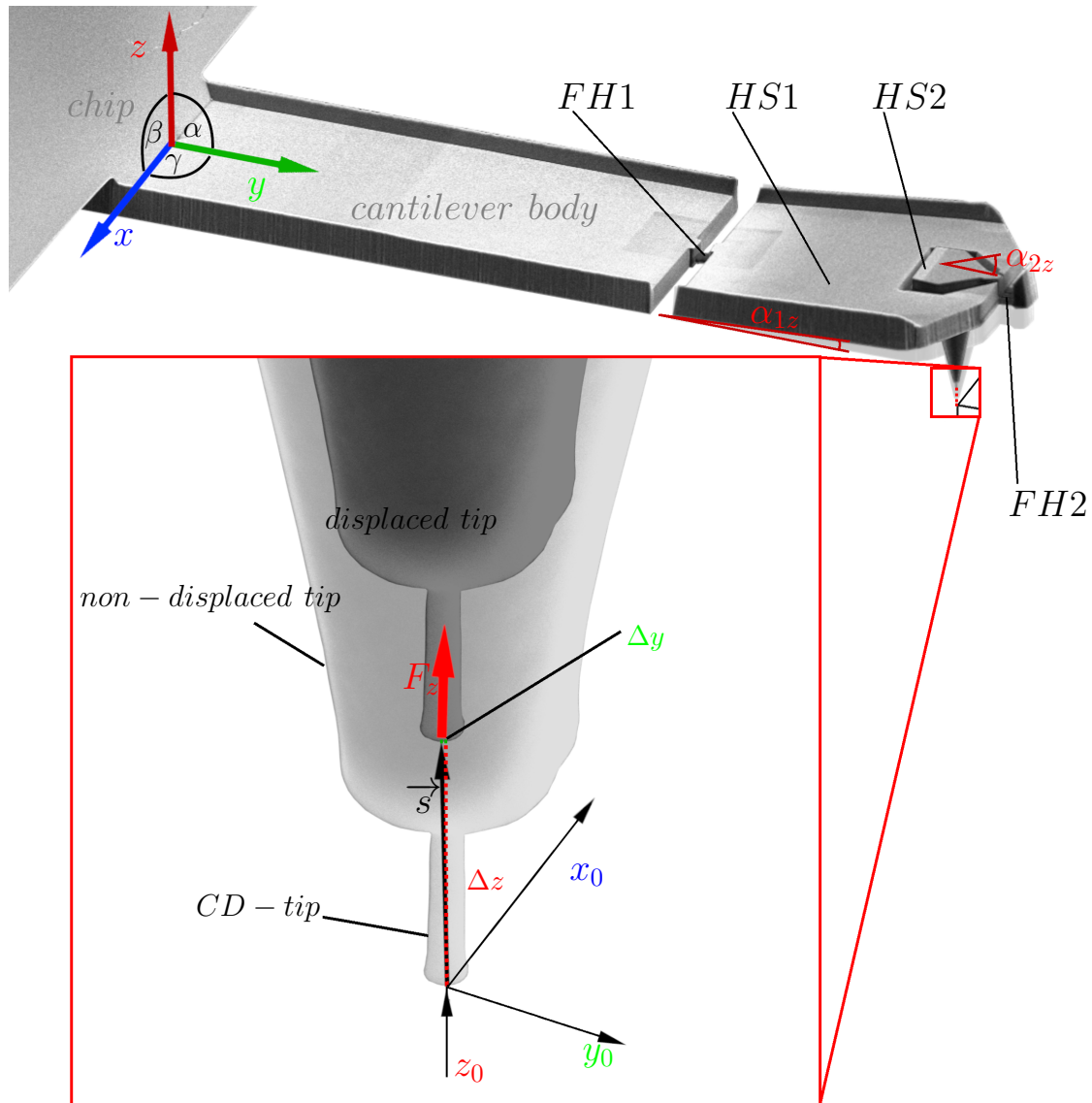


Figure A.1: The 3D-Nanoprobes drawing of the elastic CD-tip apex displacements (in x,y,z) by interaction with a tip-sample interaction force in z -direction F_z . The tip apex displacement is given by the vector $\vec{s}$.

In y-direction, the 3D-Nanoprobe's tip displacement and motion is shown in **Figure A.2** and described by the compliance components c_{yy} , c_{zy} and the inclination angles α_{1y} and α_{2y} . All other components in y-direction such as a crosstalk in x-direction c_{xy} or inclination angles $\beta_1(F_y)$ and $\beta_2(F_y)$ or $\gamma_1(F_y)$ and $\gamma_2(F_y)$ are negligible and therefore set to zero.

The inclination angle of the separated head section 2 is therefore given with $M_y = -F_y L_{tip}$ by,

$$\begin{aligned}\alpha_{2y}^* &= \frac{du_{2y}^*}{dy} = \frac{du}{dy}\bigg|_{y=L_{k2}} + \frac{du}{dy}\bigg|_{y=L_2} \\ &= \frac{M_y}{E} \left(-\frac{y}{J_{2z}}\bigg|_{L_3} + \frac{y}{J_{2z}}\bigg|_{L_{k2}} - \frac{y}{J_{k2z}}\bigg|_{L_{k2}} \right) \\ &= \frac{L_{tip}F_y}{E} \left(\frac{L_3}{J_{2z}} - \frac{L_{k2}}{J_{2z}} + \frac{L_{k2}}{J_{k2z}} \right)\end{aligned}\quad (108)$$

After integration of the expression above, the tip apex z-displacement of the HS2 is given by

$$\begin{aligned}\Delta z_{2y}^* &= u(y)_{2y}^* \\ &= \frac{M_y}{E} \left(\frac{y^2}{2J_{2z}}\bigg|_{L_3} - \frac{y^2}{2J_{2z}}\bigg|_{L_{k2}} + \frac{y^2}{2J_{k2z}}\bigg|_{L_{k2}} \right) - \alpha_{1y}^* L_3 + \frac{F_y y}{E w_k t}\bigg|_{L_{k2}} + \frac{F_y y}{E w_2 t_2}\bigg|_{L_2} \\ &= \frac{-F_y L_{tip}}{E} \left(\frac{L_3^2}{J_{2z}} - \frac{L_{k2}^2}{2J_{2z}} + \frac{L_{k2}^2}{2J_{k2z}} \right) - \alpha_{1y}^* \left(L_3 + \frac{F_y L_{k2}}{E w_k t} + \frac{F_y L_2}{E w_2 t_2} \right)\end{aligned}\quad (109)$$

The z-displacement is reduced by the inclination angle at the very end of of HS1, reduced by the tip location with $\alpha_{1y}^* L_3$. Furthermore, the influence of the small compression of $\frac{F_y L_{k2}}{E w_k t} + \frac{F_y L_2}{E w_2 t_2}$ of the structure induced by F_y on the z-displacement is negligible, because it is multiplied by the small α_{1y}^* . The momentum induced bending angle of the very end of HS1 α_{1y}^* is given by

$$\begin{aligned}\alpha_{1y}^* &= \frac{du_{1y}^*}{dy} = \frac{L_{tip}F_y}{E} \left(\frac{y}{J_z}\bigg|_{L_{eff1}} - \frac{y}{J_z}\bigg|_{L_{k1}+L_1} + \frac{y}{J_{1z}}\bigg|_{L_{k1}+L_1} - \frac{y}{J_{1z}}\bigg|_{L_{k1}} \right. \\ &\quad \left. + \frac{y}{J_z}\bigg|_{L_{k1}} - \frac{y}{J_z}\bigg|_{L_k+L_2} + \frac{y}{J_{zu}}\bigg|_{L_k+L_2} - \frac{y}{J_{zu}}\bigg|_{L_2} + \frac{y}{J_{z2u}}\bigg|_{L_2} \right) \\ &= \frac{L_{tip}F_y}{E} \left(\frac{L_{eff1}}{J_z} - \frac{L_{k1}+L_1}{J_z} + \frac{L_{k1}+L_1}{J_{1z}} - \frac{L_{k1}}{J_{1z}} \right. \\ &\quad \left. + \frac{L_{k1}}{J_z} - \frac{L_k+L_2}{J_z} + \frac{L_k+L_2}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{z2u}} \right)\end{aligned}\quad (110)$$

The detectable bending inclination angle of HS1 for a laser spot location in the center of the wide part without the HS2 surrounding structures is given by

$$\begin{aligned}\alpha_{1y} &= \frac{L_{tip}F_y}{E} \left(\frac{L_{eff1}}{J_z} - \frac{L_{k1}+L_1}{J_z} + \frac{L_{k1}+L_1}{J_{1z}} - \frac{L_{k1}}{J_{1z}} \right. \\ &\quad \left. + \frac{L_{k1}}{J_z} - \frac{L_k+L_2}{J_z} \right)\end{aligned}\quad (111)$$

The delectable bending angle of HS2 is a summation of (110) and (108) and is given by

$$\begin{aligned}\alpha_{2y} &= \alpha_{1y}^* + \alpha_{2y}^* \\ &= \frac{L_{tip}F_y}{E} \left(\frac{L_{eff1}}{J_z} - \frac{L_{k1} + L_1}{J_z} + \frac{L_{k1} + L_1}{J_{1z}} - \frac{L_{k1}}{J_{1z}} \right. \\ &\quad \left. + \frac{L_{k1}}{J_z} - \frac{L_k + L_2}{J_z} + \frac{L_k + L_2}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{2zu}} + \frac{L_3}{J_{2z}} - \frac{L_{k2}}{J_{2z}} + \frac{L_{k2}}{J_{k2z}} \right)\end{aligned}\quad (112)$$

The total tip displacement in z-direction from F_y is described by integration of (110) along the 3D-Nanoprobe's length and addition of (109). The influence on the z-displacement of the compression and elongation of the structure in y-direction is approximated by multiplying it with its bending inclination angle. The tip displacement is therefore described by:

$$\begin{aligned}\Delta z_{1y}^* &= \Delta z_{1y}^*(F_y) + \Delta z_{1y}^*(M_y) = \alpha_{1y}^* \Delta y_{1y}^*(F_y) + \Delta z_{1y}^*(M_y) = \\ &= \alpha_{1y}^* \left(\frac{F_y y}{E w t} \Big|_{L_{eff1}-L_{k1}-L_1} + \frac{F_y y}{E w_1 t_1} \Big|_{L_1} + \frac{F_y y}{E w t} \Big|_{L_{k1}-L_{k2}-L_2} + \frac{F_y y}{E(w-w_k)t} \Big|_{L_{k2}} + \frac{F_y y}{E(w-w_k)t} \Big|_{L_2} \right) \\ &\quad + \frac{L_{tip}F_y}{E} \left(\frac{y^2}{2J_z} \Big|_{L_{eff1}} - \frac{y^2}{2J_z} \Big|_{L_{k1}+L_1} + \frac{y^2}{2J_{1z}} \Big|_{L_{k1}+L_1} - \frac{y^2}{2J_{1z}} \Big|_{L_{k1}} \right. \\ &\quad \left. + \frac{y^2}{2J_z} \Big|_{L_{k1}} - \frac{y^2}{2J_z} \Big|_{L_k+L_2} + \frac{y^2}{2J_{zu}} \Big|_{L_k+L_2} - \frac{y^2}{2J_{zu}} \Big|_{L_2} + \frac{y^2}{2J_{2zu}} \Big|_{L_2} \right) - \alpha_{1z}^* * L_3 \\ &= \alpha_{1y}^* \left(\frac{F_y(L_{eff1} - L_{k1} - L_1)}{E w t} + \frac{F_y L_1}{E w_1 t_1} + \frac{F_y(L_{k1} - L_{k2} - L_2)}{E w t} + \frac{F_y L_{k2}}{E(w-w_k)t} + \frac{F_y L_2}{E(w-w_k)t} \right) \\ &\quad + \frac{L_{tip}F_y}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} \right. \\ &\quad \left. + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{2zu}} \right) - \alpha_{1z}^* * L_3\end{aligned}\quad (113)$$

In (109) the z-displacement is influenced by the small elongation of the structure induced by F_y in y-direction. Because it is multiplied by the small α_{1y}^* , it is negligible. Consequently, with $\Delta z_{2y} = \Delta z_{1y}^* + \Delta z_{2y}^*$ the tip z-displacement is given by

$$\begin{aligned}\Delta z_{2y} &= \frac{L_{tip}F_y}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} \right. \\ &\quad \left. + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{2zu}} \right) \\ &\quad + \frac{-F_y L_{tip}}{E} \left(\frac{L_3^2}{J_{2z}} - \frac{L_{k2}^2}{2J_{2z}} + \frac{L_{k2}^2}{2J_{k2z}} \right) - \alpha_{1y}^* L_3\end{aligned}\quad (114)$$

and $c_{zy} = \frac{\Delta z_{2y}}{F_y}$. The tip displacement in y-direction is a combination of the bending angle of HS2, induced by the bending momentum and elongation or compression of the structure in

(109) and (113).

$$\begin{aligned} \Delta y_{2y} = & \alpha_{2y} L_{tip} + \frac{F_y}{E} \left(\frac{(L_{eff1} - L_{k1} - L_1)}{wt} + \frac{L_1}{w_1 t_1} + \frac{(L_{k1} - L_{k2} - L_2)}{wt} \right. \\ & \left. + \frac{L_{k2}}{(w - w_k)t} + \frac{L_2}{(w - w_k)t} + \frac{L_{k2}}{w_k t} + \frac{L_2}{w_2 t_2} \right) \end{aligned} \quad (115)$$

The compliance matrix component of the 3D-Nanoprobe in y-direction under F_y is $c_{yy} = \frac{\Delta y_{2y}}{F_y}$ and the elements of the matrix of inclination angles of HS1 and HS2 are $a_{\alpha 1y} = \frac{\alpha_{1y}}{F_y}$ and $a_{\alpha 2y} = \frac{\alpha_{2y}}{F_y}$, respectively.

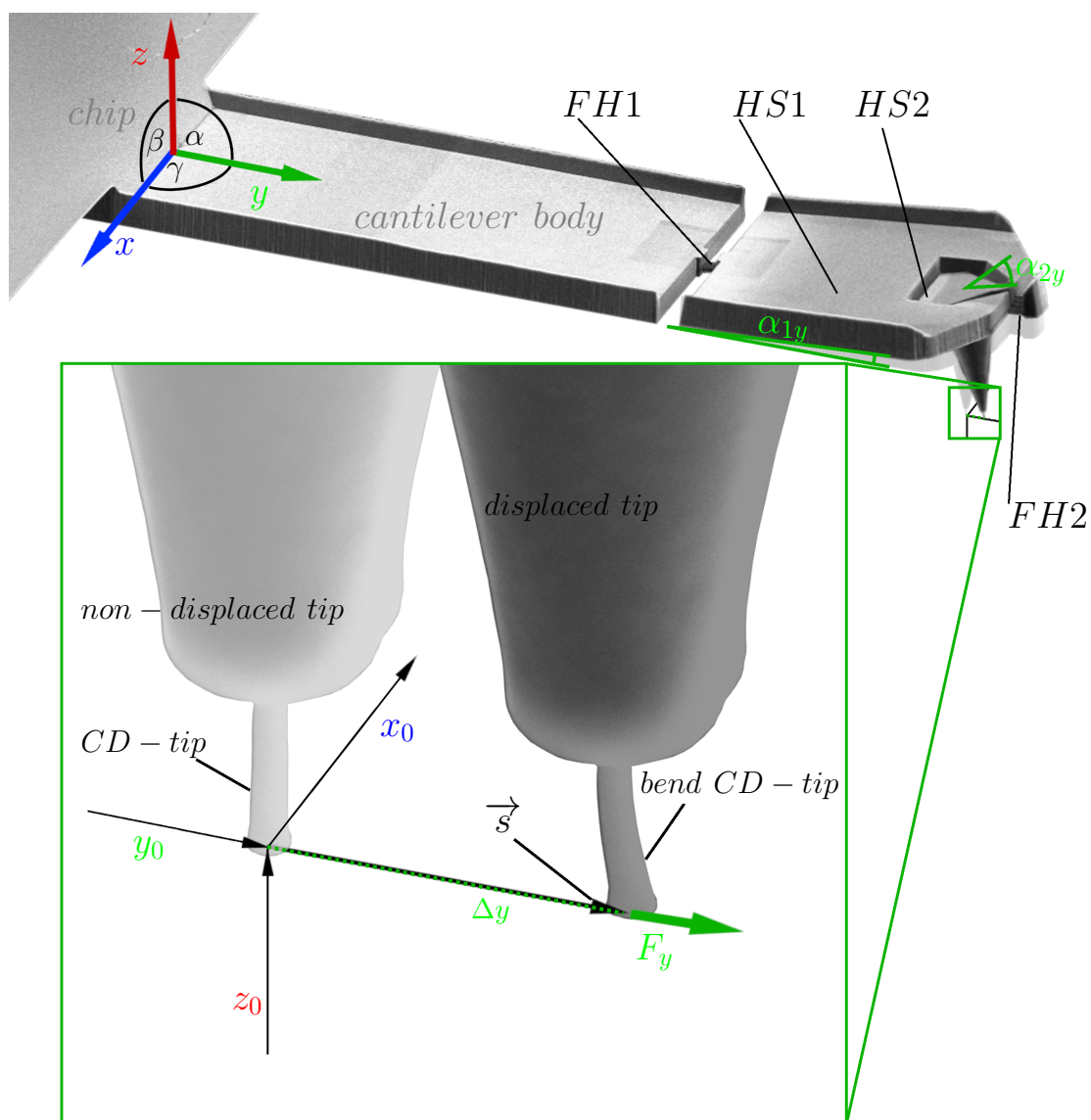


Figure A.2: The 3D-Nanoprobes drawing of the elastic CD-tip apex displacements (in x,y,z) by interaction with a tip-sample interaction force in y-direction F_y . The tip apex displacement is given by the vector $\vec{s}$.

The tip apex displacement under a force in x-direction F_x of the 3D-Nanoprobe is shown in **Figure A.3**. The displacement in x-direction is given by a Δx , which is proportional to the force for small displacements. Also in this tip displacement direction cosine-errors are neglected, because HS1 and HS2 have small inclination angles. Consequently, Δy and Δz are zero.

With $c_{xy} = \frac{\Delta y_{2x}}{F_x} = 0$, $c_{xz} = \frac{\Delta z_{2x}}{F_x} = 0$ both compliance matrix components are zero and only $c_{xx} = \frac{\Delta x_{2x}}{F_x}$ is calculated. Because the x-direction is perpendicular to the yz-plane, no out-of-plane bending angle is induced and the inclination angles and angle matrix components are $a_{\alpha 1x} = \frac{\alpha_{1x}}{F_x} = 0$ and $a_{\alpha 2x} = \frac{\alpha_{2x}}{F_x} = 0$. The force F_x induces an in-plane bending and a torsion of the 3D-Nanoprobe structure, both are treated individually and $\gamma_1(F_x)$, $\gamma_2(F_x)$ and $\beta_1(F_x)$, $\beta_2(F_x)$ are calculated for HS1 and HS2, respectively. The x-displacement of the tip is described by $\Delta x = \Delta x_{1x}^* + \Delta x_{2x}^*$ with the compliance of FH1 and HS1 added to the compliance of FH2 and HS2. The displacement of FH2 and HS2 is given by

$$\Delta x_{2x}^* = \Delta x_{2xtorsion}^* + \Delta x_{2xbend}^* \quad (116)$$

At first, the in-plane bending of FH2 and HS2 is calculated with $M_x = F_x(L_3 - y)$ to

$$\begin{aligned} \gamma_{2x}^* &= \frac{du_{2xbend}^*}{dy} \\ &= \frac{F_x}{E} \left(-\frac{L_{k2}y + \frac{1}{2}y^2}{J_{2x}}|_{L_{k2}} + \frac{-L_3y + \frac{1}{2}y^2}{J_{2x}}|_{L_3} - \frac{-L_{k2}y + \frac{1}{2}y^2}{J_{k2x}}|_{L_2} \right) \\ &= \frac{-F_x}{E} \left(\frac{L_{k2}^2}{2J_{2x}}|_{L_{k2}} - \frac{L_3^2}{J_{2x}} + \frac{L_2^2}{J_{k2x}} \right) \end{aligned} \quad (117)$$

with $J_{2x} = \frac{w_k^3 t_2}{12}$ and $J_{k2} = \frac{w_k^3 t}{12}$. Secondly, the torsion angle of the front HS2 and FH2 part is calculated. Saint-Venant torsion is used for the bulky part of HS2 and warping torsion [196] is used for the delicate FH2. The free warping of the flexure hinge at both ends is affected by their boundary conditions. The flexure hinges are always located between two bulk parts which are modeled in a first approximation as rigid. As already mentioned, boundary itself is modeled later separately by FEM.

$$\begin{aligned} \beta_{2x}^* &= \frac{3L_{k2}M_x(2+2\mu)}{Ew_k t^3} + \beta_{2x FH2}^* = \frac{3L_{k2}M_x(2+2\mu)}{Ew_k t^3} \\ &+ \frac{F_x L_{tip} L_2 (2+2\mu)}{E J_{T2}^2} \left\{ 1 + \frac{2}{\lambda_2 L_2} \left[\tanh\left(\frac{\lambda_2 L_2}{2}\right) \left(\cosh\left(\frac{\lambda_2 L_2}{2}\right) - 1 \right) - \sinh\left(\frac{\lambda_2 L_2}{2}\right) \right] \right\} \end{aligned} \quad (118)$$

with $\lambda_2 = \sqrt{\frac{J_{T2}}{J_{M2}(2+2\mu)}}$, $J_{M2} = \frac{1}{24} t_2 w_2^3 (w_2 - t_2)^2$ and polar area momentum of inertia for a rectangle $J_{T2} = \eta_{rect} t_2 w_2^3$ and torsion momentum $M_x = F_x L_{tip}$, where η_{rect} is the correction factor for rectangular cross-sections (e.g. section A). Integrating (117) and multiplying the torsion angle β_{2x}^* with L_{tip} leads to the F_x force dependent tip x-displacement of the HS1 and

FH1 component by

$$\begin{aligned}
 \Delta x_{2x}^* &= \Delta x_{2xbend}^* + \Delta x_{2xtorsion}^* \\
 &= \frac{F_x}{E} \left(\frac{3L_3 y^2 - y^3}{6J_{2x}} \Big|_{y=L_3} - \frac{3L_{k2} y^2 - y^3}{6J_{2x}} \Big|_{y=L_{k2}} + \frac{3L_{k2} y^2 - y^3}{6J_{2kz}} \Big|_{y=L_{k2}} \right) + \beta_{2x}^* * L_{tip} \\
 &= \frac{F_x}{E} \left(\frac{L_3^3}{3J_{2x}} - \frac{L_{k2}^3}{3J_{2x}} + \frac{L_{k2}^3}{3J_{2kz}} \right) + \beta_{2x}^* * L_{tip}
 \end{aligned} \tag{119}$$

The HS1 and FH1 contribution to the tip x-displacement, in-plane bending angles and torsion angles are calculated as follows. First, the in plane bending angle γ_{1x} of HS1 is calculated. The tip-sample interaction force F_x bends the structure horizontally in the xy-plane in x-direction, while the momentum from HS2 and FH2 with $M_{xbend} = -L_3 F_x$ reduces the total tip x-displacement by bending it in the -x-direction.

$$\begin{aligned}
 \gamma_{1x}^* &= \frac{du_{1xbendF}^*}{dy} + \frac{du_{1xbendM}^*}{dy} \\
 &= \frac{F_x}{E} \left(\frac{L_{eff1} y - \frac{1}{2} y^2}{J_x} \Big|_{y=L_{eff1}} - \frac{(L_{k1} + L_1) y - \frac{1}{2} y^2}{J_x} \Big|_{y=L_{k1} + L_1} \right. \\
 &\quad + \frac{(L_{k1} + L_1) y - \frac{1}{2} y^2}{J_{x1}} \Big|_{y=L_{k1} + L_1} - \frac{L_{k1} y - \frac{1}{2} y^2}{J_{x1}} \Big|_{y=L_{k1}} + \frac{L_{k1} y - \frac{1}{2} y^2}{J_x} \Big|_{y=L_{k1}} \\
 &\quad - \frac{(L_k - L_2) y - \frac{1}{2} y^2}{J_x} \Big|_{y=L_k - L_2} + \frac{(L_k - L_2) y - \frac{1}{2} y^2}{J_{xu}} \Big|_{y=L_k - L_2} - \frac{L_2 y - \frac{1}{2} y^2}{J_{xu}} \Big|_{y=L_2} \\
 &\quad \left. + \frac{L_2 y - \frac{1}{2} y^2}{J_{x2u}} \Big|_{y=L_2} \right) - \frac{F_x L_3}{E} \left(\frac{y}{J_x} \Big|_{y=L_{eff1}} - \frac{y}{J_x} \Big|_{y=L_{k1} + L_1} + \frac{y}{J_{x1}} \Big|_{y=L_{k1} + L_1} \right. \\
 &\quad \left. - \frac{y}{J_{x1}} \Big|_{y=L_{k1}} + \frac{y}{J_x} \Big|_{y=L_{k1}} - \frac{y}{J_x} \Big|_{y=L_k - L_2} + \frac{y}{J_{xu}} \Big|_{y=L_k - L_2} - \frac{y}{J_{xu}} \Big|_{y=L_2} + \frac{y}{J_{x2u}} \Big|_{y=L_2} \right)
 \end{aligned} \tag{120}$$

with $J_x = \frac{w_3^3 t}{12}$, $J_1 = \frac{w_1^3 t_1}{12}$, $J_{x2u} = \frac{(w_4^3 - w_3^3) t_3}{12}$ and $J_{xu} \approx J_x$ the expression is shortened to

$$\begin{aligned} \gamma_{1x}^* &= \frac{du_{1xbendF}^*}{dy} + \frac{du_{1xbendM}^*}{dy} \\ &= \frac{F_x}{E} \left(\frac{L_{eff1}y - \frac{1}{2}y^2}{J_x} \Big|_{y=L_{eff1}} - \frac{(L_{k1} + L1)y - \frac{1}{2}y^2}{J_x} \Big|_{y=L_{k1}+L1} \right. \\ &\quad + \frac{(L_{k1} + L1)y - \frac{1}{2}y^2}{J_{x1}} \Big|_{y=L_{k1}+L1} - \frac{L_{k1}y - \frac{1}{2}y^2}{J_{x1}} \Big|_{y=L_{k1}} + \frac{L_{k1}y - \frac{1}{2}y^2}{J_x} \Big|_{y=L_{k1}} \\ &\quad \left. - \frac{L_2y - \frac{1}{2}y^2}{J_x} \Big|_{y=L_2} + \frac{L_2y - \frac{1}{2}y^2}{J_{x2u}} \Big|_{y=L_2} \right) - \frac{F_x L_3}{E} \left(\frac{y}{J_x} \Big|_{y=L_{eff1}} - \frac{y}{J_x} \Big|_{y=L_{k1}+L1} \right. \\ &\quad \left. + \frac{y}{J_{x1}} \Big|_{y=L_{k1}+L1} - \frac{y}{J_{x1}} \Big|_{y=L_{k1}} + \frac{y}{J_x} \Big|_{y=L_{k1}} - \frac{y}{J_x} \Big|_{y=L_2} + \frac{y}{J_{x2u}} \Big|_{y=L_2} \right) \\ &= \frac{F_x}{E} \left(\frac{L_{eff1}^2}{2J_x} - \frac{(L_{k1} + L1)^2}{2J_x} + \frac{(L_{k1} + L1)^2}{2J_{x1}} - \frac{L_{k1}^2}{2J_{x1}} + \frac{L_{k1}^2}{2J_x} - \frac{L_2^2}{2J_x} + \frac{L_2^2}{2J_{x2u}} \right) \\ &\quad - \frac{F_x L_3}{E} \left(\frac{L_{eff1}}{J_x} - \frac{L_{k1} + L1}{J_x} + \frac{L_{k1} + L1}{J_{x1}} - \frac{L_{k1}}{J_{x1}} + \frac{L_{k1}}{J_x} - \frac{L_2}{J_x} + \frac{L_2}{J_{x2u}} \right) \end{aligned} \quad (121)$$

Integrating (121) leads to the contribution of the in-plane tip x-displacement with

$$\begin{aligned} \Delta x_{1xplane}^* &= du_{1xbendF}^* + du_{1xbendM}^* \\ &= \frac{F_x}{E} \left(\frac{3L_{eff1}y^2 - y^3}{6J_x} \Big|_{y=L_{eff1}} - \frac{3(L_{k1} + L1)y^2 - y^3}{6J_x} \Big|_{y=L_{k1}+L1} \right. \\ &\quad + \frac{3(L_{k1} + L1)y^2 - y^3}{6J_{x1}} \Big|_{y=L_{k1}+L1} - \frac{3L_{k1}y^2 - y^3}{6J_{x1}} \Big|_{y=L_{k1}} + \frac{3L_{k1}y^2 - y^3}{6J_x} \Big|_{y=L_{k1}} \\ &\quad \left. - \frac{2L_2y^2 - y^3}{6J_x} \Big|_{y=L_2} + \frac{2L_2y^2 - y^3}{6J_{x2u}} \Big|_{y=L_2} \right) - \frac{F_x L_3}{E} \left(\frac{y^2}{2J_x} \Big|_{y=L_{eff1}} - \frac{y^2}{2J_x} \Big|_{y=L_{k1}+L1} \right. \\ &\quad \left. + \frac{y^2}{2J_{x1}} \Big|_{y=L_{k1}+L1} - \frac{y^2}{2J_{x1}} \Big|_{y=L_{k1}} + \frac{y^2}{2J_x} \Big|_{y=L_{k1}} - \frac{y^2}{2J_x} \Big|_{y=L_2} + \frac{y^2}{2J_{x2u}} \Big|_{y=L_2} \right) \\ &= \frac{F_x}{E} \left(\frac{L_{eff1}^3}{3J_x} - \frac{(L_{k1} + L1)^3}{3J_x} + \frac{(L_{k1} + L1)^3}{3J_{x1}} - \frac{L_{k1}^3}{3J_{x1}} + \frac{L_{k1}^3}{3J_x} - \frac{L_2^3}{3J_x} + \frac{L_2^3}{3J_{x2u}} \right) \\ &\quad - \frac{F_x L_3}{E} \left(\frac{L_{eff1}^2}{2J_x} - \frac{(L_{k1} + L1)^2}{2J_x} + \frac{(L_{k1} + L1)^2}{2J_{x1}} - \frac{L_{k1}^2}{2J_{x1}} + \frac{L_{k1}^2}{2J_x} - \frac{L_2^2}{2J_x} + \frac{L_2^2}{2J_{x2u}} \right) \end{aligned} \quad (122)$$

The total contribution of the tip x-displacement of HS1 is $\Delta x_{1x}^* = \Delta x_{1xplane}^* + \Delta x_{1xtorsion}^* - \gamma_{1x}^* L_3$ with the torsion component of HS1 as $\Delta x_{1xtorsion}^* = \beta_{1x}^* L_{tip}$. The torsion angle of HS1 β_{1x} and surrounding support structure of HS2 is calculated similar to (118) with warping

torsion of FH1.

$$\begin{aligned}
 \beta_{1x}^* &= \frac{3L_2M_x(2+2\mu)}{E(w_4-w_3)t_3^3} + \frac{3L_{k1}M_x(2+2\mu)}{Ewt^3} \\
 &+ \frac{3(L_{eff1}-L_{k1}-L_1)M_x(2+2\mu)}{Ewt^3} + \beta_{1xFH1}^* \\
 &= \frac{3L_2M_x(2+2\mu)}{E(w_4-w_3)t_3^3} + \frac{3L_{k1}M_x(2+2\mu)}{Ewt^3} + \frac{3(L_{eff1}-L_{k1}-L_1)M_x(2+2\mu)}{Ewt^3} \\
 &+ \frac{F_xL_{tip}L_1(2+2\mu)}{EJ_{T1}^2} \left\{ 1 + \frac{2}{\lambda_1L_1} \left[\tanh\left(\frac{\lambda_1L_1}{2}\right) \left(\cosh\left(\frac{\lambda_1L_1}{2}\right) - 1 \right) - \sinh\left(\frac{\lambda_1L_1}{2}\right) \right] \right\}
 \end{aligned} \tag{123}$$

with $\lambda_1 = \sqrt{\frac{J_{T1}}{J_{M1}(2+2\mu)}}$, $J_{M1} = \frac{1}{24}t_1w_1^3(w_1-t_1)^2$ and polar area momentum of inertia for a rectangle $J_{T1} = \eta_{rect1}w_1t_1^3$. Without the surrounding support structure of HS1 the torsion angle of HS1 is therefore given by

$$\beta_{1x} = \beta_{1x}^* - \frac{3L_2M_x(2+2\mu)}{E(w_4-w_3)t_3^3}. \tag{124}$$

The the torsion angle of HS2 is given by

$$\beta_{2x} = \beta_{1x}^* + \beta_{2x}^*. \tag{125}$$

The in plane bending angles of HS1 and HS2 are $\gamma_1 = \gamma_{1x}^* - \frac{F_x}{E} \left(\frac{L_2^2}{2J_{x2u}} - \frac{L_3L_2}{J_{x2u}} \right)$ and $\gamma_2 = \gamma_{1x}^* + \gamma_{2x}^*$, respectively.

As a result, the compliance matrix component of the 3D-Nanoprobe in x-direction of F_x is $c_{xx} = \frac{\Delta x}{F_x}$ and the elements of the matrix of inclination angles of HS1 and HS2 are $a_{\beta 1x} = \frac{\beta_1}{F_x}$ and $a_{\beta 2x} = \frac{\beta_2}{F_x}$ and $a_{\gamma 1x} = \frac{\gamma_1}{F_x}$ and $a_{\gamma 2x} = \frac{\gamma_2}{F_x}$, respectively.

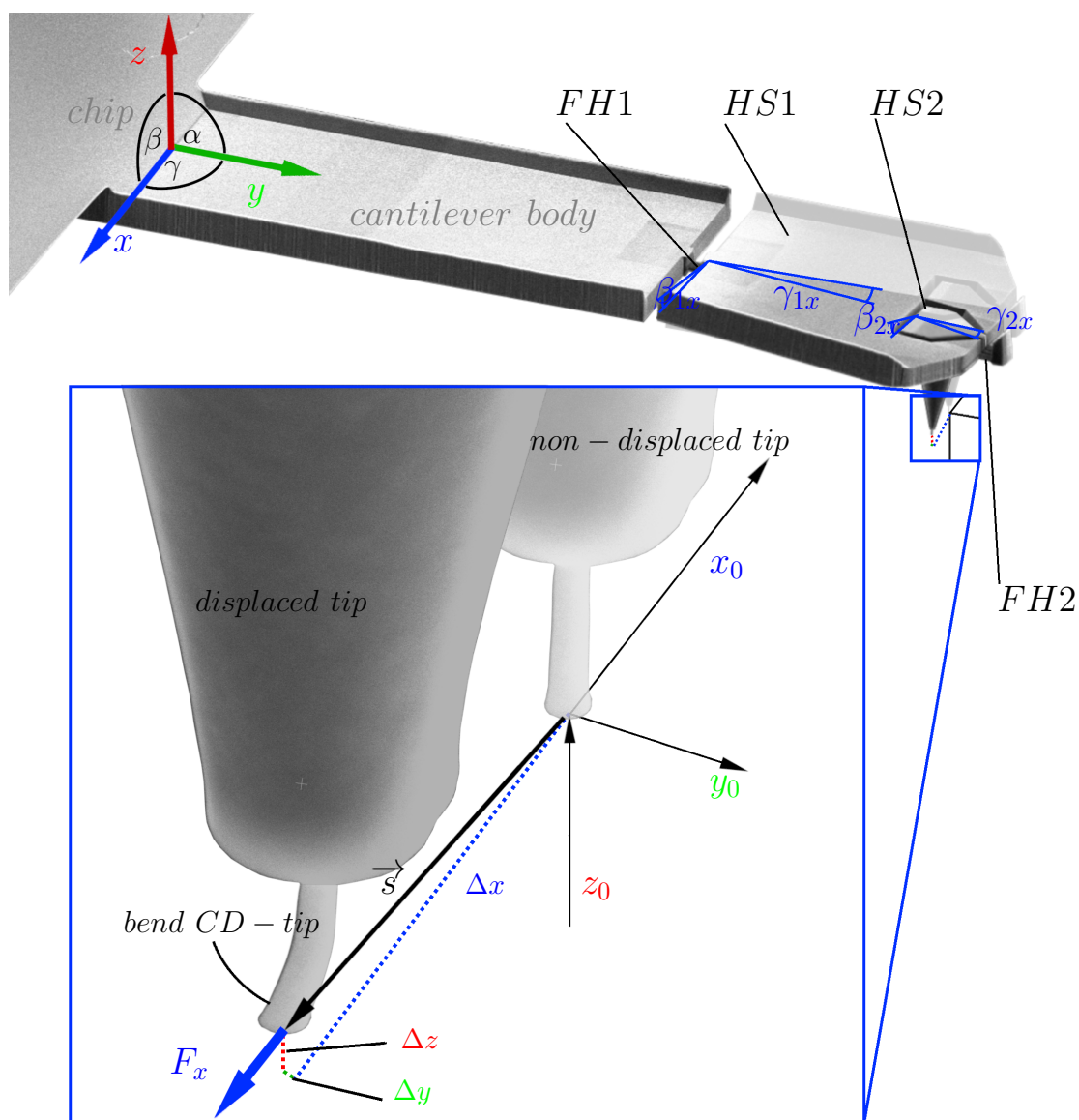


Figure A.3: The 3D-Nanoprobe's drawing of the elastic CD-tip apex displacements (in x,y,z) by interaction with a tip-sample interaction force in x-direction F_x . The tip apex displacement is given by the vector $\vec{s}$.

As previously mentioned, this linear analytical model to describe the probe's mechanical properties is not accurate enough to be used in an optimization process. Consequently it needs to be enhanced. In the following the maximum strain in the boundary conditions of HS1 and HS2 is used to model a correction factor for bending and torsion by a FEM simulation. The simulation is necessary, because the 3D-Nanoprobe will be made of the anisotropic crystalline material silicon (here crystallographic orientation [110]) which is very difficult to model for a flexure hinge structure and would go far beyond the scope of this work [198]. The corrections are valid for a width w_i to thickness t_i ratio of 1/6 to 6 for bending and torsion [72]. The correction factor for bending in horizontal and vertical direction is given by

$$B_{hi} = k_{b2} \cdot \exp \left(k_{b2} \cdot \left(\frac{t_i}{w_i} \right)^{k_{b3}} \right) + k_{b4} \quad (126)$$

and

$$B_{vi} = k_{b2} \cdot \exp \left(k_{b2} \cdot \left(\frac{w_i}{t_i} \right)^{k_{b3}} \right) + k_{b4}, \quad (127)$$

respectively, with $k_{b1}=-0.962$, $k_{b2}=-1.870$, $k_{b3}=0.432$ and $k_{b4}=0.713$, for HS1 and HS2 ($i=1,2$). The boundary condition of the base of the 3D-Nanoprobe is neglected [72]. The correction factor for torsion is given by

$$B_{ti} = k_{b2} \cdot \exp \left(k_{b2} \cdot \left(\frac{w_i}{t_i} \right)^{k_{b3}} \right) + k_{b4}, \quad (128)$$

respectively, with $k_{b1}=1.103$, $k_{b2}=-0.554$, $k_{b3}=1.329$ and $k_{b4}=0.055$, for HS1 and HS2 ($i=1,2,3$). During the modeling process a deviation of the torsion angle of the warping torsion was found [196]. Thus, the dimensionless warping parameter λ_i was FEM optimized for an-isotropic silicon [110] ($i=1,2$) and the polar momentum of inertia J_{Ti} was simplified by adapting the geometry dependent $\eta_{recti} = \frac{1}{3} \left(1 - 0.63 \frac{t_i}{w_i} + 0.052 \frac{w_i^5}{t_i^5} \right)$ fro rectangular cross-sections [197] (parameter e.g. in section A).

Because the torsion angle was showing also a length dependent deviation, the warping constant J_{Mi} was also adapted to $J_{Mi} = \frac{1}{100} t_i^3 w_i (w_i - t_i)^2 \cdot \left(\frac{L_i}{w_i} \right)^{1.7}$ and implemented in the model ($i=1,2$).

L_{tip1} (not shown in the figures) is introduced to improve flexibility in the positioning of the FH1 relative to FH2. This is most important to allow a slight decoupling of the x- and y-directions during optimization. Moreover, shear is added to the compliant sections (FH1 and FH2) forming a *Timoshenko* beam. The influence of shear is negligible for the thicker and stiff HS1 and HS2. A *Timoshenko* coefficient $\kappa_{si}=0.84$ was used for silicon [110] [195]. For polycrystalline silicon $\kappa_{si}=0.86$ can be used [195]. Finally, the compliance $\mathbf{C}_s$ of the CD-tip is added, enhanced by an FEM based bedding factor for the boundary condition between tip cone and CD-tip of $c_{sb} = \frac{352 L_s^2}{25 \pi d_s^3 E_s}$ in horizontal direction (x and y), with Young's modulus of the tip E_s , and the d_s and L_s as the nominal CD-tip diameter and length, respectively. The corrections to the model are simply added to the individual matrix coefficients. For better coefficient comparison, the expression is not completely rewritten. Finally, the relevant

semi-analytical, model based, detectable angles α_{1z} , α_{2z} , α_{1y} , α_{2y} , β_{1z} and β_{2z} are given by

$$\alpha_{1z} = \frac{F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} + \frac{B_{v1}6(L_{k1} + L_1)}{w_1 t_1^2} + \frac{B_{v1}6L_{k1}}{w_1 t_1^2} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} \right) - \frac{L_3 F_z}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)}{J_{1z}} - \frac{L_{k1}}{J_{1z}} + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} + \frac{2B_{v1}6}{w_1 t_1^2} \right) \quad (129)$$

$$\alpha_{2z} = \frac{F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} + \frac{B_{v1}6(L_{k1} + L_1)}{w_1 t_1^2} + \frac{B_{v1}6L_{k1}}{w_1 t_1^2} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{zu}} \right) + \frac{F_z B_{v3}(L_{k2} + L_2)6}{E 2w_3 t_3^2} + \frac{F_z B_{v3}L_{k2}6}{E 2w_3 t_3^2} - \frac{L_3 F_z}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)}{J_{1z}} - \frac{L_{k1}}{J_{1z}} + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} + \frac{(L_k + L_2)}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{zu}} + \frac{2B_{v1}6}{w_1 t_1^2} + \frac{B_{v3}(L_{k2} + L_2)6}{2w_3 t_3^2 L_3} + \frac{B_{v3}L_{k2}6}{2w_3 t_3^2 L_3} \right) - \frac{F_z}{E} \left(\frac{L_3^2}{2J_{2z}} - \frac{L_{k2}^2}{2J_{2z}} + \frac{L_{k2}^2}{2J_{k2z}} + \frac{B_{v2}(L_{k2} + L_2)6}{w_2 t_2^2} + \frac{B_{v2}L_{k2}6}{w_2 t_2^2} \right), \quad (130)$$

$$\alpha_{1y} = \frac{L_{tip} F_y}{E} \left(\frac{L_{eff1}}{J_z} - \frac{L_{k1} + L_1}{J_z} + \frac{(L_{k1} + L_1)L_{tip1}}{J_{1z}L_{tip}} - \frac{L_{k1}L_{tip1}}{J_{1z}L_{tip}} + \frac{6B_{v1}L_{tip1}}{L_{tip}w_1 t_1^2} + \frac{6B_{v1}L_{tip1}}{L_{tip}w_1 t_1^2} + \frac{L_{k1}}{J_z} - \frac{L_k + L_2}{J_z} \right) \quad (131)$$

$$\alpha_{2y} = \frac{L_{tip} F_y}{E} \left(\frac{L_{eff1}}{J_z} - \frac{L_{k1} + L_1}{J_z} + \frac{(L_{k1} + L_1)L_{tip1}}{J_{1z}L_{tip}} - \frac{L_{k1}L_{tip1}}{J_{1z}L_{tip}} + \frac{6B_{v1}L_{tip1}}{L_{tip}w_1 t_1^2} + \frac{6B_{v1}L_{tip1}}{L_{tip}w_1 t_1^2} + \frac{L_{k1}}{J_z} - \frac{L_k + L_2}{J_z} + \frac{L_k + L_2}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{zu}} + \frac{6B_{v2}}{w_2 t_2^2} + \frac{6B_{v2}}{w_2 t_2^2} + \frac{L_3}{J_{2z}} - \frac{L_{k2}}{J_{2z}} + \frac{L_{k2}}{J_{k2z}} + \frac{6B_{v2}}{2w_3 t_3^2} + \frac{6B_{v2}}{2w_3 t_3^2} \right) \quad (132)$$

$$\begin{aligned}\beta_{1x} = & \frac{3L_{k1}M_x(2+2\mu)}{Ewt^3} + \frac{3(L_{eff1} - L_{k1} - L_1)M_x(2+2\mu)}{Ewt^3} + \frac{2L_{tip1}\frac{w_1}{4}(2-2\mu)\eta_{rect1}B_{t1}}{Et_1^3w_1} \\ & + \frac{F_xL_{tip1}L_1(2+2\mu)}{EJ_{T1}^2} \left\{ 1 + \frac{2}{\lambda_1L_1} \left[\tanh\left(\frac{\lambda_1L_1}{2}\right) \left(\cosh\left(\frac{\lambda_1L_1}{2}\right) - 1 \right) - \sinh\left(\frac{\lambda_1L_1}{2}\right) \right] \right\}\end{aligned}\quad (133)$$

$$\begin{aligned}\beta_{2x} = & \frac{3L_2M_x(2+2\mu)}{E(w_4 - w_3)t_3^3} + \frac{3L_{k1}M_x(2+2\mu)}{Ewt^3} + \frac{3(L_{eff1} - L_{k1} - L_1)M_x(2+2\mu)}{Ewt^3} \\ & + \frac{F_xL_{tip1}L_1(2+2\mu)}{EJ_{T1}^2} \left\{ 1 + \frac{2}{\lambda_1L_1} \left[\tanh\left(\frac{\lambda_1L_1}{2}\right) \left(\cosh\left(\frac{\lambda_1L_1}{2}\right) - 1 \right) - \sinh\left(\frac{\lambda_1L_1}{2}\right) \right] \right\} \\ & + \frac{3L_{k2}M_x(2+2\mu)}{Ew_kt^3} + \frac{2L_{tip}\frac{w_2}{4}(2-2\mu)\eta_{rect2}B_{t2}}{Et_2^3w_2} + \frac{2L_{tip1}\frac{w_1}{4}(2-2\mu)\eta_{rect1}B_{t1}}{Et_1^3w_1} \\ & + \frac{F_xL_{tip}L_2(2+2\mu)}{EJ_{T2}^2} \left\{ 1 + \frac{2}{\lambda_2L_2} \left[\tanh\left(\frac{\lambda_2L_2}{2}\right) \left(\cosh\left(\frac{\lambda_2L_2}{2}\right) - 1 \right) - \sinh\left(\frac{\lambda_2L_2}{2}\right) \right] \right\}\end{aligned}\quad (134)$$

The final semi-analytical model based compliance matrix coefficients c_{xx} , c_{yy} , c_{zz} , $c_{yz} = c_{zy}$ are given by

$$\begin{aligned}
c_{xx} = & \frac{1}{E} \left(\frac{L_3^3}{3J_{2x}} - \frac{L_{k2}^3}{3J_{2x}} + \frac{L_{k2}^3}{3J_{2kz}} + \frac{6B_{h2}(L_{k2} + L_2)^2}{w_2^2 t_2} + \frac{6B_{h2}L_{k2}^2}{w_2^2 t_2} + \frac{L_2(2 + 2\mu)}{\kappa w_2 t_2} \right) \\
& + \frac{3L_{k2}L_{tip}^2(2 + 2\mu)}{Ew_k t^3} + \frac{2L_{tip}^2 \frac{w_2}{4} (2 - 2\mu) \eta_{rect2} B_{t2}^2}{Et_2^3 w_2} + \frac{3(L_{k1} - L_2)L_{tip}^2(2 + 2\mu)}{Ewt^3} \\
& + \frac{L_{tip}^2 L_2(2 + 2\mu)}{EJ_{T2}^2} \left\{ 1 + \frac{2}{\lambda_2 L_2} \left[\tanh\left(\frac{\lambda_2 L_2}{2}\right) \left(\cosh\left(\frac{\lambda_2 L_2}{2}\right) - 1 \right) - \sinh\left(\frac{\lambda_2 L_2}{2}\right) \right] \right\} \\
& + \frac{1}{E} \left(\frac{L_{eff1}^3}{3J_x} - \frac{(L_{k1} + L_1)^3}{3J_x} + \frac{(L_{k1} + L_1)^3}{3J_{x1}} - \frac{L_{k1}^3}{3J_{x1}} + \frac{L_{k1}^3}{3J_x} - \frac{L_2^3}{3J_x} + \frac{L_2^3}{3J_{x2u}} \right) \\
& + \frac{6B_{h1}(L_{k1} + L_1)^2}{w_1^2 t_1} + \frac{6B_{h1}L_{k1}^2}{w_1^2 t_1} + \frac{L_1(2 + 2\mu)}{\kappa w_1 t_1} \\
& - \frac{2L_3}{E} \left(\frac{L_{eff1}^2}{2J_x} - \frac{(L_{k1} + L_1)^2}{2J_x} + \frac{(L_{k1} + L_1)^2}{2J_{x1}} - \frac{L_{k1}^2}{2J_{x1}} + \frac{L_{k1}^2}{2J_x} - \frac{L_2^2}{2J_x} \right) \\
& + \frac{6B_{h2}(L_{k2} + L_2)^2}{(w_4^2 - (w_4 - 2w_3)^2) t_3} + \frac{6B_{h2}L_{k2}^2}{(w_4^2 - (w_4 - 2w_3)^2) t_3} + \frac{L_2(2 + 2\mu)}{\kappa 2w_3 t_3} + \frac{L_2^2}{2J_{x2u}} \\
& + \beta_{1x} \cdot L_{tip1} + \frac{3L_2L_{tip}^2(2 + 2\mu)}{E(w_4 - w_3)t_3^3} + \frac{21.333L_s^3}{E_s d^4 \pi} + \frac{352L_s^2}{25\pi d_s^3 E_s} + \\
& + \frac{L_2^3}{E} \left(\frac{L_{eff1}}{J_x} - \frac{L_{k1} + L_1}{J_x} + \frac{L_{k1} + L_1}{J_{x1}} - \frac{L_{k1}}{J_{x1}} + \frac{L_{k1}}{J_x} - \frac{L_2}{J_x} \right) \\
& + \frac{6B_{h3}(L_{k2} + L_2)^2}{(w_4^2 - (w_4 - 2w_3)^2) t_3 L_3^2} + \frac{6B_{h3}L_{k2}^2}{E(w_4^2 - (w_4 - 2w_3)^2) t_3 L_3^2} + \frac{L_2(2 + 2\mu)}{\kappa 2w_3 t_3 L_3^2} + \frac{L_2}{J_{x2u}}
\end{aligned} \tag{135}$$

The elongation of the 3D-Nanoprobe in y-direction is not significant for the expected geometry. Consequently it is neglected in the following.

$$\begin{aligned}
c_{yy} = & \frac{\alpha_{2y} L_{tip}}{F_y} + \frac{1}{E} \left(\frac{(L_{eff1} - L_{k1} - L_1)}{wt} + \frac{L_1}{w_1 t_1} + \frac{(L_{k1} - L_{k2} - L_2)}{wt} \right) \\
& + \frac{L_{k2}}{(w - w_k)t} + \frac{L_2}{(w - w_k)t} + \frac{L_{k2}}{w_k t} + \frac{L_2}{w_2 t_2} \\
& \approx \frac{L_{tip}^2}{E} \left(\frac{L_{eff1}}{J_z} - \frac{L_{k1} + L_1}{J_z} + \frac{(L_{k1} + L_1)L_{tip1}^2}{J_{1z}L_{tip}^2} - \frac{L_{k1}L_{tip1}^2}{J_{1z}L_{tip}^2} + \frac{12B_{v1}L_{tip1}^2}{L_{tip}^2 w_1 t_1^2} \right) \\
& + \frac{L_{k1}}{J_z} - \frac{L_k + L_2}{J_z} + \frac{L_k + L_2}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{z2u}} + \frac{12B_{v2}}{w_2 t_2^2} \\
& + \frac{L_3}{J_{2z}} - \frac{L_{k2}}{J_{2z}} + \frac{L_{k2}}{J_{k2z}} + \frac{12B_{v2}}{2w_3 t_3^2} + \frac{21.333L_s^3}{E_s d^4 \pi} + \frac{352L_s^2}{25\pi d_s^3 E_s}
\end{aligned} \tag{136}$$

$$\begin{aligned}
 c_{zz} = & \frac{F_z}{E} \left(\frac{L_{eff1}^3}{3J_z} - \frac{(L_{k1} + L_1)^3}{3J_z} + \frac{(L_{k1} + L_1)^3}{3J_{1z}} - \frac{L_{k1}^3}{3J_{1z}} + \frac{L_{k1}^3}{3J_z} - \frac{(L_k + L_2)^2}{3J_z} \right. \\
 & + \frac{(L_k + L_2)^3}{3J_{zu}} - \frac{L_2^3}{3J_{zu}} + \frac{L_2^3}{3J_{z2u}} \left. \right) + \frac{6B_{v1}(L_{k1} + L_1)^2}{Ew_1t_1^2} \\
 & + \frac{6B_{v1}L_{k1}^2}{Ew_1t_1^2} + \frac{L_1(2 + 2\mu)}{E\kappa w_1t_1} + \frac{6B_{v3}L_2^2}{2Ew_3t_3^2} + \frac{L_2(2 + 2\mu)}{2E\kappa w_3t_3} \\
 & - \frac{2L_3F_z}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2}{2J_{1z}} - \frac{L_{k1}^2}{2J_{1z}} \right. \\
 & + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{z2u}} \left. \right) \\
 & + \frac{6B_{v1}L_2^2}{2Ew_3t_3^2} + \frac{6B_{v3}L_3}{Ew_3t_3^2} + \frac{6B_{v3}L_{k2}}{Ew_3t_3^2} \\
 & + \frac{L_3^2F_z}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)}{J_{1z}} - \frac{L_{k1}}{J_{1z}} \right. \\
 & + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} + \frac{(L_k + L_2)}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{6B_{v3}L_3^2}{Ew_3t_3^2} + \frac{6B_{v3}L_{k2}L_3}{Ew_3t_3^2} \frac{L_2}{J_{z2u}} \left. \right) \\
 & + \frac{F_z}{E} \left(\frac{L_3^3}{3J_{2z}} - \frac{L_{k2}^3}{3J_{2z}} + \frac{L_{k2}^3}{4J_{k2z}} + \frac{6B_{v2}L_3^2}{Ew_2t_2^2} + \frac{6B_{v2}L_{k2}^2}{Ew_2t_2^2} + \frac{L_2(2 + 2\mu)}{E\kappa w_2t_2} \right) + \frac{4L_s}{Ed^2\pi}
 \end{aligned} \tag{137}$$

$$\begin{aligned}
 c_{yz} = & \frac{L_{tip}}{E} \left(\frac{L_{eff1}^2}{2J_z} - \frac{(L_{k1} + L_1)^2}{2J_z} + \frac{(L_{k1} + L_1)^2L_{tip1}}{2J_{1z}L_{tip}} - \frac{L_{k1}^2L_{tip1}}{2J_{1z}L_{tip}} + \frac{B_{v1}6(L_{k1} + L_1)L_{tip1}}{w_1t_1^2L_{tip}} \right. \\
 & + \frac{B_{v1}6L_{k1}L_{tip1}}{w_1t_1^2L_{tip}} + \frac{L_{k1}^2}{2J_z} - \frac{(L_k + L_2)^2}{2J_z} + \frac{(L_k + L_2)^2}{2J_{zu}} - \frac{L_2^2}{2J_{zu}} + \frac{L_2^2}{2J_{z2u}} \left. \right) + \frac{L_{tip}B_{v3}L_26}{E2w_3t_3^2} \\
 & - \frac{L_3L_{tip}}{E} \left(\frac{L_{eff1}}{J_z} - \frac{(L_{k1} + L_1)}{J_z} + \frac{(L_{k1} + L_1)L_{tip1}}{J_{1z}L_{tip}} - \frac{L_{k1}L_{tip1}}{J_{1z}L_{tip}} + \frac{L_{k1}}{J_z} - \frac{(L_k + L_2)}{J_z} \right. \\
 & + \frac{(L_k + L_2)}{J_{zu}} - \frac{L_2}{J_{zu}} + \frac{L_2}{J_{z2u}} + \frac{12B_{v1}L_{tip1}}{w_1t_1^2L_{tip}} + \frac{B_{v3}(L_{k2} + L_2)6}{2w_3t_3^2L_3} + \frac{B_{v3}L_{k2}6}{2w_3t_3^2L_3} \left. \right) \\
 & - \frac{L_{tip}}{E} \left(\frac{L_3^2}{2J_{2z}} - \frac{L_{k2}^2}{2J_{2z}} + \frac{L_{k2}^2}{2J_{k2z}} + \frac{B_{v2}(L_{k2} + L_2)6}{w_2t_2^2} + \frac{B_{v2}L_{k2}6}{w_2t_2^2} \right),
 \end{aligned} \tag{138}$$

B. Manual for 3D-Nanoprobe manufacturing with FIB:

1. Mark the CD-tip position: The optimized geometries are strongly influenced by the CD-tip's y-position (lengthwise). Therefore this position needs to be visible from the operator side in top view and side view on the cantilever body. During this process the CD-tip should not be imaged by the ion source. The CD-tip cantilever is rotated by 180° . The position is taken from the middle of the bottom CD-tip cantilever's tip cone, shown in **Figure B.1**. In **Figure B.2** the manufactured mark is visible as a small groove and was milled into the cantilever body from the side.

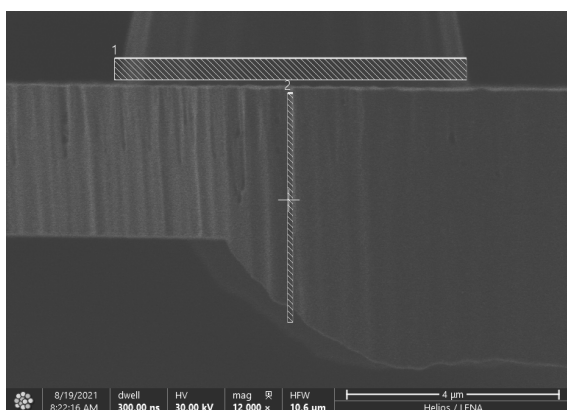


Figure B.1: Manufacturing the mark for the CD-tip position of the 3D-Nanoprobe with two rectangles, the bottom rectangle is activated (ion image)

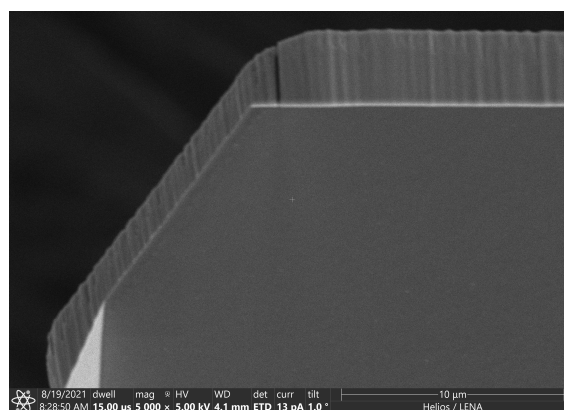


Figure B.2: Manufactured mark for the CD-tip position of the 3D-Nanoprobe (SEM image)

Parameter: rotation = 180° , tilt = 0° , rectangle $4.0 \mu\text{m} \times 0.1 \mu\text{m} \times 0.5 \mu\text{m}$, current = 26 pA, time = 26 s.

2. Rough milling of FH2 from the top: The position of FH2 and outer dimension is defined by removing material at the free end of the cantilever. The cantilever is rotated back to 0° and tilted 14° for FIB manufacturing from the top. **Figure B.3** shows two polygons (triangles), which are symmetrical positioned with the optimized distance from the marked CD-tip position with two drawn rectangles. The rectangles are disabled during the milling. **Figure B.4** shows the cantilever after milling with the used drawn rectangles and polygons, with an offset of the pattern for better visibility.

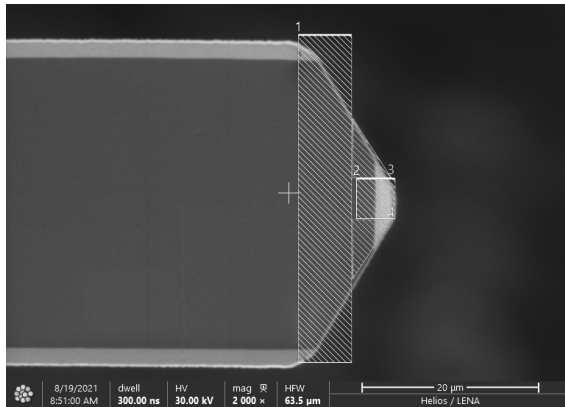


Figure B.3: Rough milling of the shape of FH2 from the top.

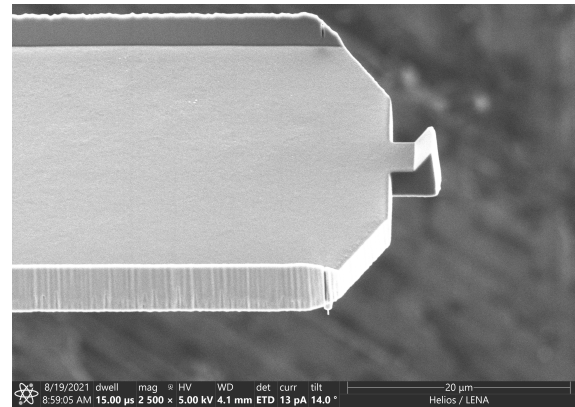


Figure B.4: Rough milled shape of FH2 from the top.

Parameter: rotation = 0° , tilt = 14° , two polygon $3.0 \mu\text{m}$, current = 2.4 nA , time = 1 min 23 s.

3. Rough milling of HS2 from the top: The position of HS2 and outer dimension is defined by cutting a trench around the cantilevers tip from the top. **Figure B.5** shows a total of five enabled rectangles that are symmetrically positioned with the optimized distance from the marked CD-tip position with three disabled rectangles (no.1, 2, and 8). The milling/etching depth is set to an about $0.5 \mu\text{m}$ smaller than the cantilever body thickness value, because the divergent ion beam and eroded debris will damage the CD-tip, if milled through at high current. **Figure B.6** shows the cantilever at rotation of 0° and tilt of 14° after milling of the trench in an SEM image.

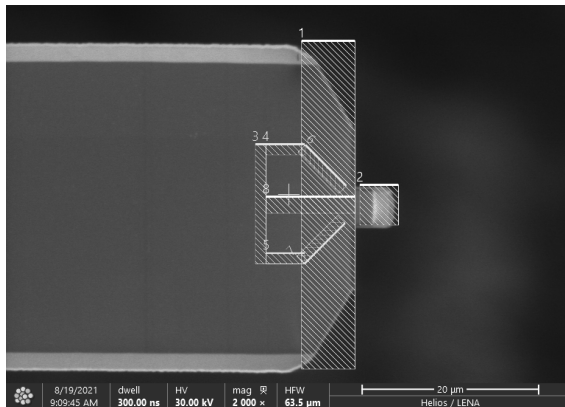


Figure B.5: Rough milling of HS2 from the top.

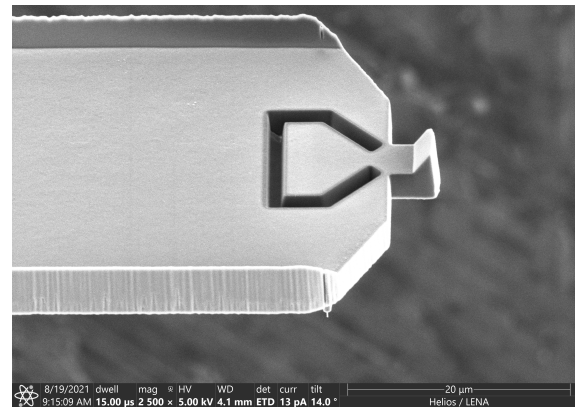


Figure B.6: Rough milled structure of HS2 from the top, SEM view.

Parameter: rotation = 0° , tilt = 14° , rectangle $13.4 \mu\text{m} \times 1.2 \mu\text{m} \times 1.6 \mu\text{m}$ and two rectangles rotated 90° $5.0 \mu\text{m} \times 1.2 \mu\text{m} \times 1.6 \mu\text{m}$ and two rectangles rotated $\pm 45^\circ$ $6.5 \mu\text{m} \times 1.2 \mu\text{m} \times 1.6 \mu\text{m}$, current = 2.4 nA , time = 1 min 39 s.

4. Fine milling of HS2 from the top: To separate HS2 from the cantilever body the trench is cut deeper at the bottom, forming a slot. **Figure B.8** shows a pattern of five rectangles, which are again symmetrically positioned via the distance from the marked CD-tip position with three rectangles for alignment. The current is reduced to 0.26 nA and the milling depth is set to about 0.2 μm . The milling direction of the individual rectangle is set from the inner HS2 side to the outer HS1 side. This process is repeated about 2 to 3 times until HS2 is separated and edges of HS2 show clean cuts. **Figure B.7** shows the cantilever body after the second milling of the trench imaged in the SEM to evaluate the progress. The **Figure B.7** shows that the step should be repeated one more time because the image shows some material is left in the slot.

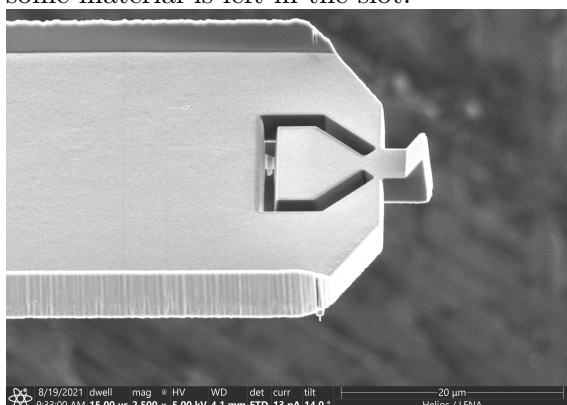


Figure B.7: Fine milling of HS2 from the top, SEM view.

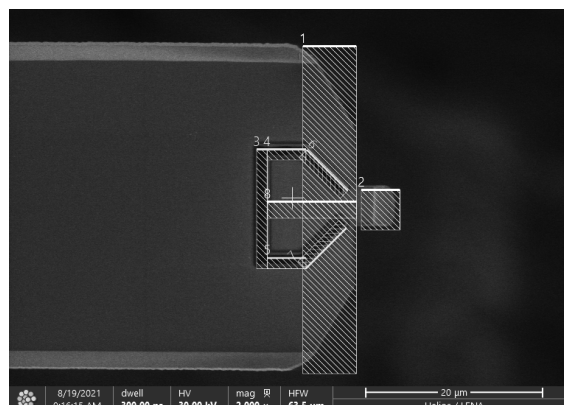


Figure B.8: Fine milling of HS2 from the top, ion image.

Parameter: rotation = 0°, tilt = 14°, rectangle 13.6 μm x 1.0 μm x 0.2 μm and two rectangles rotated 90° 5.0 μm x 1.0 μm x 0.2 μm and two rectangles rotated $\pm 45^\circ$ 6.5 μm x 1.0 μm x 0.2 μm , current = 0.26 nA, time = 1 min 39 s.

5. Fine milling of the transition to HS2: The transition between the slot of HS2 and HS1 and the FH2 is milled by two polygon pattern. **Figure B.9** shows the polygons placed symmetrically and reach into the slot milled in the previous step and the beginning of the region of FH2 (align flush with the edges milled in 2. step). The separation distance of the polygons on the side of the region of FH2 is 1.1 μm , two disabled rectangles are used for the alignment. The width of the milled slots taper from about 1.0 μm to about 0.2 μm . **Figure B.10** shows the cantilever body after milling of the trench in the SEM and **Figure B.9** shows the cantilever body after milling of the trench in the Ion image with the offset pattern and disabled rectangles. If the first cut has no sufficient edges one can repeat the milling step with a sharp 90 pA beam.

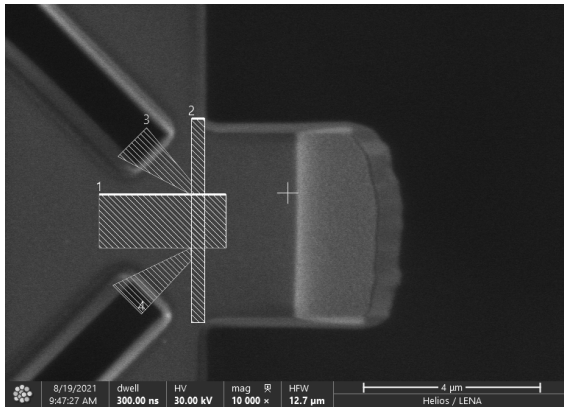


Figure B.9: Fine milling of the transition to HS2.

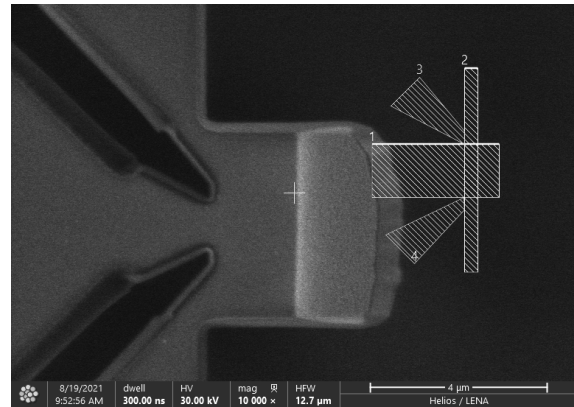


Figure B.10: Fine milled structure of the transition to HS2.

Parameter: rotation = 0° , tilt = 14° , polygon $2.5 \mu\text{m}$, current = 0.26 nA , time = 1 min 40 s and for cleaning the edges (polygon $0.5 \mu\text{m}$, current = 90 pA , time = 2 min).

6. Rough milling of FH1 from the top: The excess material surrounding FH1 is roughly cut and the position and rough outer dimension of FH1 is defined. **Figure B.11** shows two rectangles are positioned relative to the mark of the CD-tip and the width of the FH1 region is manufactured with an oversize of $1.2 \mu\text{m}$. To center FH1, two disabled rectangles are used for positioning. Usually, FH1 is far away from the CD-tip and the quality of the edges are not critical, so the slots can be cut fast with high current. The milling/etching depth is set to an about $0.8 \mu\text{m}$ larger than the actual thickness of the cantilever, because of redepositing of material and the typical tub like structure on the edges of the CD-tip cantilever. **Figure B.12** shows the cantilever at rotation 0° and tilted 14° after milling in the SEM.

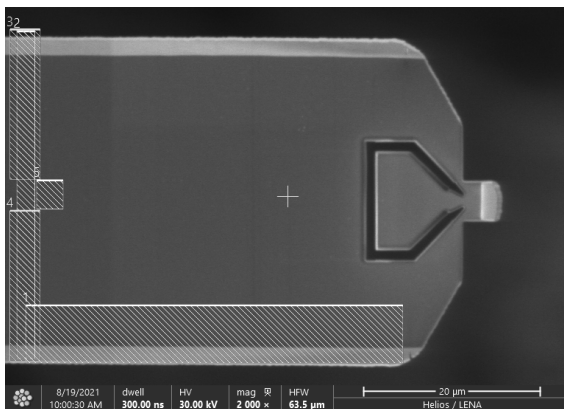


Figure B.11: Rough milling of FH1 from the top.

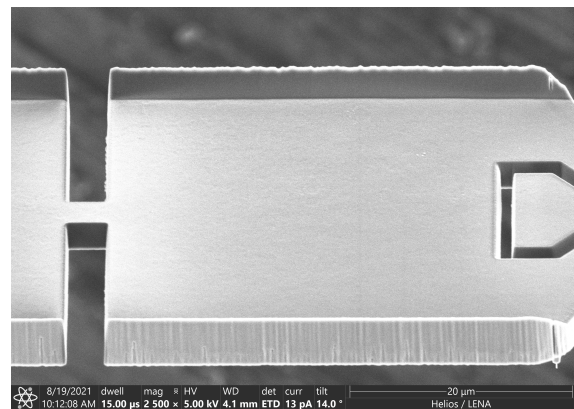


Figure B.12: Rough milled structure of FH1 from the top.

Parameter: rotation = 0° , tilt = 14° , two rectangles rotated 90° $15.0 \mu\text{m} \times 3.4 \mu\text{m} \times 3.4 \mu\text{m}$ and, current = 2.4 nA , time = 10 min.

7. Fine milling of width FH1: The final width of FH1 is manufactured with two rectangular patterns. The rectangles should be placed with about 100 nm offset and also 100 nm shorter in length to archive the desired geometry. **Figure B.13** shows the two symmetrically placed rectangles with a third disabled rectangle, that is used for the correct spacing. The two rectangles are placed in the middle of the previous cut, because the mark of the CD-tip position is not visible at the selected magnification. **Figure B.14** shows the cantilever body after milling in an SEM image.

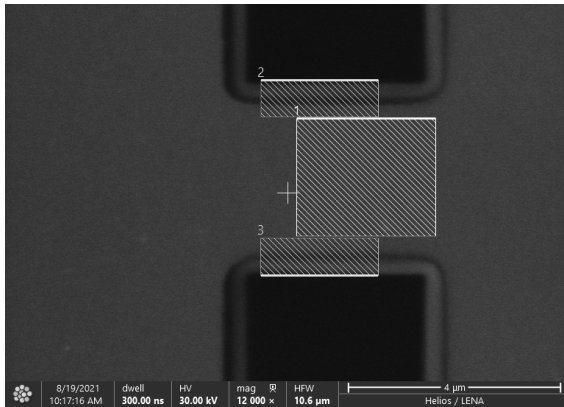


Figure B.13: Fine milling of width of FH1 from the top.

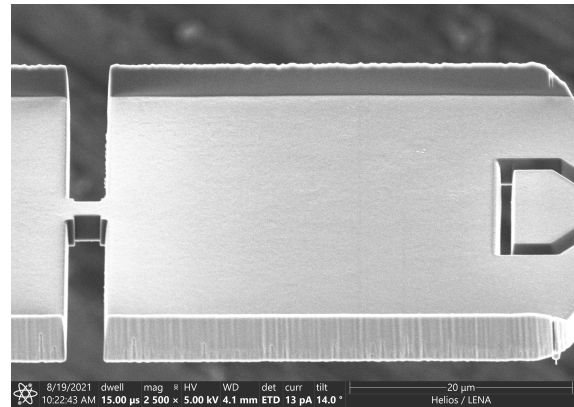


Figure B.14: Fine milled structure of width of FH1 from the top.

Parameter: rotation = 0° , tilt = 14° , two rectangles $2.1 \mu\text{m} \times 0.72 \mu\text{m} \times 3.5 \mu\text{m}$, current = 0.26 nA, time = 2 min 24 s.

8. Fine milling of FH1 from the side: The excess material surrounding FH1 is removed. Similar to the step before, the rectangles should be placed with about 100 nm offset and also 100 nm shorter in length to achieve the desired geometry around the third disabled rectangle, that can be used for correct spacing. **Figure B.15** shows the three rectangles used in this step at an offset for better visibility. **Figure B.16** shows the FH1 after milling in the ion image from the side. The images show the view along the edges from the two previous steps into the cut of the cantilever body. One can see that the edges of the cantilever body are thicker, because of the tub like structure on the side edges of the cantilever body. The CD-tip cantilever can be mounted with an error in rotation angle, which would not allow the direct view on the FH1 at this angle, this is compensated and corrected by adjusting rotation and tilt by a few degrees.

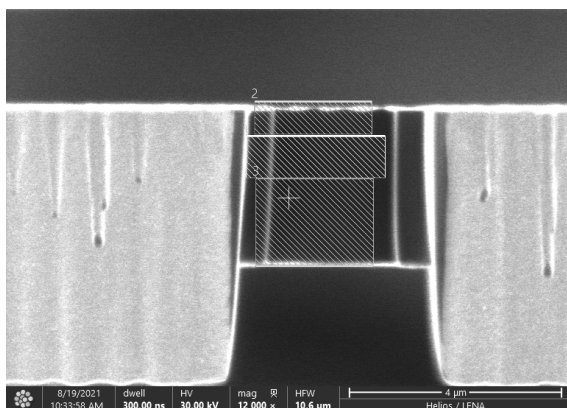


Figure B.15: Fine milling of FH1 from the side.

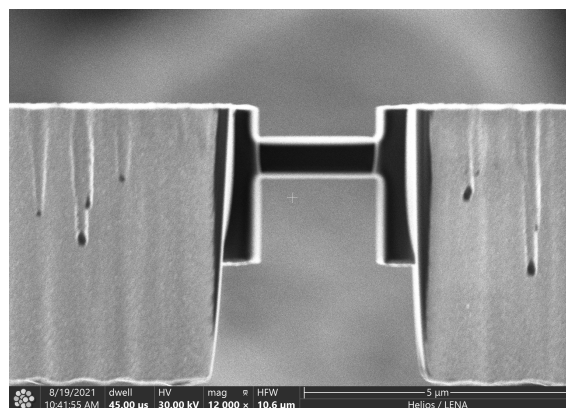


Figure B.16: Fine milled structure of FH1 from the side.

Parameter: rotation = 179° (180°), tilt = 1° , two rectangles $0.61 \mu\text{m}$ and $1.6 \mu\text{m} \times 2.1 \mu\text{m} \times 3.4 \mu\text{m}$, current = 0.26 nA , time = 2 min.

9. Fine milling of FH2 from the side: The excess material surrounding FH2 is removed. Similar to the step before, the rectangles should be placed with about 100 nm offset and also 100 nm shorter in length to archive the desired geometry around a third disabled rectangle, that can be used for correct spacing shown in **Figure B.17**. **Figure B.18** shows the FH2 after milling in the ion image from the side with the mark of the CD-tip position on the left side of the image. The tub like structure on the side edges of the CD-tip Cantilever is clearly visible also at the very end of the cantilever body.

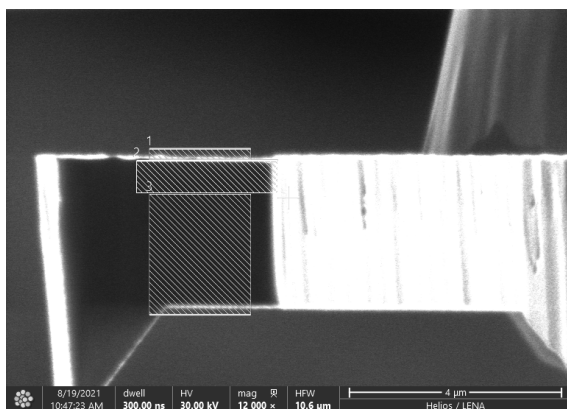


Figure B.17: Fine milling of FH2 from the side.

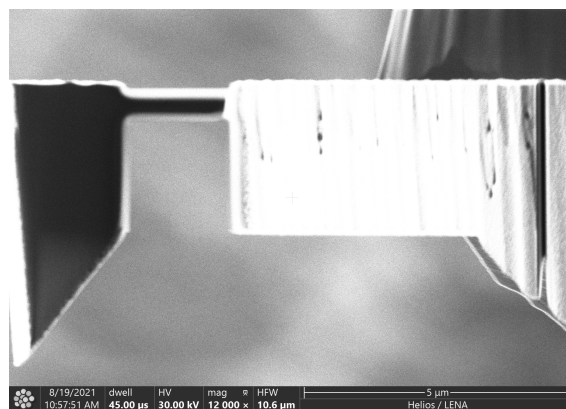


Figure B.18: Fine milled structure of FH2 from the side.

Parameter: rotation = 179° (180°), tilt = 1° , two rectangles $0.2 \mu\text{m}$ and $2.0 \mu\text{m} \times 1.9 \mu\text{m} \times 4 \mu\text{m}$, current = 0.26 nA , time = 3 min.

10. Fine milling of FH2 from the top: The FH2 is cut into 3 sections by two rectangular

pattern, a third rectangle is used for correct spacing and positioning, shown in **Figure B.19**. Similar to the step before, the rectangles should be about 100 nm narrower than the gap used in the optimization (300 nm). This shape of FH2 is specifically designed to be manufactured by FIB from two sides to connect HS1 with HS2. **Figure B.20** shows the FH2 after milling. The milling depth of 1 μm and a current of 90 pA is sufficient because FH2 is thinned from the step before.

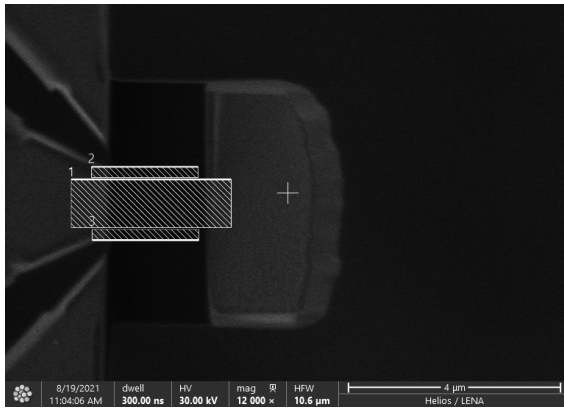


Figure B.19: Fine milling of FH2 from the top.

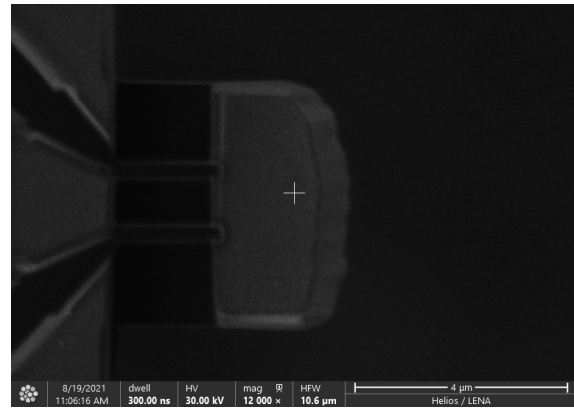


Figure B.20: Fine milled structure of FH2 from the top.

Parameter: rotation = 0° , tilt = 14° , two rectangles $2 \mu\text{m} \times 0.2 \mu\text{m} \times 1 \mu\text{m}$, current = 90 pA, time = 28 s.

11. Fine milling of FH2 to HS2 transition: The milled edges in the gap in transition region from FH2 to HS2 can be sometimes uneven, because of a big difference in material thickness. Two small rectangles rotated by $\pm 30^\circ$ are used to clean the cut and assure a separation between HS2 and HS1, shown in **Figure B.21**. **Figure B.22** shows the FH2 region after milling in the SEM image.

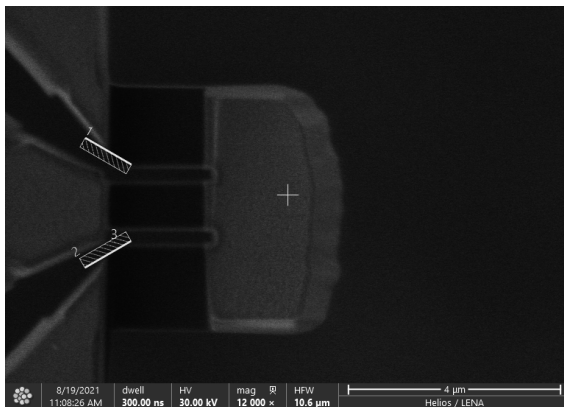


Figure B.21: Fine milling of FH2 to separate HS1 and HS2.

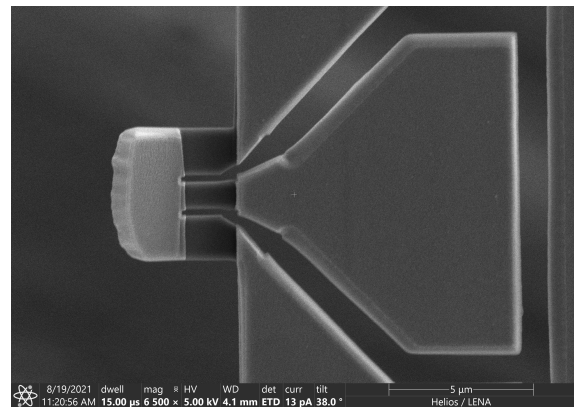


Figure B.22: Final milled structure of FH2 in the SEM image.

Parameter: rotation = 0° , tilt = 14° , two rectangles $\pm 30^\circ$ with $0.6\ \mu\text{m} \times 0.2\ \mu\text{m} \times 1\ \mu\text{m}$, current = 90 pA, time = 4 s.

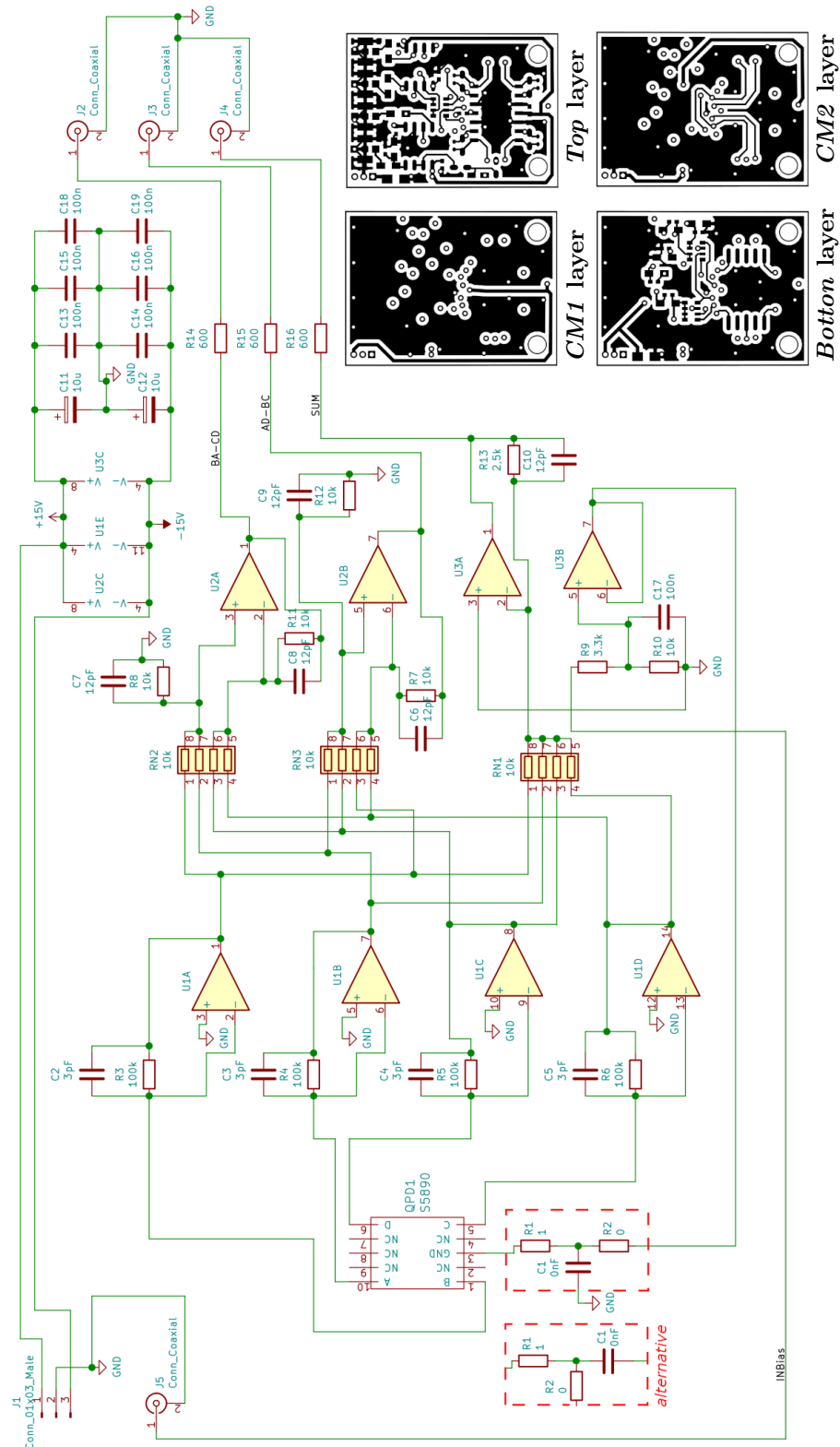


Figure B.23: Circuit and layout of the QPD Printed Circuit Board (PCB) for the optical lever detection system. The layout is drawn up on a PCB board with four copper layers denoted as *Top*, *CM1*, *CM2* and *Bottom*.

C. Used software and hardware

List of the relevant used devices and software in this thesis.

Python 3.8 and Python 3.11.10, 64-bit

- *Spyder* 6.0.3 environment
- Used packages for data processing: numpy 2.2.0, matplotlib 3.9.3, scipy 1.14.1, allantools 2019.07 and 2024.04

More information at <https://www.spyder-ide.org/>.

Finite element method software

- Software *Ansys 19.2* for Computer-Aided Design and Finite Element Method (FEM) simulation.
- Headquarter: Southpointe 2600 Ansys Drive, Canonsburg, PA 15317 United States
- CAD: with *ANSYS workbench* bundled software, *Spaceclaim* and *Design Modeler*

Personal Computer (PC) 1

- Software Edition: Win7 Pro (until 2012-04-16), Win10 Pro (present), 64 bit
- Software Version: 22H2 (Win10 Pro)
- CPU: Intel® Core™ i5-6500 CPU @ 3.20GHz
- RAM: 32 GB

Personal Computer (PC) 2

- Betriebssystem: Win7 Professional
- Prozessor: Intel(R) Core(TM) i5 M560
- RAM: 6 GB

Personal Computer (PC) 3

- Software Edition: Win10 Pro, 64 bit
- Software Version: 22H2
- CPU: AMD Ryzen™ 9 5950X
- RAM: 128 GB (ECC)

Focused Ion Beam (FIB), Dual-Beam-FIB/SEM

- Manufacturer: *Thermo Fisher Scientific*, 168 Third Avenue, Waltham, MA USA 02451

- Device: HELIOS NANO LAB 600, FIB/SEM (ZELMI, Berlin)
- Gallium Ion source current: 0.1 pA to 65 nA
- SEM current: 0.7 pA to 22 nA
- Resolution (e-beam): 1 nm at 15 kV and 2.5 nm at 1 kV (beam energies)
- Stage tilt: -10° to $+60^{\circ}$; tilting accuracy 0.1° (50° to 54°)
- Rotation: $n \times 360^{\circ}$ (endless), piezo-driven
- Mounting angle between electron beam and ion beam column: 52°

and after *January 2020*

- Manufacturer: *Thermo Fisher Scientific*, 168 Third Avenue, Waltham, MA USA 02451
- Device: HELIOS 5 UX (located at *Technische Universität Braunschweig (TU-BS)*, *Laboratory for Emerging Nanometrology (LENA)*)
- Gallium Ion source current: 1 pA to 65 nA (Phoenix Ion Column)
- Resolution (e-beam): 0.6 nm from 30 kV to 2 kV
- Resolution (ion-beam): 4.0 nm at 30 kV
- Stage tilt: -10° to $+60^{\circ}$
- Stage rotation: 360° (endless), piezo-driven
- Stage travel: 150 mm x 150 mm x 10 mm (x,y,z)
- Stage repeatability (x,y): $1 \mu\text{m}$
- Sample weight (max.): 500 g (including sample holder)
- Mounting angle between electron beam and ion beam column: 52°

More information at <https://assets.thermofisher.com/TFS-Assets/MSD/Datasheets/Helios-5-UX-DualBeam-Datasheet.pdf>.

Scanning electron microscope (SEM) device

- Manufacturer: *Thermo Fisher Scientific*, 168 Third Avenue, Waltham, MA USA 02451
- Device: VERIOS 5 HP SEM
- SEM current: 0.8 pA to 100 nA
- Resolution: 0.6 nm at 2-15 kV
- Stage tilt: -10° to $+60^{\circ}$, chamber mounted

- Stage rotation: $n \times 360^\circ$ (endless), piezo-driven

More information at <https://assets.thermofisher.com/TFS-Assets/MSD/Datasheets/verios5-datasheet.pdf>

Laser power meter

- Manufacturer: *Coherent Corp.*, 375 Saxonburg Blvd. Saxonburg, PA 16056
- Device: Coherent™ FieldMate™
- Resolution: 0.3% of full scale (3s scale)
- Accuracy: $\pm 1.0\%$ (reading, digital display) + ± 2 LSD (Least Significant Digit)
- Standard uncertainty: $\pm 0.8\%$ (digital display), calibration uncert. $\pm 1\%$ ($k=2$)
- Display: 2.99 nW to 99.9 mW (optical)
- Operating Temp.: 5°C to 40°C
- Sensor: OP-2 VIS Semiconductor Power Sensor, 10 nW to 30 mW, resolution 1 nW, calib. uncertainty ($k=2$) $\pm 5\%$ (450 nm to 1064 nm), power linearity $\pm 1.5\%$

More information at https://coherentinc.my.site.com/Coherent/laser-measurement/power-energy-meters/1098297?cclcl=en_US.

Superluminescent Diode (SLED)

- Manufacturer: *SUPERLUM*, Unit B3, Fota Point Enterprise Park, Carrigtwohill, Co. Cork, Ireland
- Type: SLD-261-HP2-DBUT-PM-PD-FC/APC
- Package: 14-Pin Butterfly
- Center wavelength (typ.): 670 nm
- Spectrum width (FWHM): 7.5 nm (typ.)
- Optical power (max.): about 5 mW

Camera in the 3D-AFM head

- Manufacturer: *IDS Imaging Development Systems GmbH*, Dimbacher Str. 6-8, 74182 Obersulm, Germany
- Type: UI-3070CP-C-HQ Rev.2
- Interface: USB 3.0
- Sutter: global shutter

- Sensor type: CMOS color, *Sony IMX252LQR-C*
- Sensor optical size: 7.093 mm x 5.320 mm
- Pixel size: 3.45 μm
- Color depth (camera): 12 bit
- Resolution (h x v): 2056 pixel x 1542 pixel

More information at <https://de.ids-imaging.com/store/ui-3070cp-rev-2.html>

Industrial Computer

- Manufacturer: *GRAFENTHAL GmbH*, von-Monschaw-Straße 3, 47574 Goch
- Type: *Grafenthal™ DAVIDMini*
- Software Edition: Win10 Pro, 64 bit
- Software Version: 22H2
- CPU: Intel® Core™ i7-7700 CPU @ 3.60GHz
- RAM: 16 GB

Coarse xy-stage

- Manufacturer: *Steinmeyer Mechatronik GmbH*, Fritz-Schreiter-Str. 32, D-01259 Dresden, Germany
- Type: KT305-EDLM
- Controller: Steinmeyer, SNr.:011414-G
- Actuator: linear actuator
- Travel: 210 mm x 210 mm
- Load: max. 80 N
- Repeatability: $\pm 0.4 \mu\text{m}$ (bidirectional)
- Positioning accuracy: $\pm 2.7 \mu\text{m}$
- Break: magnetic (passive)

More information at <https://www.steinmeyer-mechatronik.de/positioniersysteme/standardachsen/kreuztische/kt305-edlm/>.

Coarse Z-stage

- Manufacturer: *OWIS GmbH*, Im Gaisgraben 7, 79219 Staufen i. Br., Germany

- Version: HUMES 60-12
- Controller: OWIS® PS 35
- Material: Aluminium
- Actuator: stepper motor with ball screw
- Bearing: mechanical, recirculating ball bearing guides
- Travel (z): 12 mm
- Load: max. 100 N
- Resolution(calc.): less than $2.5 \mu\text{m}$
- Repeatability: less than $2.5 \mu\text{m}$ (bidirectional)
- Positioning error: less than $20 \mu\text{m}$

More information see <https://www.owis.eu/produkte/artikel/HUMES-60-12-HiSM/0>
or https://www.owis.eu/uploads/tx_aimeos/1.d/files/4/d/4dafec39_pi_humes_60.pdf.

XYZ-piezo stage

- Manufacturer: *Physik Instrumente (PI) SE & Co. KG*, Auf der Römerstraße 1, 76228 Karlsruhe, Germany
- Type: 6-axis piezo stage, P-915K514 (SN111013197)
- Version: customized
- Controller: E-712K109, calibrated with 6-axis piezo stage
- Material: Aluminium
- Actuator: piezo crystals
- Travel (x,y,z): $12 \mu\text{m} \times 12 \mu\text{m} \times 10 \mu\text{m}$
- Resolution: about 0.1 nm in x-, y-, z-axis direction
- Bandwidth: about 1 kHz
- Accuracy: -

Interferometer

- Manufacturer: *SmarAct Metrology GmbH & Co. KG*, August-Wilhelm-Kuenholz-Str. 1, D-26135 Oldenburg, Germany
- Device: *SmarAct PICOSCALE*
- Version: Firmware 2.1.2

- Coupling (opt.): singlemode fiber, FC/APC
- Hardware enhancements: *Breakout Box*
- Software enhancements: *CalcSys*
- Wavelength: 1532 nm, (nominal 1550 nm or 1540 nm)
- Accuracy: $1 \cdot 10^{-6}$
- Target velocity: max. 1 m/s
- Resolution: less than 0.5 nm (Freq. bandwidth 1 kHz to 10 kHz, working distance 20 mm), less than 2.1 nm (Freq. bandwidth 1 kHz to 10 kHz, working distance 1 m)
- Periodic nonlinearities: below 6 nm (peak to peak)
- Interferometer head: *C01 interferometer head* (used), similar to current *C03 interferometer head*

More information see F and <https://www.smaract.com/de/picoscale-accessories/product/picoscale-interferometer> and <https://www.smaract.com/pdf-details/de/picoscale-interferometer>.

Illumination source

- Manufacturer: *Thorlabs Inc.*, Maria-Goeppert-Straße 9, 23562 Lübeck, Germany
- Version: Fiber-Coupled LED, MWWHF2
- Coupling (opt.): SMA (multimode fiber)
- Illumination power: 7.9 mW with opt. fiber (200 μ m core diameter)
- Electrical power: 2900 mW
- Spectral: VIS (broadband 4000K)
- Driver: manual, T-cubeTM LED driver, 1200 mA, Product. no. *LEDD1B*

More information at <https://www.thorlabs.com/drawings/cb6ac02e4550cfcb-8B5159C6-02CF-ABCC-A3CFB2A46BC12B96/MBB1F1-SpecSheet.pdf>.

microscope objective lens

- Manufact: *Mitutoyo Corporation*, 20-1, Sakado 1-Chome, Takatsu-ku, Kawasaki-shi, Kanagawa 213-8533, Japan
- Model: M Plan Apo NIR 50X
- Magnification: 50x
- Numerical aperture: 0.42

- Working distance: 17 mm
- Focal length: 4 mm
- Parfocal distance: 95 mm
- Corrected wavelength range: 480 nm to 1800 nm
- Resolution: 0.7 μm
- Depth of focus: 1.6 μm

More information at [https://shop.mitutoyo.de/web/mitutoyo/de_DE/mitutoyo/NIR_Main.category/M_20Plan_20Apo_20NIR_2050X/\\$catalogue/mitutoyoData/PR/378-825-17/\\$region/MML/index.xhtml;jsessionid=4BC3E4495DF8309750CA63364047E0CC](https://shop.mitutoyo.de/web/mitutoyo/de_DE/mitutoyo/NIR_Main.category/M_20Plan_20Apo_20NIR_2050X/$catalogue/mitutoyoData/PR/378-825-17/$region/MML/index.xhtml;jsessionid=4BC3E4495DF8309750CA63364047E0CC).

Lock-in Amplifier

- Manufacturer: *Zurich Instruments AG*, Technoparkstrasse 1, 8005 Zurich, Switzerland
- Type: HF2LI Lock-in Amplifier
- Interface: USB
- Frontpanel (el.): BNC connector
- Input impedance: 50 Ω or 1 M Ω || 20 pF
- Bandwidth: DC to 50 MHz
- Sampling rate (input A/D): 210 MSa/s
- Dynamic reserve: 120 dB
- Dyn. range (input A/D): 14 bit
- Input noise: 5 nV/ $\sqrt{\text{Hz}}$
- Input range: ± 3.3 V
- Input AC range: ± 1.5 V with DC coupling
- Signal output ranges: ± 10 mV, ± 100 mV, ± 1 V, ± 10 V
- Signal output (output D/A): 16 bit
- Signal output freq.: DC to 50 MHz (210 MSa/s)
- Oscillators: 2
- Phase resolution: 1 μdeg
- Auxiliary Outputs (used): ± 10 V, 16 bit, 1 MSa/s

More information at https://www.zhinst.com/sites/default/files/documents/2024-06/zi_hf2li_leaflet-v2.pdf and https://docs.zhinst.com/hf2_user_manual/.

D. Noise calculation of a trans-impedance amplifier

```
# -*- coding: utf-8 -*-
import numpy as np

#formulas from book
#Operational amplifier noise
#Author(s): Kay, Art (Auth.)
#Publisher: Newnes, Year: 2012
#ISBN: 978-0-7506-8525-2

#calculation of noise of a diode amplifier OPAx140
#####
Brickwallfactor=1.22 #for one pole 1.57 , for 2nd order 1.22 (-40dB per dec.)
BW3dB=721000 #from simulation
#BW3dB=10000
NBW=BW3dB*Brickwallfactor #Hz usable noise bandwidth, about -3dB frequency of first
#transimpedance stage (TIA)
Rfeedback=100000 # feedback resistor in Ohm
Cfeedback=3*10**(-12) #feedback capacitor, range of 2 pF to 10 pF
fugain= 11000000 #unity gain frequency in Hz, specified in the data sheet of
# the operational amplifier
bbnoise=5.1*10**(-9) #broadband voltage noise spectral density from data sheet
# in V/sqrt(Hz)
iinopv=0.8*10**(-15) #Ampere/sqrt(HZ) input noise spectral density value of
#the operational amplifier (from data sheet)
fLow=0.1 #low frequency in Hz, set to 0.1 Hz, (10 seconds of measuring time)
fc=50 # corner frequency in Hz of flicker noise and white noise, taken from
#data sheet graph
Rshunt=2000000000 #shunt resistance of the photo diode in Ohm, S5980 diode at about 3 V
Ilight=0 #current flow of the photodiode in Ampere, quantum efficiency multiplied
#Ilight=0.000030 # in Ampere
# with the optical power
Idark=180*10**(-15) #dark current of the photodiode in Ampere, S5980 diode at about 3 V
Covpcommon=6.25*10**(-12) # common mode input capacitance of the operational
#amplifier, data sheet
Covpdiff=7.5*10**(-12) # common mode input capacitance of the operational
#amplifier, data sheet
Cdiode=15*10**(-12) #capacitance of the photodiode, usually 2 pF to 50 pF, S5980 diode at about 3 V
q=1.6022*10**(-19) # electric charge in coulomb
T=300 #in K absolute temperature
kb=1.38065*10**(-23) #Joule/K Boltzmann constant
#####

noiseVfeedbackR=np.sqrt(4*kb*T*Rfeedback*NBW) #RMS noise
#in our circuit no kTC noise because thermal noise of the feedback resistor
# is a magnitude larger than the noise induced by the feedback and diode
# capacitor, neglectable
ish= np.sqrt(4*kb*T/Rshunt) # thermal noise from shunt resistance
isdiodeidark=np.sqrt(4*Idark*q) #Ampere/sqrt(HZ) dark current noise spectral
#density value of the diode (from data sheet)
isl=np.sqrt(4*Ilight*q) #Ampere/sqrt(HZ) input noise spectral density value#
# of the operational amplifier (from data sheet)
noisecurrentsources=Rfeedback*np.sqrt(ish**2+isdiodeidark**2+isl**2+iinopv**2)*np.sqrt(NBW)
noisecurrentonlyfeedbackR=Rfeedback*np.sqrt(iinopv**2)*np.sqrt(NBW)
#####
#Noise RMS Output voltage values from voltage sources over bandwidth
Cin=Covpcommon+Covpdiff+Cdiode
fw2= 1/(2*np.pi*Rfeedback*(Cfeedback+Cin)) #zero frequency in Hz, end of white
#noise region
fcut=1/(2*np.pi*Rfeedback*Cfeedback) # cutoff frequency in Hz of the feedback circuit
finter=(Cfeedback/(Cfeedback+Cin))*fugain #intersection frequency of noise
#gain and open loop gain of the operational amplifier
Vnv1out=bbnoise*np.sqrt(fc*np.log(fc/fLow)) #1/f noise, low frequency "flow"
#usually 0.1 Hz up to corner frequency fc
Vnv2out=bbnoise*np.sqrt(fw2-fc) #white noise part
Vnv3out=bbnoise*np.sqrt((fcut**3-fw2**3)/(3*fw2**2)) #noise gain peaking,
#because of small feedback capacitor, BW enhancement
Vnv4out=bbnoise*(1+Cin/Cfeedback)*np.sqrt(finter-fcut) #noise gain peak of capacitor
Vnv5out=bbnoise*np.sqrt(fugain**2/finter)
noiseofinputvoltagesources=np.sqrt(Vnv1out**2+Vnv2out**2+Vnv3out**2+Vnv4out**2+Vnv5out**2)
#noiseofinputvoltagesources=np.sqrt(Vnv1out**2+Vnv2out**2)

print('thermal gen. noise, in V')
print(noiseVfeedbackR)
print('current gen. noise, in V')
print(noisecurrentsources)
print('voltage gen. noise, in V')
print(noiseofinputvoltagesources)
print('contribution of current noise of OPV through feed back R in \u03BCV')
print(noisecurrentonlyfeedbackR*1000000)
noisetotal=np.sqrt(noiseVfeedbackR**2+noisecurrentsources**2+noiseofinputvoltagesources**2)
print('total voltage noise in \u03BCV for ADA8674')
print(noisetotal*1000000) #total noise: thermal, current, and voltage noise in microvolts
print('total voltage noise density form RMS value in \u03BCV/sqrt(Hz)')
noisedensitytotal=noisetotal/np.sqrt(NBW)
```

```

print(noisedensitytotal*1000000)
print('total voltage noise density assuming white noise in \u03BCV/sqrt(Hz)')
totnoisedens=np.sqrt(noiseVfeedbackR**2+noisecurrentsources**2+(bbnoise*np.sqrt(NBW))**2)/np.sqrt(NBW)
print(totnoisedens*1000000)
noiselevelVfeedbackR=np.sqrt(4*kb*T*Rfeedback)
print('voltage noise density of feedback resistor \u03BCV/sqrt(Hz)')
print(noiselevelVfeedbackR*1000000)

#####differential opamp #####
R1=10000 #Ohm
R2=10000 #Ohm
#R2=2500 #Ohm
Cfeedbackdiff=12*10**(-12)
fcutdiff=1/(2*np.pi*R2*Cfeedbackdiff)
Brickwallfactor=1.57 #for one pole 1.57 , for 2nd order 1.22
BW3dB=fcutdiff #from simulation
NBW=BW3dB*Brickwallfactor
#NBW=NBW #ENB
Verh=(R1+R2)/R1
fcur=fccur #current noise corner frequency
themDiffpower=NBW*8*kb*T*R2*Verh
currentDiffpower=2*(iinopv**2*R2**2)*(fcur*np.log(fcutdiff/fLow)+NBW)
voltageDiffpower=2*(bbnoise**2*Verh**2)*(fc*np.log(fcutdiff/fLow)+NBW)
NoisedifftotalRMS=np.sqrt(themDiffpower+currentDiffpower+voltageDiffpower)

print('#####')
print('###total RMS voltage noise \u03BCV###')
print(NoisedifftotalRMS*1000000)
print('###total voltage noise density from RMS value diff amp in \u03BCV/sqrt(Hz)###')
print(NoisedifftotalRMS*1000000/np.sqrt(NBW))
print('noise density of circuit in \u03BCV/sqrt(Hz), 4x noise power (only white noise) + 1x diffamp noise power with gain=1')
print(np.sqrt(((NoisedifftotalRMS*1000000/np.sqrt(NBW))**2)+4*(totnoisedens*1000000)**2))
print('noise density of circuit in \u03BCV/sqrt(Hz), 4x noise power (from RMS) + 1x diffamp noise power with gain=1')
print(np.sqrt(((NoisedifftotalRMS*1000000/np.sqrt(NBW))**2)+4*(noisedensitytotal*1000000)**2))

```

E. Optimization of t_1 , t_2 and w_2 of a 3D-Nanoprobe

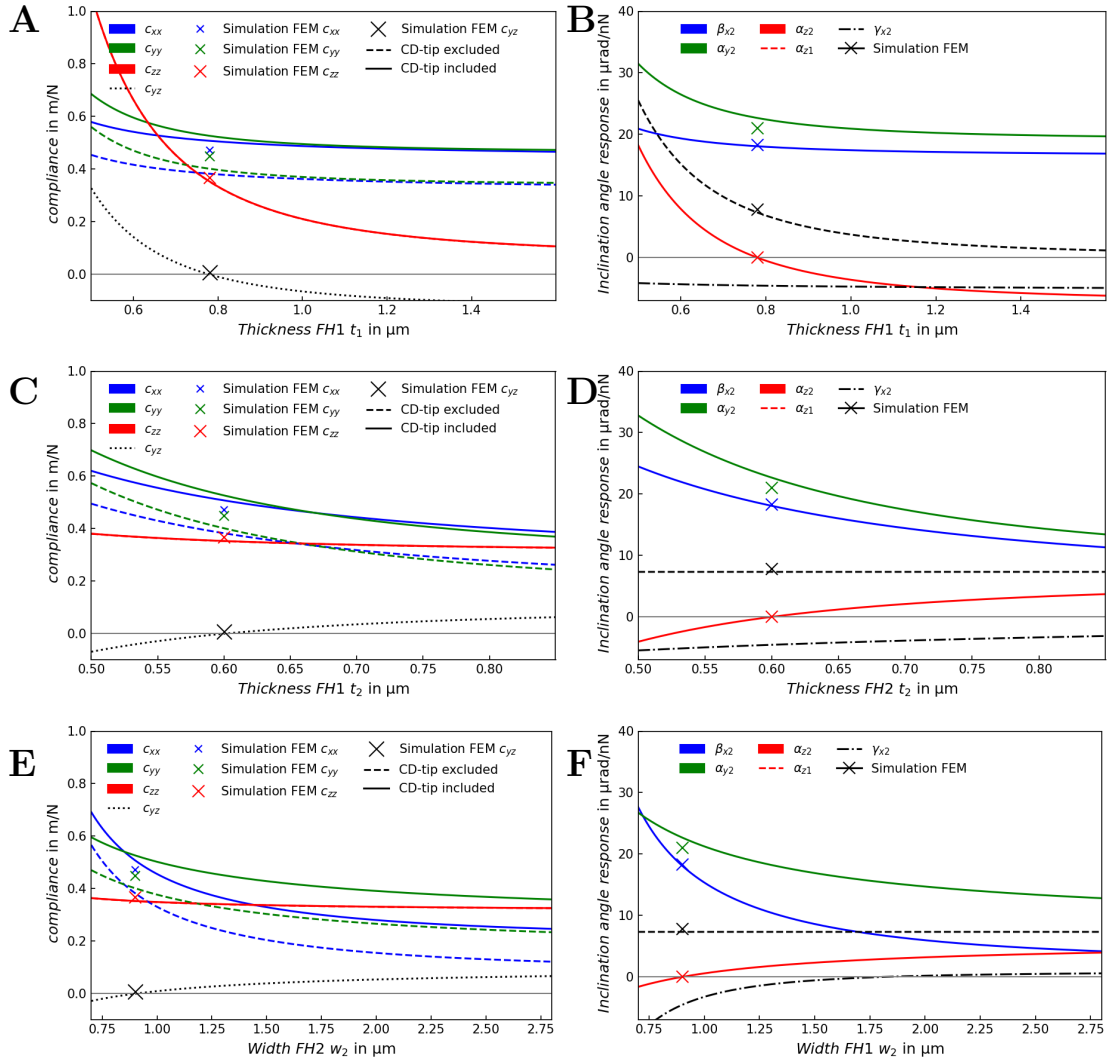


Figure E.1: Optimization of force dependent inclination angles and stiffness of a 3D-Nanoprobe of t_1 , t_2 and w_2 A, C and E show compliance dependence and B, D and F show the corresponding force dependent inclination angles. The FEM simulation results of section 4.3 are included in the graphs.

F. Interferometer settings and device information

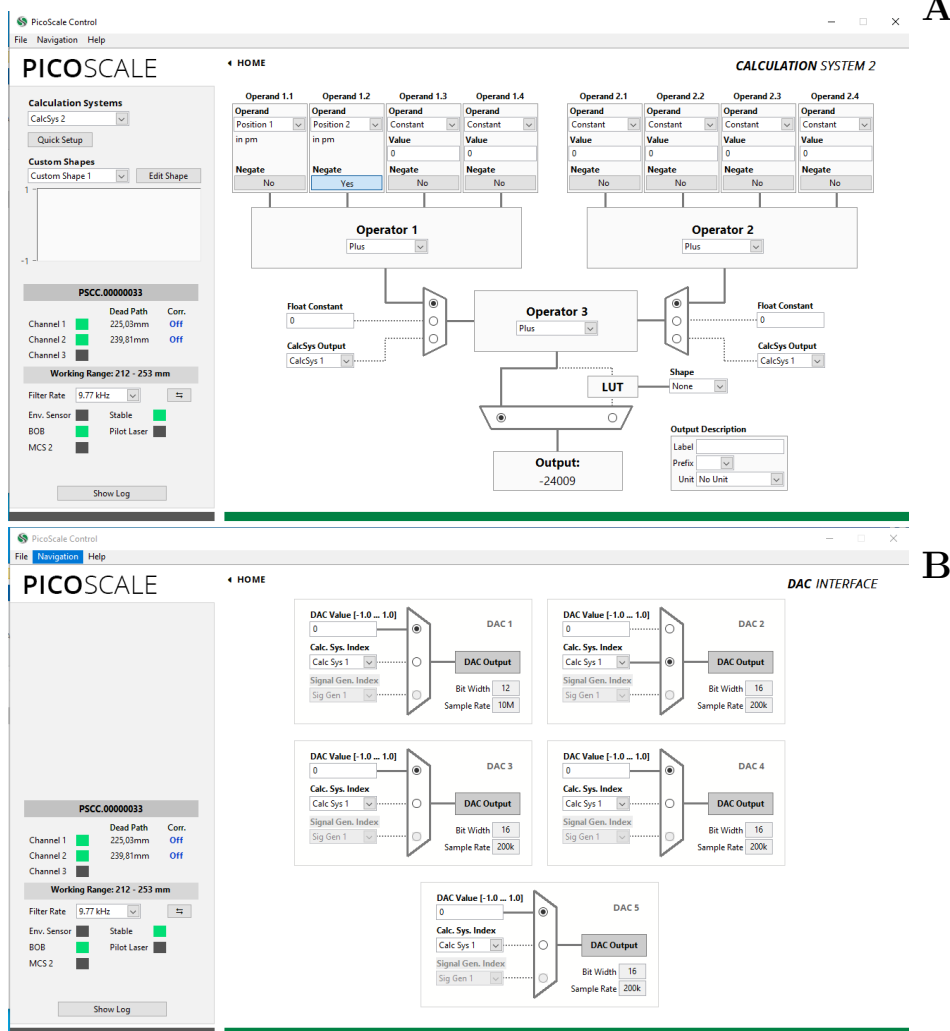


Figure F.1: Interferometer settings (screenshot) of the *SmarAct PicoScale* device. Image A shows the settings of the signal calculation also denoted as *calcsys* in the GUI of the device. Image B shows the setting of the settings of the DAC for signal transmission via a *beackout box* to the digital signal processor.

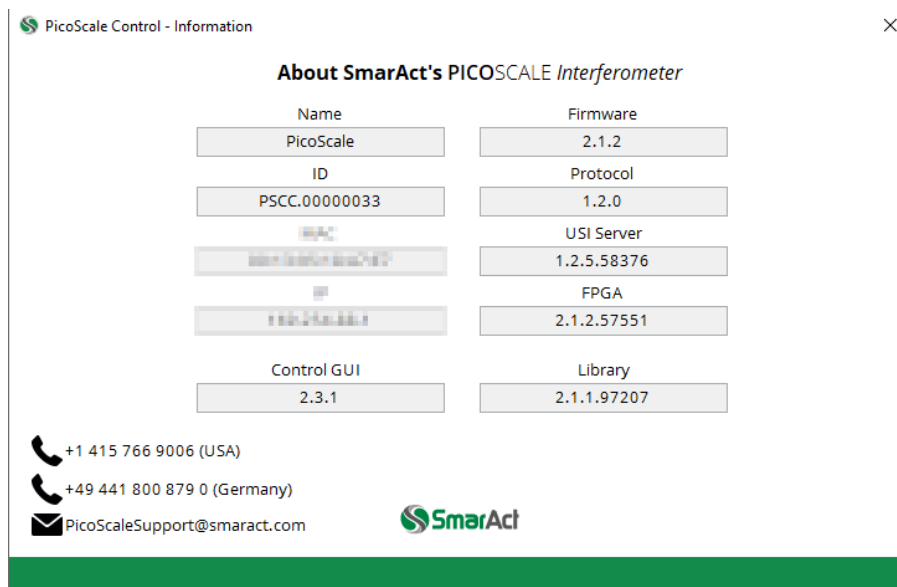


Figure F.2: Interferometer version of the *SmarAct PicoScale* device with the used firmware and GUI version, (unnecessary information is blurred).

G. Raw interferometer signal during fluctuation

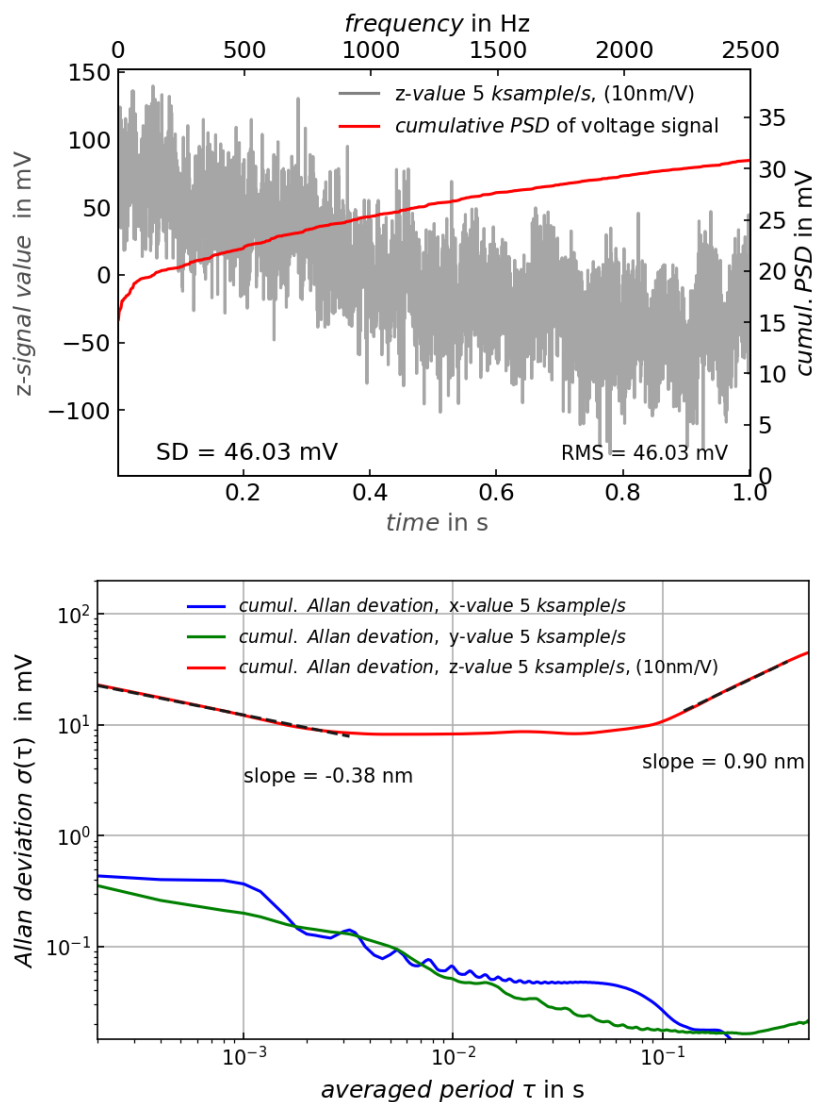


Figure G.1: PSD and Allan deviation of the raw interferometer signal noise during signal fluctuation. The Allan deviation show a large value compared to the signal shown in **Figure 6.4** and **6.5**

H. True 3D-AFM head with preliminary adjustment system

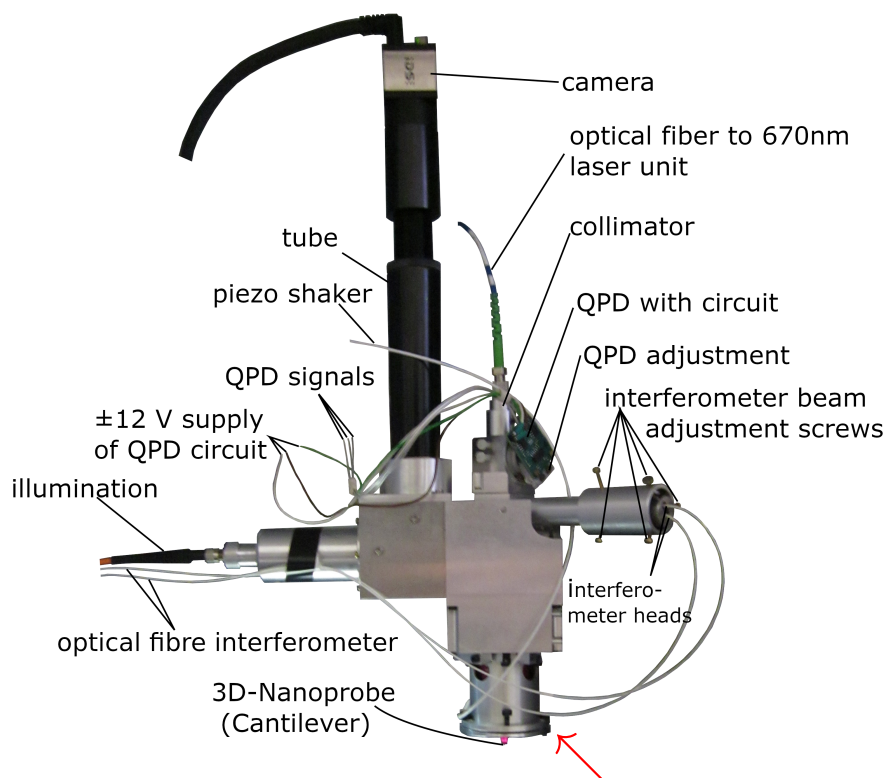


Figure H.1: The 3D-AFM head with preliminary adjustment system (*arrow*) and hybrid detection system (own image, reused from [106])



Die Physikalisch-Technische Bundesanstalt, das nationale Metrologieinstitut, ist eine wissenschaftlich-technische Bundesoberbehörde im Geschäftsbereich des Bundesministeriums für Wirtschaft und Energie.



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