Establishing Traceability for On-Wafer S-Parameter Measurements of Membrane Technology Devices up to 110 GHz

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***Abstract*—In this paper we report on progress towards establishing traceability for fully calibrated on-wafer measurements of planar devices built in membrane technology. For the first time, we present a comprehensive uncertainty budget for on-wafer S-parameter measurements, including instrumentation errors, connector repeatability and calibration standard uncertainties. Preliminary results are shown for three typical devices.**

***Index Terms*—on-wafer, calibration, S-parameters, traceability, uncertainty budget.**

I. Introduction

In contrast to coaxial and rectangular waveguide S-parameter measurements, traceability for on-wafer S-parameters has not been fully established yet. This is because planar devices and calibration standards are fabricated on different substrate materials in a great variety of technologies, and instead of standardized connectors nowadays a number of microwave probes from several vendors can be used. Therefore, reliable uncertainties for on-wafer S-parameters can only be specified in a given enviroment for selected combinations of substrate materials, planar waveguides, and probes.

The evaluation of S-parameter uncertainty depends on a number of factors such as instrumentation errors, cable and connector repeatability, standard uncertainties, the calibration algorithm chosen, and the DUT itself. This complicated task is greatly simplified with modern software tools such as [1] or [2], which have been recently compared in [3] and [4]. In our approach, we established a comprehensive uncertainty budget for the entire measurement process using the linear uncertainty propagation library Metas.UncLib [5], which is based on the automatic differentiation techniques of [6].

In this paper we focus on planar devices built in membrane technology, as the influence of the thin supporting dielectric material is significantly reduced in comparison to the influence of several-hundred-μm thick substrates which are conventionally used. In essence, membrane technology enables us to employ air-line-like coplanar waveguides (CPWs) as calculable calibration standards [7].

In the following sections, we outline the technology steps required, describe modeling and characterization of the airline-like CPW standards and the measurement setup, give an overview of the input quantities considered in the uncertainty budget, and show some preliminary results.

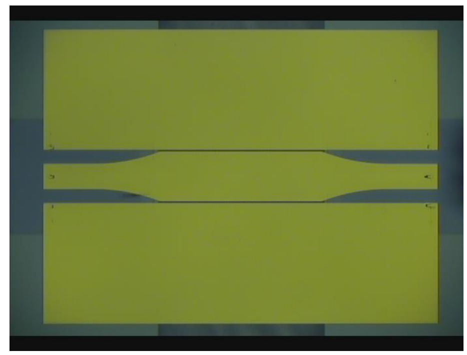

Fig. 1. Thru calibration standard fabricated in membrane technology.

II. Technology

The membrane technology CPWs were fabricated on double-side-polished high-resistivity <100> silicon wafers. In the first step, a thin film of silicon dioxide (SiO_2) is deposited on both sides of the high-resistivity silicon (HRSi) wafer by plasma-enhanced chemical vapor deposition (PECVD) to form an etching barrier. This is followed by the deposition of a thin layer of PECVD silicon nitride (Si_3N_4) as dielectric membrane. Multi-frequency plasma-enhanced chemical vapor deposition is used to minimize the mechanical stress within the membrane layer. After the deposition of the dielectric material, a thin adhesive layer of titanium-tungsten (TiW) and a gold (Au) layer is sputtered on the top side of the wafer. The conductor geometry is then formed by optical lithography and wet chemical etching processes. Subsequently, using an appropriate photoresist mask, openings in top side silicon dioxide and silicon nitride layers are patterned by dry and wet chemical etching processes.

The final step is the partial removing of the silicon wafer itself to create silicon nitride membranes under the conductor geometry. Openings are structured on the back side silicon dioxide and silicon nitride. Anisotropic etching of the silicon wafer from the back side is done with a potassium hydroxide solution, leaving the dielectric membrane carrying the CPW line structure.

Figure 1 shows an interconnect structure serving as Thru calibration standard consisting of silicon-to-membrane transitions at both sides of a CPW section supported by a thin membrane. The silicon-to-membrane transitions contain contact pads, which allow for ground-signal-ground microwave probing, and a short interconnect segment on silicon.

III. CPW Modeling and Characterization

Figure 2 shows the cross section of a coplanar airline resulting from the technology described in the previous section together with its geometrical and material parameters.

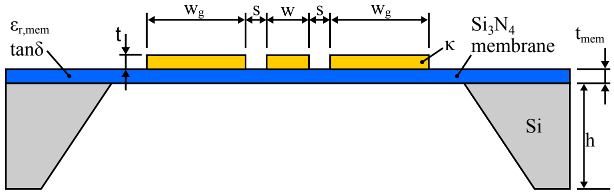

Fig. 2. Cross section of CPW built in membrane technology.

To calculate the wideband electromagnetic properties of the CPW, we used the extension of the model of [8] introduced in [9]. In [9] the effect of the membrane is taken into account by using equivalent dielectric material values $\varepsilon_{\mathrm{r,\,LHP}}$ and $\tan\delta_{\mathrm{LHP}}$ of a fictitious infinitely-expanded lower half-plane (LHP). The value of the dielectric constant $\varepsilon_{\mathrm{r,\,mem}}$ of the membrane material was estimated in previous studies [10].

Propagation constant and characteristic impedance of the fabricated CPW lines were calculated with both the model of [8] and the extended model of [11], which considers modal dispersion and radiation losses. However, no indications of modal dispersion or radiation losses were found in the frequency range under investigation.

Table I shows the cross-section parameters obtained for the membrane CPW part according to Fig. 1 after performing the dimensional and material characterization at PTB. Dimensional characterization was carried out with a high-precision optical coordinate measuring machine and an atomic-force microscope.

TABLE I
Parameters of membrane CPW on HRSi.

Parameter	value
w_g	(408.6 ± 0.5) μm
w	(168.7 ± 0.5) μm
s	(6.3 ± 0.5) μm
t	(0.550 ± 0.05) μm
k	(16.5 ± 1) MS/m
$\varepsilon_{\mathrm{r,\,LHP}}$	(1.706 ± 0.1)
t_{mem}	1.2 μm
$\tan\delta_{\mathrm{LHP}}$	$(1 \pm 0.5) \cdot 10^{-4}$
h	295 μm

IV. VNA Measurement Model and Calibration

For the calculation of corrected S-parameters from the measured raw data and the propagation of measurement as well as calibration standard uncertainties to the final results, the VNA measurement model described in [12] and [2] has been applied.

Figure 3 shows a block diagram of the general N-port measurement model (in our case N=2). The symbols M, R, W, V, E, D, C and S denote the the raw data measured by the VNA, the noise/linearity influences, the switch terms, the drift of the switch terms, the calibration error terms, the drift of the calibration error terms, the cable stability/connector repeatability and DUT uncertainty influences, and the error corrected data (or calibration kit standard definitions), respectively.

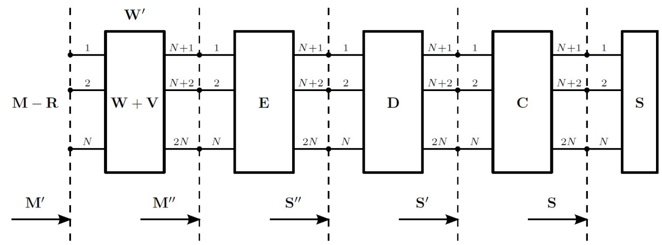

Fig. 3. VNA measurement model (from [2]).

The error terms of the underlying 7-term error model were calculated with the multiline TRL calibration algorithm described in [13] and [14]. Seven lines with membrane CPW lengths between 500 and 20190 μm were used, assuming a length uncertainty of 10 μm.

Since the multiline TRL method, as a self-calibration technique, does not allow for a straightforward propagation of calibration standard uncertainties, the influence of these uncertainties was calculated using the Microwave Uncertainty Framework developed at NIST [1]. In future studies we will compare these calculations to the results of the recursive approaches described in [15] and [16].

V. Input Quantities

In the following, most input quantities relevant for the measurement process are listed with their respective values and/or uncertainties (coverage factor is k=2 unless indicated otherwise). They are typical for the on-wafer measurement setup used at PTB for frequencies up to 120 GHz. Measurements were performed on a ceramic chuck utilizing an Anritsu VectorStar VNA with mm-wave extension modules for frequencies up to 125 GHz, connected to GGB ground-signal-ground microwave probes with 100 μm pitch.

Cable movement was not considered, as the 1-mm cables connecting to the GSG probes were fixed during the measurements. The movement of the cables leading to the mm-wave extensions essentially affects only measurements up to 30 GHz and is currently neglected.

A. VNA Characterization

1) Noise and Error Term Drift: VNA characterization was performed following the procedures outlined in [12]. Due to space limitations, the values used have been omitted.

2) Linearity: The uncertainty in linearity was estimated to the values of 0.01 dB for the magnitude and 0.066° for the phase over the used magnitude and frequency range.

B. Connector Repeatability

Connector repeatability has been considered with an uncertainty of -60 dB. This value was determined from a series of repeat measurements.

C. DUT Uncertainty/Crosstalk

Due to the lack of resistive elements in the current membrane wafer, the crosstalk correction of [17] could not be applied. Instead, the DUT uncertainty approximation as described in [2] has been employed. For the sake of brevity, the values used in the approximation are not shown here.

D. Calibration Standards

The influence of the uncertainties in the calibration standard uncertainties was calculated using the Microwave Uncertainty Framework [1] and the values indicated in Table I.

VI. Measurement-Model Comparison

Figure 4 compares measured and model-based values of reflection and transmission S-parameters of a 500 μm-long matched line. Solid lines indicate nominal values, shaded areas indicate the expanded uncertainty intervals at a coverage probability of 95% (k=2). The S-parameters are normalized to 50 Ω. The expanded uncertainty intervals fully comprise the model values in the frequency range from 1 to 110 GHz.

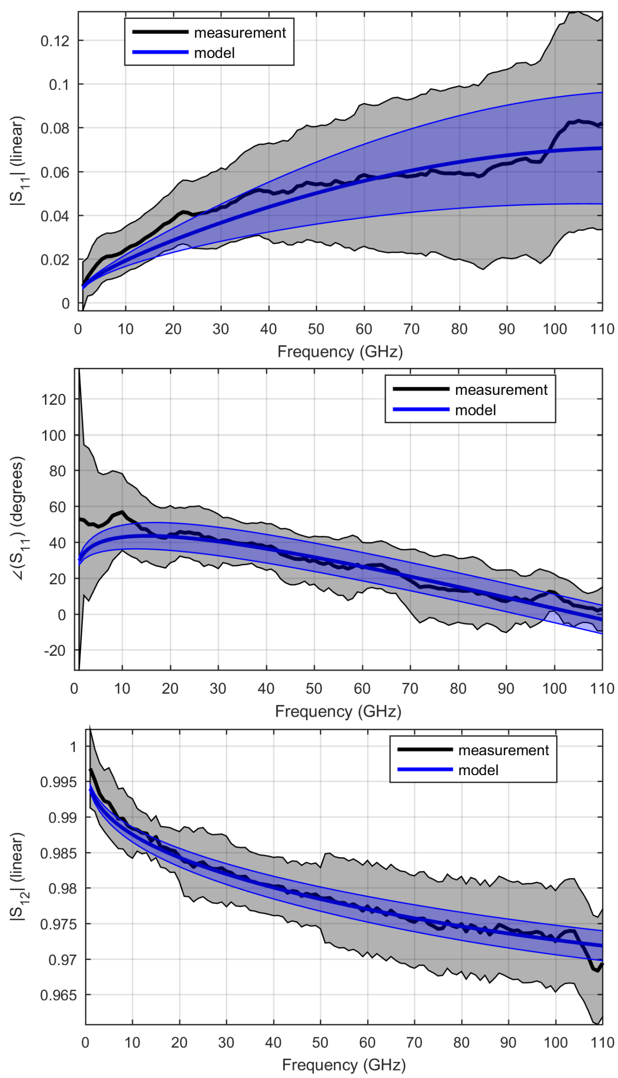

Fig. 4. Comparison between measured (black) and modeled (blue) reflection and transmission S-parameters of a 500 μm-long matched line.

VII. DUT Uncertainty Results

In the following results for three typical devices are shown, covering a large portion of the impedance range measurable by a VNA: a 20190 μm-long matched line (termed 'match') , a 7065 μm-long mismatched line (termed 'mismatch'), and a 2-port open (high-reflect device, termed 'open')).

TABLE II

Preliminary uncertainty budget for magnitude of S_{11} (linear) at 55 GHz.

Device	match	mismatch	open
Value	0.03663	0.47942	0.99603
Standard Uncertainty	0.01216	0.00559	0.00346
Description	Unc. comp.	Unc. comp.	Unc. comp.
Calibration Standards	0.01214	0.00555	0.00320
Connector Repeatability	0.00051	0.00060	0.00066
DUT Uncertainty	0.00007	0.00023	$< 10^{-5}$
VNA Drift	0.00047	0.00037	0.00112
VNA Linearity	$< 10^{-5}$	0.00001	0.00004
VNA Noise	0.00002	0.00003	0.00005

TABLE III

Preliminary uncertainty budget for phase of S_{11} (degrees) at 55 GHz.

Device	match	mismatch	open
Value	-32.91004	-72.35470	-40.48126
Standard Uncertainty	7.19505	1.22936	1.29353
Description	Unc. comp.	Unc. comp.	Unc. comp.
Calibration Standards	7.11245	1.22219	1.27407
Connector Repeatability	0.79520	0.07083	0.03819
DUT Uncertainty	0.11457	0.02784	$< 10^{-5}$
VNA Drift	0.73194	0.10839	0.22017
VNA Linearity	$< 10^{-5}$	0.00139	0.00238
VNA Noise	0.02499	0.00520	0.00514

TABLE IV

Preliminary uncertainty budget for magnitude of S_{21} (linear) at 55 GHz.

Device	match	mismatch	open
Value	0.43230	0.77150	0.00732
Standard Uncertainty	0.00288	0.00749	0.00838
Description	Unc. comp.	Unc. comp.	Unc. comp.
Calibration Standards	0.00056	0.00555	0.00020
Connector Repeatability	0.00001	0.00025	$< 10^{-5}$
DUT Uncertainty	0.00281	0.00501	0.00838
VNA Drift	0.00032	0.00030	$< 10^{-5}$
VNA Linearity	$< 10^{-5}$	0.00003	$< 10^{-5}$
VNA Noise	0.00002	0.00004	$< 10^{-5}$

TABLE V

Preliminary uncertainty budget for phase of S_{21} (degrees) at 55 GHz.

Device	match	mismatch	open
Value	-149.72412	-168.66761	-49.69122
Standard Uncertainty	1.00119	1.21283	32.44710
Description	Unc. comp.	Unc. comp.	Unc. comp.
Calibration Standards	0.91378	1.15114	2.14989
Connector Repeatability	0.00184	0.01853	0.03814
DUT Uncertainty	0.37232	0.37235	32.37532
VNA Drift	0.16952	0.08251	0.16988
VNA Linearity	0.00060	0.00197	$< 10^{-5}$
VNA Noise	0.00577	0.00609	0.01985

A. Uncertainty budgets

For the three selected devices, the preliminary uncertainty budgets for magnitude and phase of S_{11} and S_{21} are listed in Tables II – V for the intermediate frequency of 55 GHz. In most cases the budget is dominated by the calibration standard uncertainties. In the magnitude and phase of S_{21}, the influence of the DUT uncertainty approximation becomes dominant at increasing frequencies for medium- to high-reflect devices. At low frequencies (not shown here), VNA drift can become significant for matched devices.

B. Expanded uncertainties

Figure 5 shows expanded uncertainty intervals at a coverage probability of 95% (k=2) of reflection and transmission S-parameters for all three devices considered.

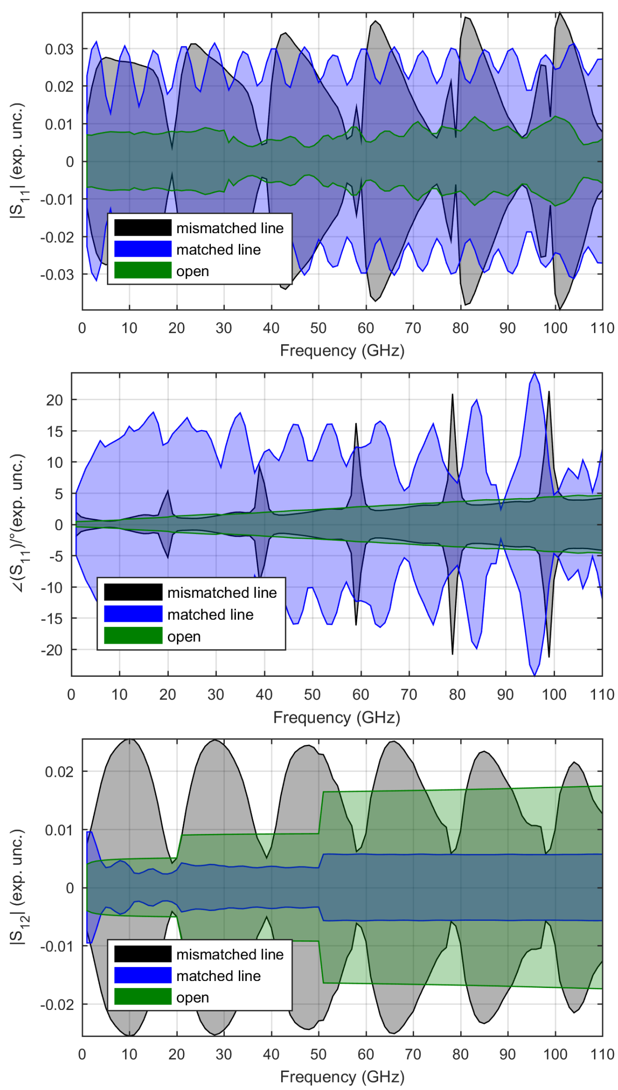

Fig. 5. Expanded uncertainty intervals at a coverage probability of 95% (k=2).

VIII. Conclusions

For the special case of membrane technology devices, we presented a comprehensive uncertainty budget for on-wafer S-parameter measurements. Traceability to dimensional measurements was demonstrated for selected devices in the frequency range from 1 to 110 GHz. Current and future research [18] will extend the methodology presented in this paper to other substrate materials and probe configurations.

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