



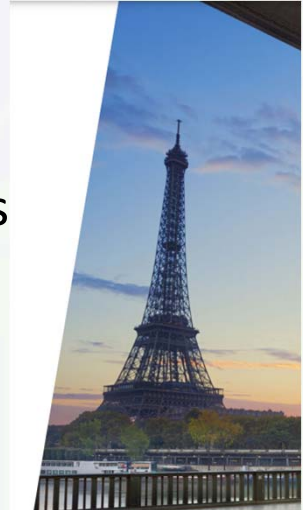
WM-02

Mechanical Investigations for High Frequency Probe Design

Sebastien FREGONESE, Tarek Bouzar, Jean-Daniel Arnould*, Simon Joly, Thomas Zimmer

Laboratoire IMS, CNRS, Univ. Bordeaux, INP, France

* Laboratoire TIMA, Univ. GRENOBLE, CNRS



Email: sebastien.fregonese@ims-bordeaux.fr



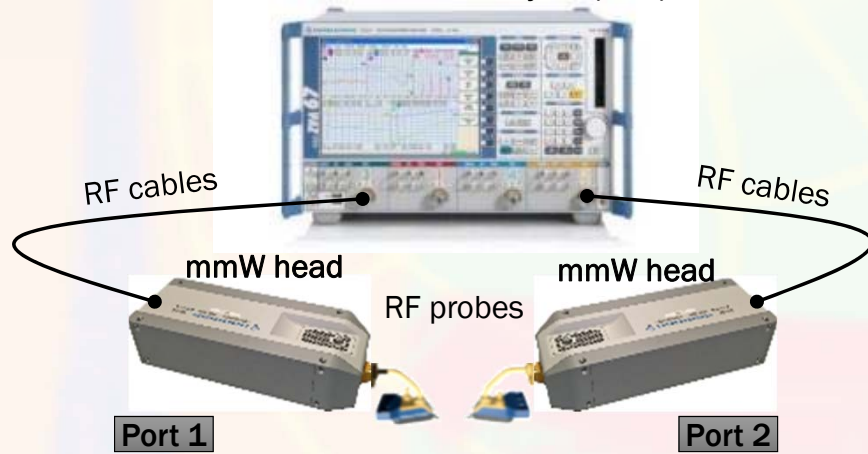
Outline



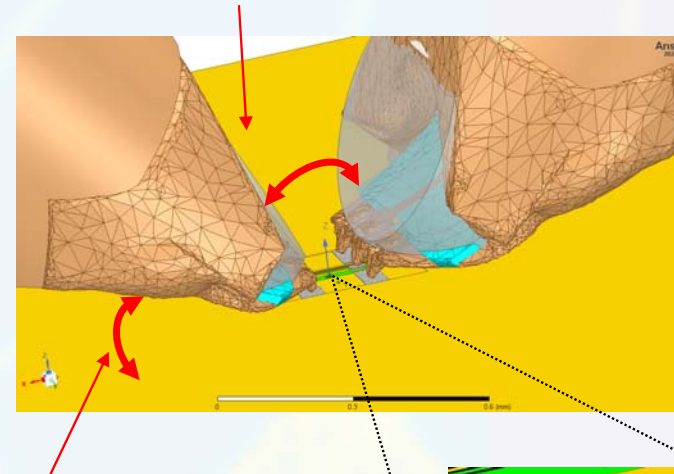
- Challenges for on wafer characterization of SiGe HBTs at high freq.
 - Calibrations and EM probe coupling
 - Probes contact impact on results
- Introduction to development of a new probe
- Mechanical simulation
- Conclusions

Introduction (1/3)

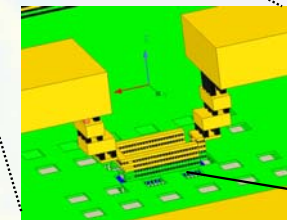
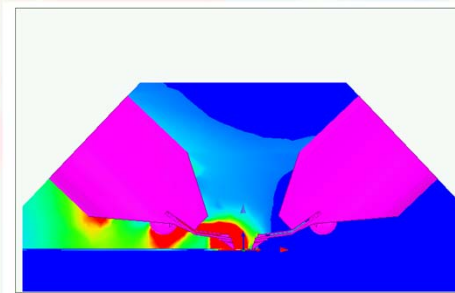
Vector Network Analyzer (VNA)



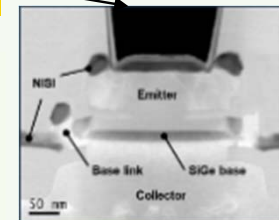
probe-probe coupling



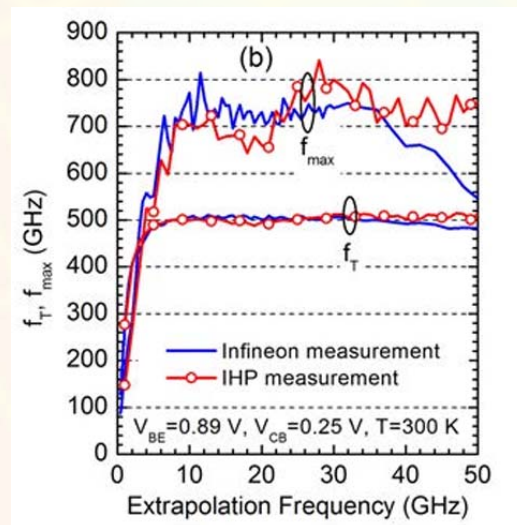
Probe to substrate coupling



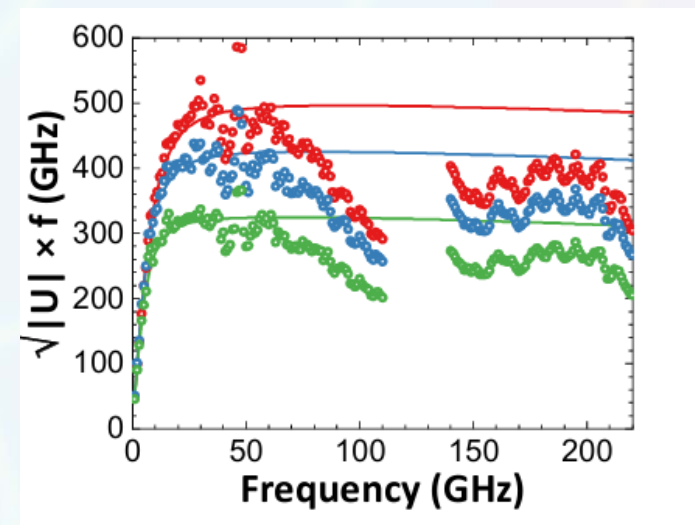
Transistor
B55X
STMicro.



Measurement difficulties to evaluate f_{MAX}



Mason's and H21 gain-bandwidth product vs frequency for the same SiGe HBT measured at IHP and Infineon
B. Heinemann *et al* IEDM 2016, [4]

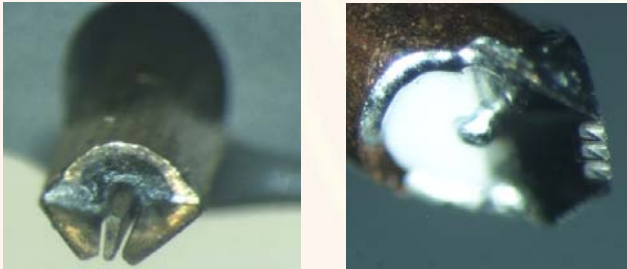


Bipolar transistors (InP DHBTs) Mason's gain-bandwidth vs frequency product at different collector current I_C and $V_{CE} = 1.6$ V
N. Davy *et al* EuMIC 2023 [5]

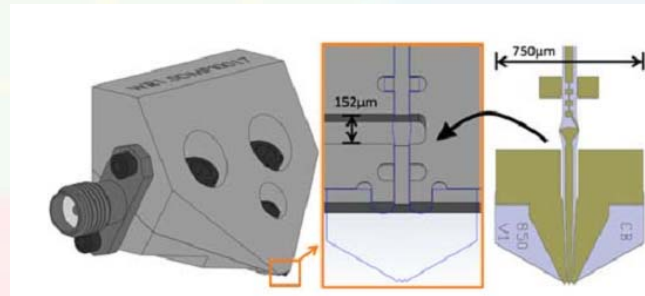
⇒ Measuring FOMs for advanced and miniaturized transistors becomes a challenge when their $f_{MAX} \gg 100$ GHz due to **EM probe coupling**

Introduction (3/3)

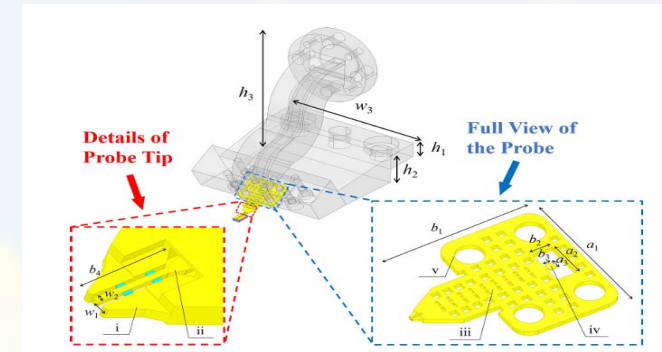
Pico-Probe and Infinity DC-110 GHz,
100 μ m pitch



University of Virginia & Dominion
[M,Bauwens ; Phd thesis ;2014]



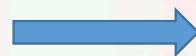
China Electronics Technology Group Corporation,
Shijiazhuang [W. Wu *et al* TIM;2022]



Images of the probes available at
Bordeaux University

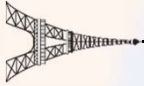
- **Broad-band**
- **EM probe coupling not negligible for HBT**

- **Minimized EM probe coupling**
- **Limited frequency band due to wave-guide**
- *New dual band FormFactor Twaves 220 GHz and broadband MPI TITAN 220 GHz probes may show interesting performances*

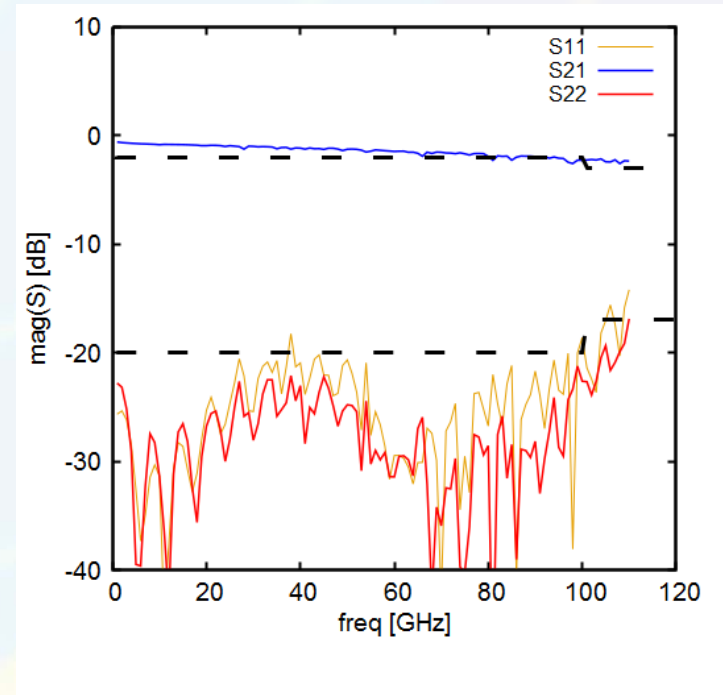
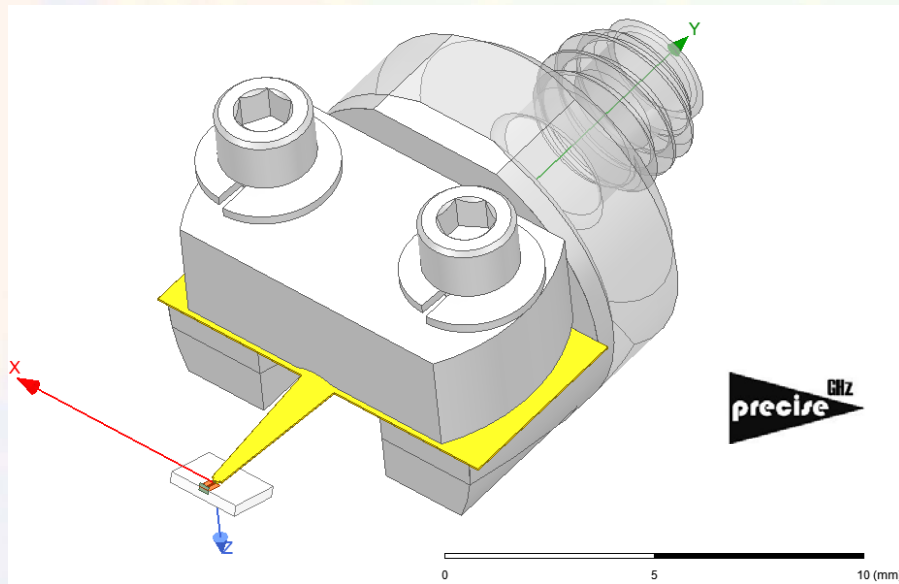


Attempt to build some broad-band RF probes within a french consortium

EM preliminary results (1/2)



Silicon MEMS probe mounted on 1 mm connector



Dashed line is MPI TITAN 220 GHz probe typical specifications for comparison
<https://www.mpi-corporation.com/>

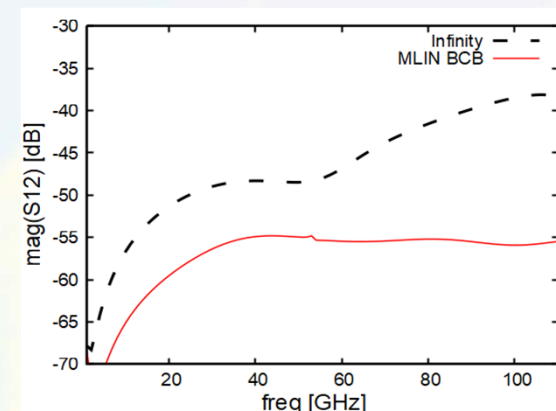
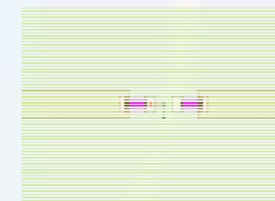
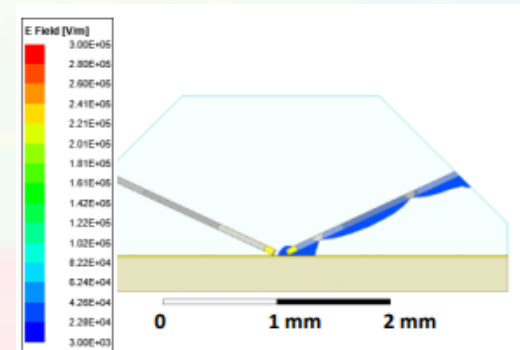
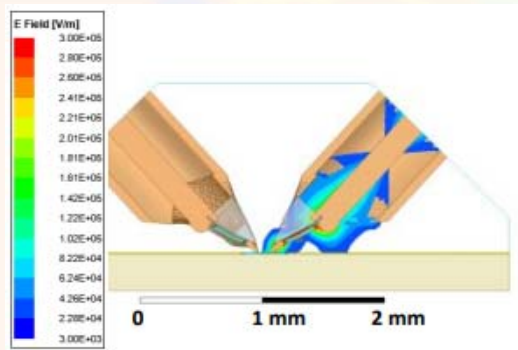


EM preliminary results (2/2)

T. Bouzar et al., JNM 2024



PAD-LOAD structure on BiCMOS

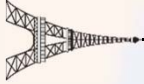


EM field distribution at 60 GHz for Infinity standard probe

EM field distribution at 60 GHz for silicon MEMS probe

- The Infinity standard probe EM model shows distributed coupling at the tips
- A clear improvement in EM confinement for the silicon MEMS probe
- Crosstalk difference > 15 dB less for the silicon MEMS probes on a 50 Ω load

Contact resistance test – IHP Bip. Technology with Al or Au pads

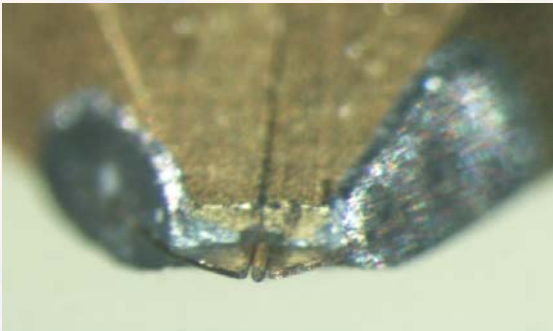


Probe skating is much larger in Al case compared to Au

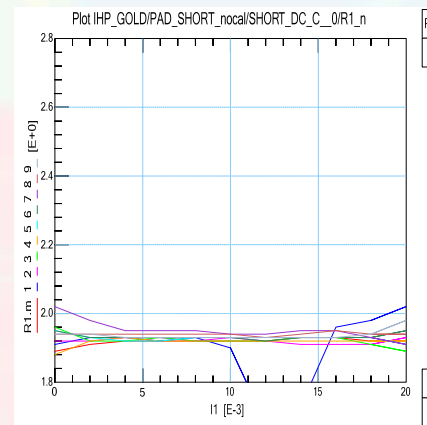
Procedure:

- 1- Make a “reliable” contact on a transistor short
- 2- Go on pad-short and make first contact
- 3- Probes are put up and down
- 4- DC & RF measurements are performed and repeated 9 times

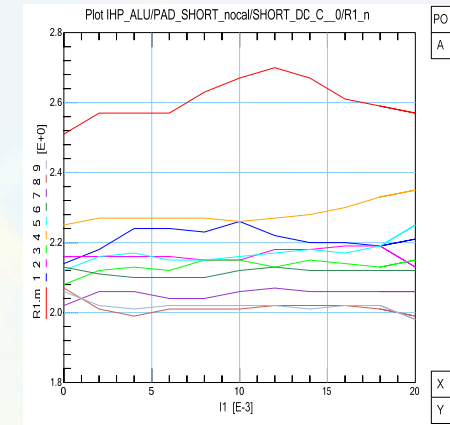
325-500 GHz GGB Pico-probe pitch 50 μm



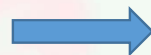
Gold pad



Aluminum pad



$R_{\text{bias_tee}} \sim 1.85 \text{ ohm}$

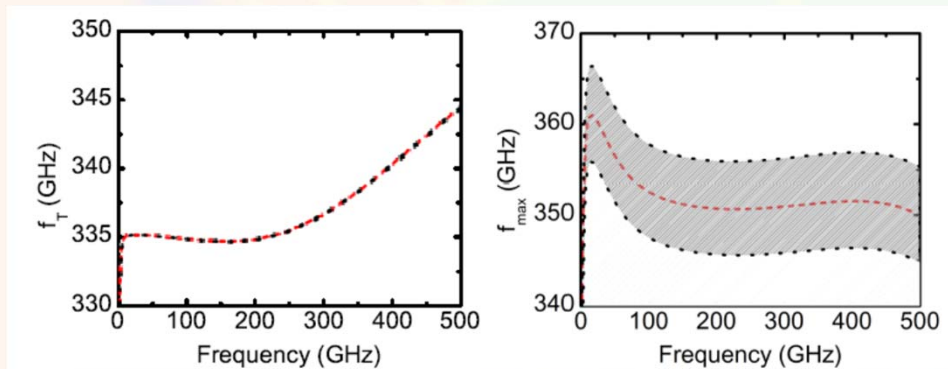


Error seems to increase for the smallest probes

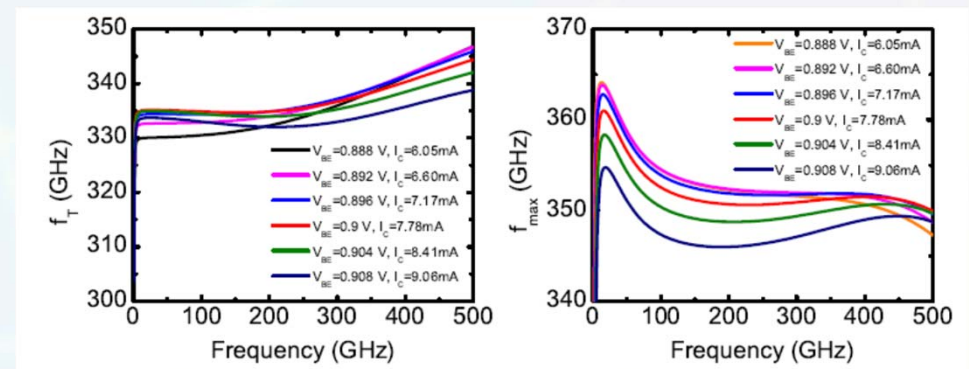
The importance of electrical contact quality

HICUM Compact model simulation

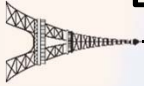
Influence of $\Delta R_{BX} = \pm 0.5 \Omega$ on FOM



Influence of bias point on FOM

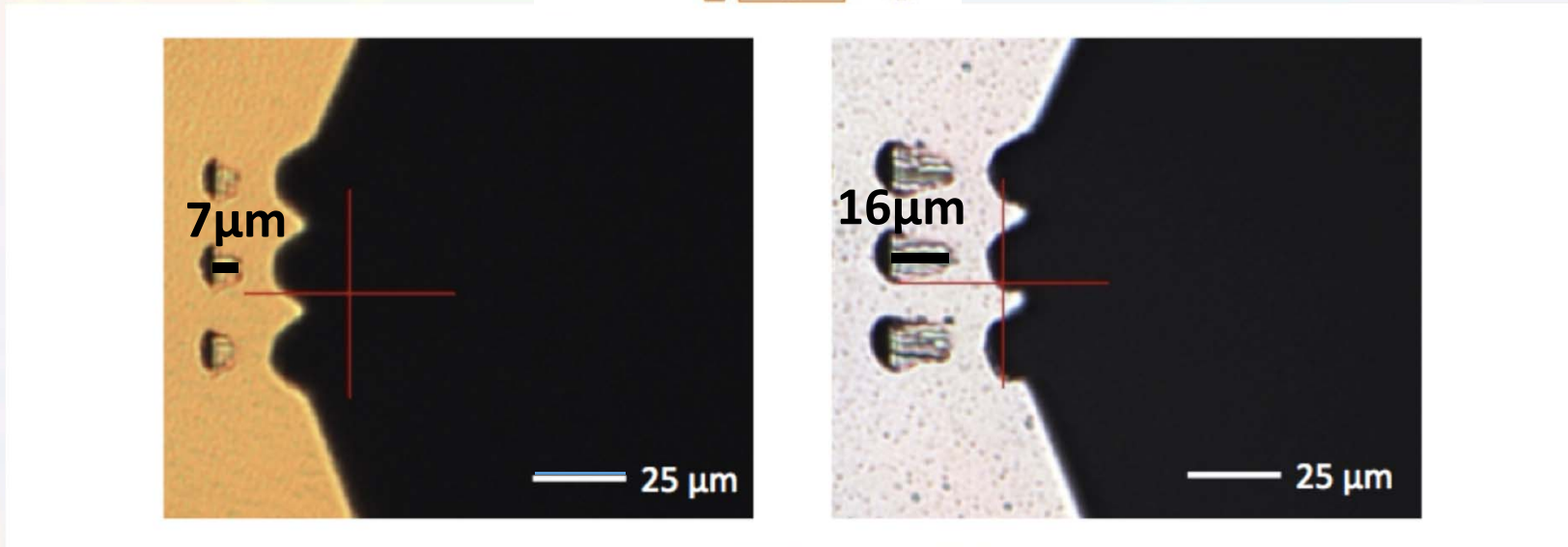
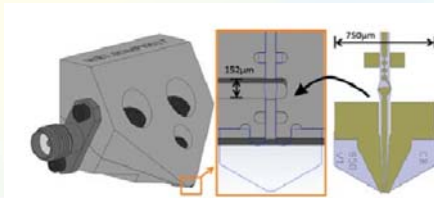


M. Cabbia, PhD thesis , Bordeaux, 2021 [3]

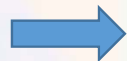


Bibliography (1/3)

Univ. Virginia, Bauwens et al., phd thesis [1]



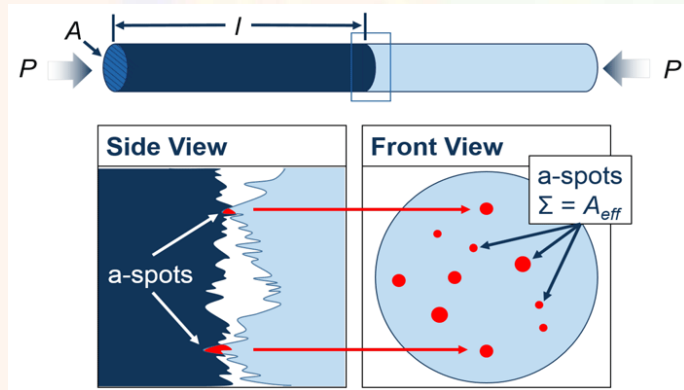
Typical scratch marks on gold and aluminum films by 15µm thick silicon micromachined probe tips



Minimum force is 3 mN on gold and 25mN on aluminum

Bibliography (2/3)

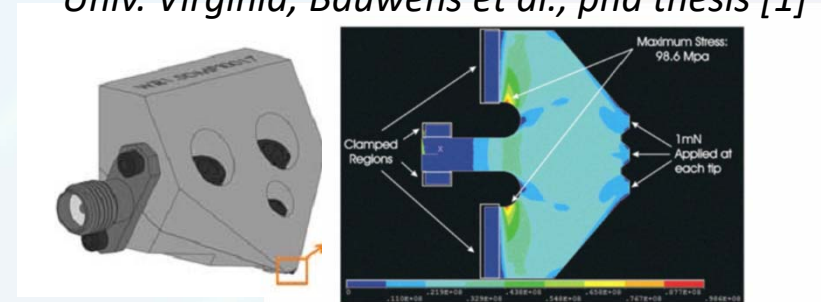
Contact resistivity vs force



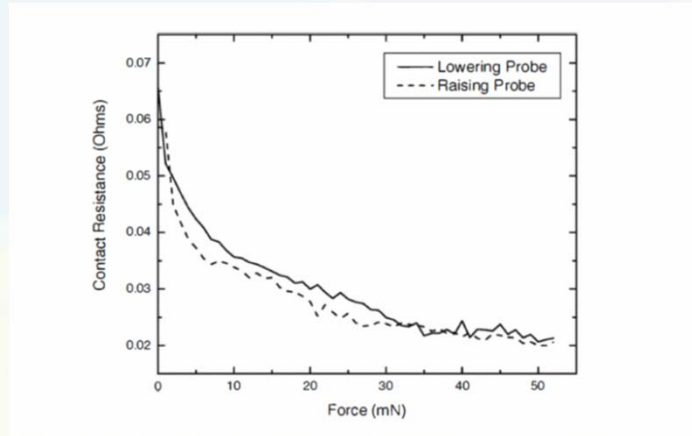
$$R_c = \frac{\rho}{2a} \text{ with } a = \sqrt{\frac{F}{\pi H}}$$

Applied force
Material hardness

Univ. Virginia, Bauwens et al., phd thesis [1]



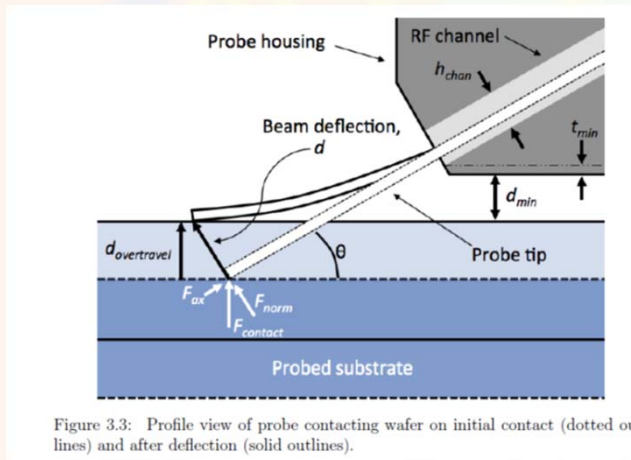
Virginia Univ. : Contour plot of the stress under 1mN load at each tip



Virginia Univ. : Measurement of the contact resistance plotted against bending force of the probe

T. J. Reck et al., "Micromachined on-wafer probes," 2010 IEEE MTT-S IMS, 2010 [2]

Force vs Overtravel



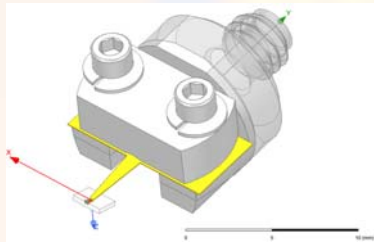
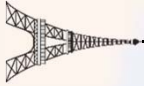
F = Applied force
 L = Cantilever length (580μm)
 E = Young modulus = 185 GPa for silicon
 t = Thickness of cantilever (5 or 15μm)
 w = Width of cantilever (75μm)

$$k = \frac{F_{contact}}{d_{overtravel}}$$

$$k = \frac{E w}{4 \cos^2(\theta)} \left(\frac{t}{l}\right)^3$$

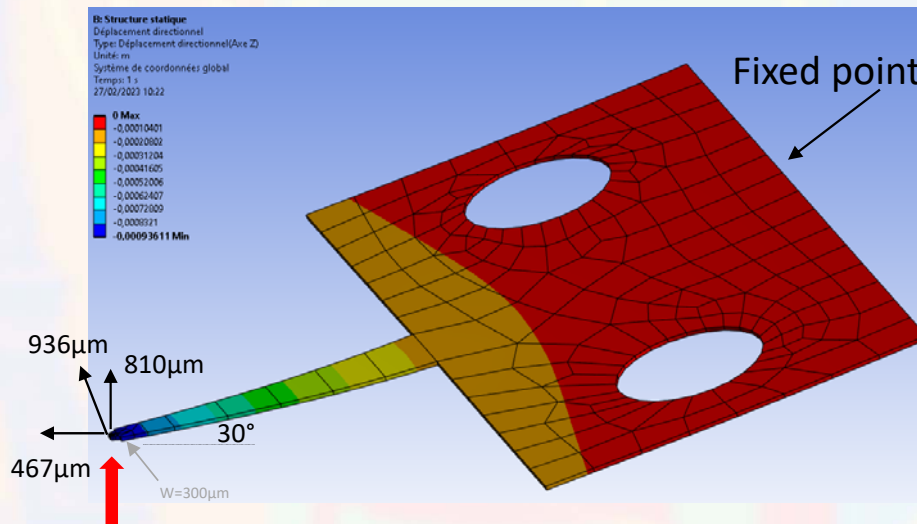
t [μm]	K [mN/μm]	Overtravel for Au (3mN) [μm]	Overtravel for Al (25mN)
5	0.03	100	840
15	0.8	3.7	31

Preliminary Mechanical simulation (1/3)



➔ Designed without mechanical consideration

Probe V0



Young modulus for Si= 166GPa
Anisotropy is settled

Overtravel = 810 µm
Skating = 467µm

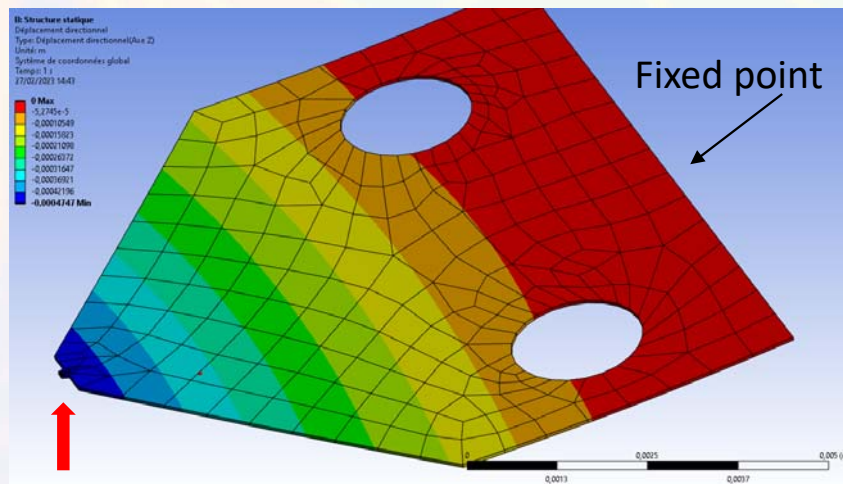
Stiffness= 30 N/m

25mN applied (30° angle)

Probe minimal force for aluminum

Preliminary Mechanical simulation (2/3)

Probe V1



25mN applied (30° angle)

Probe minimal force for aluminum

On gold
Overtravel = 40 μm
Skating = 23 μm

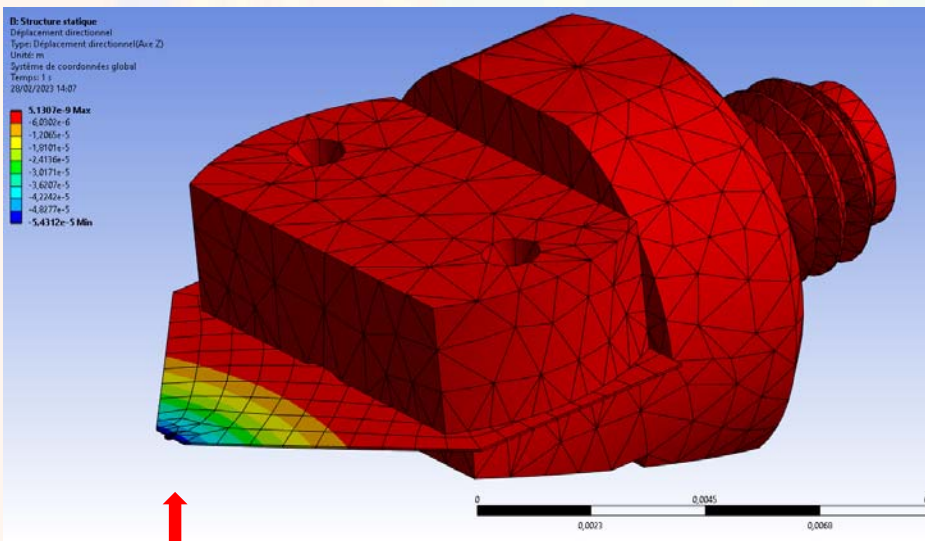
On aluminum
Overtravel = 417 μm
Skating = 236 μm

Stiffness= 60 N/m

⇒ useful on gold only but not for aluminum

Preliminary Mechanical simulation (3/3)

Probe V1 + connector clamp => *reduction of effective cantilever length*



25mN applied (30° angle)

Probe minimal force for aluminum

On gold

Overtravel = 5,6 μm

Skating = 3,2 μm

On aluminum

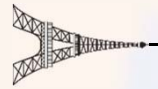
Overtravel = 46 μm

Skating = 26 μm

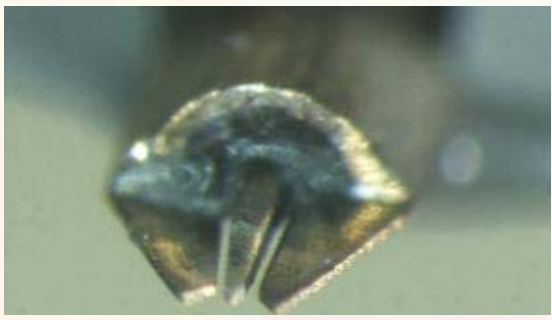
Stiffness= 540 N/m

=> useful for both gold and aluminum

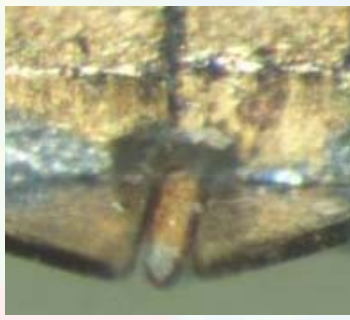
Mechanical simulation: Comparison of the 3 probes (stiffness, skating)



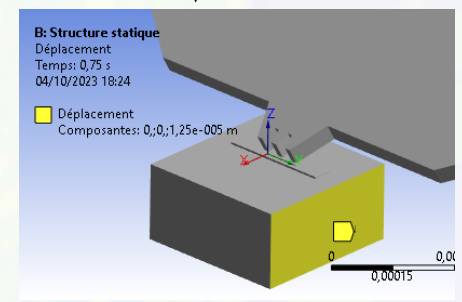
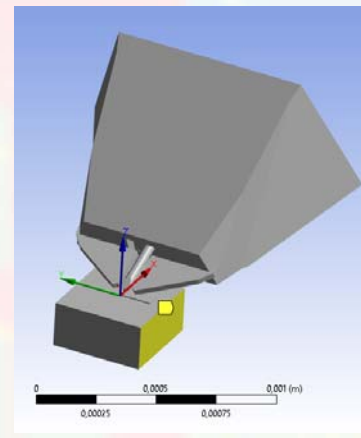
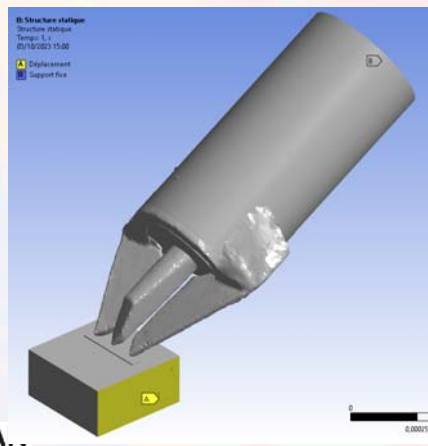
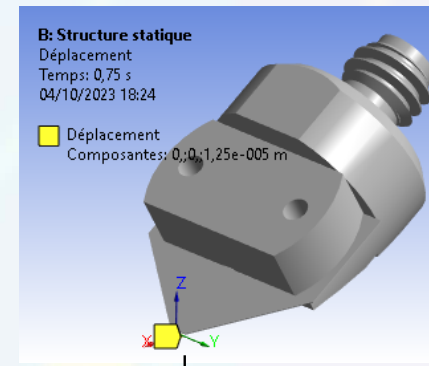
GGB DC-110 GHz
Pitch 100µm



GGB 220-325 GHz
Pitch 50µm

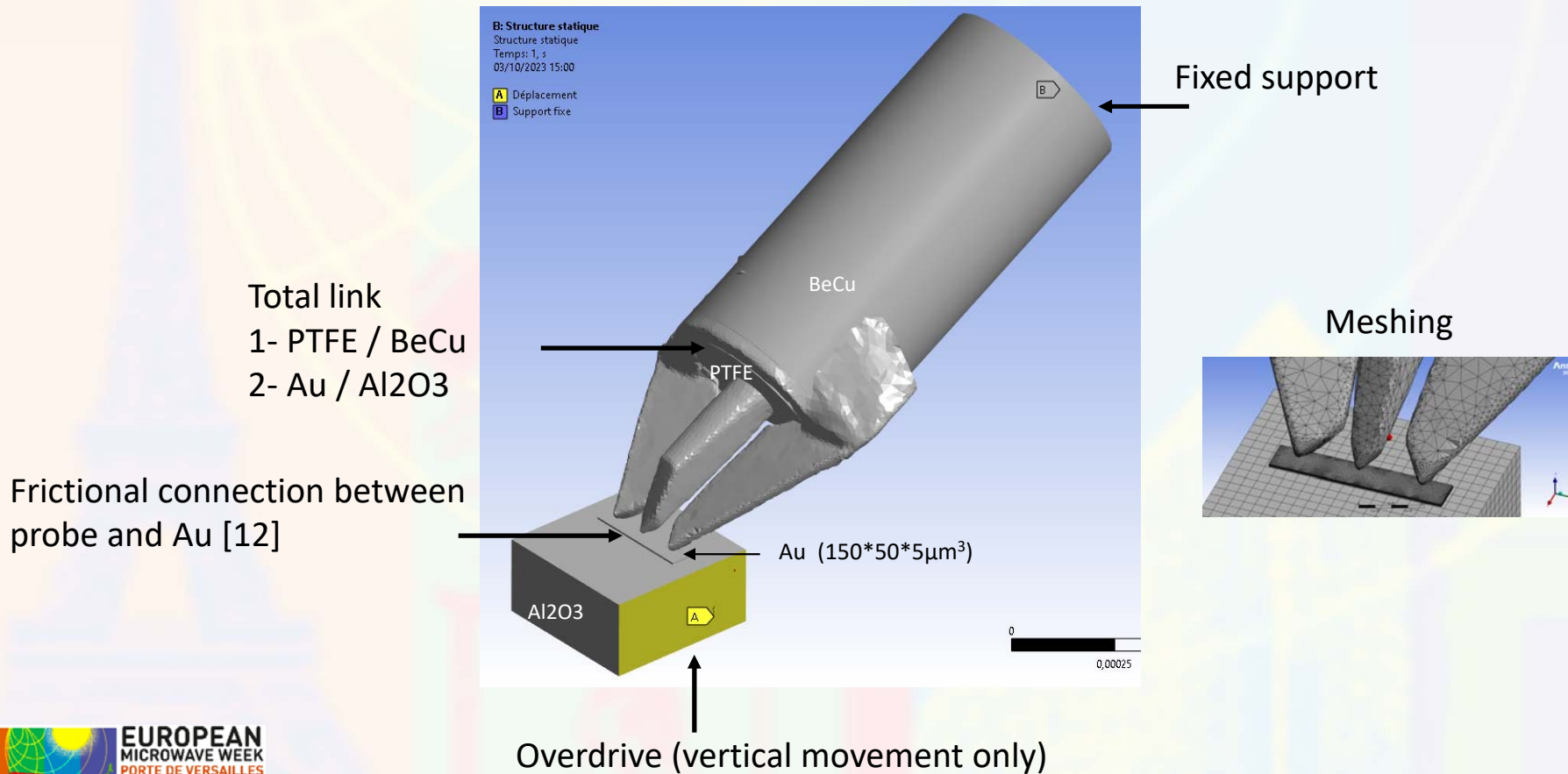


MEMS Si probe
Pitch 50µm

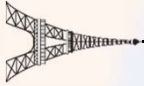


Mechanical simulation: boundary conditions

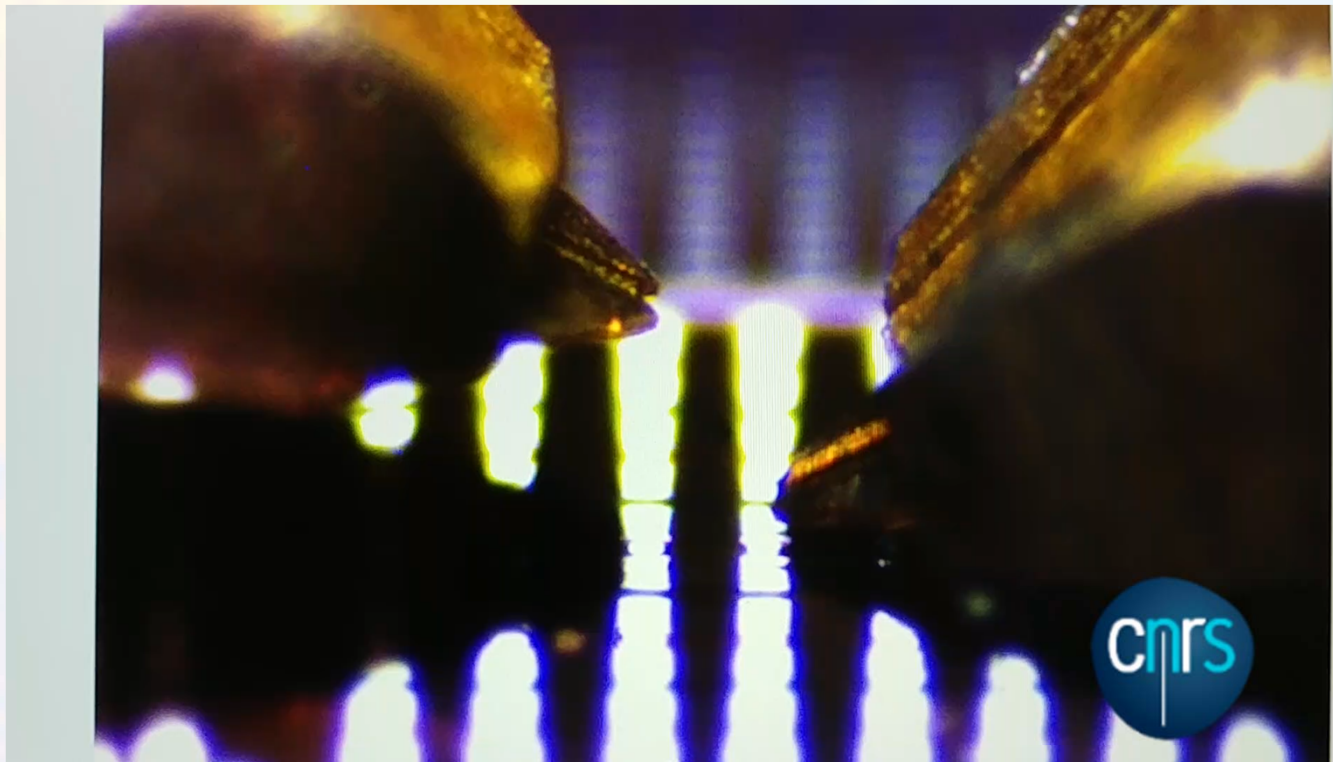
- GGB pico 110 GHz – 100 μm pitch



Side view movie showing skating and probe bending



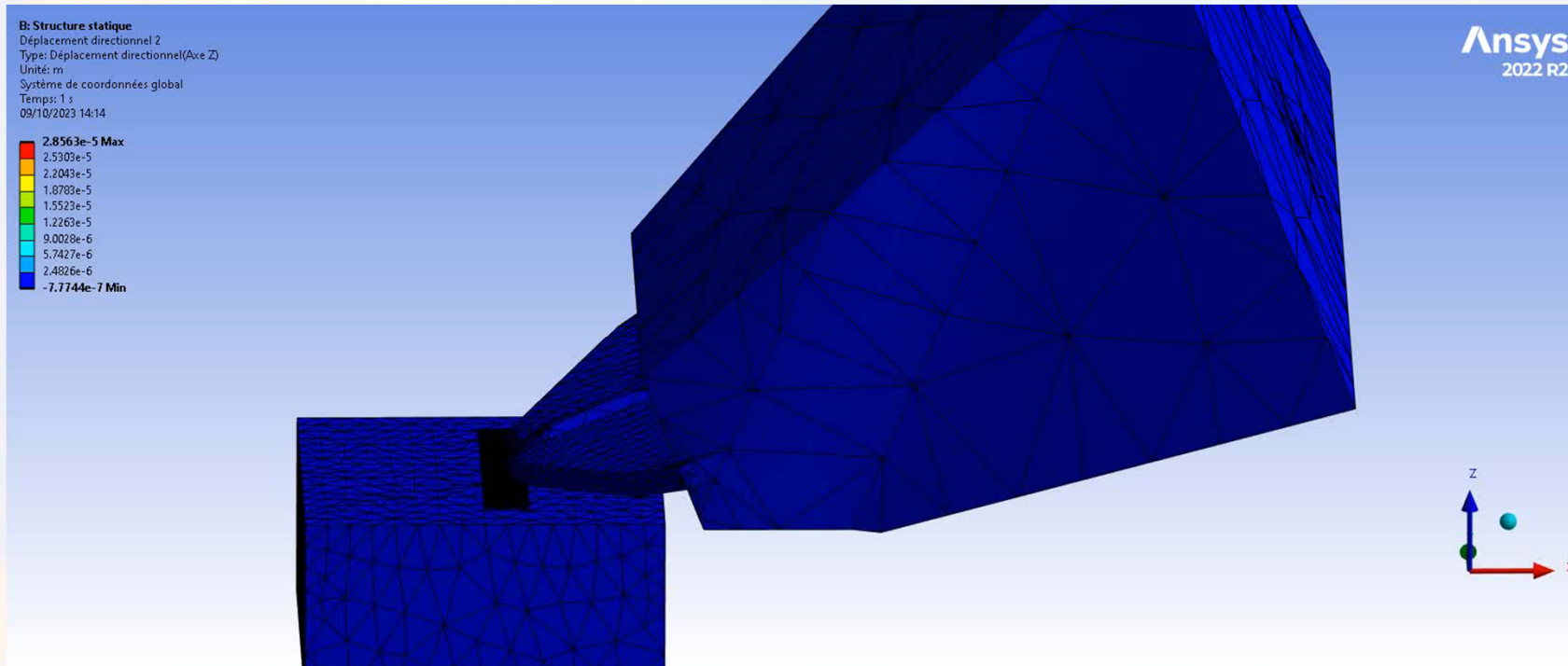
GGB Picoprobe 325 GHz



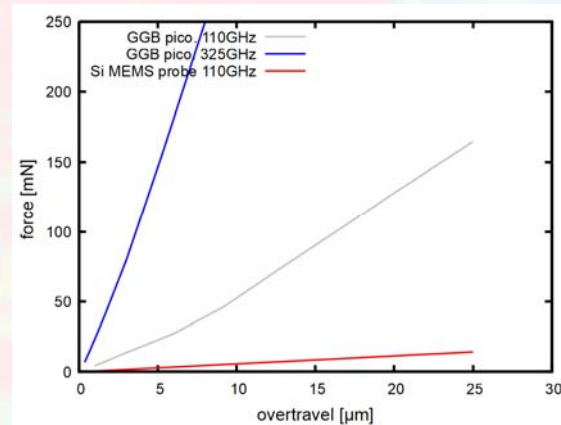
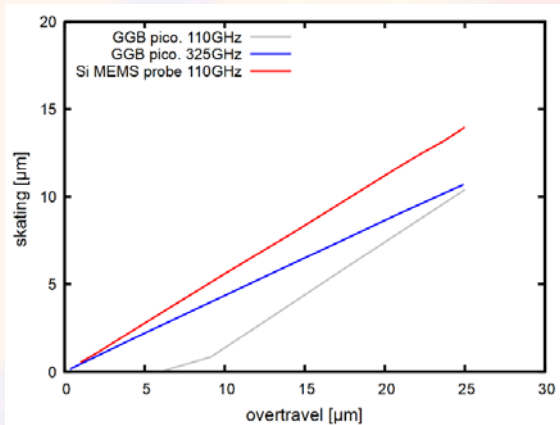
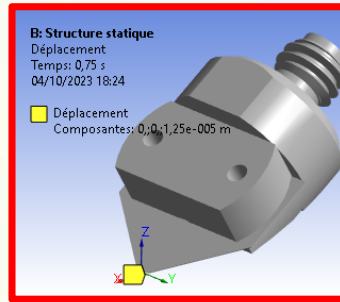
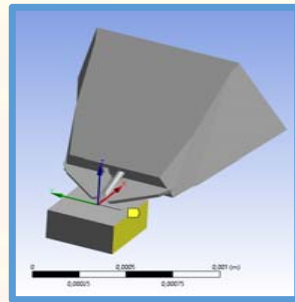
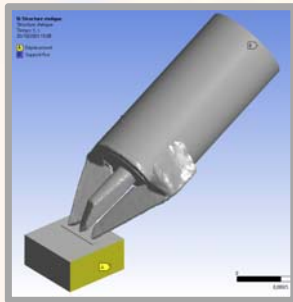
Side view simulation showing skating and probe bending



GGB Picoprobe 325 GHz

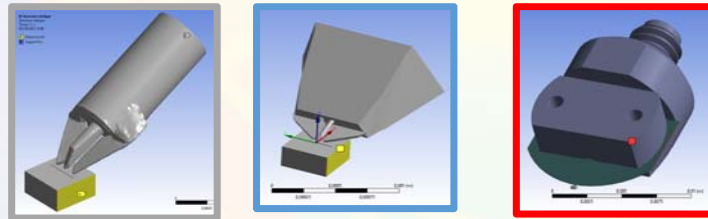


Mechanical simulation : results (1/3)

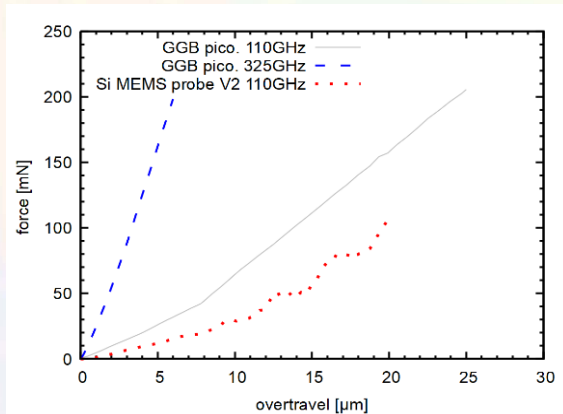


- ❑ The skating vs z-over-travel ratio seems similar for all the 3 probes
- ❑ But stiffness is different:
 - ❑ GGB 325G vs GGB 110G:
 - ❑ The metals are thinner but are compensated by a shorter structure
 - => more force on the 325 GHz
 - ❑ GGB 110 G vs Si MEMS probe:
 - ❑ Young's modulus is similar
 - ❑ Si MEMS structure is longer and finer
 - => force applied is lower for Si MEMS

Mechanical simulation : results (2/3)



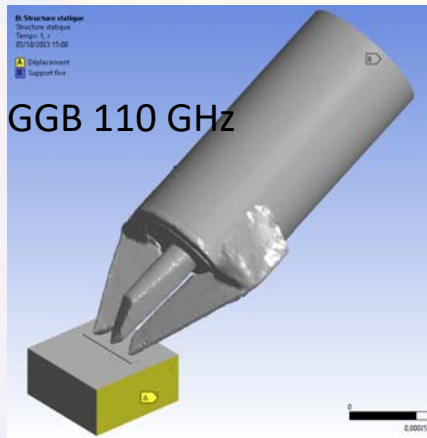
Improved geometry Probe V2



Type	stiffness[N/m]
GGB 325 GHz / simulation	~30000
GGB 110 GHz / simulation	~8000
MEMS Si 50µm (probeV2), simulation	~3000
MEMS Si 50µm (probe V1), simulation	~600
MEMS Si 50µm (probe V0), simulation / analytical equation	~88 / 99
MEMS Si 15µm , [1]	~1300
DC Needle [X]	~10 ⁶

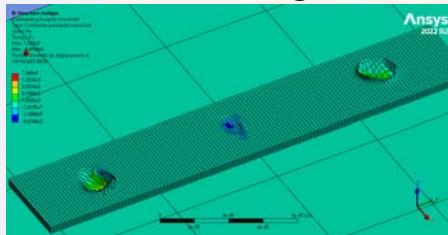
- ❑ The skating vs z-over-travel ratio seems similar for all 3 tip
- ❑ MEMS V2 probe stiffness seems sufficient compared to commercial probes

Mechanical simulation : results (3/3)

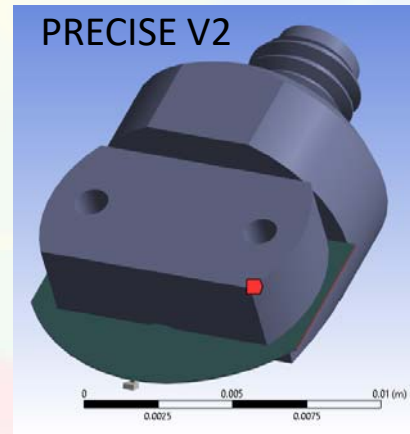


GGB 110 GHz

Scrubs on gold

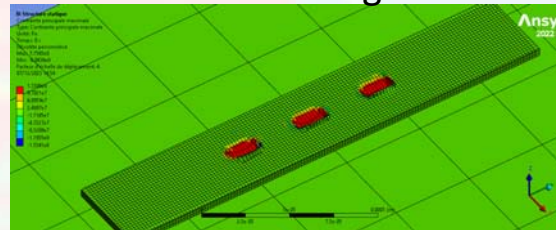


25µm overtravel
magnification **x4 (simulation)**



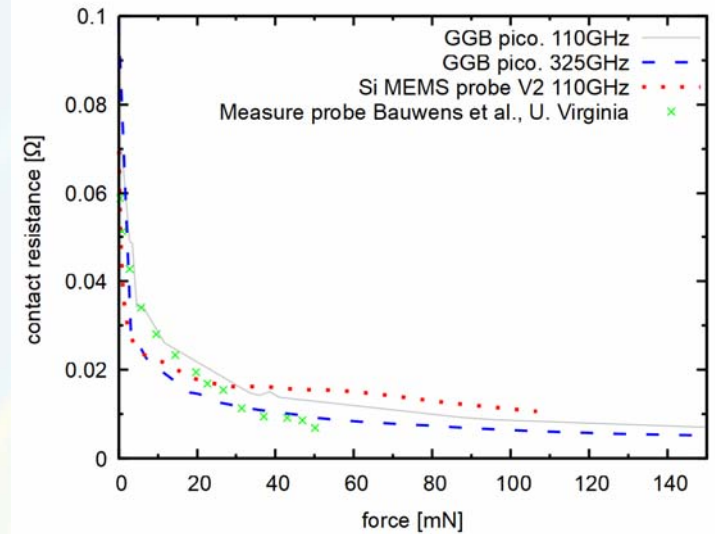
PRECISE V2

Scrubs on gold



20µm overtravel
magnification **x4 (simulation)**

$$R_C = \frac{\rho}{2a} \text{ with } a = \sqrt{\frac{F}{\pi H}}$$



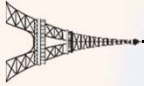
Contact resistance = $\rho / 2 a$

Conductivity on gold film $\rho=3.7\mu\Omega.cm$ [13]
 a = radius of penetration computed from contact area in Ansys

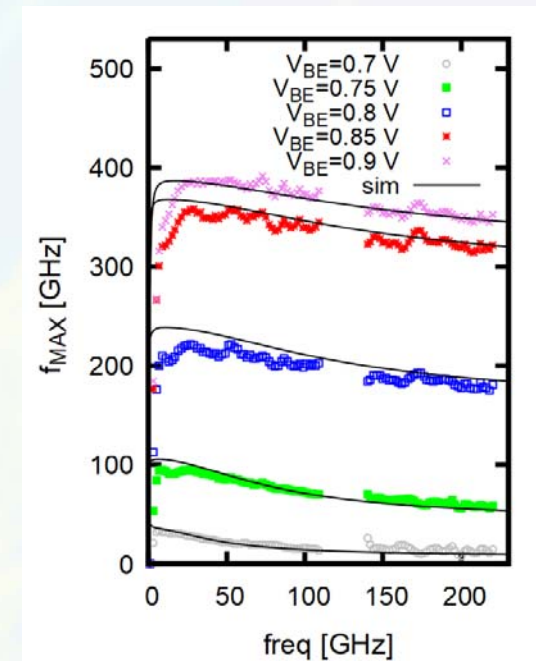
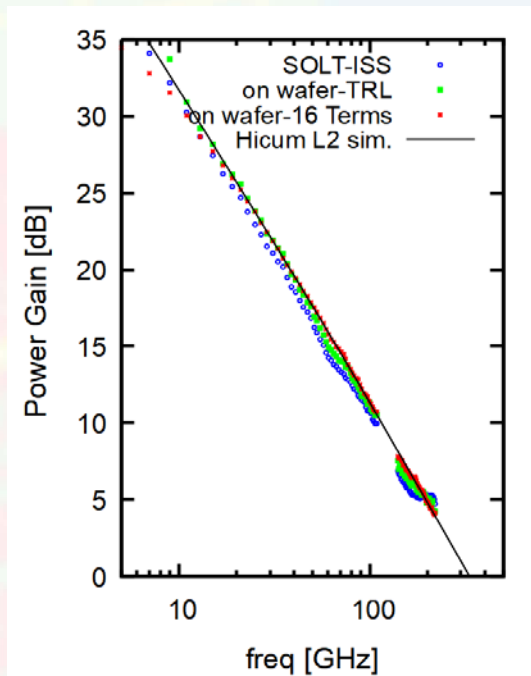


Conclusion and outlooks

- EM probe coupling needs to be decreased for the high freq. and miniaturized Si transistor
 - MEMS probes reduces EM coupling but:
 - Need to be optimized to increase the applied force
- => A tradeoff needs to be found between EM and Mechanical
- Outlooks:
 - Study the influence of the tips geometry on the contact stability
 - Attempts to fabricate a silicon probe at IEMN and MC2 technologies



- Special Session: ARFTG On-Wafer User's Forum on Tuesday morning
 - S. Fregonese et al. « Challenges in characterizing BiCMOS SiGe HBT technologies for FOM evaluation and compact modelling”





Thanks!

Email: sebastien.fregonese@ims-bordeaux.fr



Acknowledgements for providing silicon:

- IHP for SiGe HBT technology supply
- STMicroelectronics for BiCMOS 55nm supply

Work done within the framework of ANR PRECISE

Fruitfull discussion within ANR PRECISE :



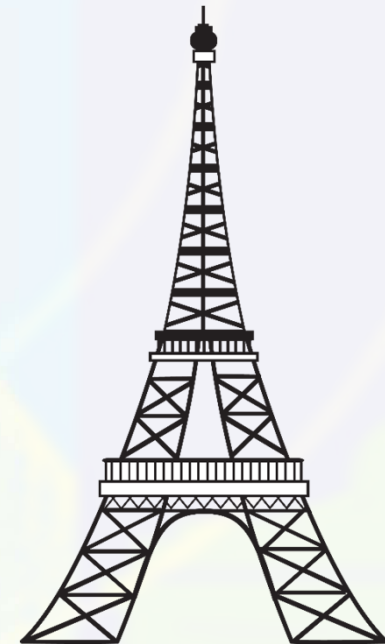
J. D. Arnould



S. Arscott, V. Merupo



C. Gaquiere



EuMW 2024 – WM-02, 23rd September 2024



Bibliography

- [1] Bauwens, Matthew, Electrical Engineering - School of Engineering and Applied Science, University of Virginia, "Micromachined On-Water Probes for Characterization of Terahertz Devices and Circuits", https://libraetd.lib.virginia.edu/public_view/7s75dc733, 2014
- [2] T. J. Reck *et al.*, "Micromachined on-wafer probes," *2010 IEEE MTT-S International Microwave Symposium*, Anaheim, CA, USA, 2010, pp. 65-68, doi: 10.1109/MWSYM.2010.5517580
- [3] M. Cabbia, PhD thesis « Calibrage sur plaquette et caractérisation des dispositifs à ondes (sub)millimétriques », 2021, Univ. Bordeaux
- [4] B. Heinemann *et al.*, "SiGe HBT with f_x/f_{max} of 505 GHz/720 GHz," *2016 IEEE International Electron Devices Meeting (IEDM)*, San Francisco, CA, USA, 2016, pp. 3.1.1-3.1.4, doi: 10.1109/IEDM.2016.7838335
- [5] N. Davy *et al.*, "InP DHBT On-Wafer RF Characterization and Small-Signal Modelling up to 220 GHz," *2023 18th European Microwave Integrated Circuits Conference (EuMIC)*, Berlin, Germany, 2023, pp. 101-104, doi: 10.23919/EuMIC58042.2023.10288849
- [6] T. Zimmer *et al.*, "SiGe HBTs and BiCMOS Technology for Present and Future Millimeter-Wave Systems," in *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 288-298, Jan. 2021, doi: 10.1109/JMW.2020.3031831
- [7] C. Yadav *et al.*, "Importance and Requirement of Frequency Band Specific RF Probes EM Models in Sub-THz and THz Measurements up to 500 GHz," in *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 5, pp. 558-563, Sept. 2020, doi: 10.1109/TTHZ.2020.3004517
- [8] M. Cabbia, C. Yadav, M. Deng, S. Fregonese, M. De Matos and T. Zimmer, "Silicon Test Structures Design for Sub-THz and THz Measurements," in *IEEE Transactions on Electron Devices*, vol. 67, no. 12, pp. 5639-5645, Dec. 2020, doi: 10.1109/TED.2020.3031575
- [9] S. Fregonese, M. Deng, M. Cabbia, C. Yadav, M. De Matos and T. Zimmer, "THz Characterization and Modeling of SiGe HBTs: Review (Invited)," in *IEEE Journal of the Electron Devices Society*, vol. 8, pp. 1363-1372, 2020, doi: 10.1109/JEDS.2020.3036135
- [10] S. Fregonese, M. De Matos, M. Deng, D. Céli, N. Derrier and T. Zimmer, "Importance of Probe Choice for Extracting Figures of Merit of Advanced mmW Transistors," in *IEEE Transactions on Electron Devices*, vol. 68, no. 12, pp. 6007-6014, Dec. 2021, doi: 10.1109/TED.2021.3118671
- [11] D. -S. Liu, M. -K. Shih and F. -M. Zheng, "An Investigation of Wafer Probe Needles Mechanical Properties and Contact Resistance Changing Under Multiprobing Process," in *IEEE Transactions on Components and Packaging Technologies*, vol. 31, no. 1, pp. 196-203, March 2008, doi: 10.1109/TCAPT.2008.916856
- [12] K. Miyoshi, T. Spalvins, et D. Buckley, « Friction and hardness of gold films deposited by ion plating and evaporation », août 1983. Consulté le: 22 novembre 2023. [En ligne]. Disponible sur: <https://www.semanticscholar.org/paper/Friction-and-hardness-of-gold-films-deposited-by-Miyoshi-Spalvins/b43d122f299aea8fe26c3a1ad18bf42258a51240>
- [13] H. Kwon *et al.*, « Investigation of the electrical contact behaviors in Au-to-Au thin-film contacts for RF MEMS switches », *J. Micromechanics Microengineering*, vol. 18, no 10, p. 105010, sept. 2008, doi: 10.1088/0960-1317/18/10/105010