



Measurement issues of on-Silicon de-embedding test structures in the Sub-THz range

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OUTLINE

➤ Motivations

- mmW and Sub-mmW Applications
- Transistor HF Characterization Challenges

➤ Sub-THz Silicon On-Wafer Calibration Kit

- On-wafer Calibration Kit for Measurements up to 500 GHz

➤ On-Wafer TRL Application up to 220 GHz

- Methodology
- Focus on Open-M1 de-embedding structure

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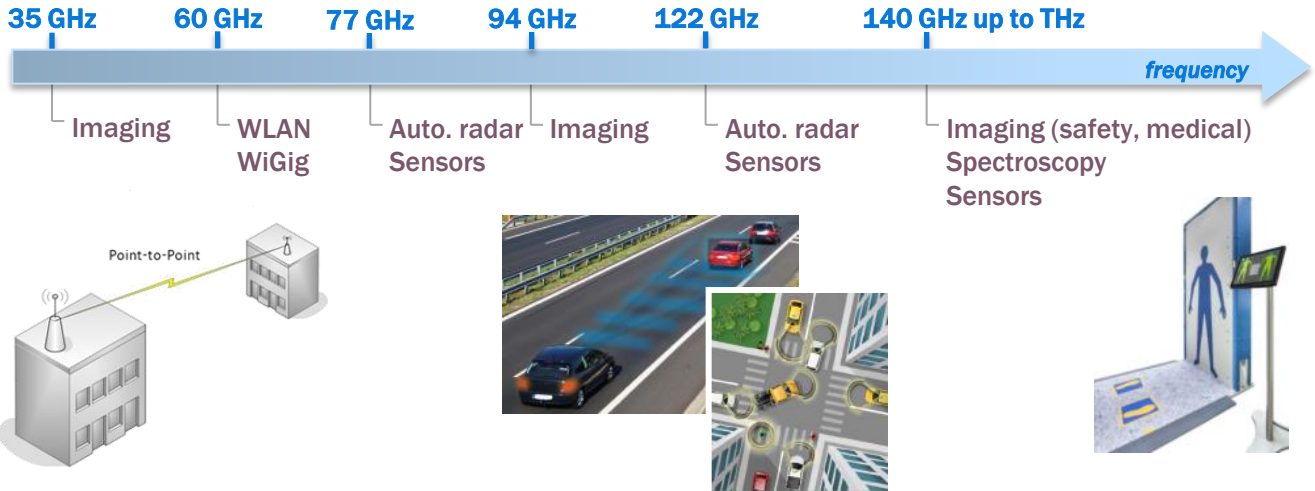
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mmW and sub-mmW Applications

➤ Millimeter and Sub-Millimeter Wave Frequency Ranges and Applications



mmW and sub-mmW Applications

➤ Silicon-Germanium State-of-the-art Technologies

	0.13 μ m SiGe BiCMOS HBT	90nm SiGe BiCMOS HBT	55nm SiGe BiCMOS HBT
f_T/f_{max}	505/720 GHz [1] 250/370 GHz [2]	300/420 GHz [3]	320/370 GHz [4]

[1] B. Heinemann et al., IEDM 2016 (IHP)

[2] J. Bock et al., BCTM 2015 (Infineon)

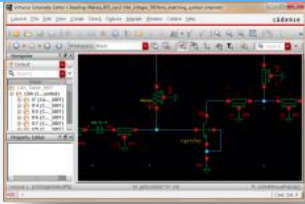
[3] R.A. Camillo-Castillo et al., BCTM 2013 (IBM)

[4] P. Chevalier et al., IEDM 2014 (STMicroelectronics)



Transistor HF Characterization Challenges

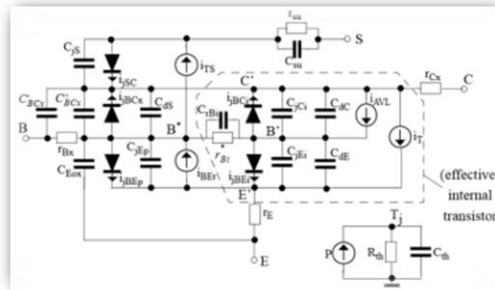
Measurement accuracy



RF circuit/system design



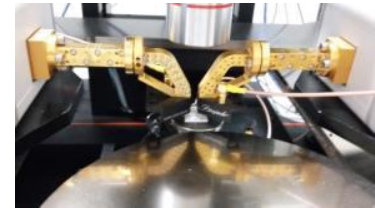
Relies on



Accurate compact models



Extracted from/validated by

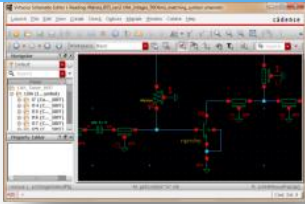


On-wafer device measurements

↳ S-parameters

Transistor HF Characterization Challenges

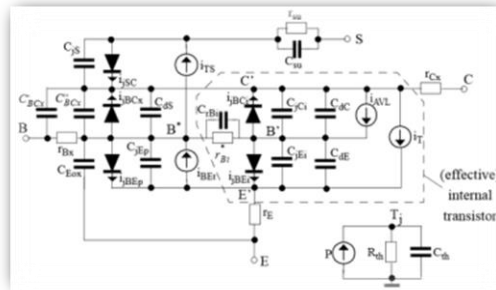
Measurement accuracy



RF circuit/system design



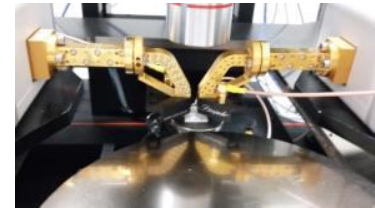
Relies on



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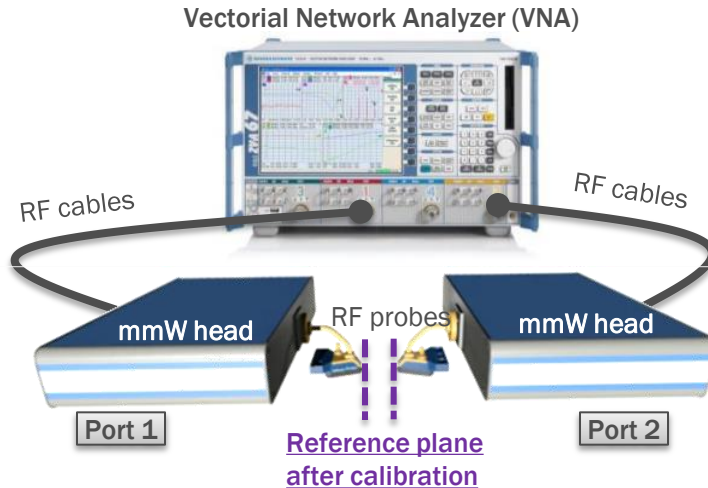
Accurate S-parameters
measurements above 110 GHz =
big challenge



Transistor HF Characterization Challenges

Calibration & De-embedding issues

- Standard procedure (2-step calibration)



1

Off-wafer
calibration on
ISS

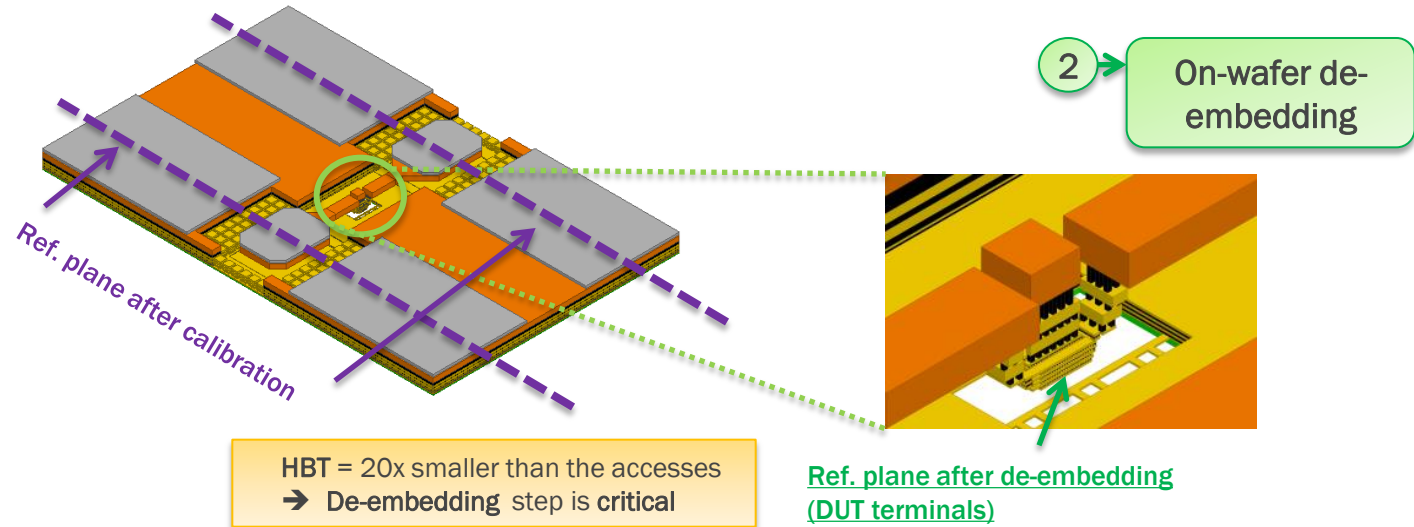


Impedance Standard Substrate
Source=Cascade Microtech

Transistor HF Characterization Challenges

Calibration & De-embedding issues

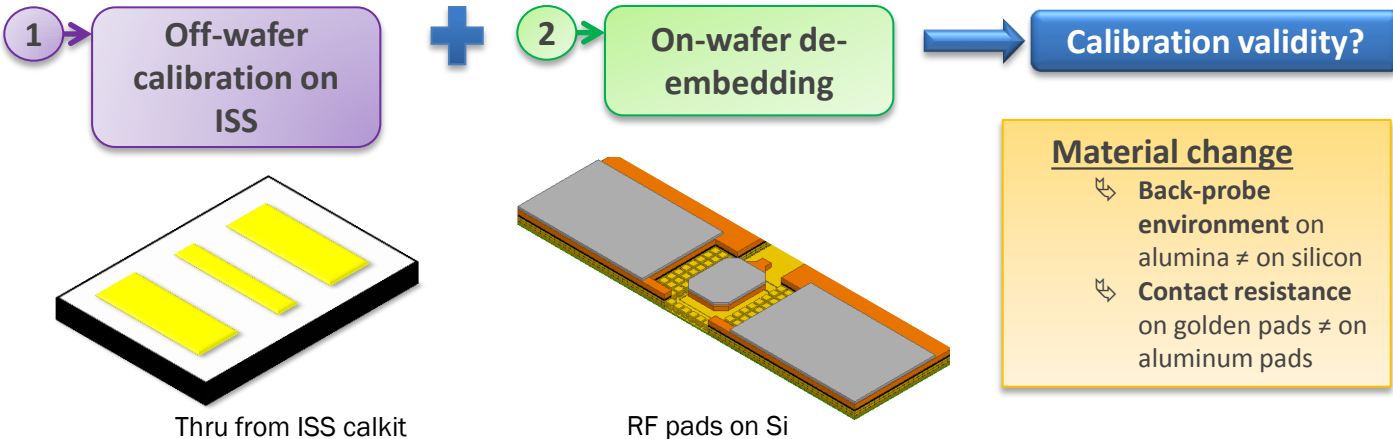
- Standard procedure (2-step calibration)



Transistor HF Characterization Challenges

Calibration & De-embedding issues

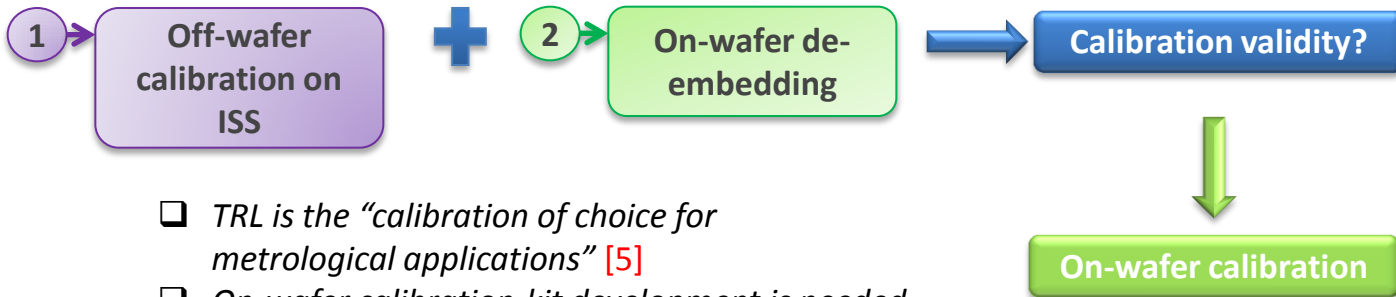
Standard procedure (2-step calibration)



Transistor HF Characterization Challenges

Calibration & De-embedding issues

- Standard procedure (2-step calibration)



- TRL is the “calibration of choice for metrological applications” [5]
- On-wafer calibration-kit development is needed

[5] D.F. Williams, T-MTT March 2014

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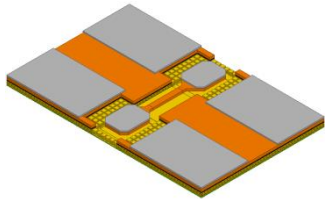
- On-wafer Calibration Kit for Measurements up to 500 GHz

➤ On-Wafer TRL Application up to 220 GHz

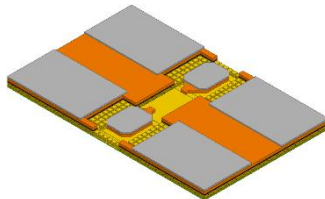
- Methodology
- Focus on Open-M1 de-embedding structure

Sub-THz On-Wafer TRL Calibration Kit

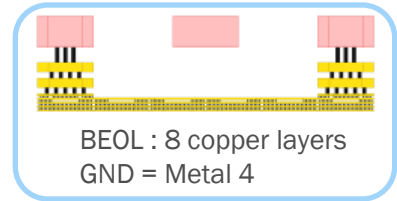
Implementation on Silicon Substrate (BiCMOS55 – STMicroelectronics)



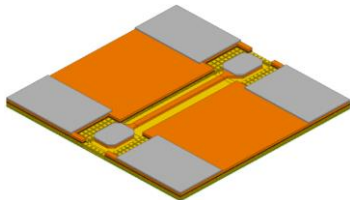
Thru



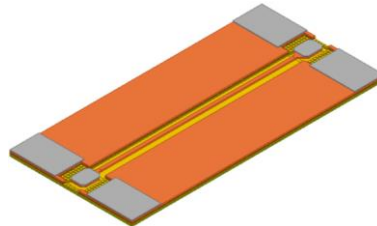
Pad Open



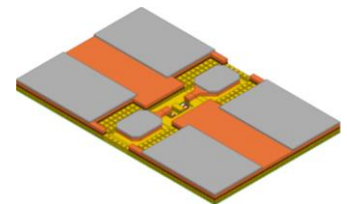
BEOL : 8 copper layers
GND = Metal 4



Line (50-500 GHz)



Line (13-120 GHz)

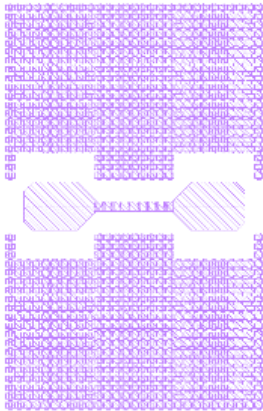


Pad Load (for impedance correction)

Sub-THz On-Wafer TRL Calibration Kit

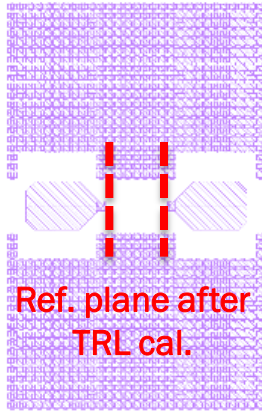
- On-wafer TRL calibration kit for 140 - 500 GHz

THRU C



THRU

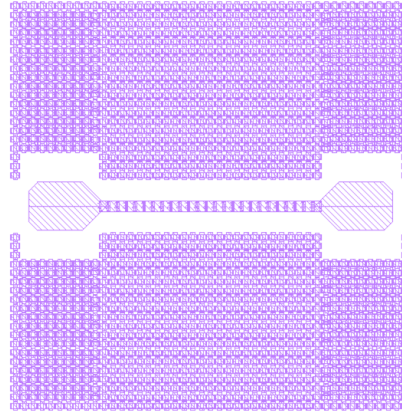
PROOPEN



Ref. plane after
TRL cal.

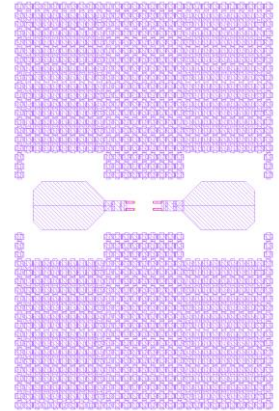
REFLECT

LINE EDGE C



LINE

PAULOAD



LOAD

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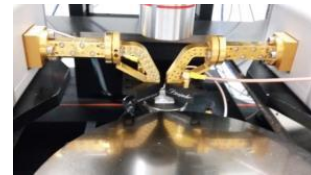
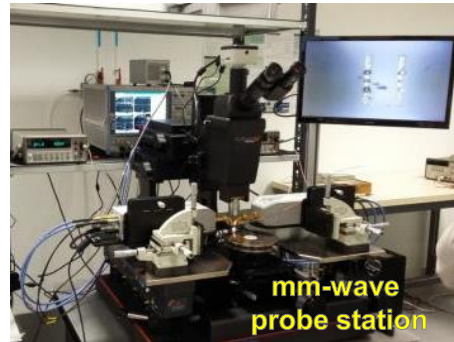
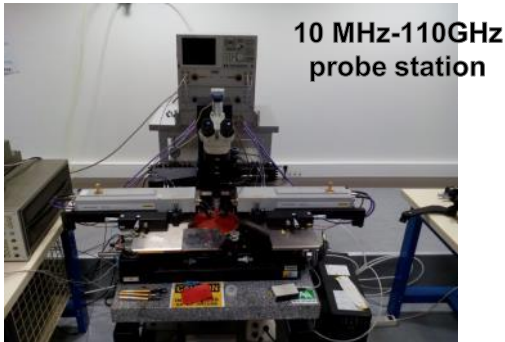
- On-wafer Calibration Kit for Measurements up to 500 GHz

➤ On-Wafer TRL Application up to 220 GHz

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On-Wafer TRL Application

➤ IMS S-parameters Measurement Benches



On-Wafer TRL Application

Methodology

➤ Measurement versus EM simulation comparison



Measurement with different probe pitches and topologies



EM sim. of intrinsic test structures

REF

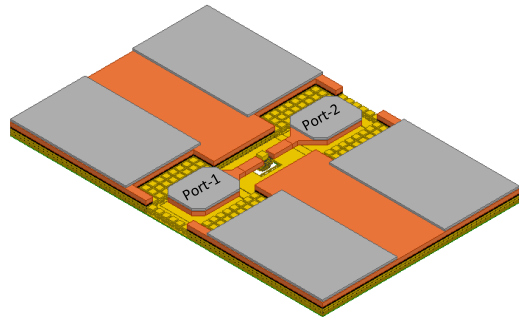


EM sim. of complete test structures

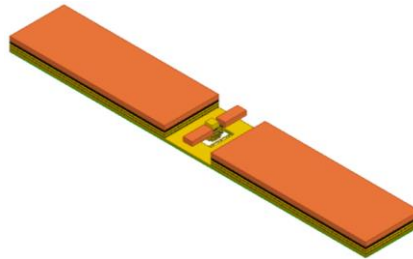
On-Wafer TRL Application

De-embedding structure

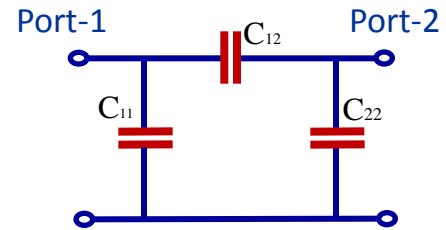
- Open M1 structure and its terminal capacitances



Open-M1



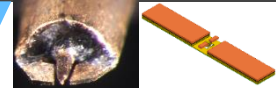
Intrinsic
Open-M1



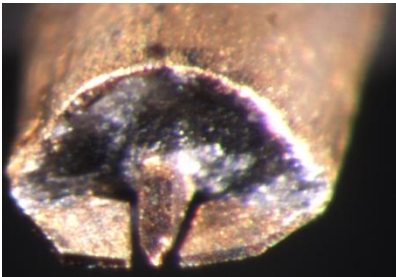
Open M1 Terminal Capacitances

On-Wafer TRL Application

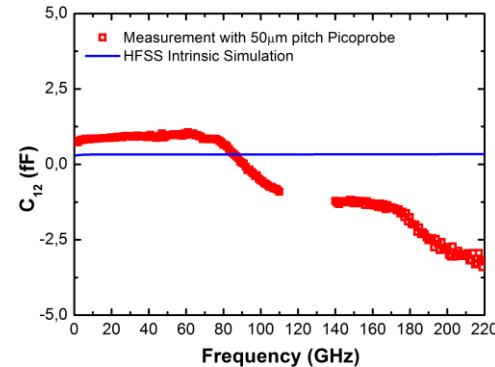
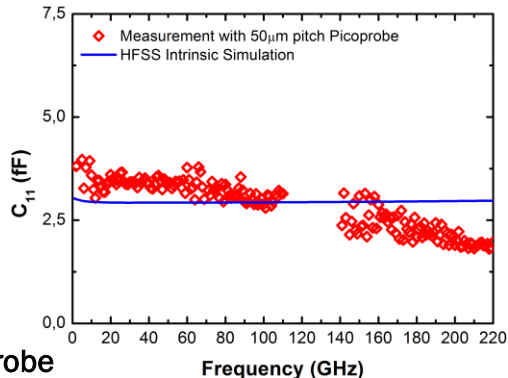
De-embedding structure



- Open-M1 measured and simulated terminal Capacitances up to 220 GHz
 - TRL cal. meas. vs intrinsic structure sim.

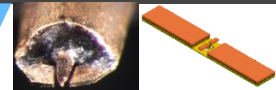


Microscopic view of Picoprobe Probe
(140 GHz – 220 GHz)

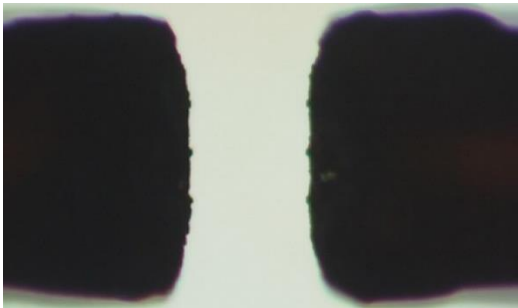


On-Wafer TRL Application

De-embedding structure : Influence of Probe design

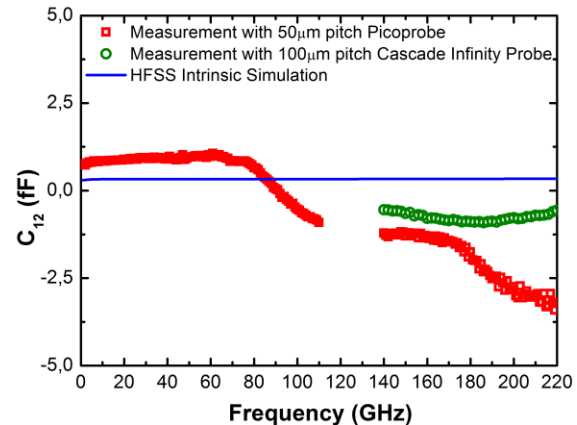


- **Open-M1** measured and simulated terminal Capacitance up to 220 GHz
 - TRL cal. meas. vs intrinsic structure sim.
 - Verification of C_{12} behavior



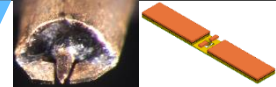
Cascade Infinity probe
(140 GHz – 220 GHz)

Can Probe design influence result ?

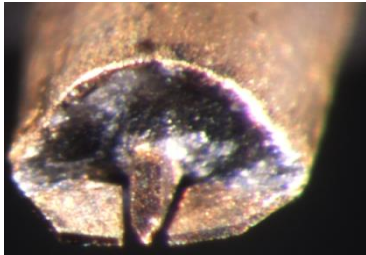


On-Wafer TRL Application

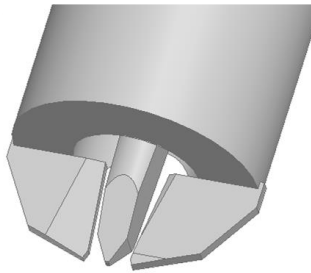
De-embedding structure : Influence of Probe design



- Open-M1 measured and simulated terminal Capacitance up to 220 GHz
 - TRL cal. meas. vs intrinsic structure sim and TRL cal. sim .
 - Verification of C_{12} behavior

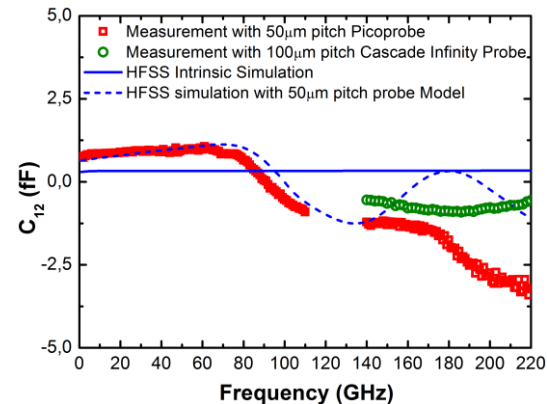


Microscopic view of Picoprobe Probe
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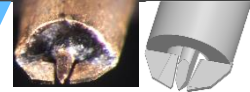
Probe Model in HFSS

Probe design can influence result!



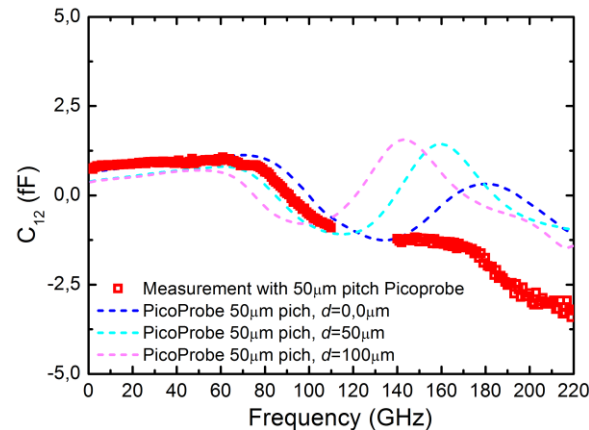
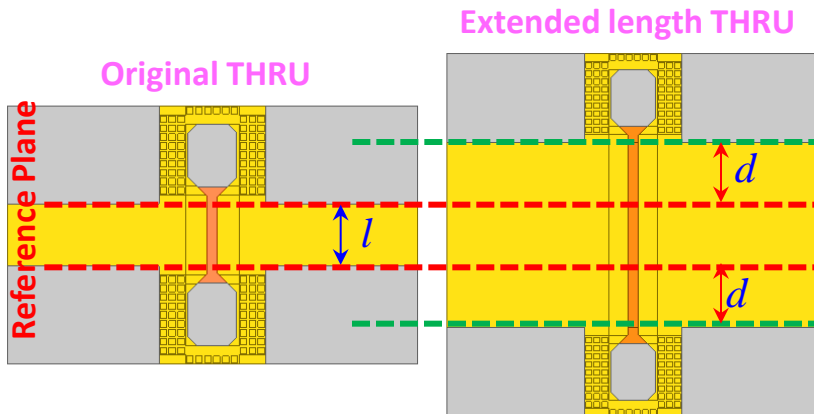
On-Wafer TRL Application

De-embedding structure : Influence of crosstalk b/w two ports



- Open-M1 measured and simulated terminal Capacitance up to 220 GHz
 - TRL cal. meas. vs TRL cal. sim .
 - Effect of crosstalk b/w two ports in C_{12}

Crosstalk is not a dominant factor in C_{12} behavior



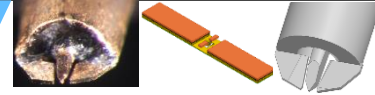
l → Original line length of THRU

d → Extended length of line in THRU

Note: Other structures length is also extended in a similar way.

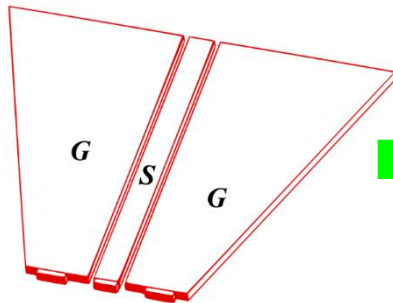
On-Wafer TRL Application

De-embedding structure : Solution for improvement



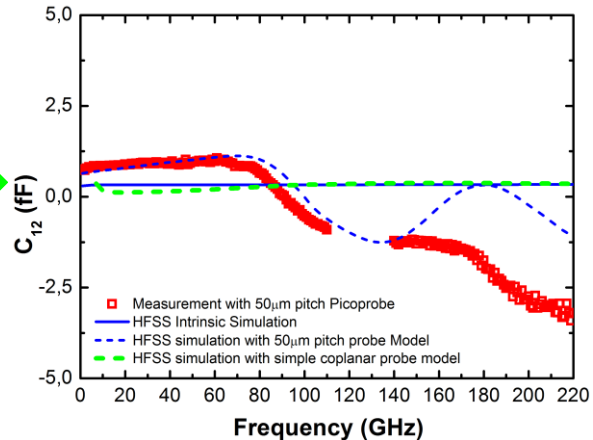
➤ Probe design- CPW probe model in HFSS

- New probe design TRL cal. sim predicts C12 behavior close to intrinsic sim.
- Depending on probe design - C12 can have only positive value



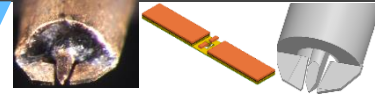
Green color

CPW Probe Model in HFSS



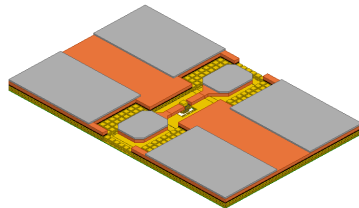
On-Wafer TRL Application

De-embedding structure : Solution for improvement



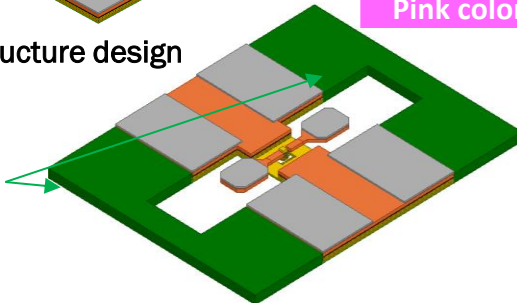
Improvement in test structures design

- Better design of test structures can lead C_{12} towards positive value

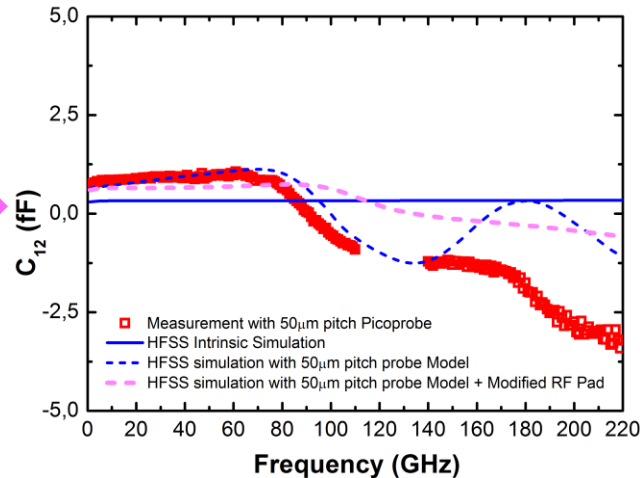


original test Structure design

Copper Metal



Modified test Structure design



Conclusions & Perspectives

- On-wafer TRL calibrated measurements for de-embedding structure up to 220 GHz
 - Probes of different pitches and topologies → some differences
- EM simulation of intrinsic and complete structures
 - Better agreement with measurements with complete structures simulation

⇒ Influence of RF pad design and probes on TRL calibration

- Perspectives:
 - Pad design improvement through layout design using EM simulation
 - Application to SiGe HBT characterization up to 500 GHz

THANK YOU !

