Impact of Calibration Procedure on Sub-Millimeter-Wave Transistor Characterization and Modeling

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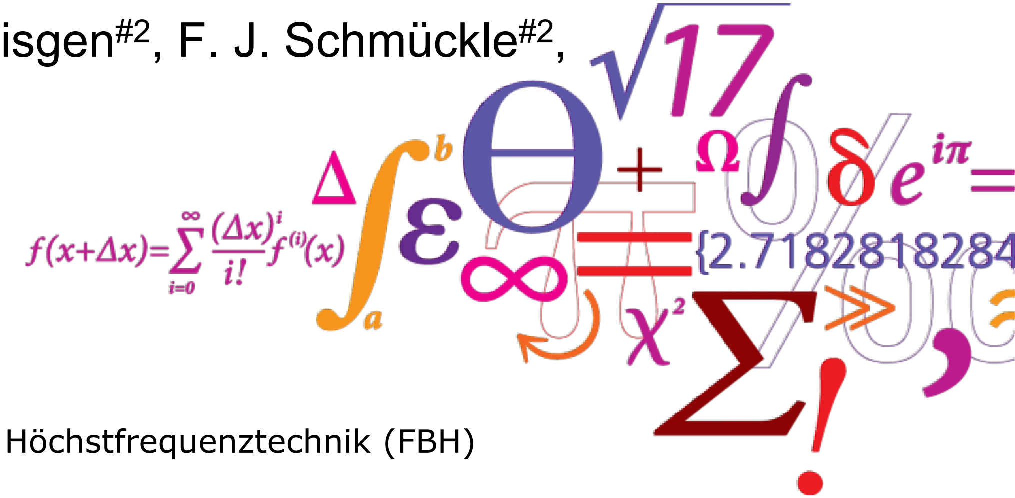
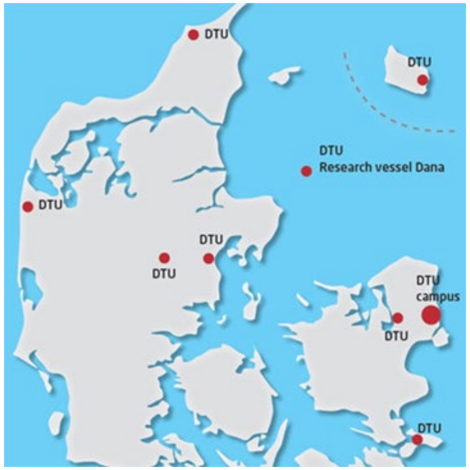
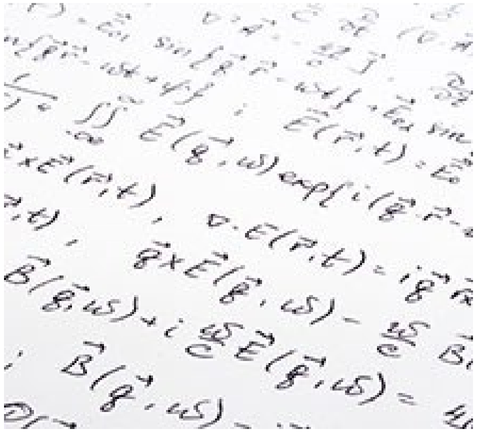
Berlin / Germany

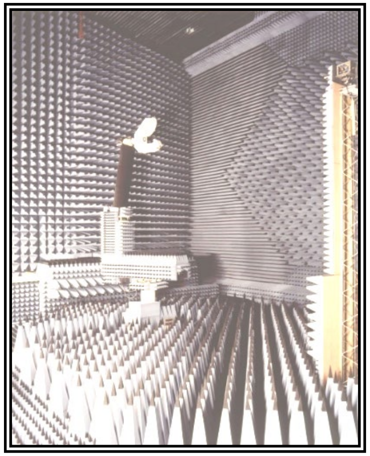


About Technical University of Denmark

- Largest technical university in Denmark
  - Most engineering students: 11.200 B.Sc/M.Sc.
  - Around 6000 employess
- 18 Departments
  - Cover most engineering disciplines
  - From civil engineering to system biolog and mangement
- Department of Electrical Engineering
  - Electromagnetic systems group



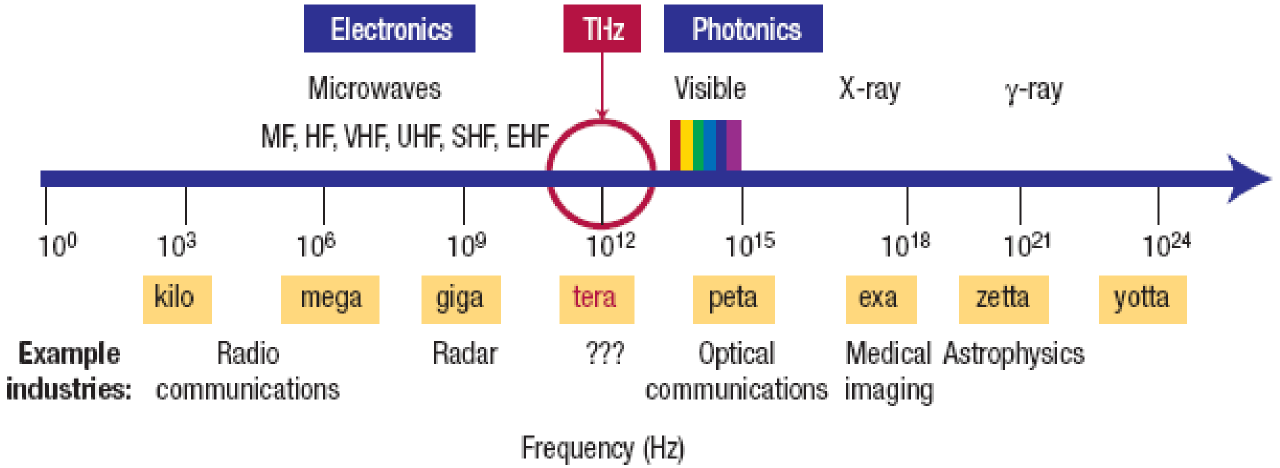




Outline

- Motivation: Sub-mm-Wave Applications
- Transferred-Substrate InP HBT Technology
- Characterization Issues for Downscaled Sub-mm-Wave Devices
- Calibration Issues Investigated by EM Simulation
- Summary

Motivation: Sub-mm-Wave Applications



The part of the electromagnetic spectrum ranging from 100 GHz to 10 THz is largely unexploited and offers large unlicensed bandwidth for high resolution imaging, sensitive radars, broadband wireless communication, spectroscopy, material characterization, etc.

Motivation: Sub-mm-Wave Applications

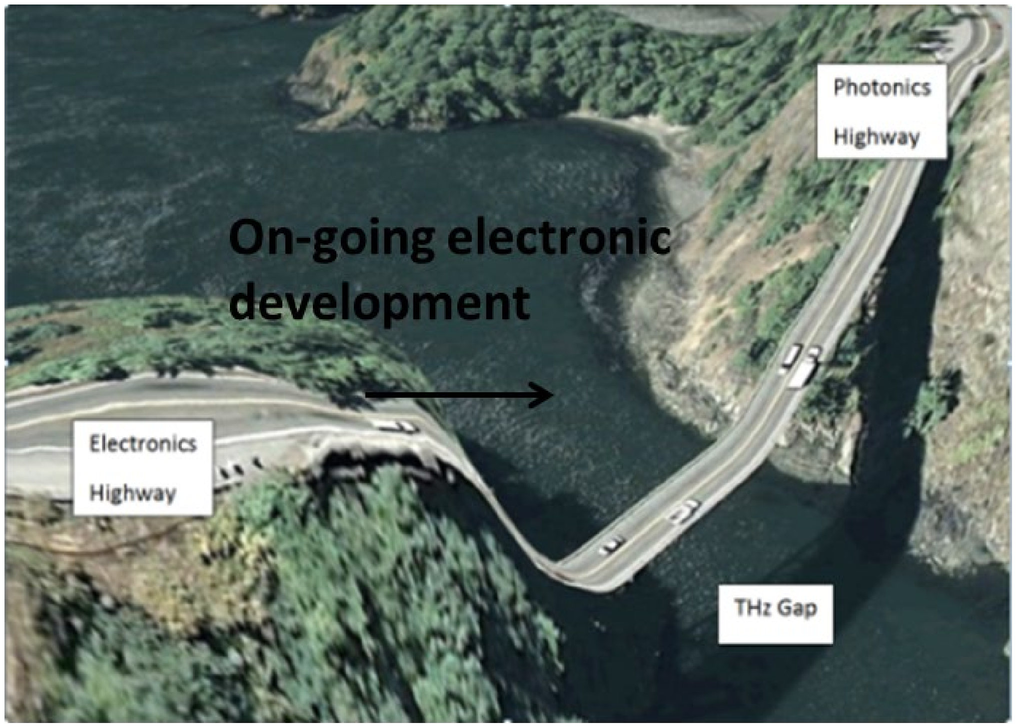
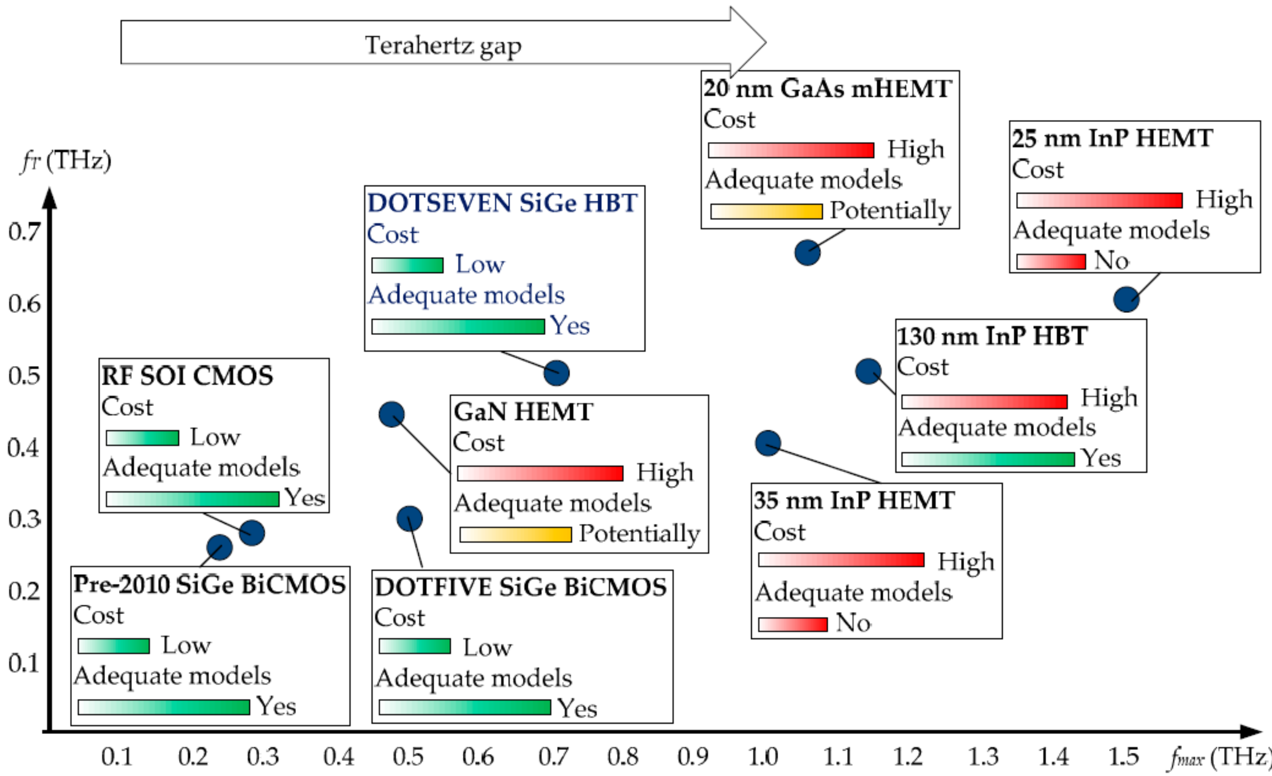


Image courtesy of CELTA ITN project (http://www.celta-itn.eu)

On-going electronic development towards low-cost, small-size and efficient signal sources to close the so-called ”Terahertz Gap”.

Motivation: Transistors for Sub-mm-Wave Electronics

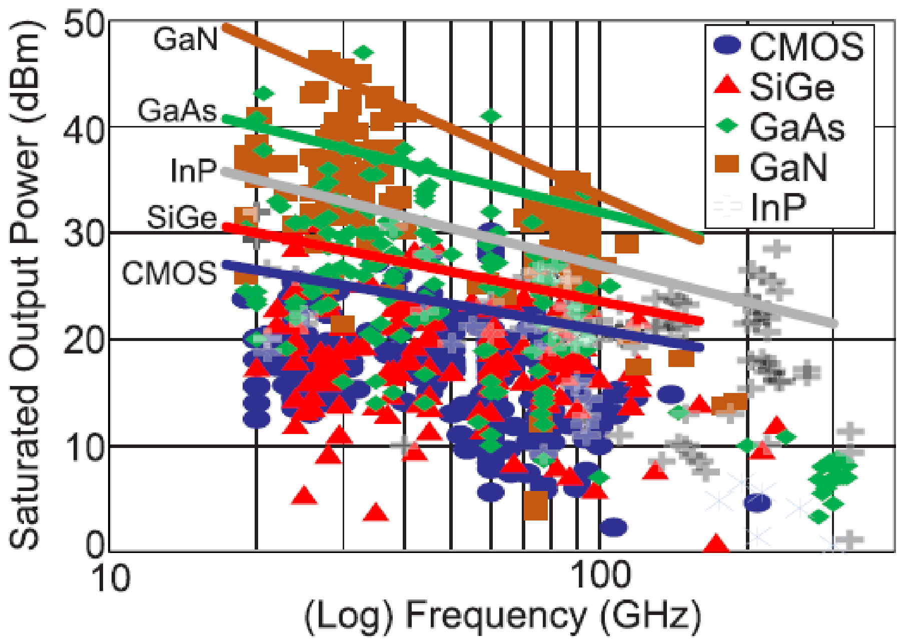


M. Bozanic and S. Sinha, Sensors, 19, 2454, May. 2019.

Motivation: Transistors for Sub-mm-Wave Electronics

Reported saturated output powers

of power amplifier MMICs



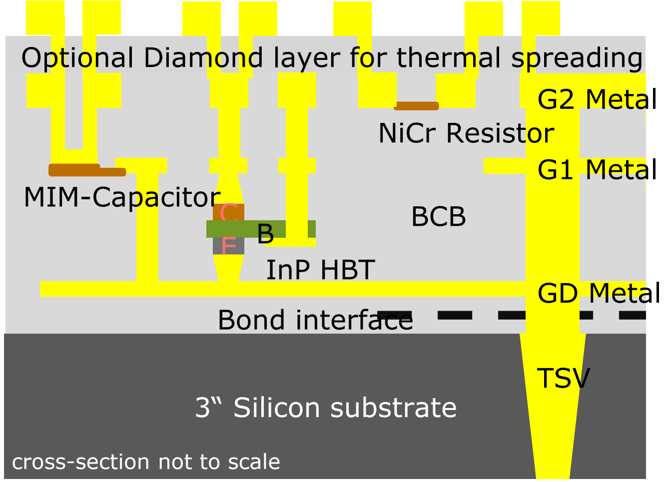
V. Camarchia et al., T-MTT,

Vol.68, No. 7, July 2020.

Of the various transistor families **InP** based transistors (InP HBT & InP HEMT) offer the best prospect for sub-mm-wave electronics

Transferred Substrate InP HBT Technology: FBH Development

FBH's transferred-substrate InP DHBT MMIC process targets high-power applications from mm-waves to sub-mm-wave frequencies….



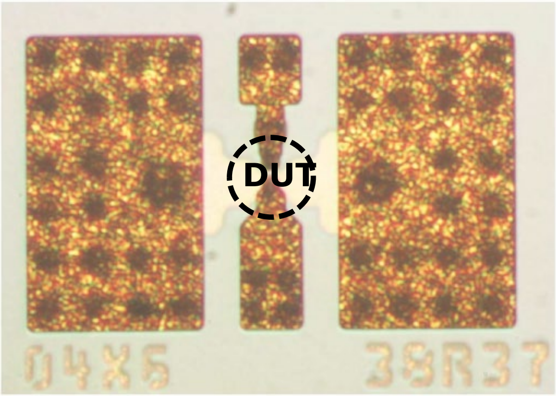
Schematic cross-section of FBH's InP HBT transferred-substrate technology

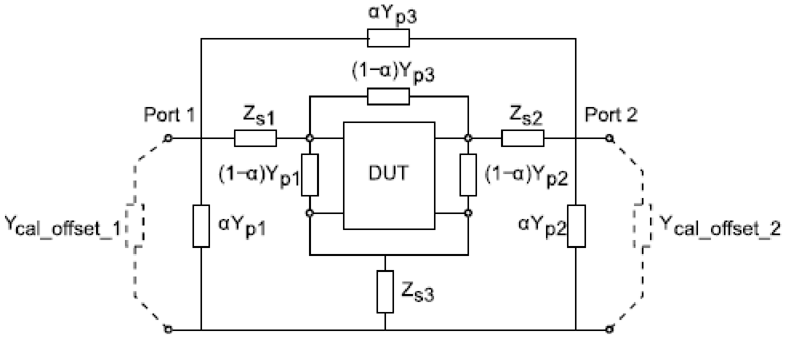
Process specs [6]:

- 3 gold metal layers in BCB
- compatible to flip-chip and wire bonding
- thin-film resistors & capacitors
- transfer to Si-Substrate
- Optional thermal spreading layer with diamond
- TSV for substrate mode suppression
- 0.8 µm node DHBTs with f_T/f_{max}~350 GHz and breakdown voltage > 4.5 V

[6] N. Weimann *et al.*, "SciFab - a wafer-level heterointegrated InP DHBT/SiGe BiCMOS foundry process for mm-wave applications," *Phys. Status Solidi A*, vol. 213, no. 4, pp. 1244–1245, 2016.

Transferred Substrate InP HBT Technology: Best Case Using InP/GaAsSb DHBT

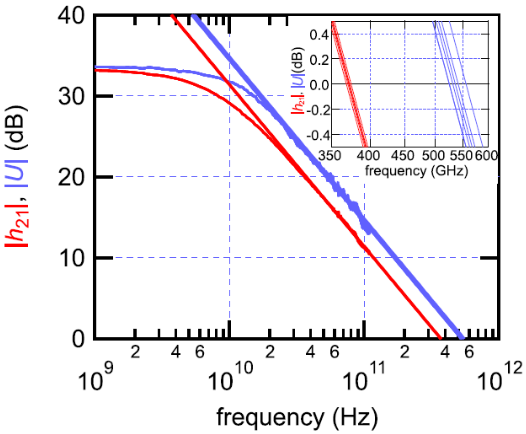




Deembedding network with compensation.

EXTRACTED UNITY-GAIN FREQUENCIES

	comp.	parameter α			iterative method [3]	
		0.0	0.6	1.0	single pole	−20 dB/dec
f_T (GHz)	no	368	370	371	373	370
	yes	374	372	371	376	373
f_{max} (GHz)	no	541	531	524	540	525
	yes	555	535	524	545	531



N. Weimann et al., “Transferred-Substrate InP/GaAsSb Heterojunction Bipolar Transistor Technology With f_{max} ~0.53 THz,” IEEE Trans. Electron Devices, vol. 65, no. 9, pp. 3704–3710, Sept. 2018.

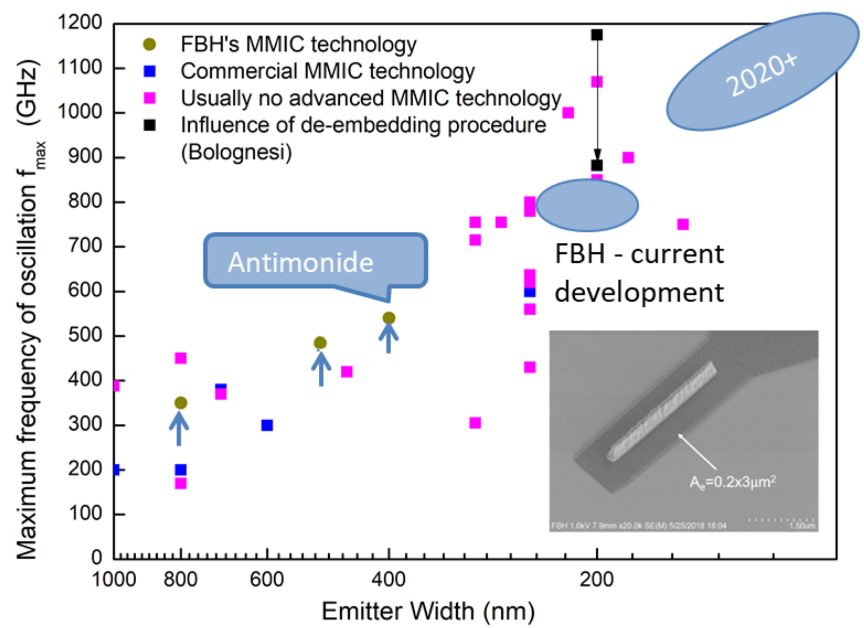
Transferred Substrate InP HBT Technology: FBH Road Map

Goal

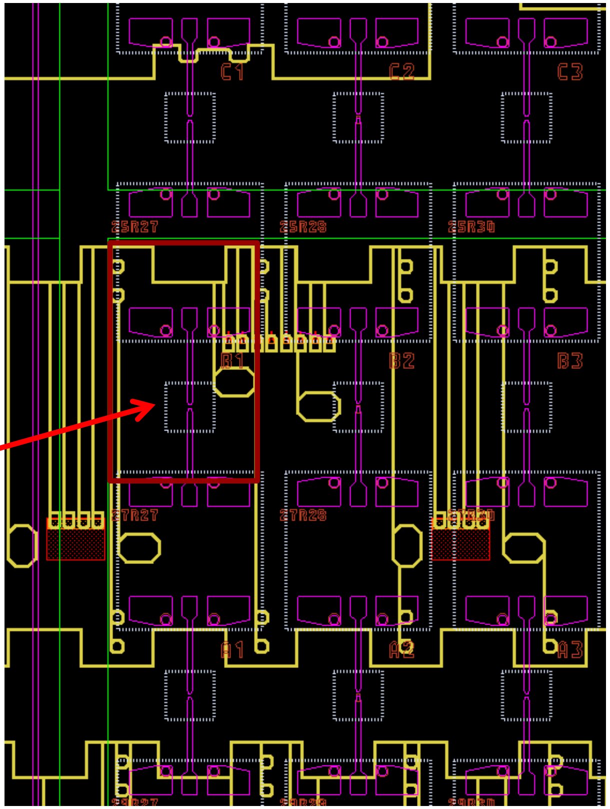
- f_{max} ~ 500 GHz with stepper technology
- f_{max} > 1000 GHz with e-beam technology

Approach

- Scaling to 100 nm
- Base contact optimization
- New Epitaxial structure
- Improved thermal properties with diamond



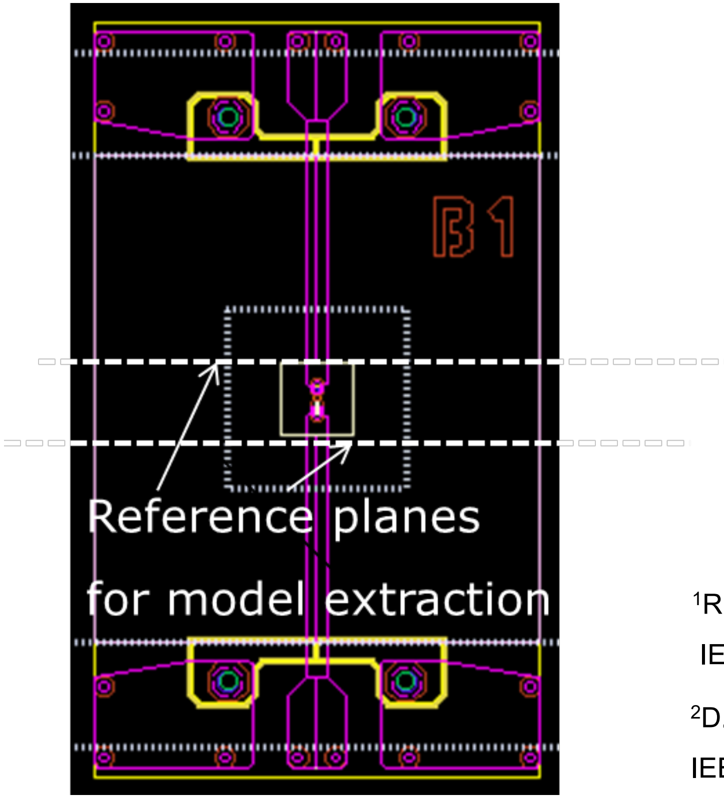
Characterization of Sub-mm-Wave InP HBT Devices using Thin-Film Microstrip Line Test Structures



device-under-test:

1 x 0.3 x 6 μm^2 InP HBT type B1

Setting the Reference Planes for Characterization



Approach:

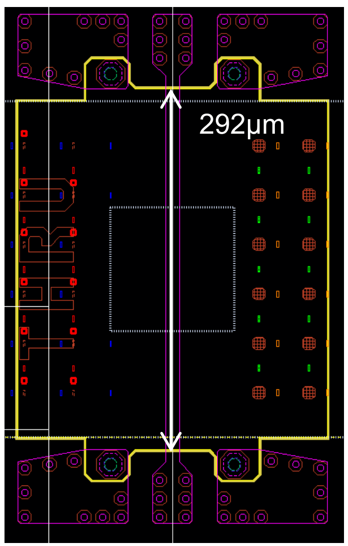
- On-wafer multiline TRL (mTRL) calibration procedure to set reference planes directly at device terminals[1,2]
- Thin-film microstrip lines to avoid slot modes and other resonances
- Z_0 normalization using embedded resistor structure

[1] R. B. Marks, A Multiline Method of Network Analyzer Calibration, IEEE Trans. Microwave Theory and Techn., July 1991.

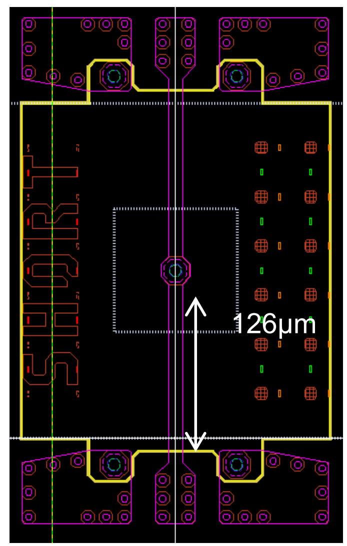
[2] D. F. Williams and R. B. Marks, Transmission Line Capacitance Measurement, IEEE Microw. Guided Wave Letts., Sept. 1991.

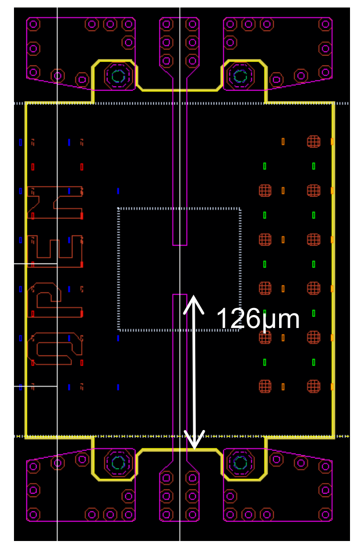
On-wafer Multi-Line TRL Calibration Structures - I

Thru structure



Reflect structures (use short or open)

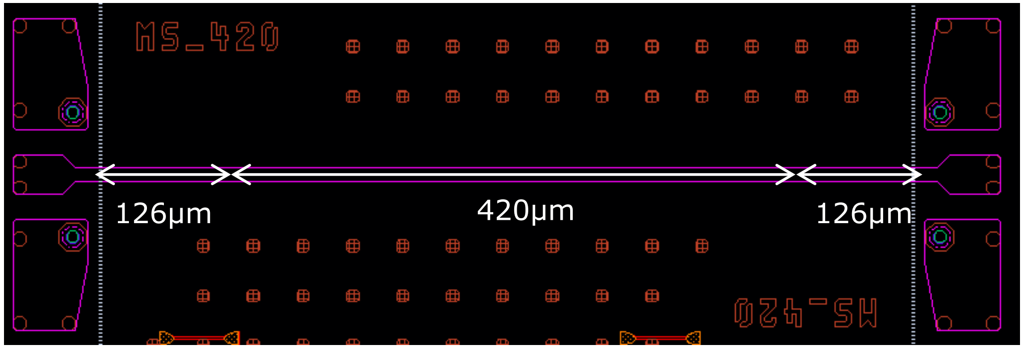




It is seen that it would be meaningful to define the reference planes at a distance of 126 μm from the pads and let the thru have a length of 40 μm.

On-wafer Multi-Line TRL Calibration Structures - II

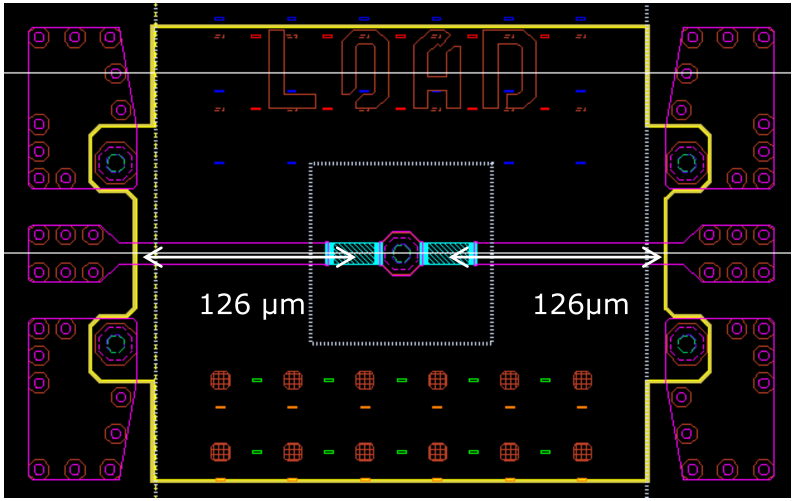
The reference planes for the line structures are all located at a distance of 126 µm from the pads.



Line structures: (MS150), MS420, MS1250, MS1950, MS2850, MS8500

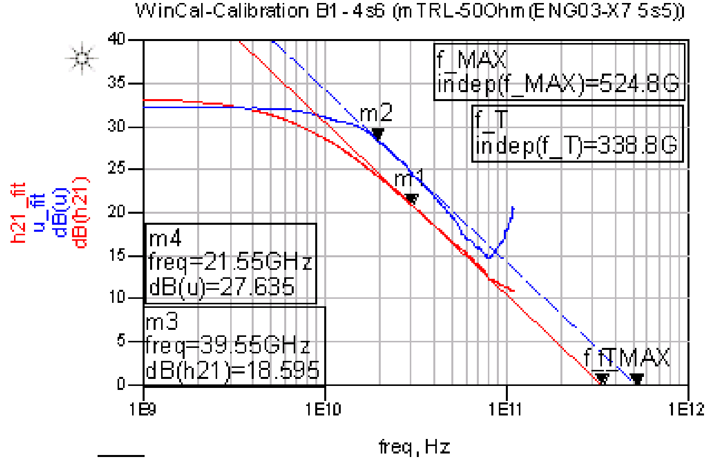
On-wafer Multi-Line TRL Calibration Structures - III

Embedded resistor structure



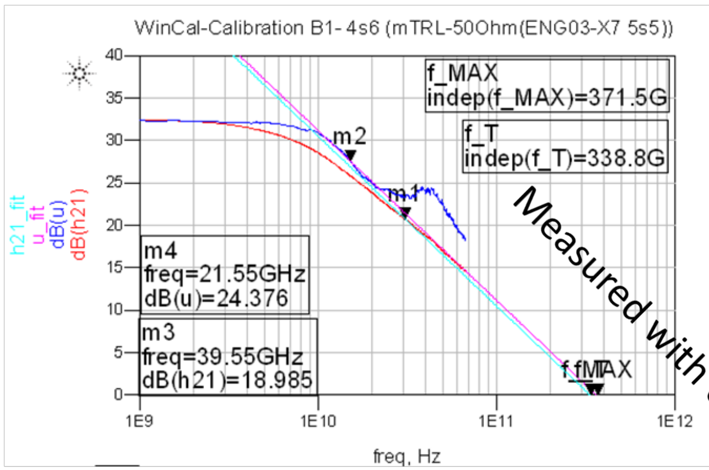
This structure is used to estimate the capacitance per unit length and thereby to set the characteristic impedance Z_0.

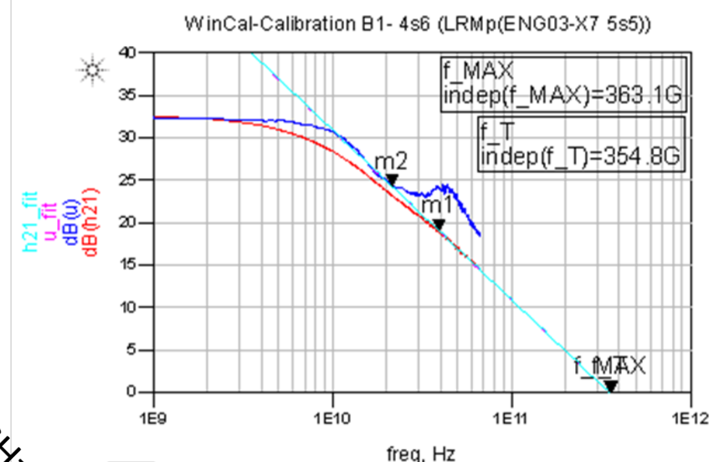
Characterization of Downscaled Sub-mm-Wave InP HBT Devices

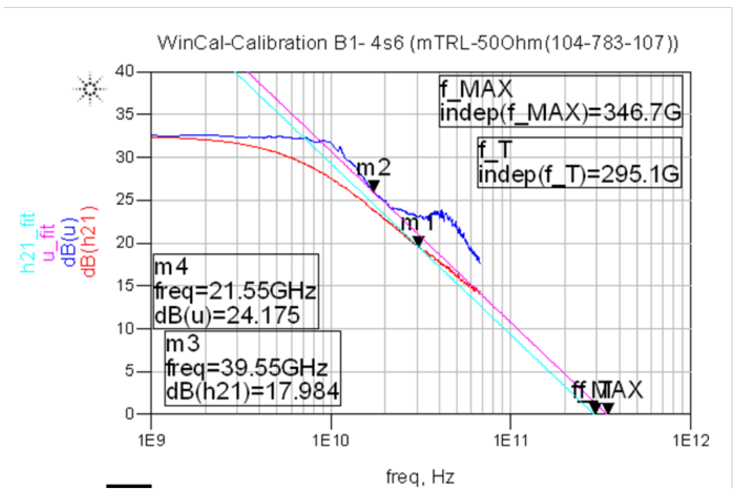


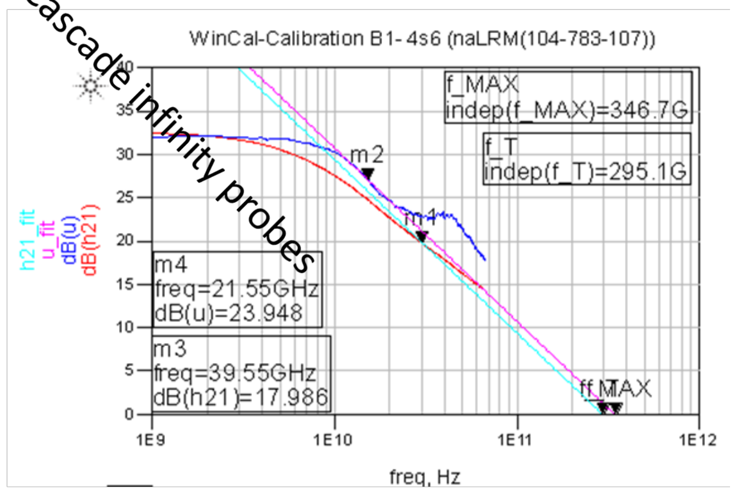
Measured with 110 GHz GGB pico-probes

Characterization of Downscaled Sub-mm-Wave InP HBT Devices







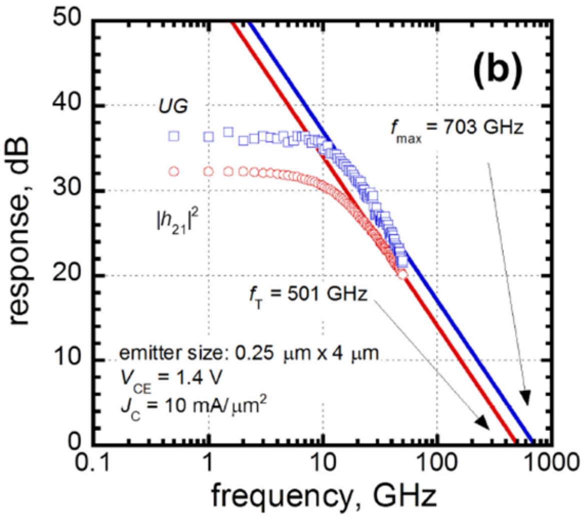


Measured with 67 GHz Cascade infinity probes

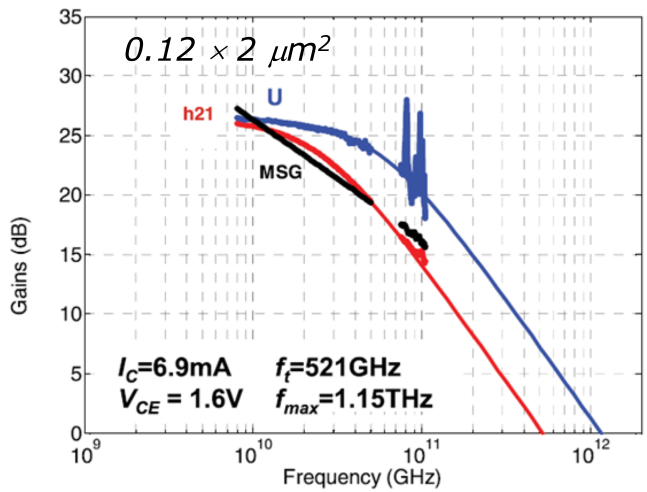
Characterization of Downscaled Sub-mm-Wave InP HBT Devices

Other research groups report similar behavior!

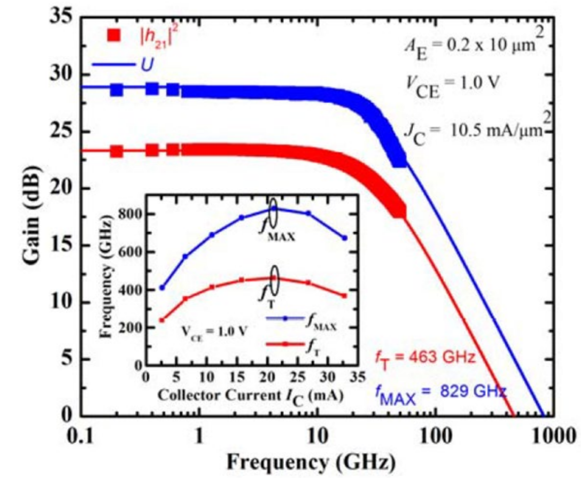
NTT[1]



Teledyne-UCSB[2]



ETH-Zürich[3]

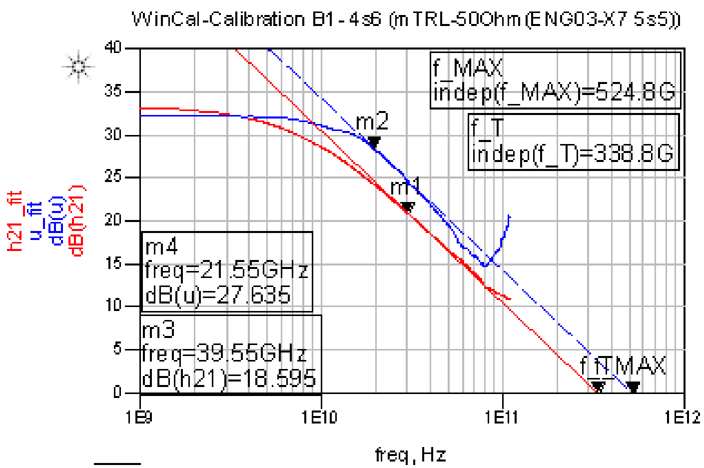


[1]T. Hoshi et al.,IEICE Electronics Express, Vol. 16, No. 3, 1-6, 2019.

[2]M. Urteaga et al., Proceedings of the IEEE, Vol. 105, No.5 , pp. 1051-1067, June 2017

[3]A. M. Arabhavi et al., IEEE BCICTS, 2018.

Characterization of Downscaled Sub-mm-Wave InP HBT Devices



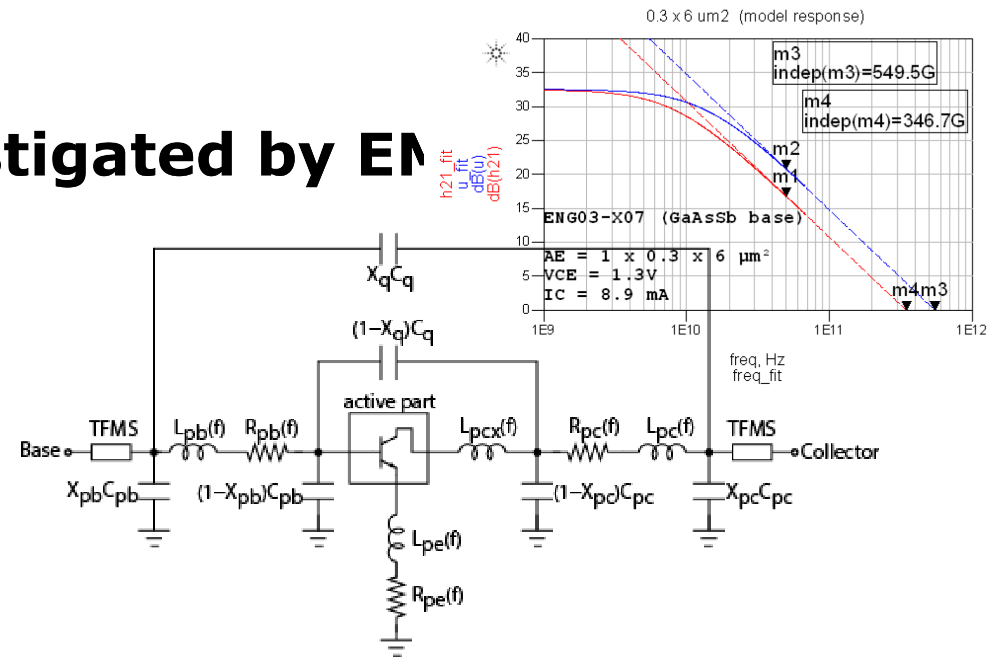
On-wafer probing creates strong ripple in Mason's gain:

$$U = \frac{|(S_{21}/S_{12}) - 1|^2}{2k|S_{21}/S_{12}| - 2\ \mathrm{Re}\,[S_{21}/S_{12}]}$$

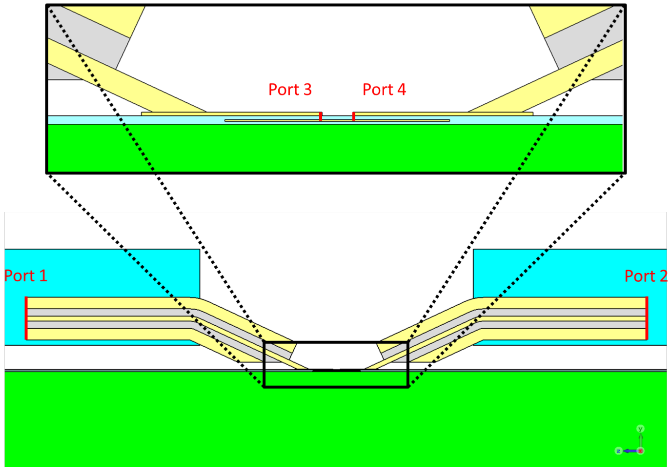
$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{21}S_{12}|^2}{2|S_{12}S_{21}|.}$$

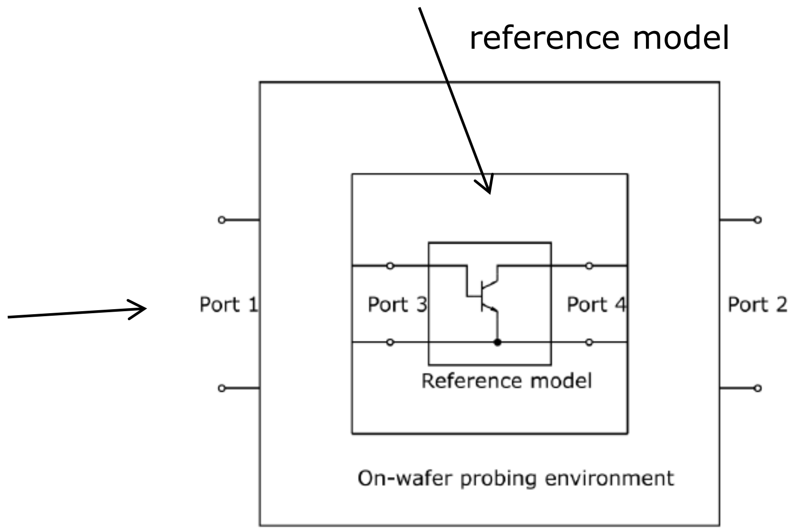
In agreement with literature this could be explained by increased influence from parasitic probe coupling effects in an on-wafer environment as the $|S_{12}|$ of down-scaled devices is small and hence easily corrupted.

Calibration Issues Investigated by EM Modeling

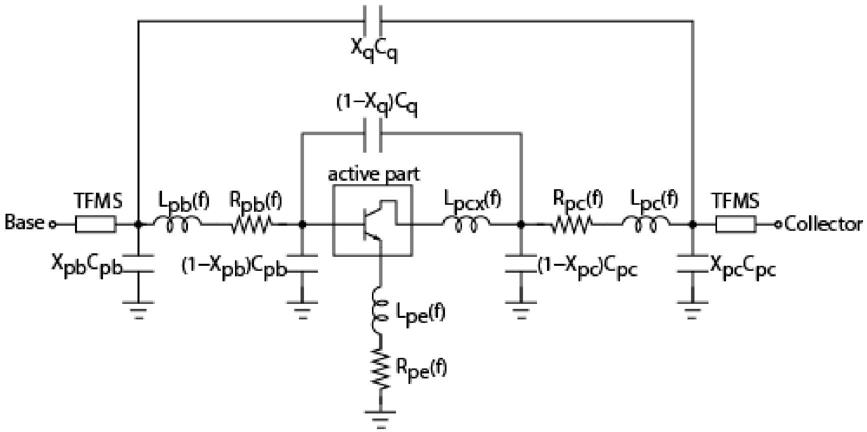


4-port EM simulation setup using GGB pico-probes or Cascade infinity probes – internal ports at transistor terminals





EM-Simulation Assisted Extraction Procedure for InP HBT Small-Signal Reference Model Extraction[1]



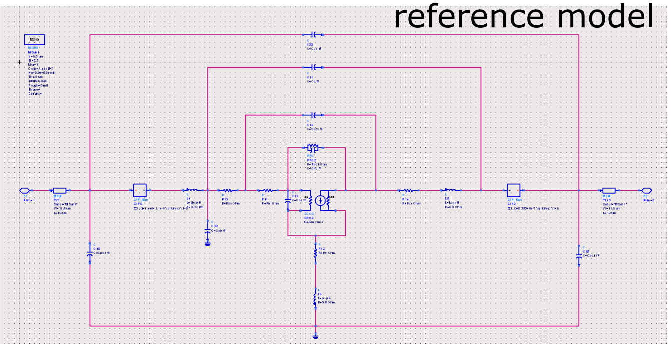
- The reference planes for model extraction are set by **multi-line Through-Reflect-Line (TRL) calibration** procedure using **on-wafer standards**
- The **extrinsic parasitic network** representing device electrodes and via transistions can be extracted from **3D EM-simulations** of the **passive device structure**
- The intrinsic model representing the **active device** can be extracted using **low-frequency** S-parameters only

Table 1. Parasitic model parameters (elements in parenthesis are extracted from cut-off mode measurements)

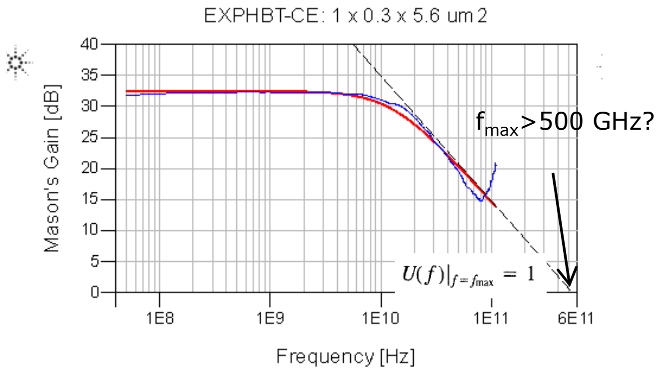
C_{pb} [fF]	X_{pb}	C_q [fF]	X_q	C_{pc} [fF]	X_{pc}
4.6 (5.6)	0.36	1.3	0.15	2.0 (1.7)	1.0
$L_{pb}(f\to\infty)$ [pH]	$R_{pb}(f=0)$ [Ω]	$R_{pb,ac}$ [$\Omega/\sqrt{\text{Hz}}$]	$L_{pe}(f\to\infty)$ [pH]	$R_{pe}(f=0)$ [Ω]	$R_{pe,ac}$ [$\Omega/\sqrt{\text{Hz}}$]
2.2	1.45	1.1E-6	0.3	0.0	0.0
$L_{pc}(f\to\infty)$ [pH]	$R_{pc}(f=0)$ [Ω]	$R_{pc,ac}$ [$\Omega/\sqrt{\text{Hz}}$]	$L_{pcx}(f\to\infty)$ [pH]	L_{TFMS} [μm]	W_{TFMS} [μm]
0.0	0.35	6.0E-7	1.7	10.0	11.6

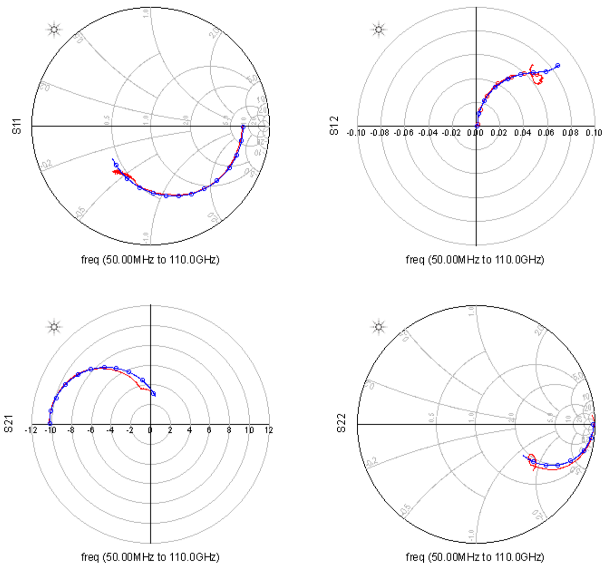
[1]T. K. Johansen et al., EM Simulation Assisted Parameter Extraction for Transferred-Substrate InP HBT Modeling, Int. Jour. Microwave and Wireless Tech., May 2018.

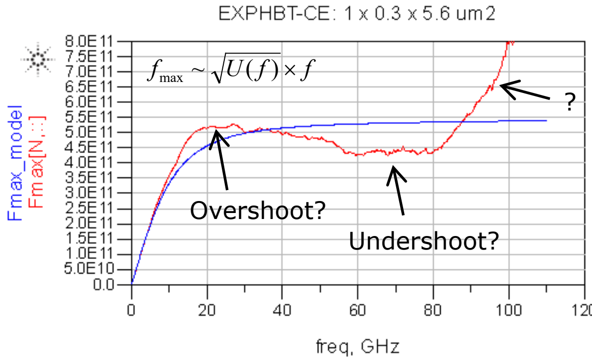
Reference Model Compared to mTRL Calibrated Data using GGB Pico-Probes



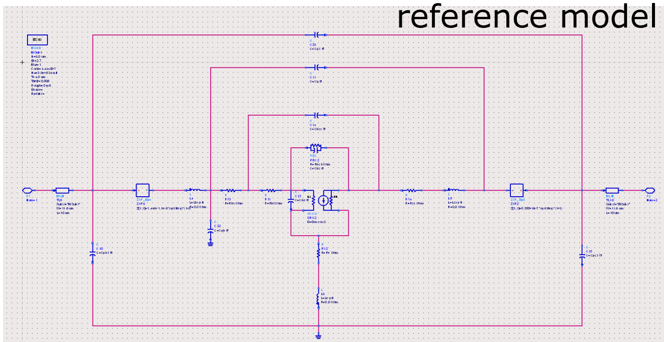
ENG3-X07 Small-Signal Modeling
(EXPHBT-CE 1x0.3x6 um2 (type B1): Vce=1.3V, Ic=8.9mA)



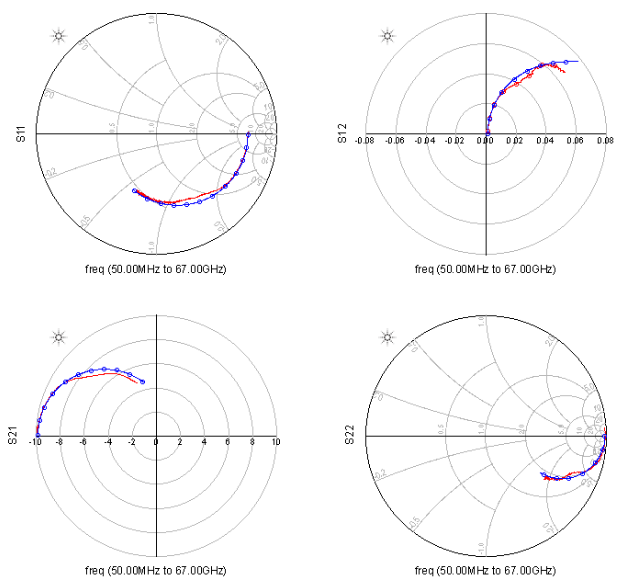


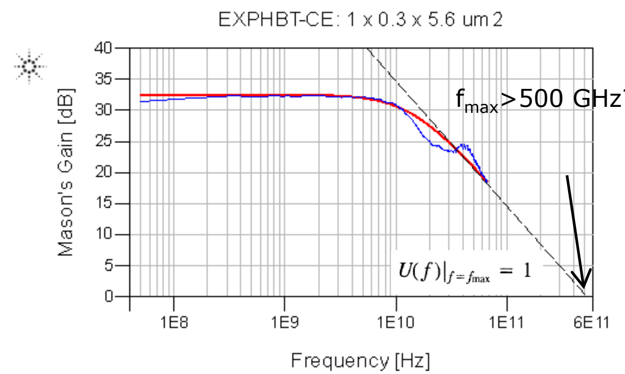


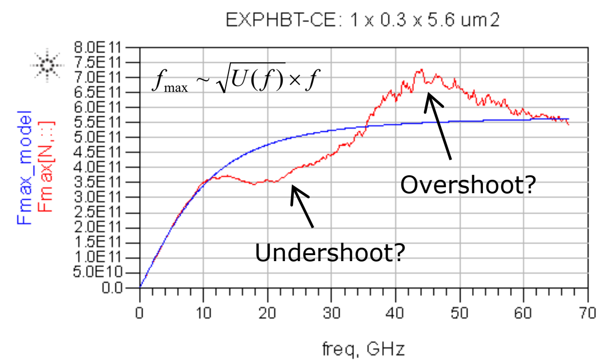
Reference Model Compared to mTRL Calibrated Data using Cascade Infinity Probes



ENG3-X07 Small-Signal Modeling
(EXPHBT-CE 1x0.3x6 um2 (type B1): Vce=1.3V, Ic=8.3mA)

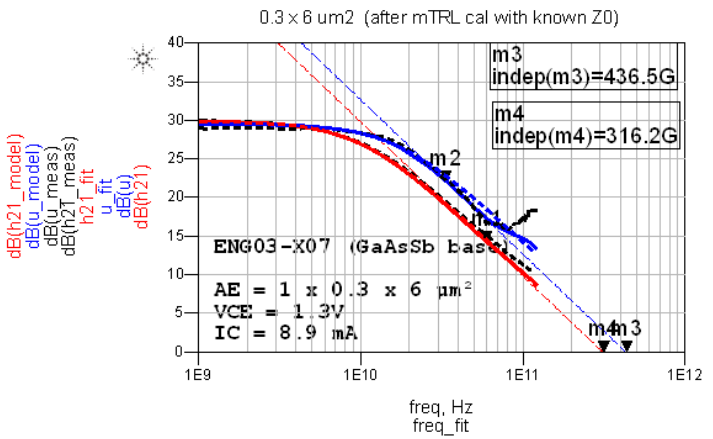


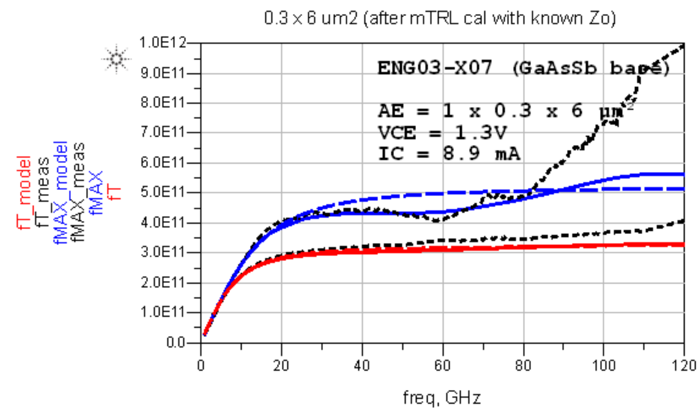




GGB Pico-probes Without Neighbour Coupling: Ceramic Carrier + Open Boundary

mTRL calibration procedure using CST simulated (MS150), MS420, MS1250, MS1950, MS2850, MS8500, Thru, Short, Open and Load





Solid lines (blue): mTRL corrected model – dB(U)

Solid lines (red): mTRL corrected model - dB(h_{21})

Dottet lines (black): mTRL corrected measurements

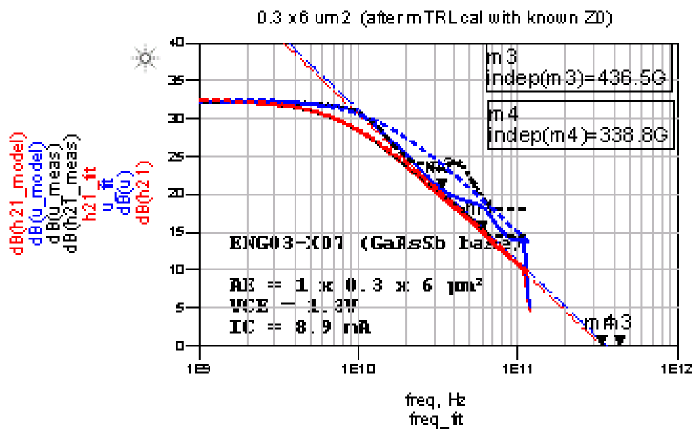
Dashed lines (blue): model reference – dB(U)

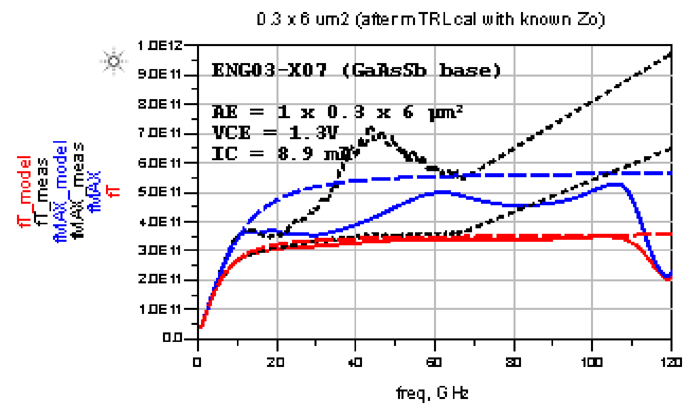
Dashed lines(red): model reference - dB(h_{21})

MASON's gain up to 80 GHz well predicted! Strong increase above 80 GHz not predicted (neighbour coupling?). Measurements are only valid up to 110 GHz.

Cascade Infinity Probes Without Neighbour Coupling: Ceramic Carrier + Open Boundary

mTRL calibration procedure using CST simulated (MS150), MS420, MS1250, MS1950, MS2850, MS8500, Thru, Short, Open and Load





Solid lines (blue): mTRL corrected model – dB(U)

Solid lines (red): mTRL corrected model - dB(h_{21})

Dottet lines (black): mTRL corrected measurements

Dashed lines (blue): model reference – dB(U)

Dashed lines(red): model reference - dB(h_{21})

Initial drop in MASON's gain around 15 - 20 GHz predicted! Overshoot frequency upshifted and of too low amplitude (neighbour coupling?). Measurements are only valid up to 67 GHz.

Summary

- Characterization and modeling issues for downscaled sub-mm-wave InP DHBT devices related to the on-wafer measurement environment has been investigated:

- A full 3D EM simulation approach is proposed to analyze the effect of the on-wafer measurement environment on the characteristics of the downscaled sub-mm-wave InP DHBT devices, in particular Mason's gain

- While the results obtained using GGB pico-probes in connection with multi-line TRL on-wafer calibration can be reasonable well predicted **the reason** for the corruption has not yet been deeply analyzed

- The results obtained using Cascade infinity probes are well predicted in the lower frequency range but may require a more careful modeling of the on-wafer measurement environment

Thank You