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Federal Institute of Metrology METAS

Comsol Simulations for Scanning Microwave Microscopy

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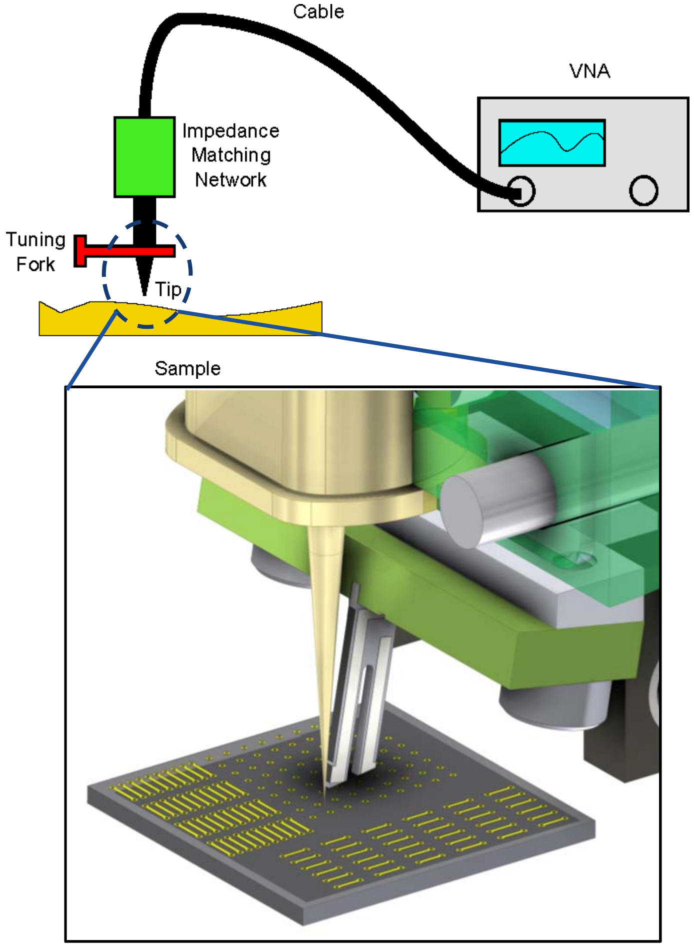
Federal Institute of Metrology METAS (Comsol conference, *Lausane, 22.10.2018)*

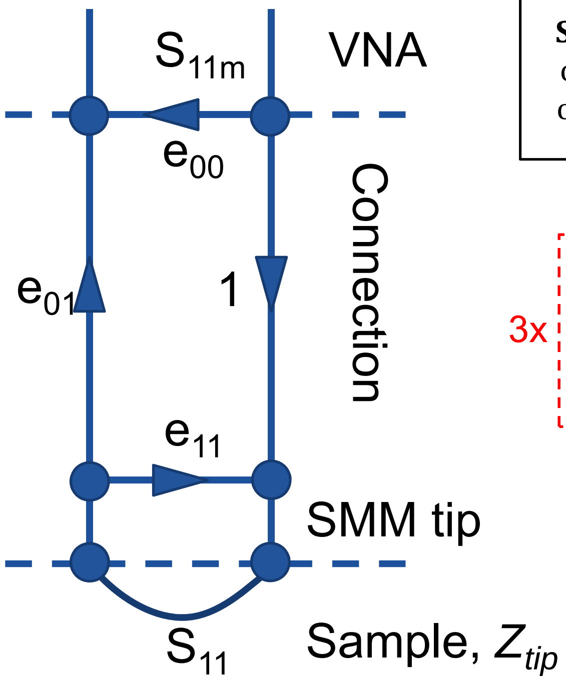
Scanning Microwave Microscope



A sketch of the Scanning Microwave Microscope (SMM) system in METAS (top panel) and 3D rendering of its tip (bottom panel)

- **Working principle**:
  - Sharp tip in contact with probed surface + microwave signals travelling between sample and Vector Network Analyzer (VNA).
  - Measured S_{11} values depend on electrical properties of materials
- Various types of Scanning Microwave Microscopes (SMM)
  - Cantilever-based (commercial version)
  - Tuning fork-based (our home-built version)
- Very versatile: different materials, environments.
- Non-invasive method + relaxed requirements on samples

Modified Short-Open-Load (SOL) calibration method for SMM



$$S_{11} = \frac{Z_{tip} - Z_{ref}}{Z_{tip} + Z_{ref}}$$

$$S_{11m} = e_{00} + \frac{e_{01} S_{11}}{1 - e_{11} S_{11}}$$

S_{11m} of three standards: obtained from simulated or real SMM experiments

Z_{tip} of three standards: obtained from numerical calculations or measurements using other methods

3x

$$S_{11} = \frac{Z_{tip} - Z_{ref}}{Z_{tip} + Z_{ref}}$$

$$S_{11m} = e_{00} + \frac{e_{01} S_{11}}{1 - e_{11} S_{11}}$$

e_{00}, e_{01} and e_{11}

S_{11m} of DUT device: from SMM experiments

$$S_{11} = \frac{S_{11m} - e_{00}}{e_{01} + e_{11}(S_{11m} - e_{00})}$$

$$Z_{extracted} = Z_{ref} \frac{1 + S_{11}}{1 - S_{11}}$$

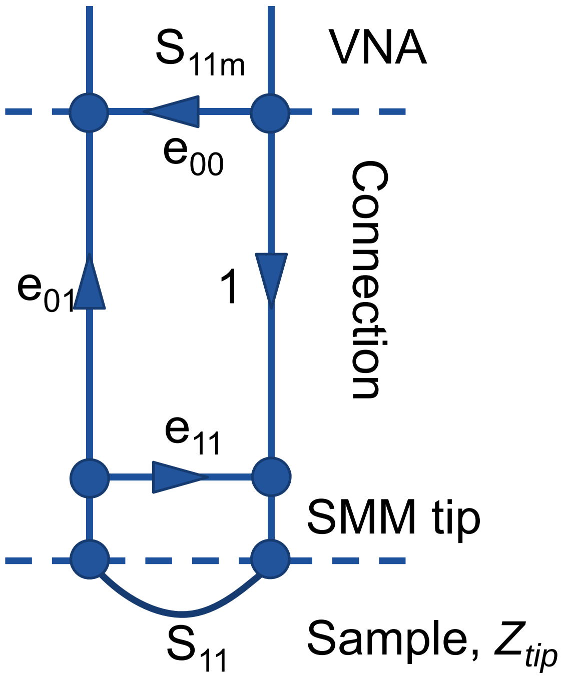
$Z_{extracted}$

Z_{tip} of DUT: from numerical calculations or other measurements

$if\ Z_{extracted} =/\approx Z_{tip}$:**SOL works**

$if\ Z_{extracted} >< Z_{tip}$:**SOL doesn't work**

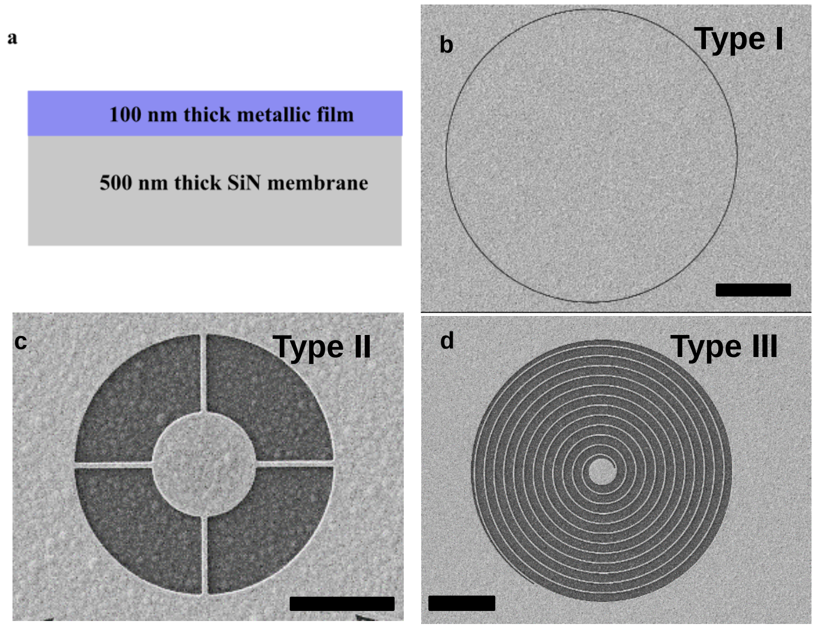
Scanning Microwave Microscopy-samples with lateral designs



$$S_{11} = \frac{Z_{tip} - Z_{ref}}{Z_{tip} + Z_{ref}}$$

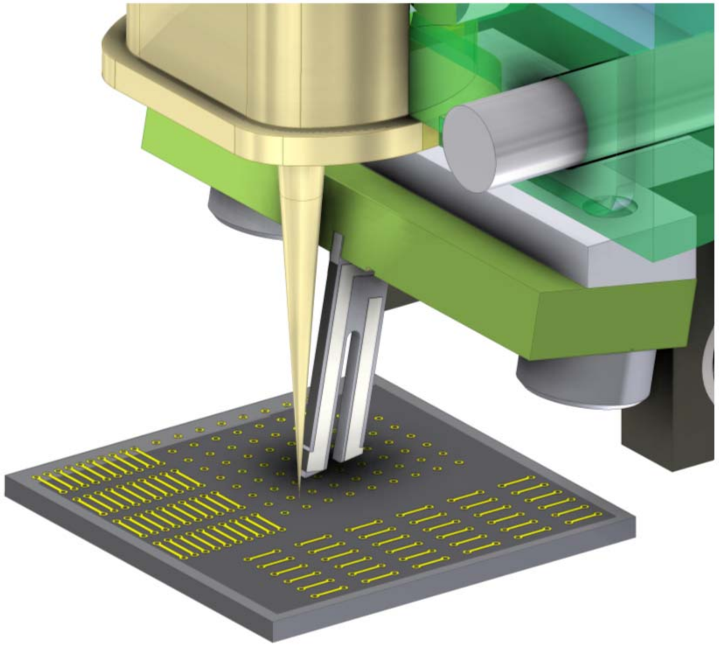
$$S_{11m} = e_{00} + \frac{e_{01} S_{11}}{1 - e_{11} S_{11}}$$

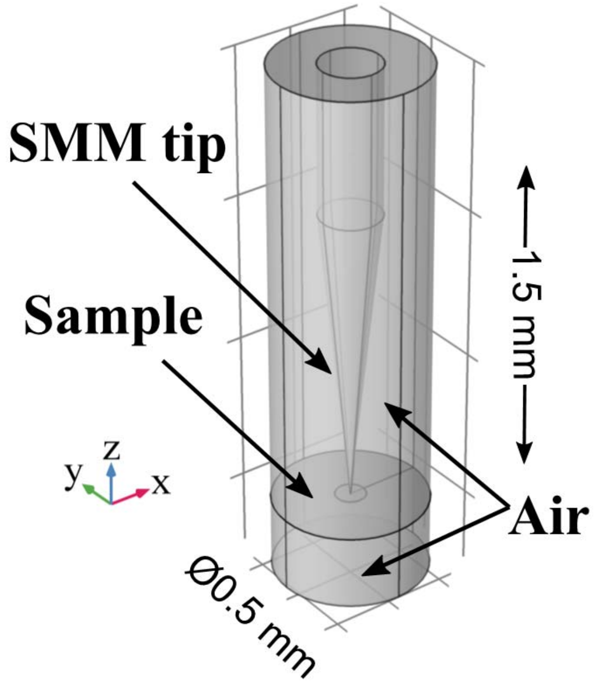
SMM experiments in progress: Patterned Au/Ti films on SiN membrane (new impedance standards). Each type of pattern has three standards and at least one DUT device to check SOL method.



Cross section view of real samples a), scanning electron microscopic top view of fabricated devices: type I b), type II c) and type III d). The scale bar are 10 µm, 2 µm and 10 µm correspondingly.

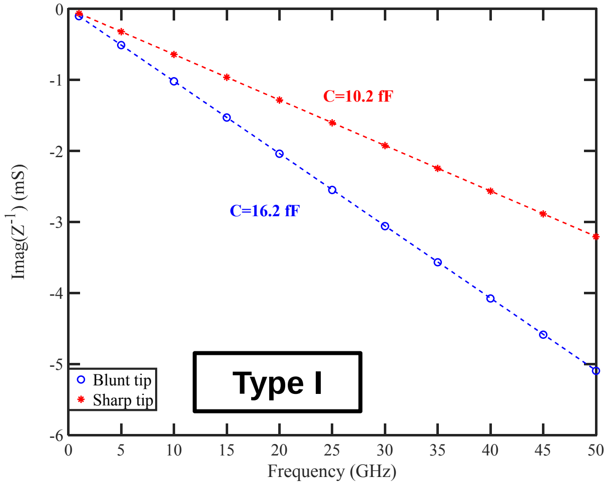
Comsol models-model construction





- Simplifications used for tip: smaller and shorter tip+ no connector/tuning fork.
- Simplification used for sample: smaller sample with only one pattern+made of only gold (a 5 nm thick Ti layer is ignored)
- Transition boundary conditions used to simulate the 100 nm thick metallic film.
- “Finer” meshing used.
- Simulations of SMM measurements using Electromagnetic wave interface, with Frequency domain. The frequency range: 1GHz-50GHz.
- S_{11m} and Z_{tip} obtained from simulations for all devices (**3 standards+1 DUT** for each type of pattern).
- Modelling for experiments using tips with different tip apex (diameter of 2 µm-blunt tip and 0.2 µm-sharp tip).

Frequency depedence of Z_{tip}



- Negative values + Imag(Z^{-1})(f)~(-f) : fingerprints of capacitor.
- Strong tip dependence?

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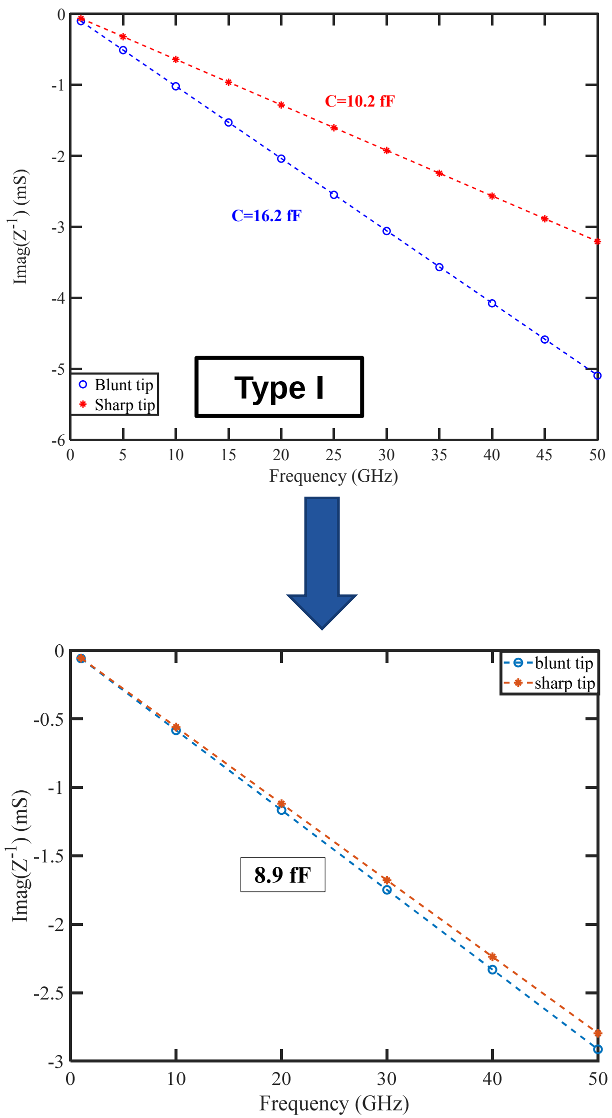
Frequency depedence of Z_{tip}

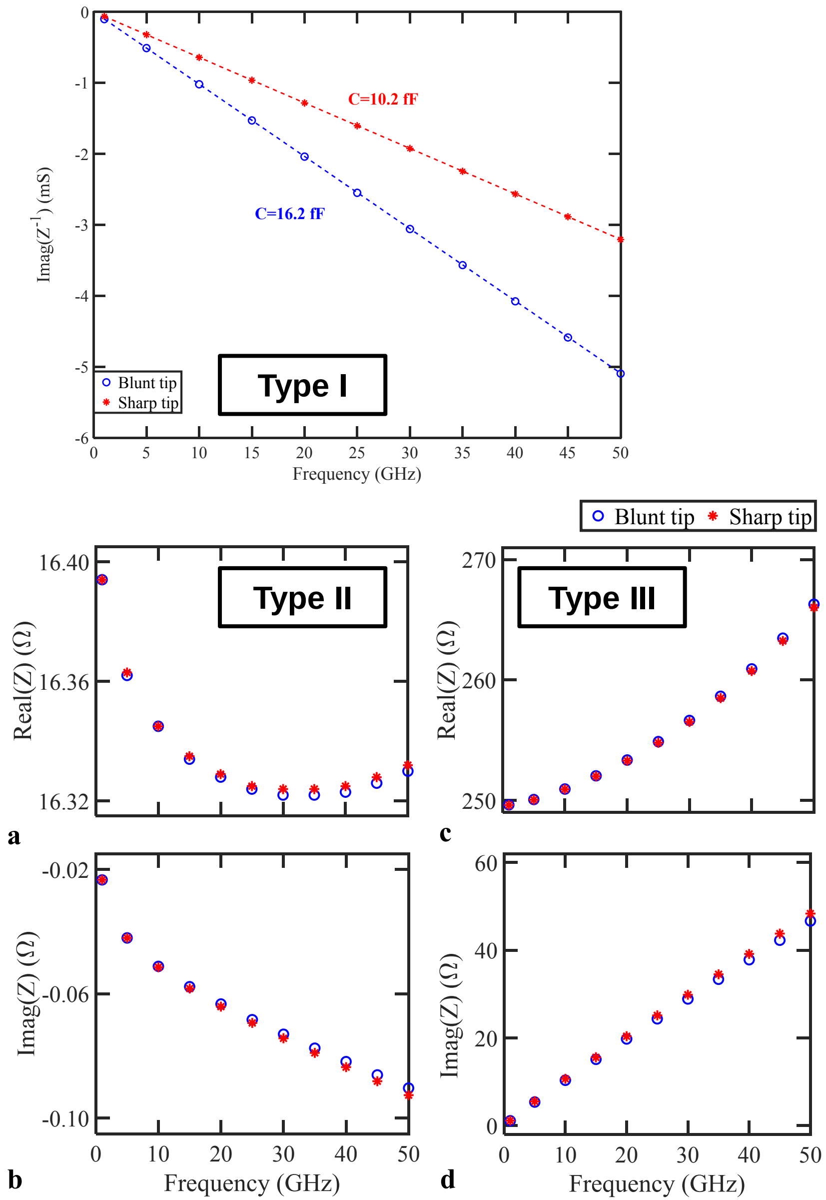


- Negative values + $Imag(Z^{-1})(f) \sim (-f)$: fingerprints of capacitor.
- Strong tip dependence? **No**

Folie 7

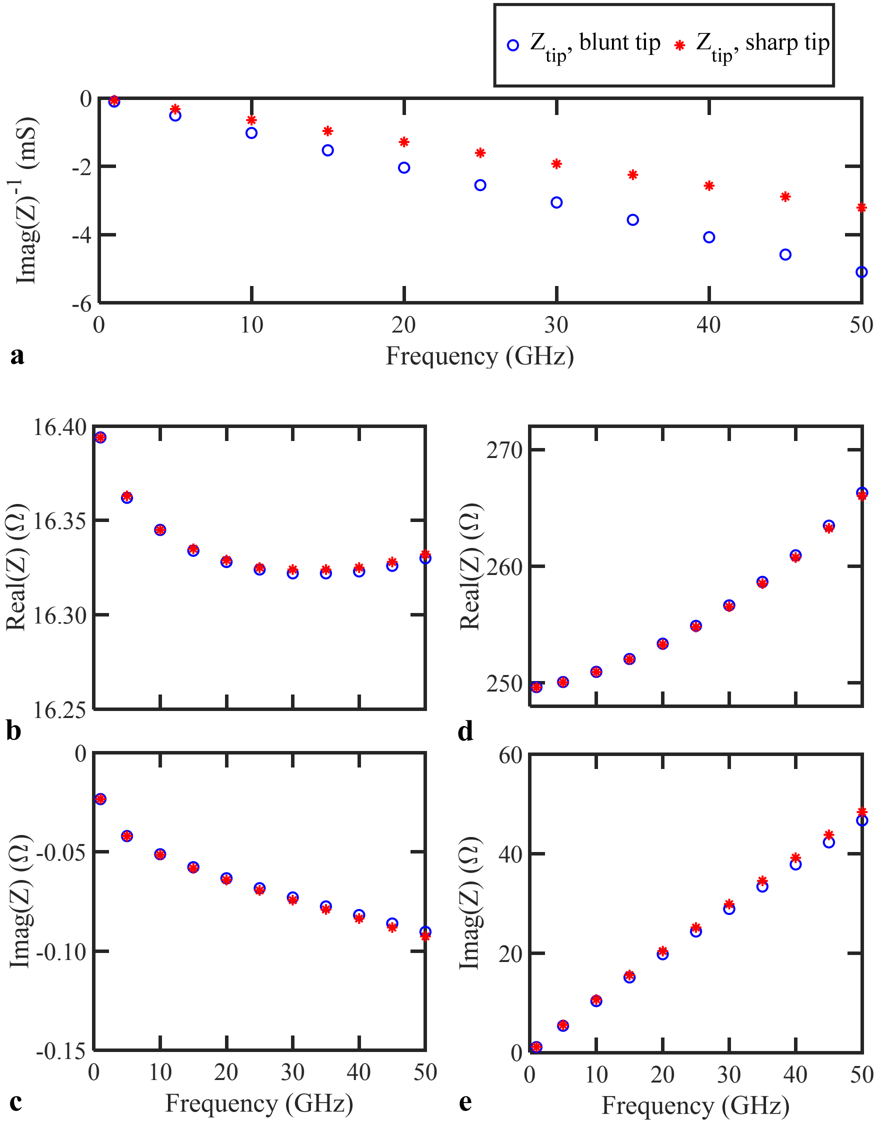
HOJO8 Hoffmann Johannes METAS; 17.10.2018

Frequency depedence of Z_{tip}



- Negative values + Imag(Z^{-1})(f)~(-f) : fingerprints of capacitor.
- Strong tip dependence? **No**
- a) + c): Resistive behavior for devices of type II and of type III.
- b): Tip-sample interaction as a source for minus sign in panel b)
- d): A presence of a strong inductance as expected for type III samples.
- Similar findings obtained for standard samples of all types.

Check the Short-Open-Load calibration method



$$S_{11}=\frac{Z_{tip}-Z_{ref}}{Z_{tip}+Z_{ref}}$$

$$S_{11m}=e_{00}+\frac{e_{01}S_{11}}{1-e_{11}S_{11}}$$

$$S_{11}=\frac{S_{11m}-e_{00}}{e_{01}+e_{11}(S_{11m}-e_{00})}$$

$$Z_{extracted}=Z_{ref}\frac{1+S_{11}}{1-S_{11}}$$

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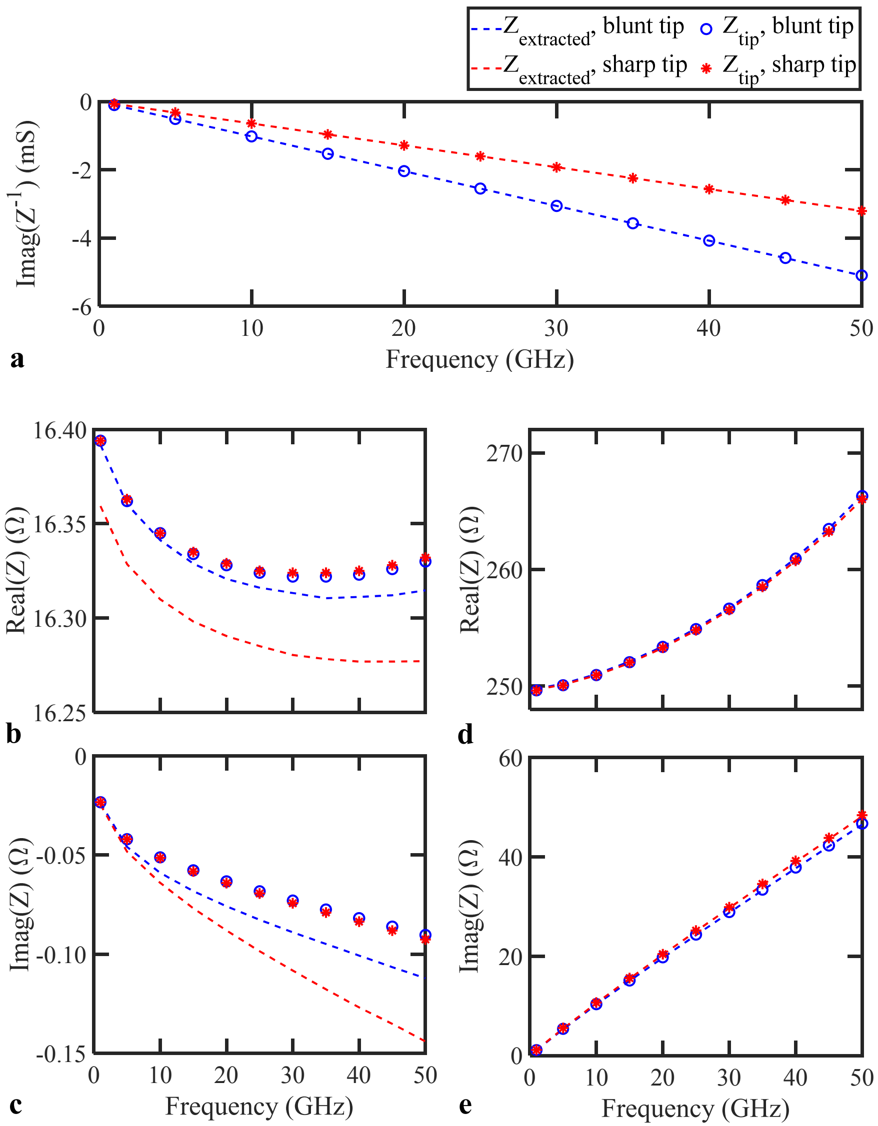

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$$Z_{extracted}=Z_{ref}\frac{1+S_{11}}{1-S_{11}}$$

- SOL works with certain uncertainty: can come from meshing issue
- Tip independence
- Frequency independence: between 1 GHz and 50 GHz

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Conclusions

- ✓ Construct simplified COMSOL models for SMM measurements
- ✓ Check Short-Open-Load calibration technique for SMM measurements

Outlook

- Use better meshing
- Simulations using patterns imported from AUTOCAD (more similar to those used in real experiments)
- Check another calibration technique and compare these two methods
- Perform real experiments

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Acknowledgements

- This research is a part of ADVENT project, which is funded by the European Metrology Programme for Innovation and Research (EMPIR). The goal of this project is to develop nanometrology adapted to characterization of advanced materials for future electronic devices

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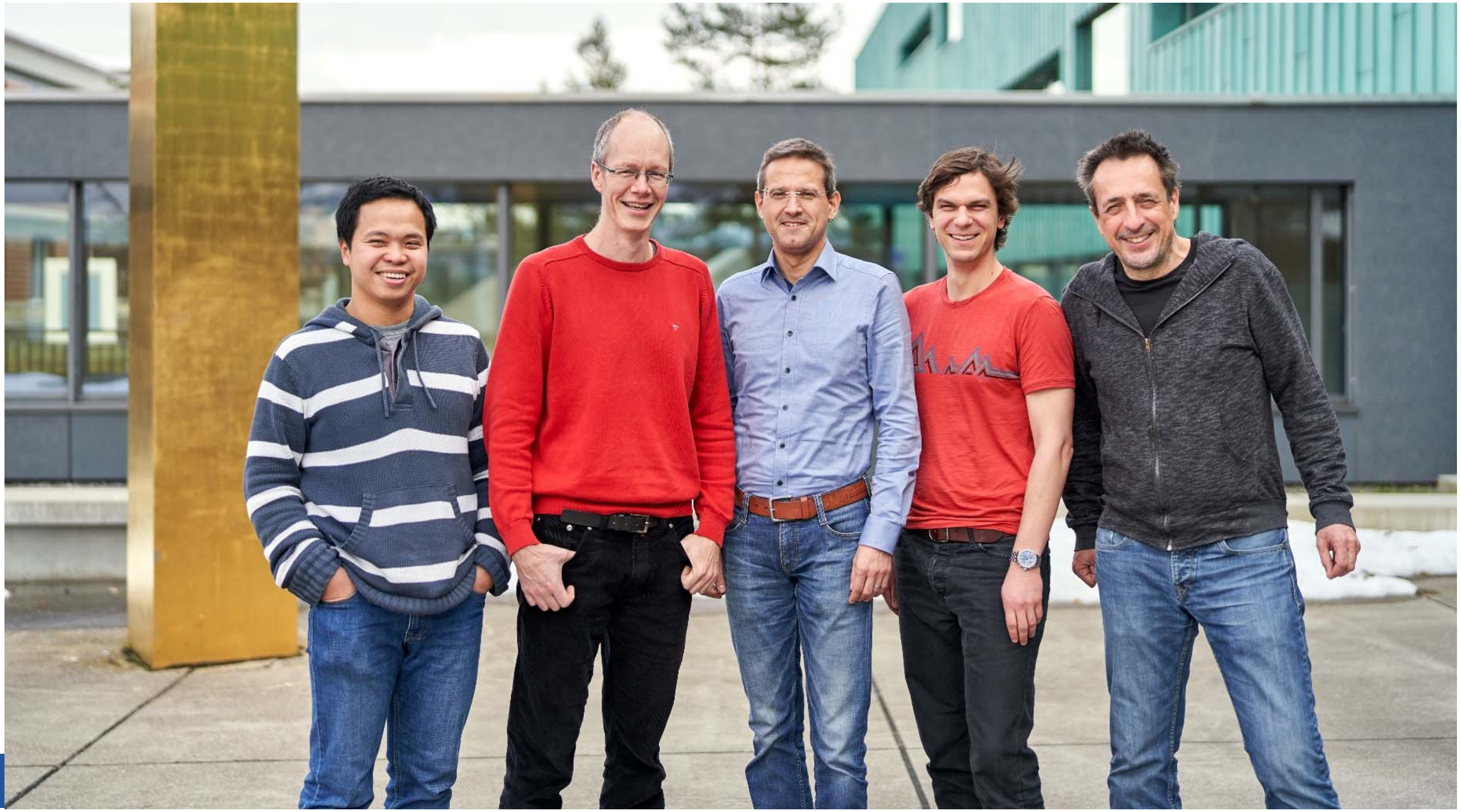
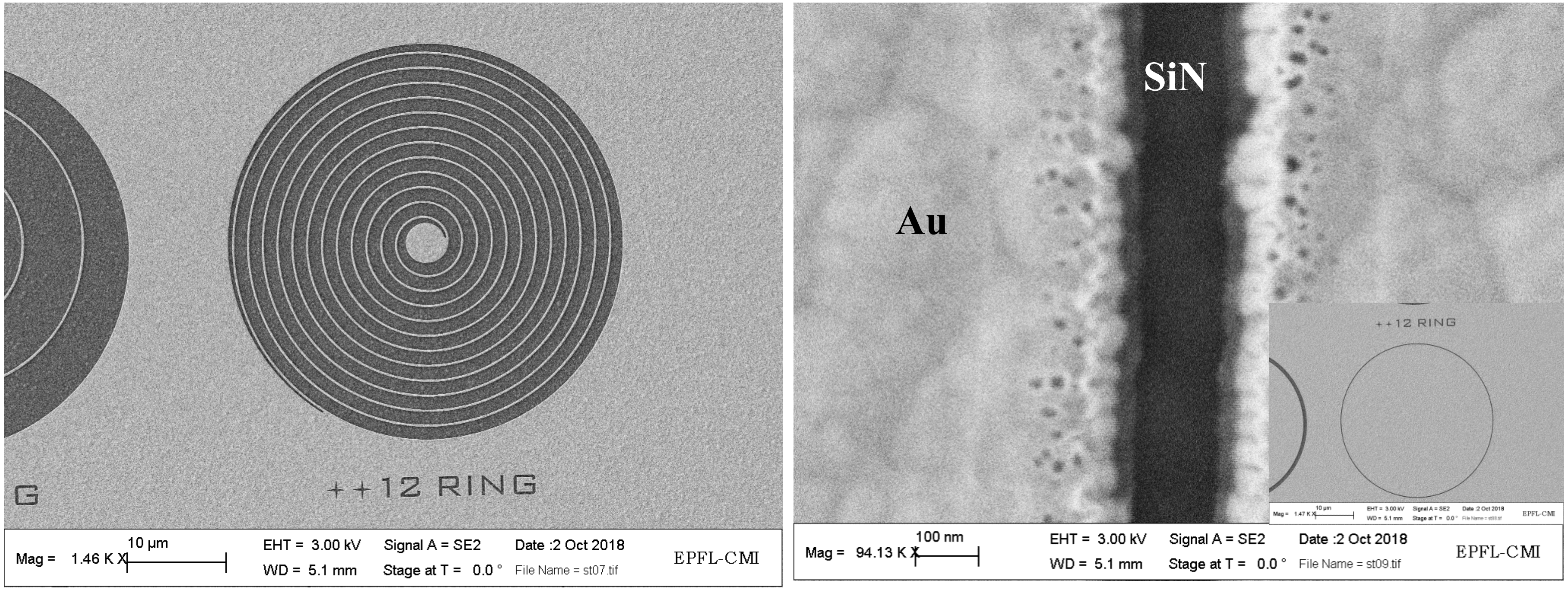


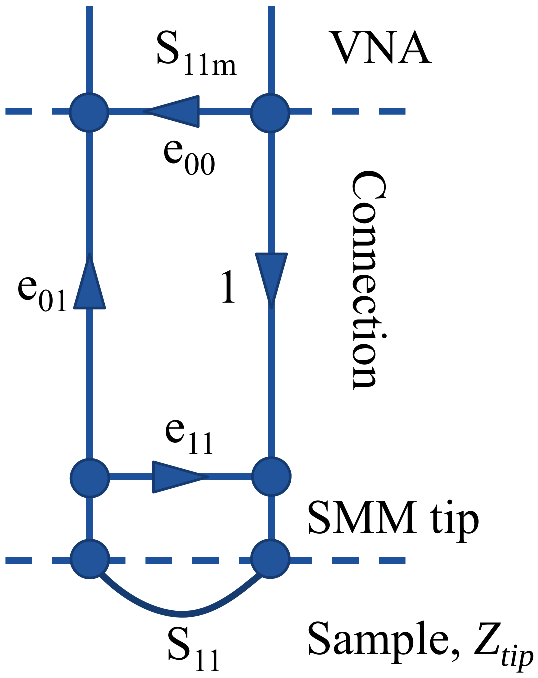
Thank you very much for your attention

Real samples



Scanning Electron Microscopic images of fabricated samples: a large view of a pattern with spiral bridge (left panel) and a zoom in of a small SiN separation in a capacitor (shown in the inset).

Modified Short-Open-Load (SOL) calibration method for SMM: study of GaAs samples

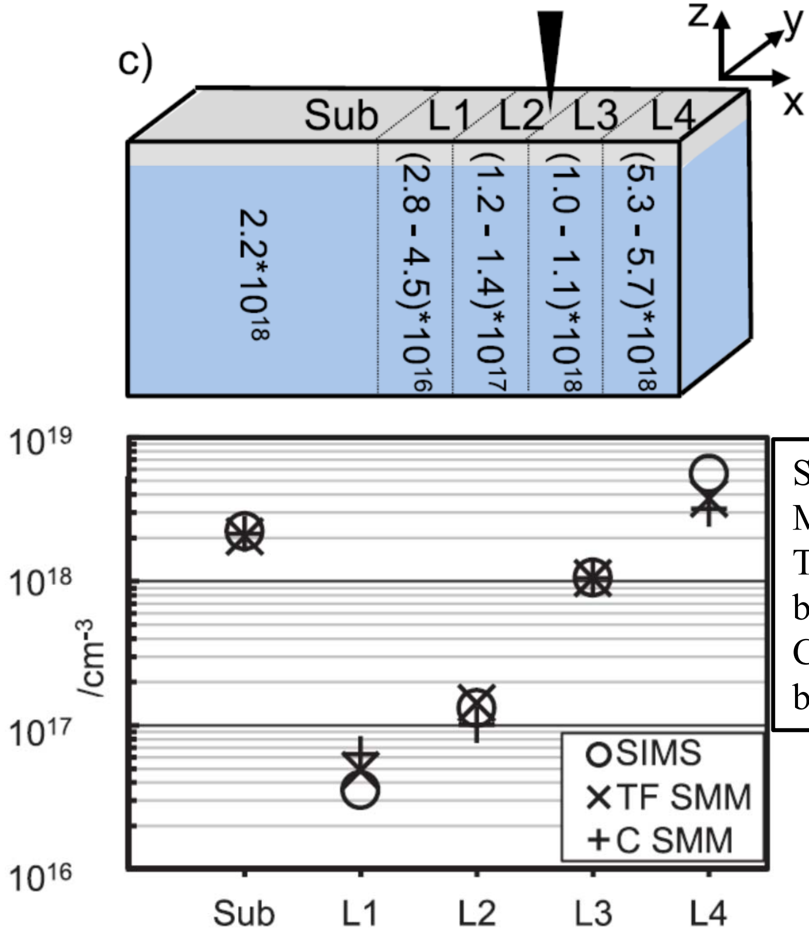


$$S_{11}=\frac{Z_{tip}-Z_{ref}}{Z_{tip}+Z_{ref}}$$

$$S_{11m}=e_{00}+\frac{e_{01}S_{11}}{1-e_{11}S_{11}}$$

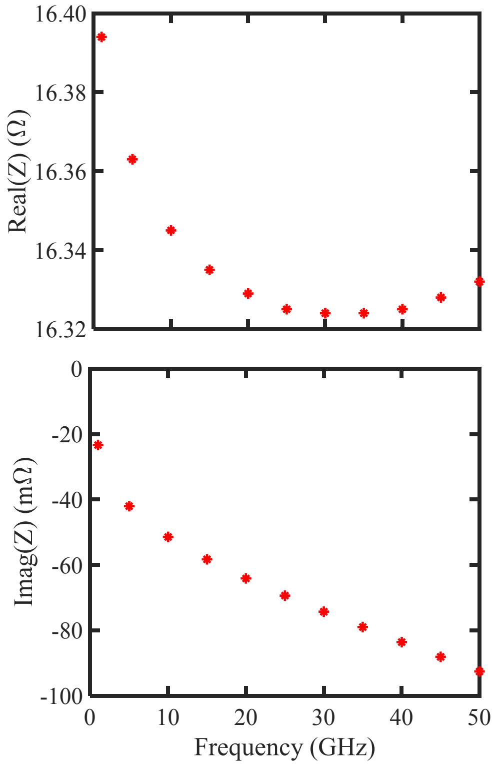
SMM measurements on a GaAs multilayer with a staircase-like dopant structure

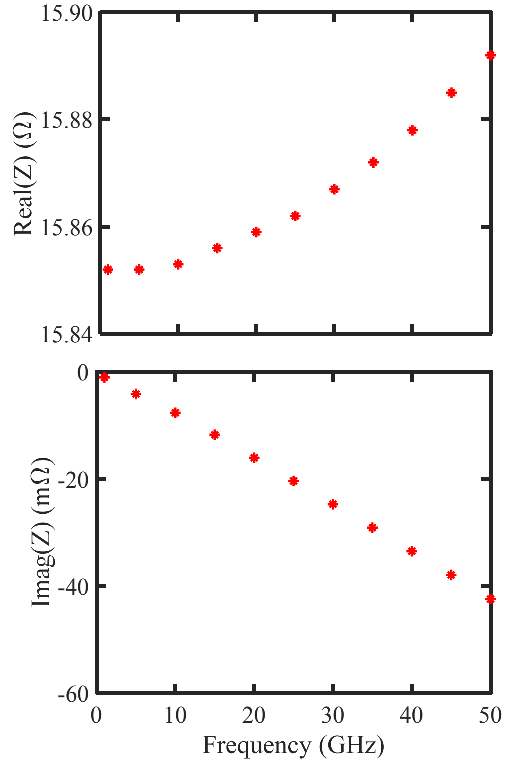
Rev. Sci. Instrum., ***89***, *023704 (2018)*



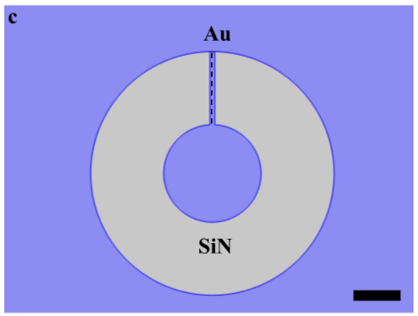
SIMS: Secondary Ion Mass Spectrometry
TF-SMM: tuning fork based SMM (METAS)
C-SMM: Cantilever-based SMM

Recovered curve





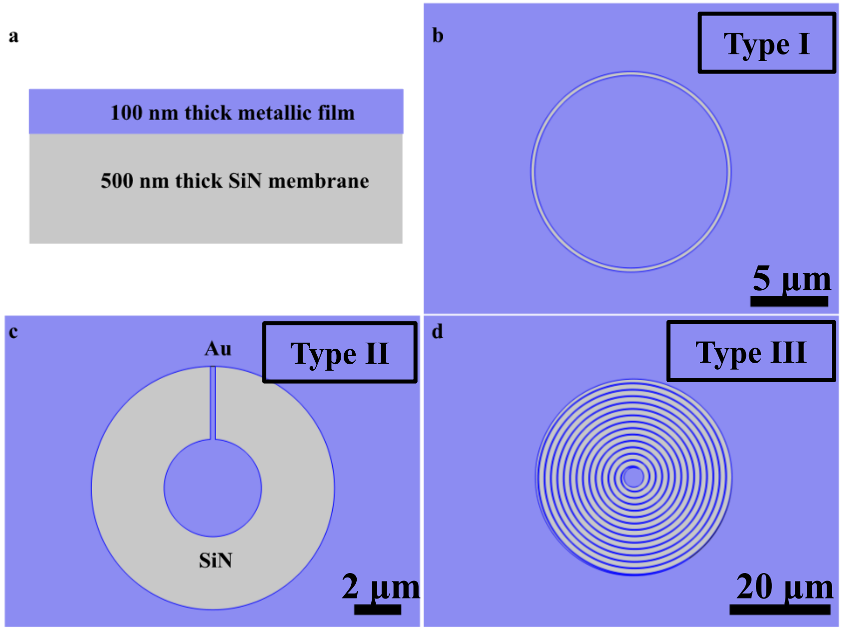
Integrating along a line connecting the landing pad and the wall (along a 248 μm long line)



Integrating **ONLY** along the existing bridge (the length is 13 μm for this line)

Measured impedance, Z_{tip}, at 1GHz

Type of circuits	Standard 1 (Ohm)	Standard 2 (Ohm)	Standard 3 (Ohm)	DUT (Ohm)	
Type I	0-84342i	0-47311i	0-10963i	2.384-15574i	Capacitor
Type II	0.707-0.008i	10.280-0.019i	22.508-0.027i	16.394-0.023i	Resistor
Type III	25.159+0.090i	48.784+0.206i	992.97+7.190i	249.61+1.142i	Resistor+inductor



Outline

1. Scanning Microwave Microscopy
2. Comsol models
3. Results
4. Conclusions