Overview of Scanning microwave microscopy (SMM)

- Calibration
- Applications (semicon, materials, bio)
- Advanced solutions

7500 SMM

Ferry Kienberger

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Agenda

- Overview & SMM Introduction
- Dopant profiling (dC/dV) for semiconductors
- Complex impedance for materials science
  - Calibration
  - Subsurface imaging
  - Resistivity from resistance
  - Dielectric quantification
  - 2D materials (graphene)
- Multi-modal SMM solutions
  - Augmented SMM (SMM plus add-ons)
  - New modes: transmission, magnetic, and QuBits
- Bio-SMM & liquid imaging
- Summary

Collaborators & Acknowledgments (selected)

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Keysight Austria

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Michael Dieudonne

TU Vienna, Austria

Juergen Smoliner

METAS (Bern)

Johannes Hoffmann

NIST USA

Pavel Kabos

IBEC Barcelona

Gabriel Gomila

CNR-IMM

Romollo Marcelli

Funding: EC FP7 VSMART, MC-ITN Nanomicrowave, Bio-SMM FFG Austria, MMAMA NMBP Project

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Agenda

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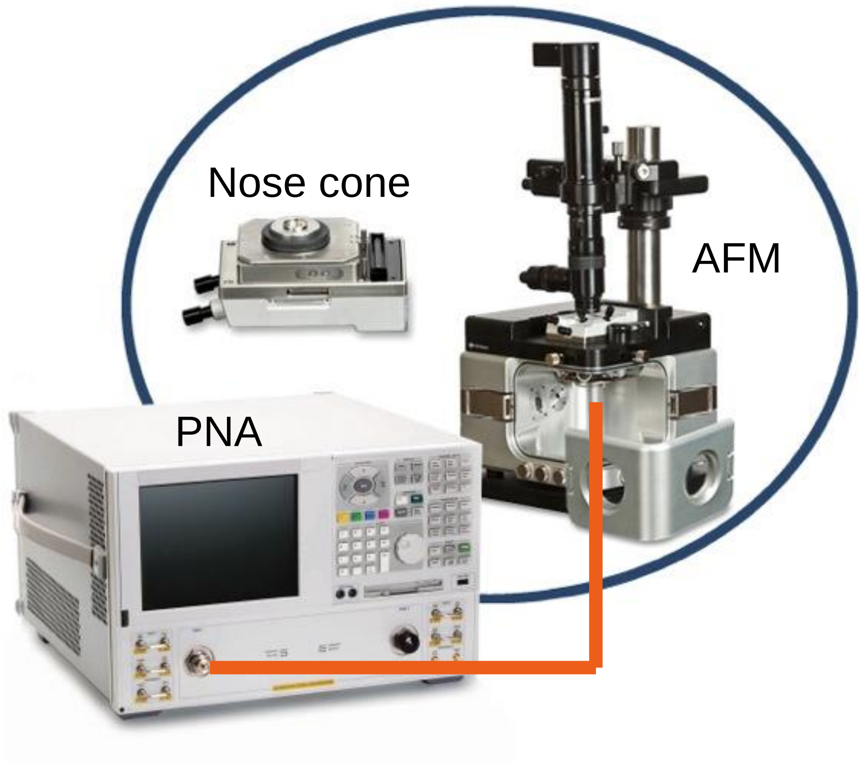
What is SMM?

SMM = PNA + AFM



– SMM: Atomic force microscope (AFM) interfaced with a Performance Network Analyzer (PNA)

– PNA Network analysis for microwave frequencies (1-20 GHz)

– PNA: stimulus-response instrument, Measuring magnitude and phase characteristics of a sample

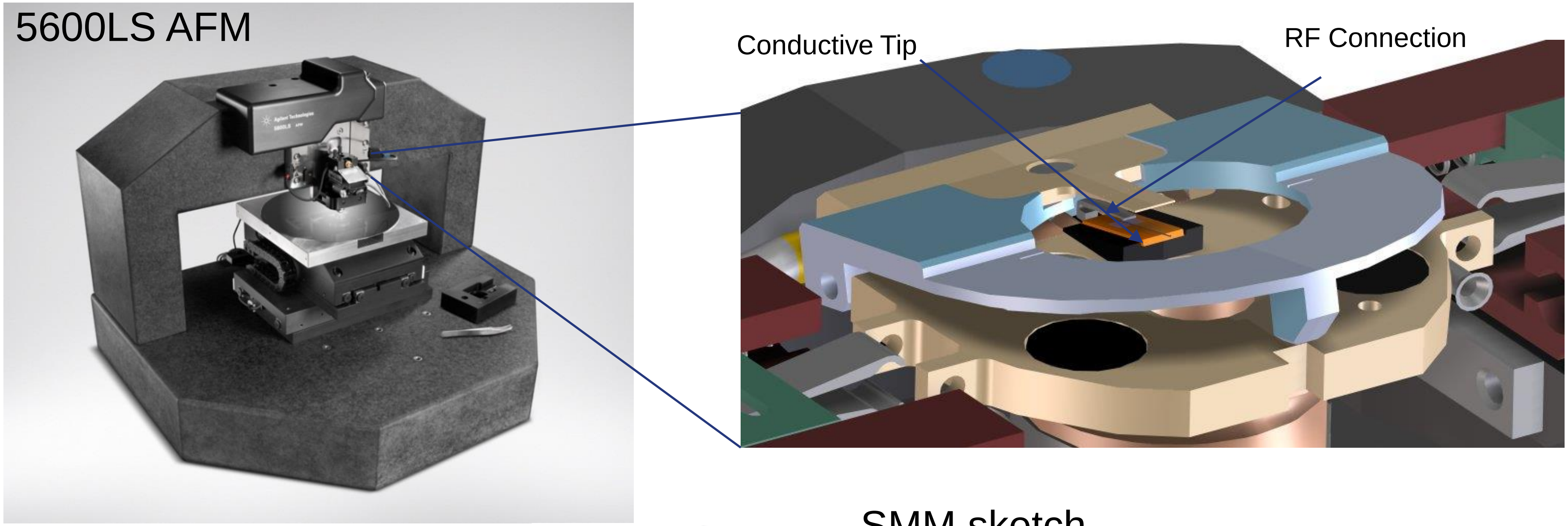
Consider:

- High Frequency allows to measure also non-conductive samples (eg DC STM only on conductive samples)

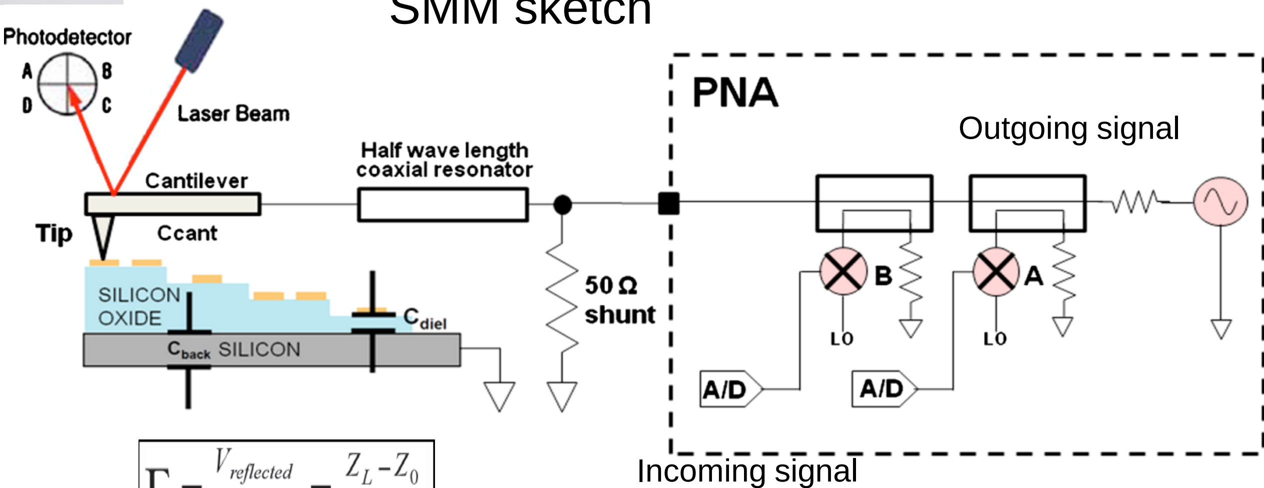
- GHz Frequency results in better sensitivity (eg compared to MHz impedance AFM)

- Microwaves have good sample penetration capabilities

The Scanning Microwave Microscope



SMM sketch



$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Huber et al., RSI, 81, 2010, 113701

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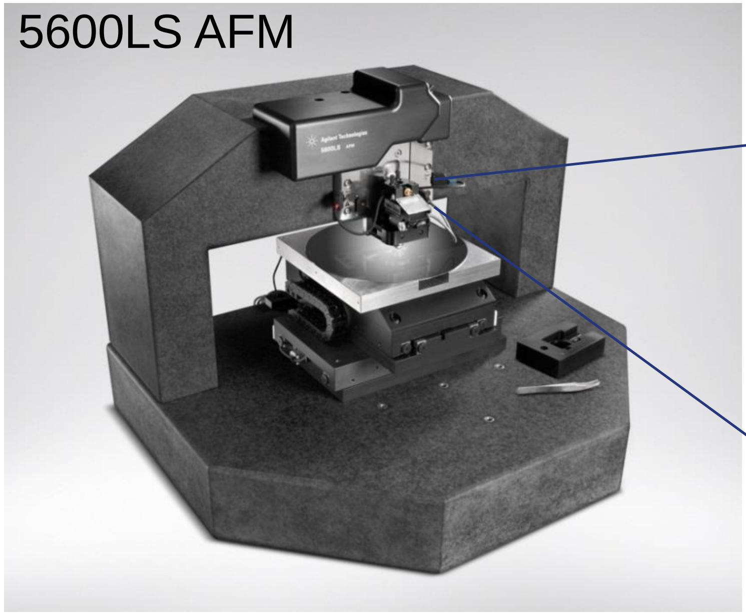
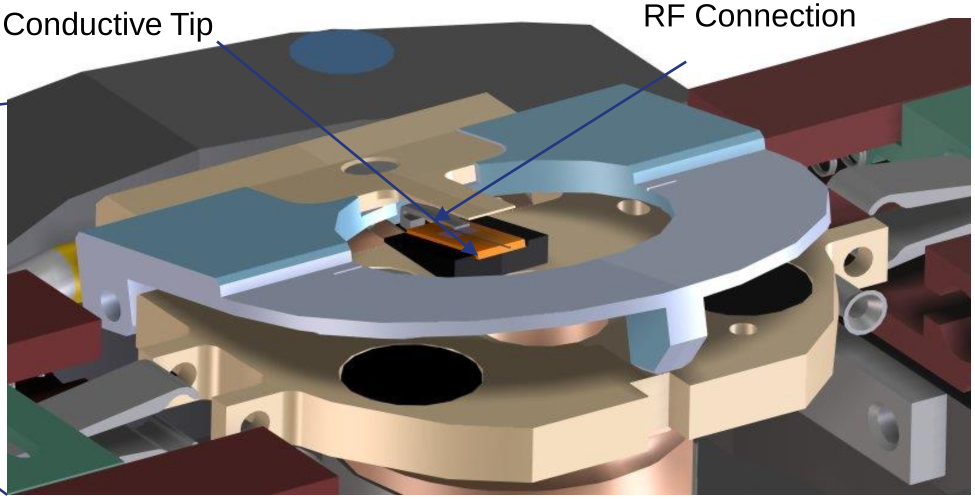
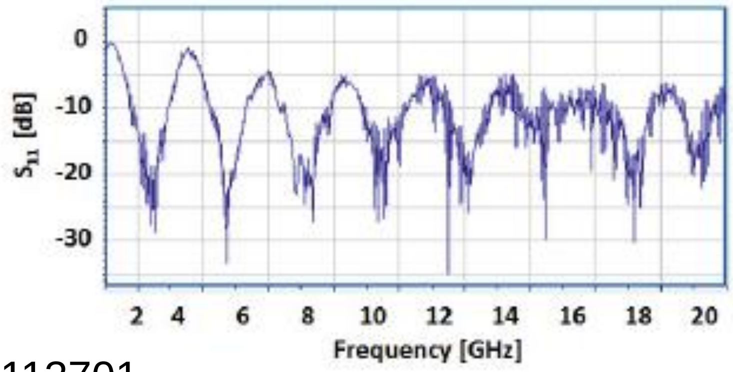
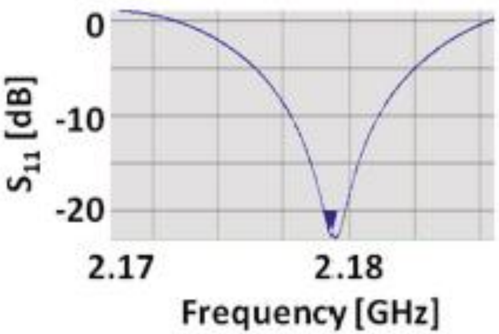
The Scanning Microwave Microscope





Resonance matches at multiple frequencies





Huber et al., RSI, 81, 2010, 113701

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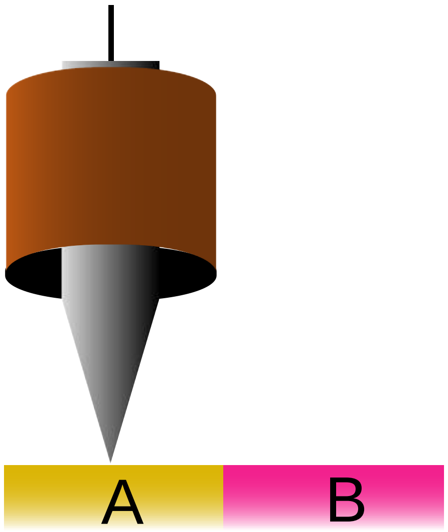
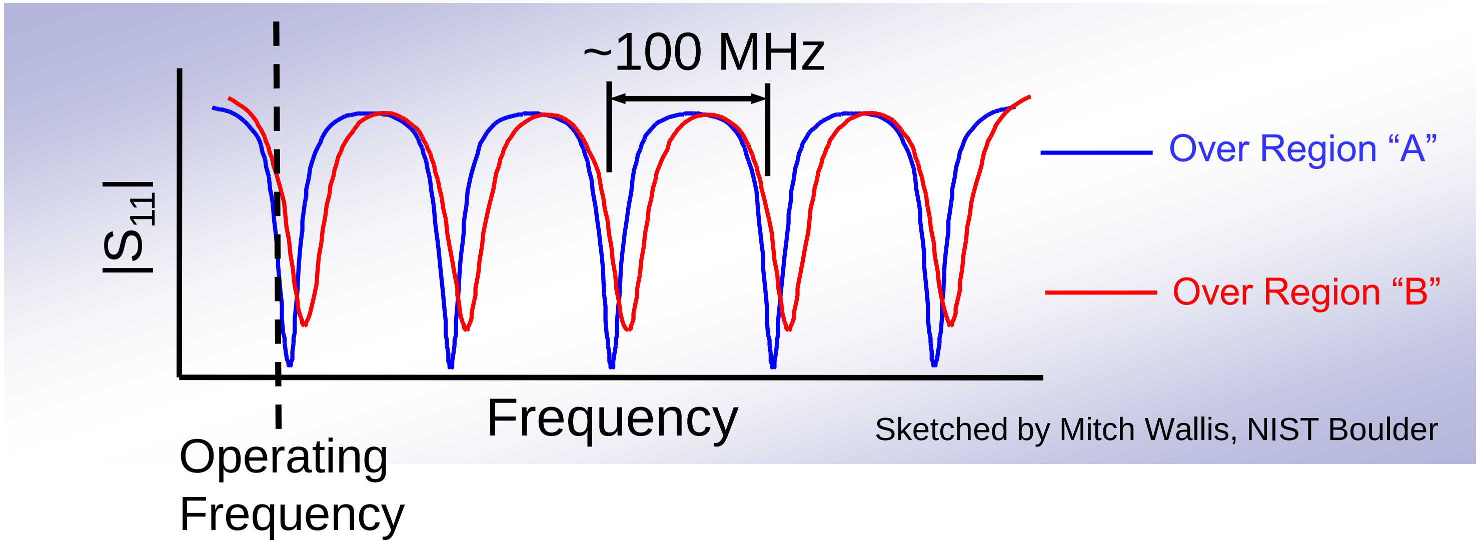
SMM Contrast Mechanism: also on non-conductive samples



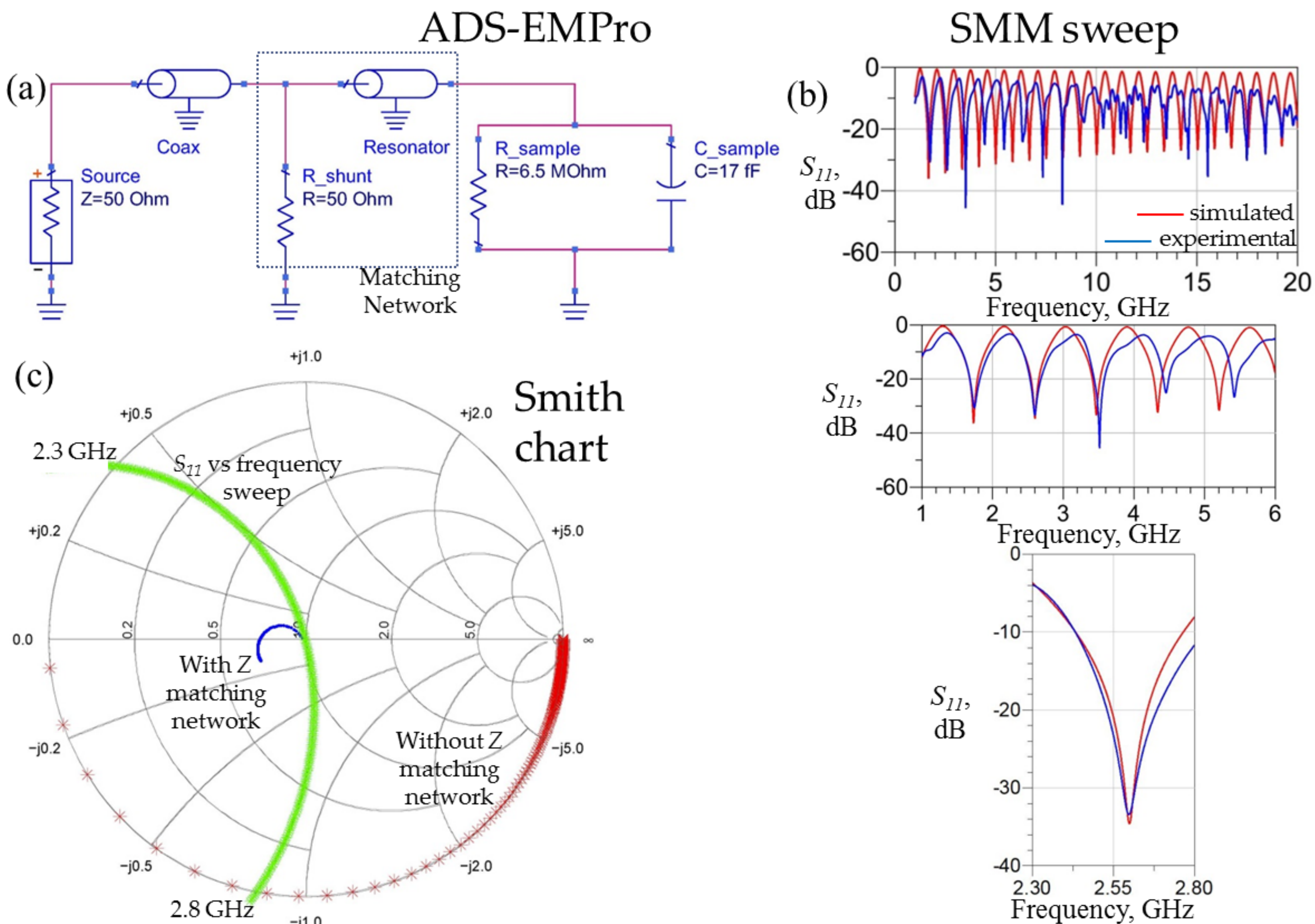
Regions "A" and "B" present different impedances and material properties of the two regions. Examples:

- complex permittivity (ε' + i ε")
- complex permeability (μ' + i μ") & magnetic prop.
- conductivity (σ)
- carrier concentration / dopant (n)



Optimization of SMM imaging parameters: CNR-Rome
Sardi, Marcelli et al, APL 107 (2015), 033107

ADS model and Smith Chart analysis



Smith chart on the PNA window

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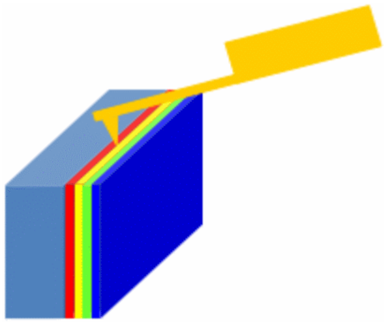
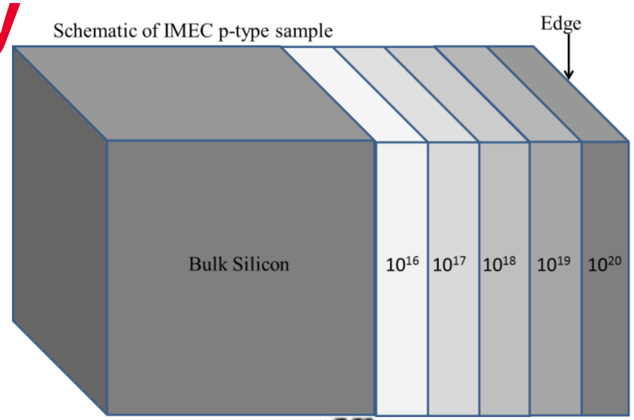
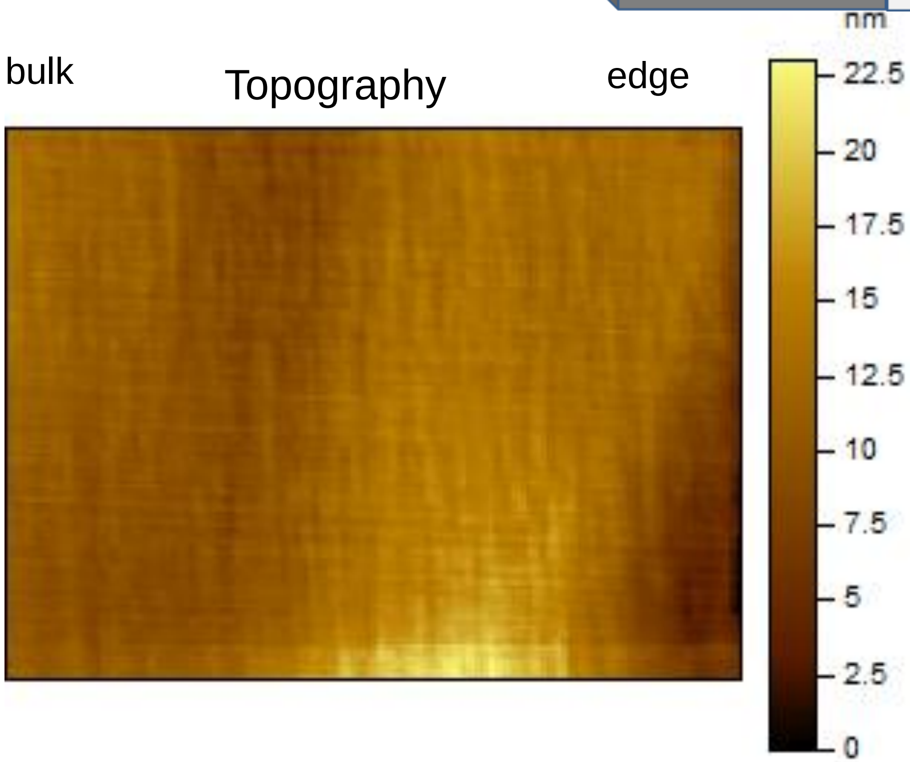
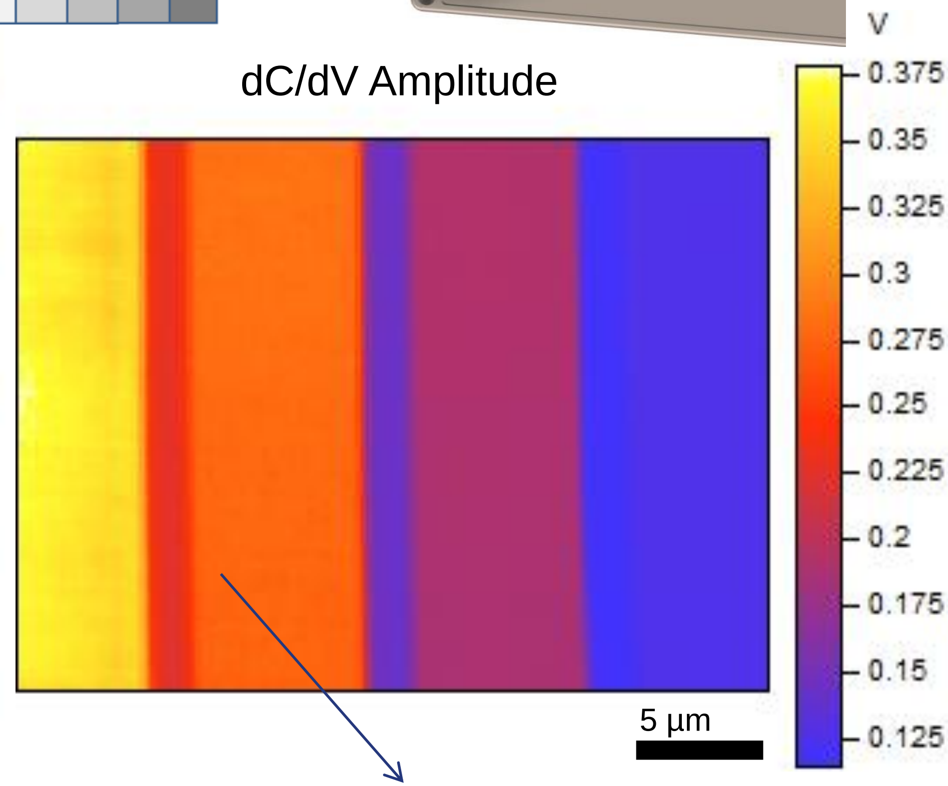
Dopant density







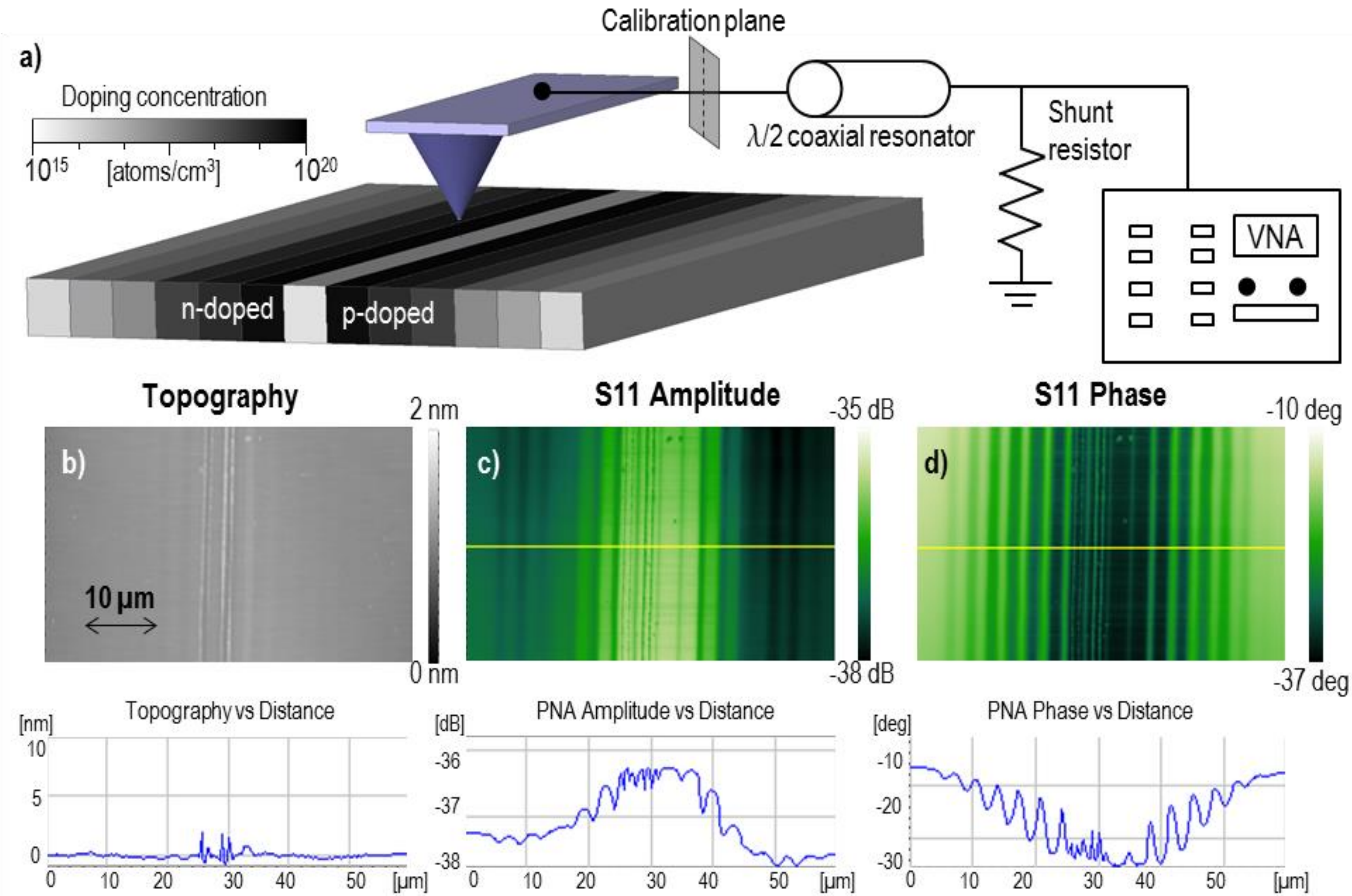


Different dopant densities

J. Appl. Physics 111, 014301, 2012

KEYSIGHT TECHNOLOGIES

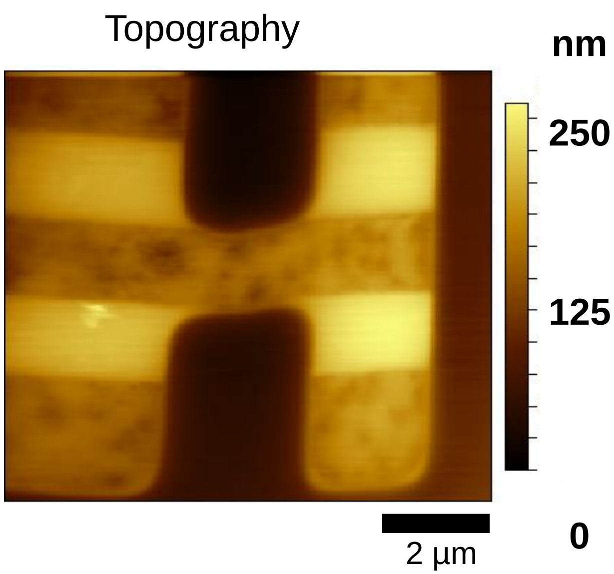
Dopant profiling on the nano-scale with a new calibration sample

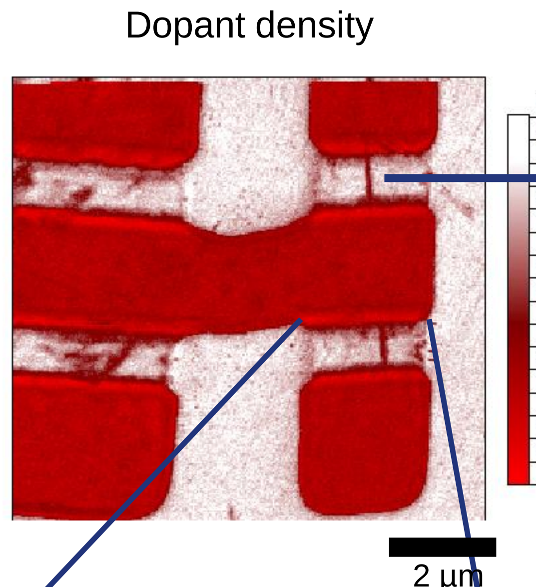


KEYSIGHT TECHNOLOGIES

Enrico Brinciotti et al., Nanoscale, Oct 2015

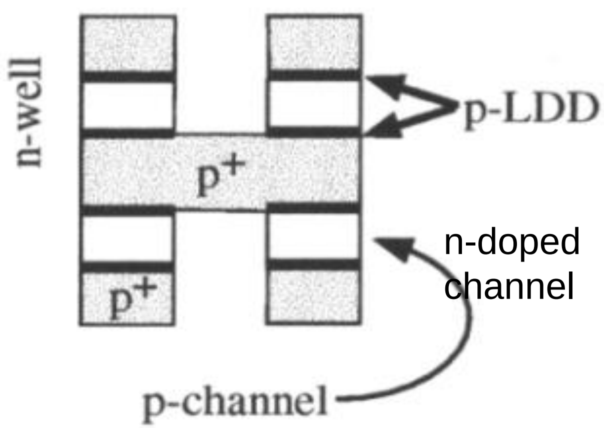
Dopant profiling application to SRAM

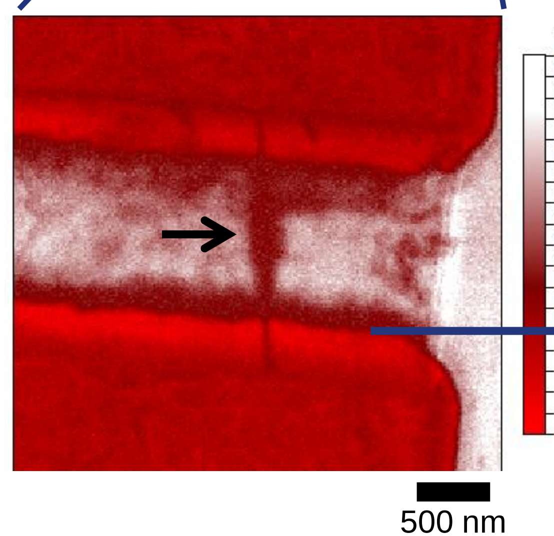




Defect structures which compromise device performance can be observed in the channels

Defect structures can't be observed in the topo image.





p-n transition region

Huber et al., J. Appl. Physics 111, 014301, 2012
Imtiaz et al., JAP 111, 093727; 2012

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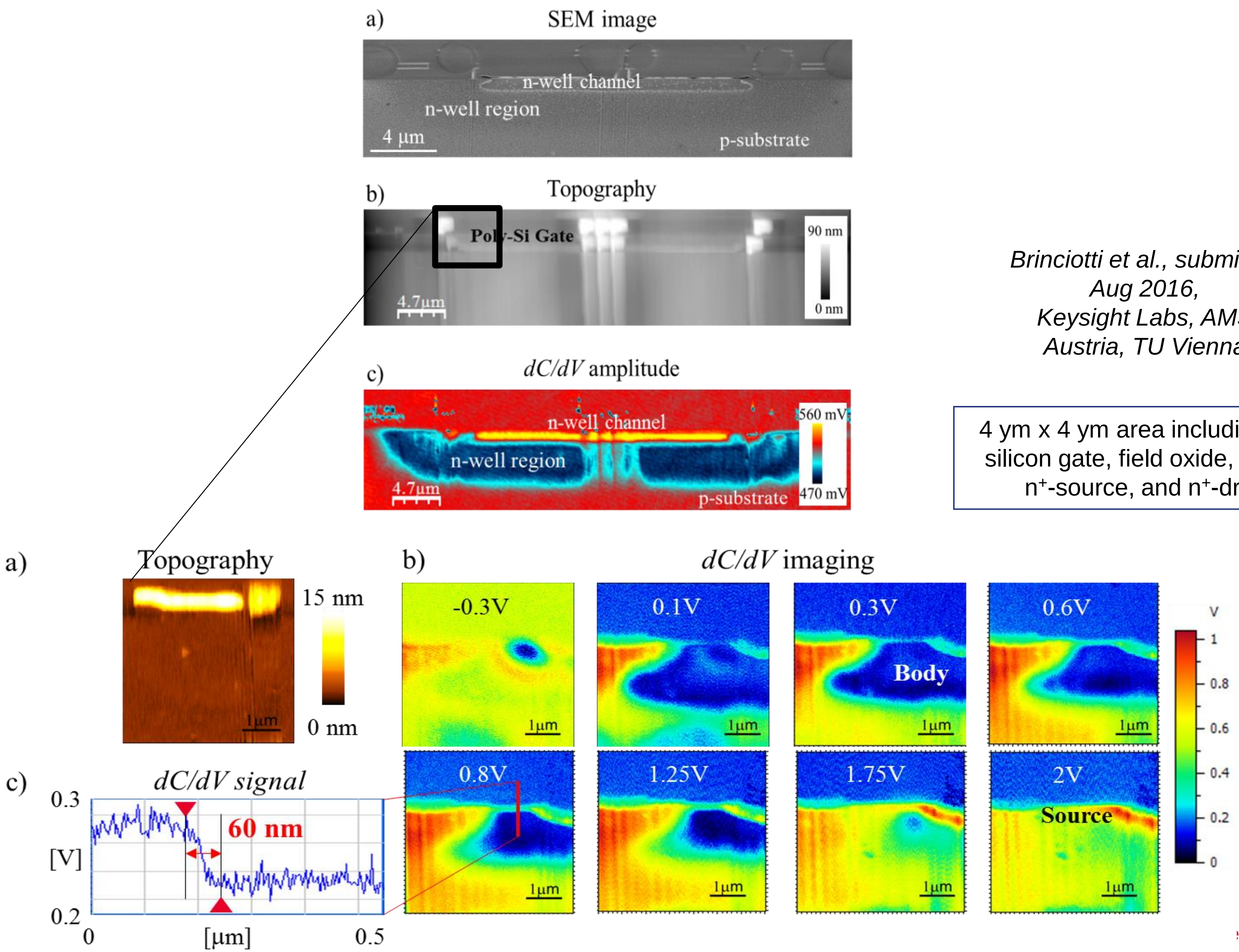
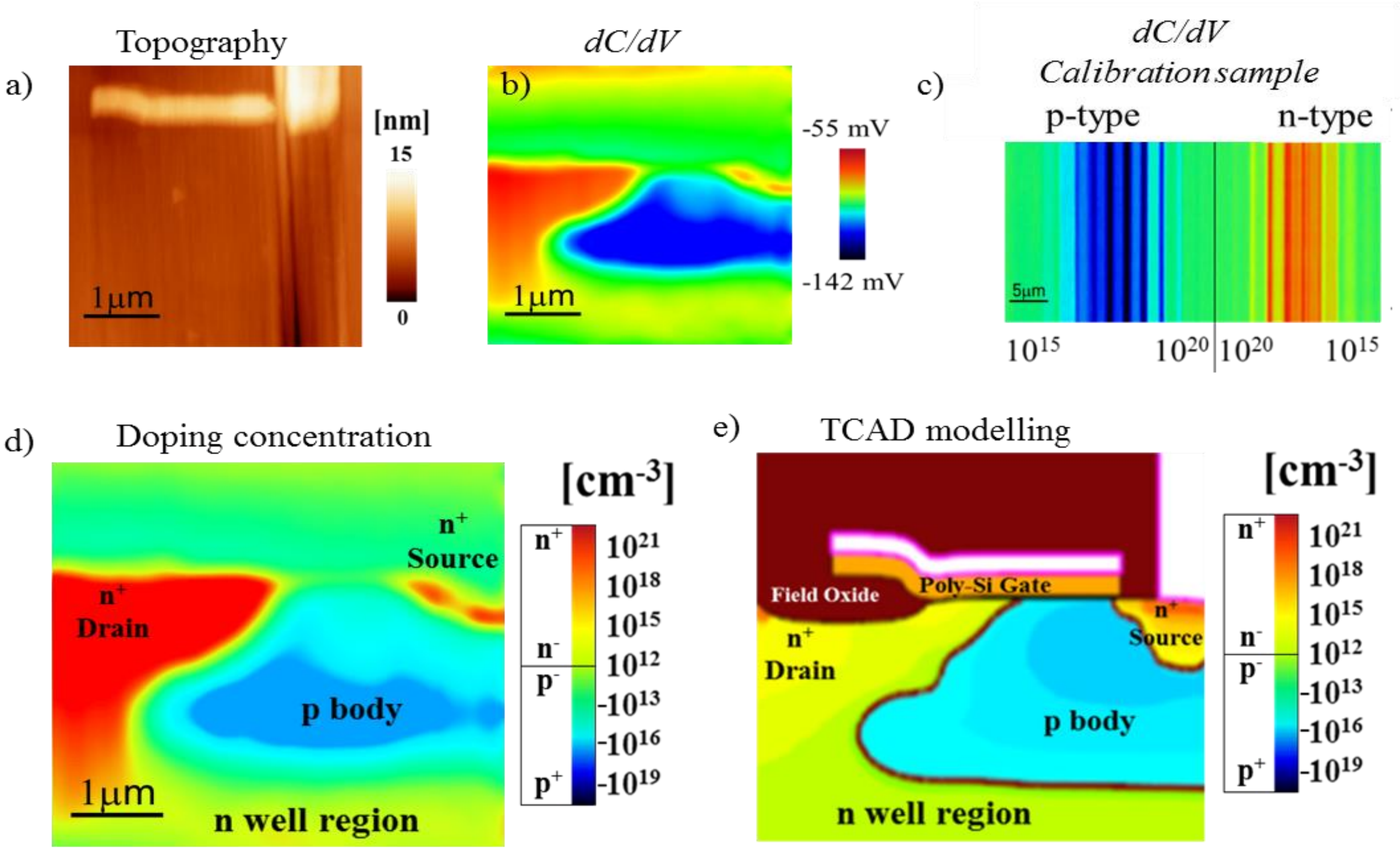
High voltage lateral diffused MOS transistor LDMOS



Brinciotti et al., submitted Aug 2016, Keysight Labs, AMS Austria, TU Vienna

4 ym x 4 ym area including poly-silicon gate, field oxide, p-body, n^+-source, and n^+-drain.

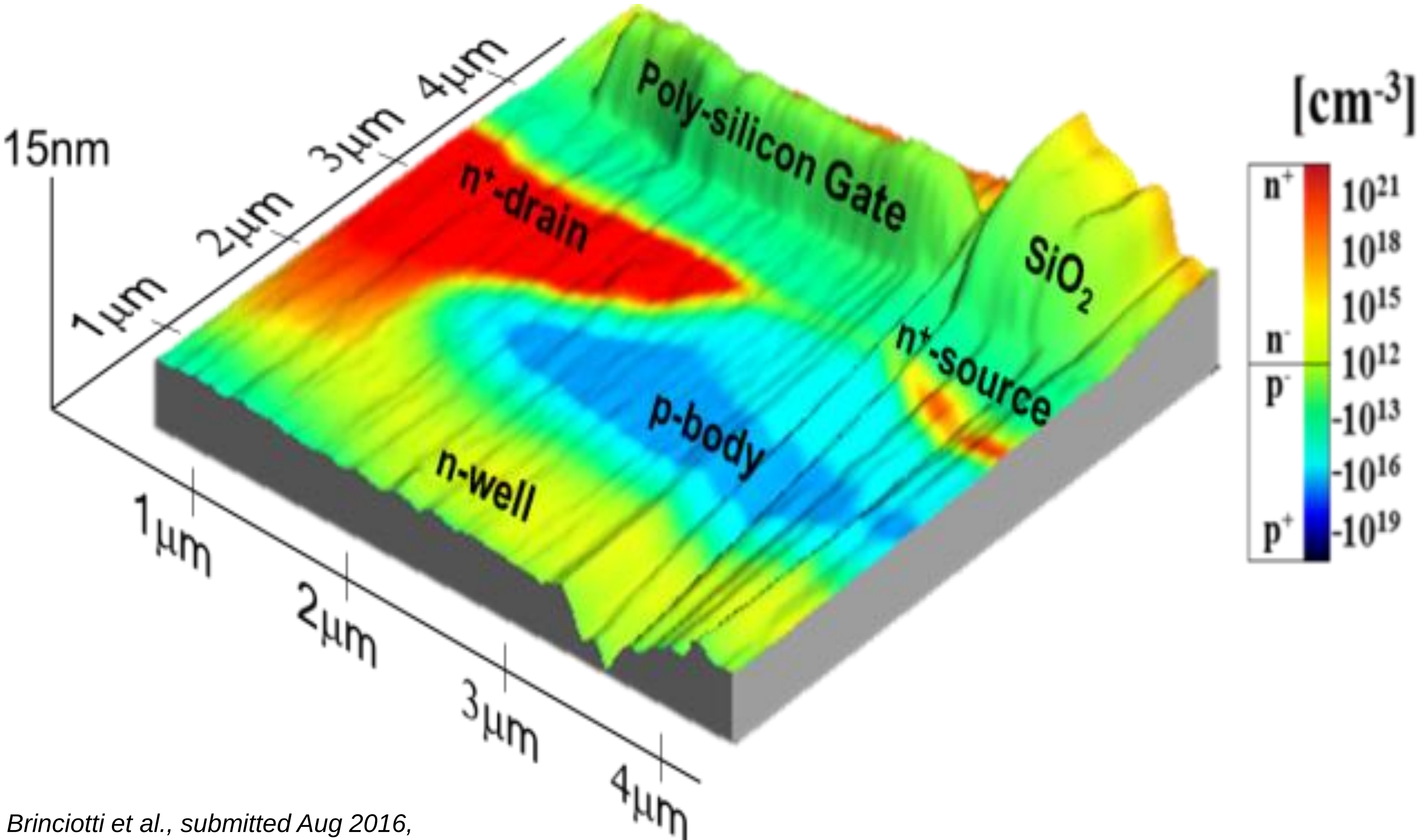
High voltage lateral diffused MOS transistor LDMOS



Brinciotti et al., submitted Aug 2016, Keysight Labs, AMS Austria, TU Vienna

Quantitative dopant calibration

High voltage lateral diffused MOS transistor LDMOS



Brinciotti et al., submitted Aug 2016, Keysight Labs, AMS Austria, TU Vienna

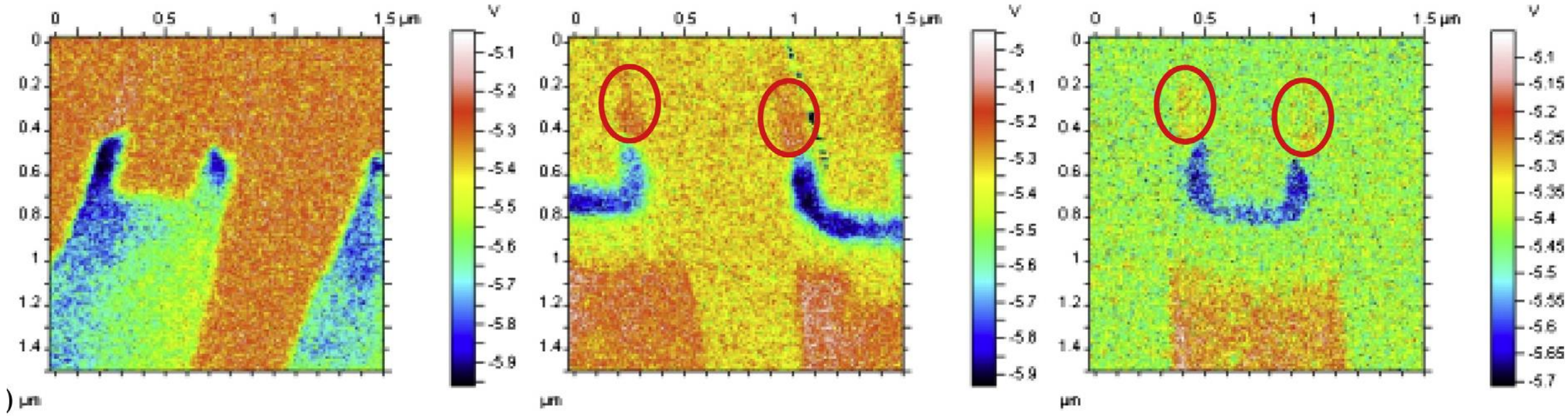
Quantitative dopant calibration

KEYSIGHT TECHNOLOGIES

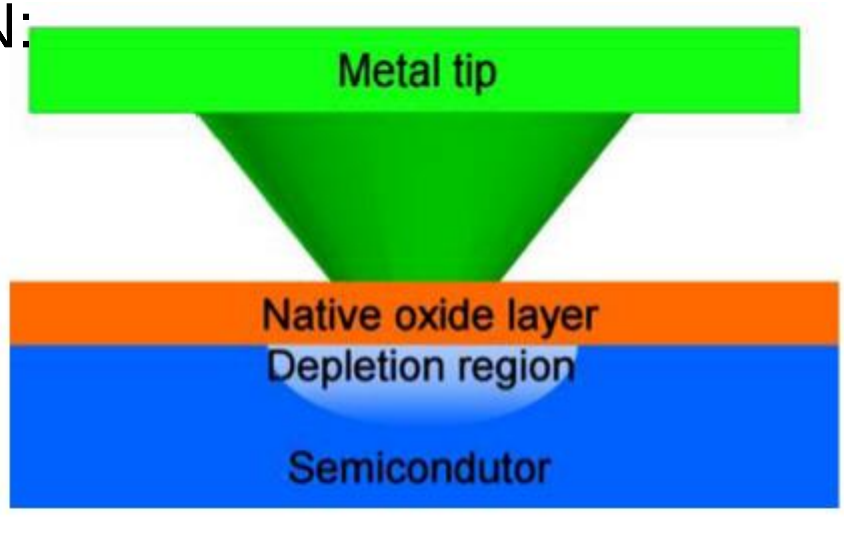
Dopant profiling on the nano-scale

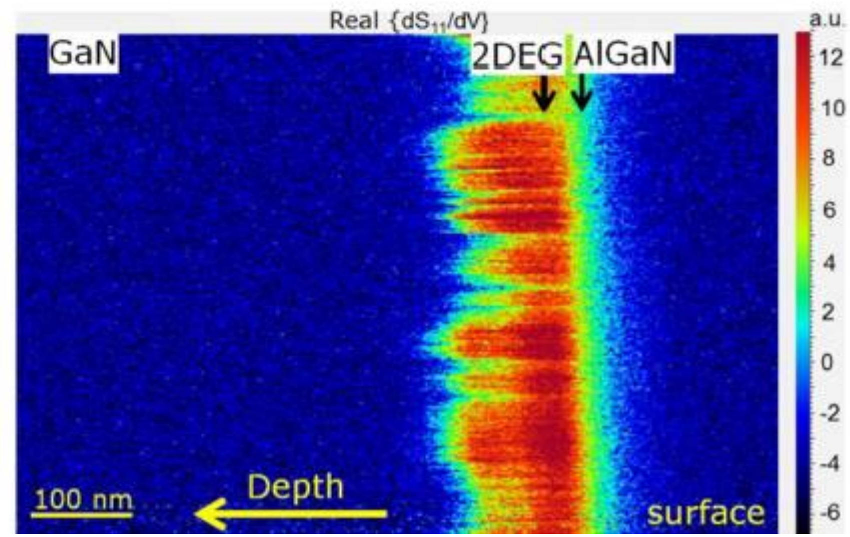
Silicon: Nanoscale DMOS measurements

DC tip bias



GaN:





T. Schweinboeck and S. Hommel (Infineon Munich)
Microelectronic Reliability 2014, 54, 2070-4 (upper part)
Microelectronic Reliability 2016 (lower part)

KEYSIGHT TECHNOLOGIES

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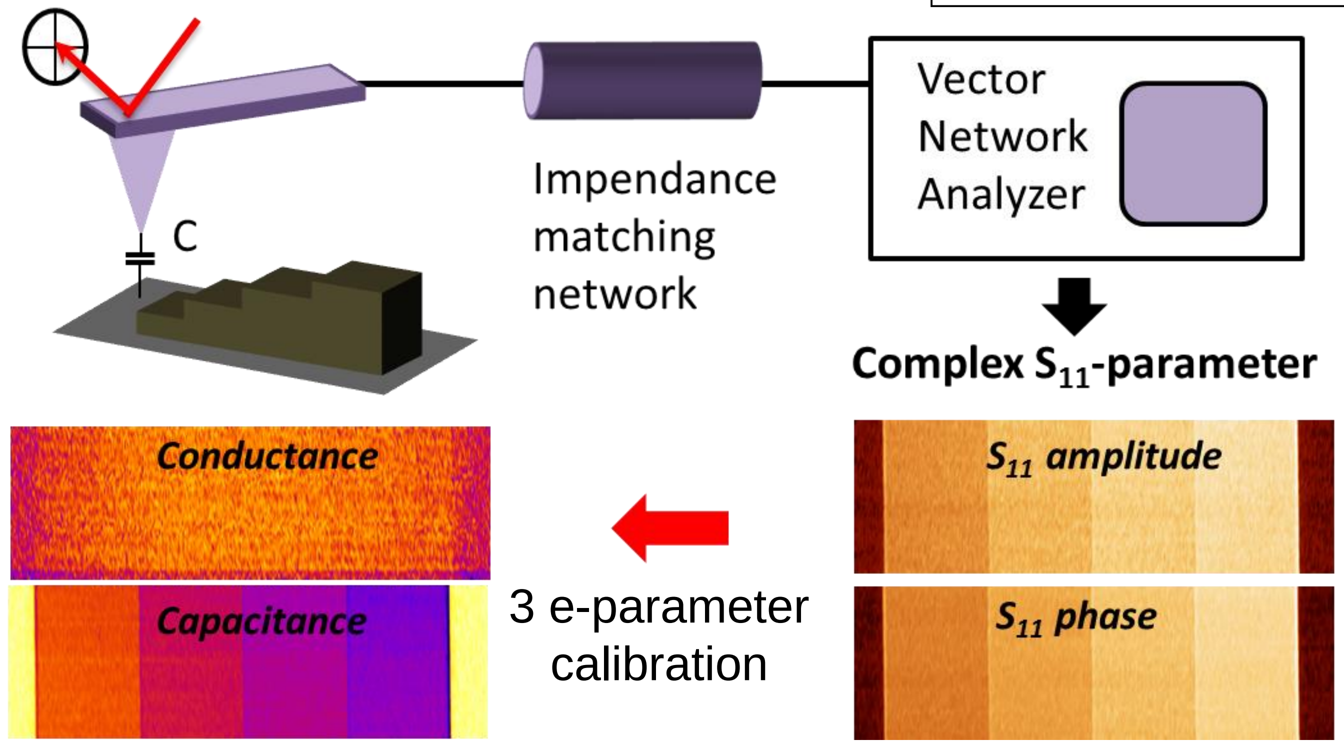
KEYSIGHT TECHNOLOGIES

Complex impedance calibration: new method

Workflow and calibration

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

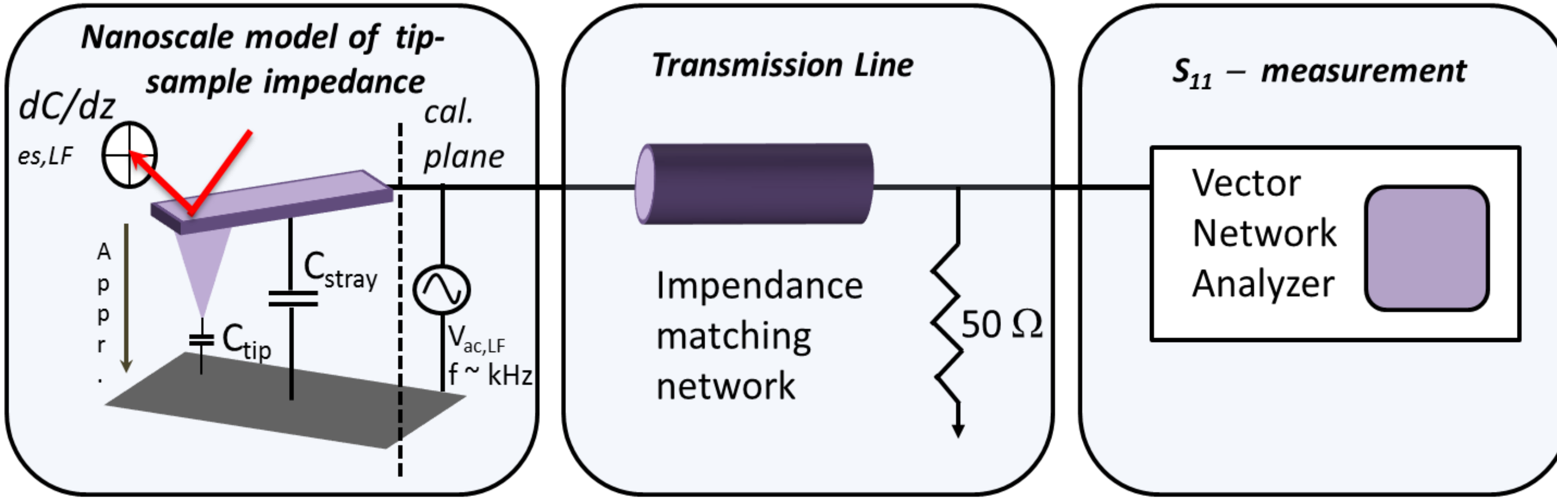
$$S_{11m} = e_{00} + \frac{S_{11} e_{01}}{1 - e_{11} S_{11}}.$$



-> NO calibration sample required

(therefore no stray capacitance issues, only for non-lossy samples like semiconductors, dielectrics and oxides; not for water)

Complex impedance calibration: new method



Z_{in} from dC/dz_{LF}-EFM curve — **Blackbox Calibration** — **Complex S_{11}-parameter**

$$S_{11,a} = \frac{Z_{in}-Z_{ref}}{Z_{in}+Z_{ref}} \longrightarrow S_{11,m} = e_{00}+e_{01}\frac{S_{11,a}}{1-e_{11}S_{11,a}} \longleftarrow S_{11,m}$$

Tip-substrate capacitance model

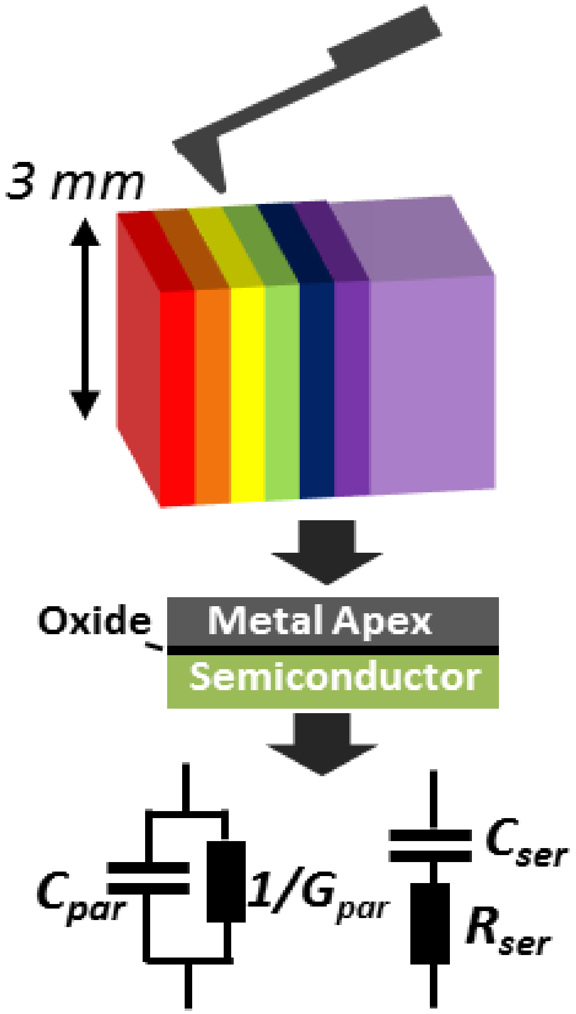
e_{00}, e_{01}, e_{11}

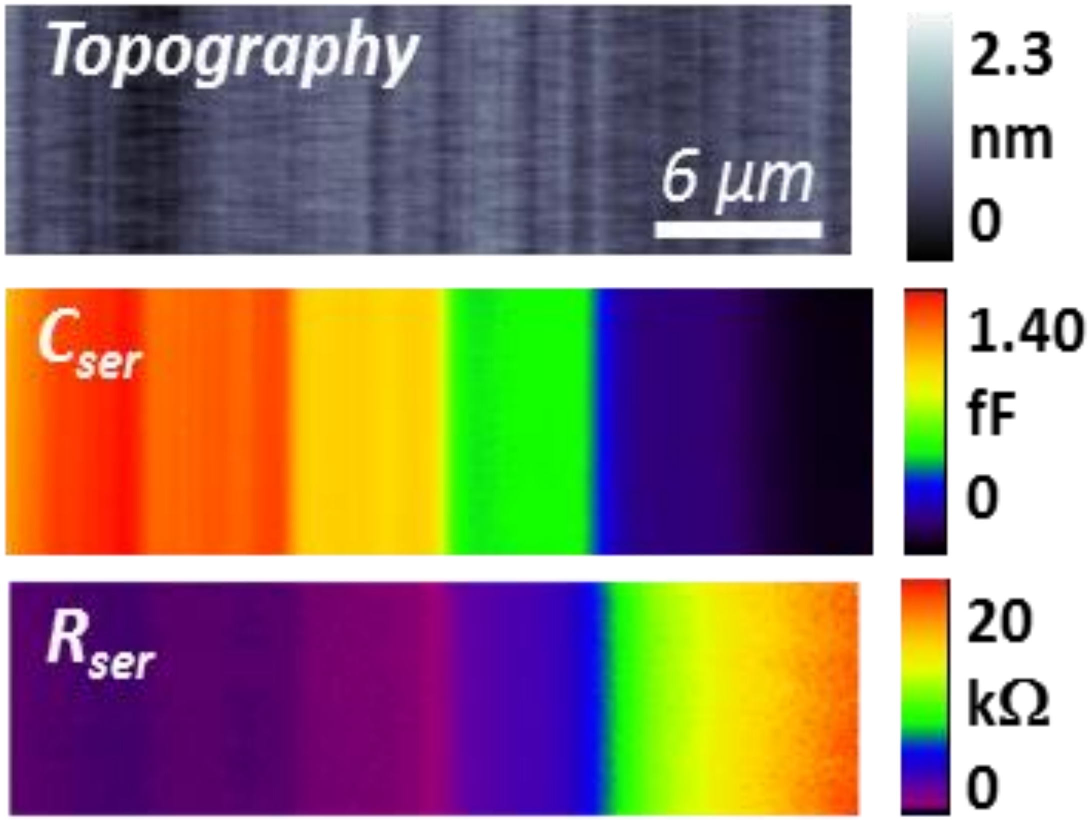
Calibrated Impedance Image/ Curve

Tip geometry Calibration + Blackbox Calibration parameters

Gramse et al., Nanotechnology 25 (2014)

Application I: Complex impedance of doped silicon

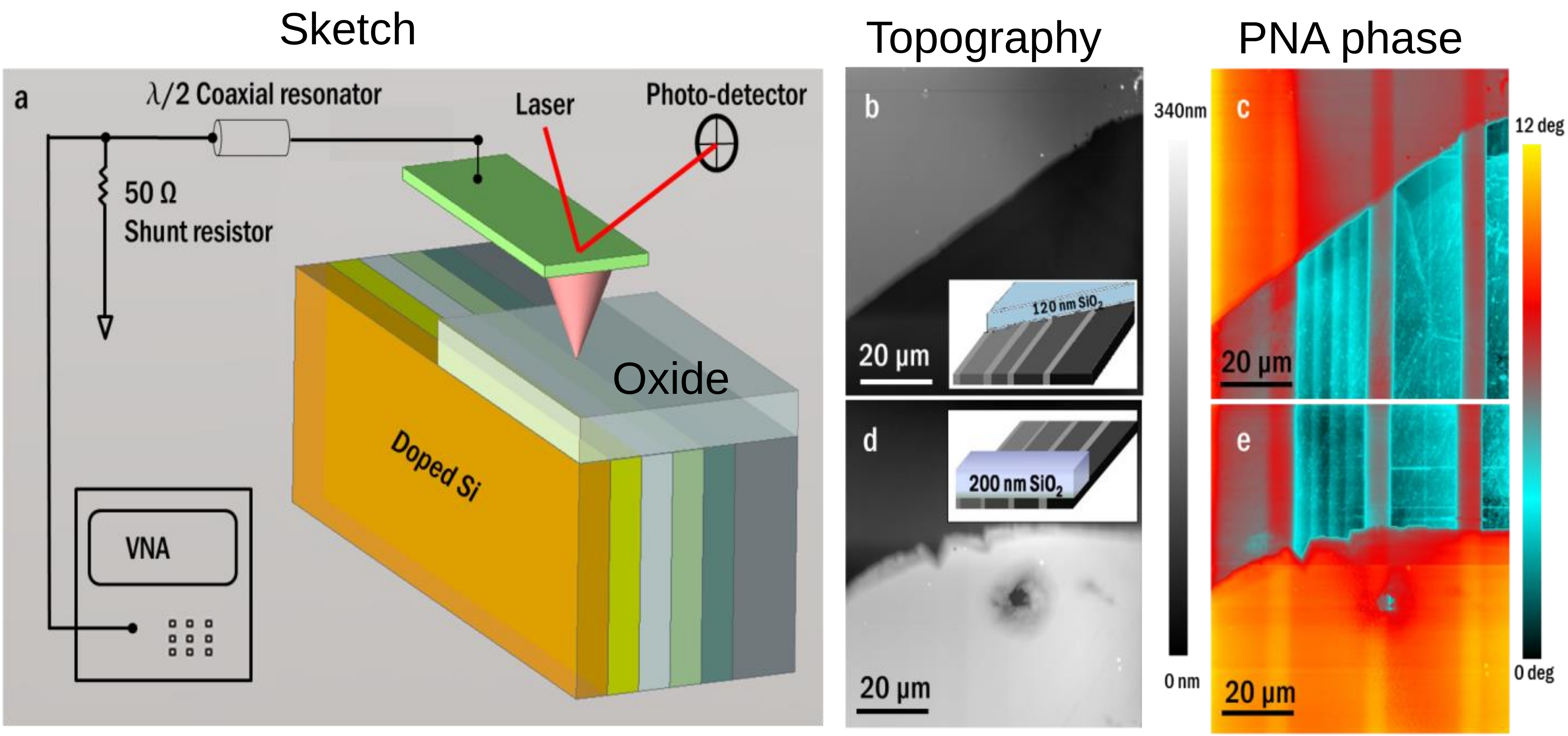




-> resistance of doped silicon

Gramse et al., Nanotechnology 25 (2014)

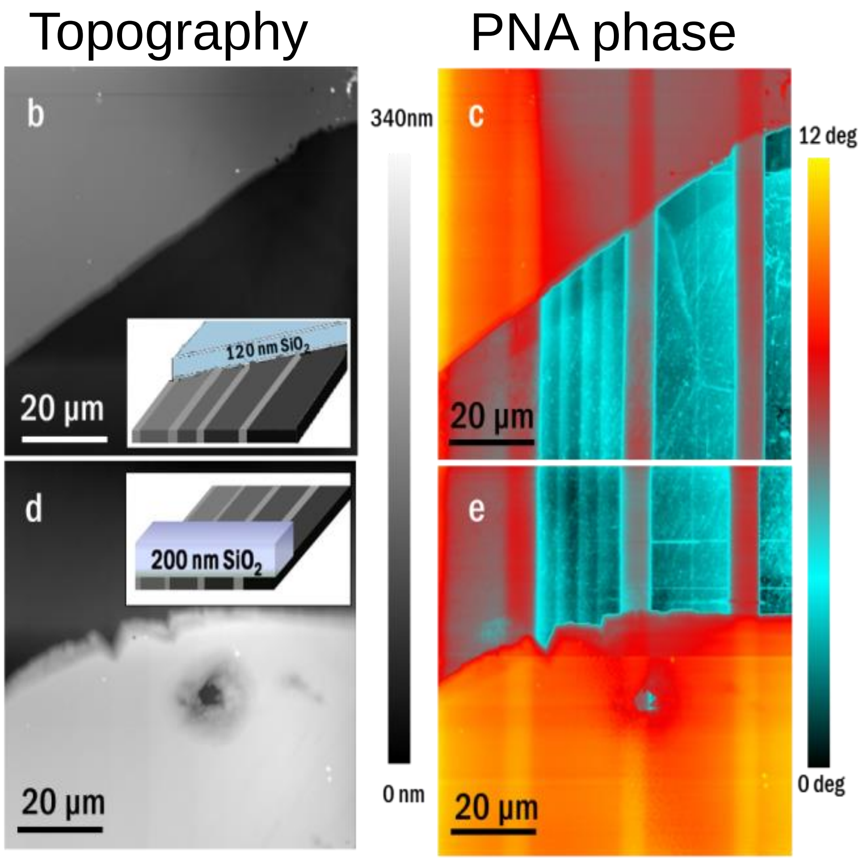
Application II: complex impedance & subsurface imaging



Gramse & Brinciotti et al., Nanotechnology (26) 2015, 35701 (9 pages)

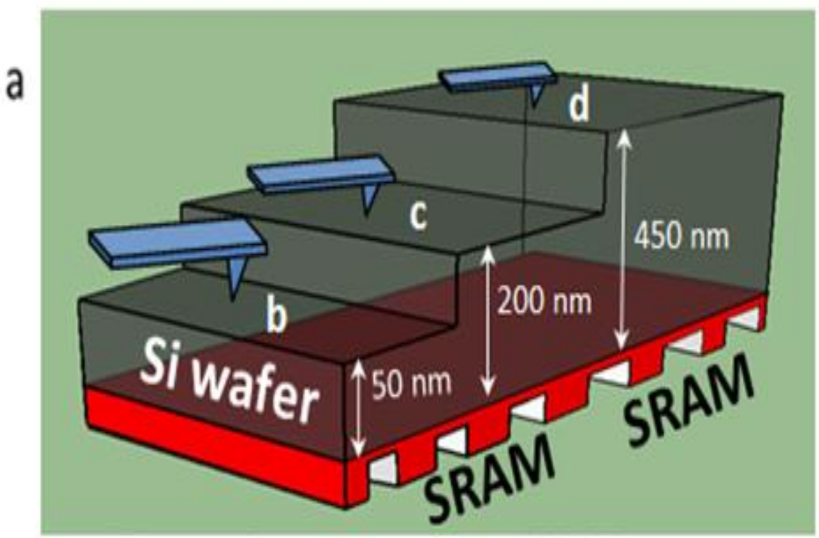
Application II: complex impedance & subsurface imaging

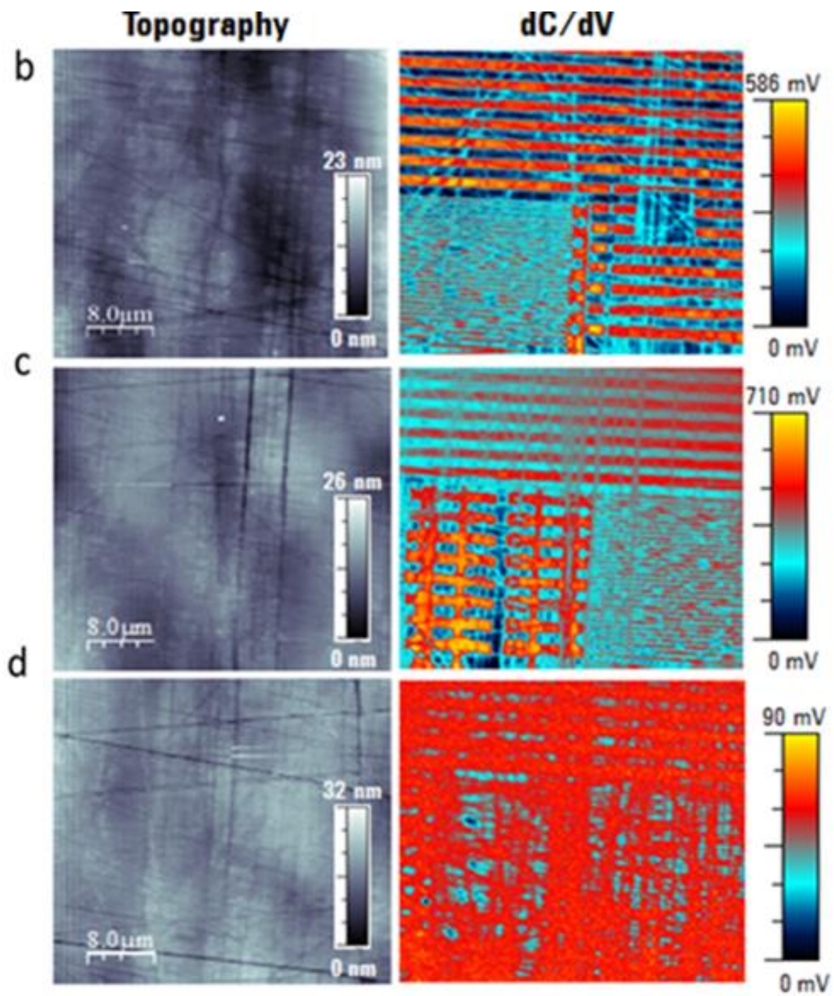
Cover story April 2015



Gramse & Brinciotti et al., Nanotechnology (26) 2015, 35701 (9 pages). Cover

Application II: subsurface imaging appplication for failure analysis labs (backwafer imaging)





-> We can image from the back of the wafer and see through it

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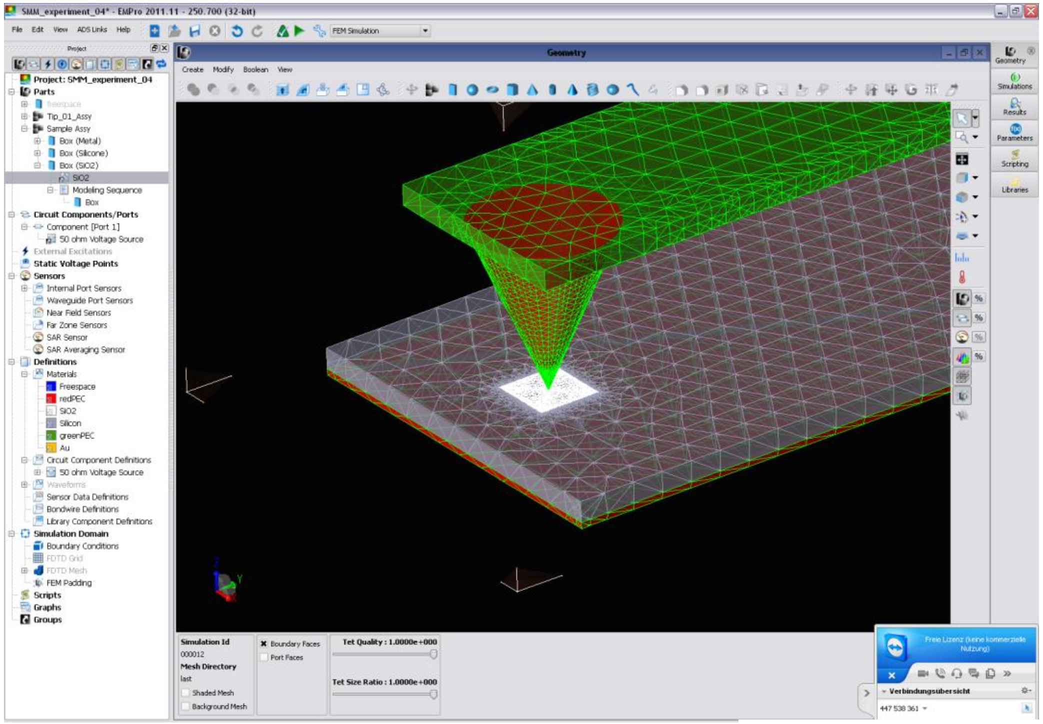
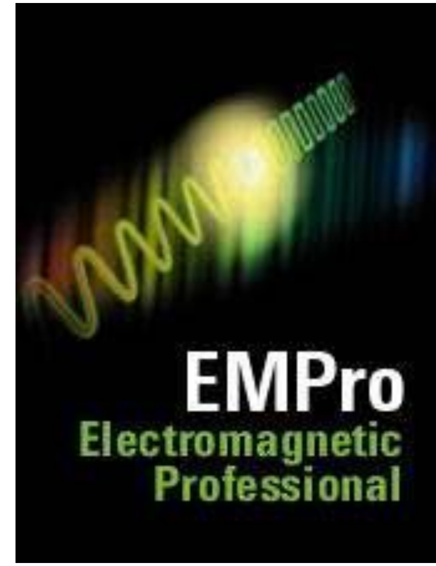
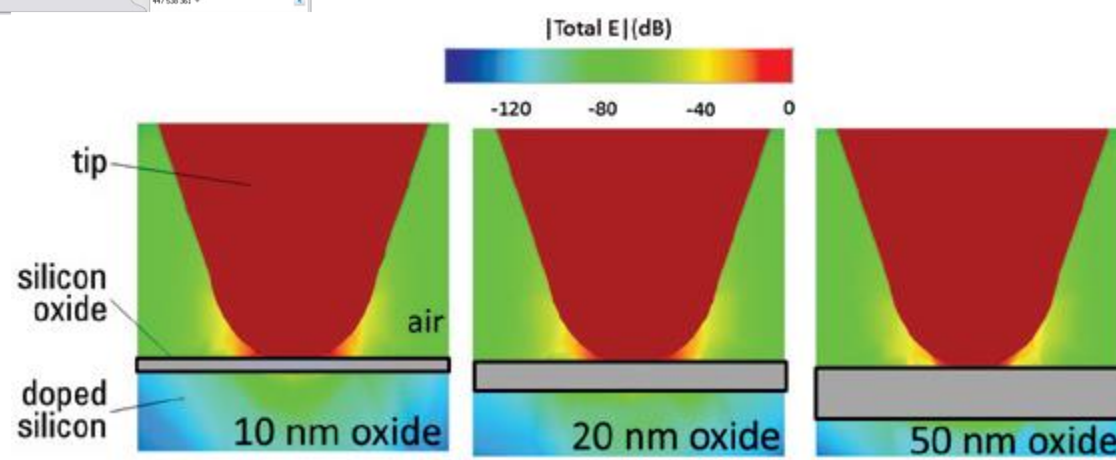
Gramse & Brinciotti et al., Nanotechnology (26) 2015, 35701 (9 pages)

SMM project in EMPro:





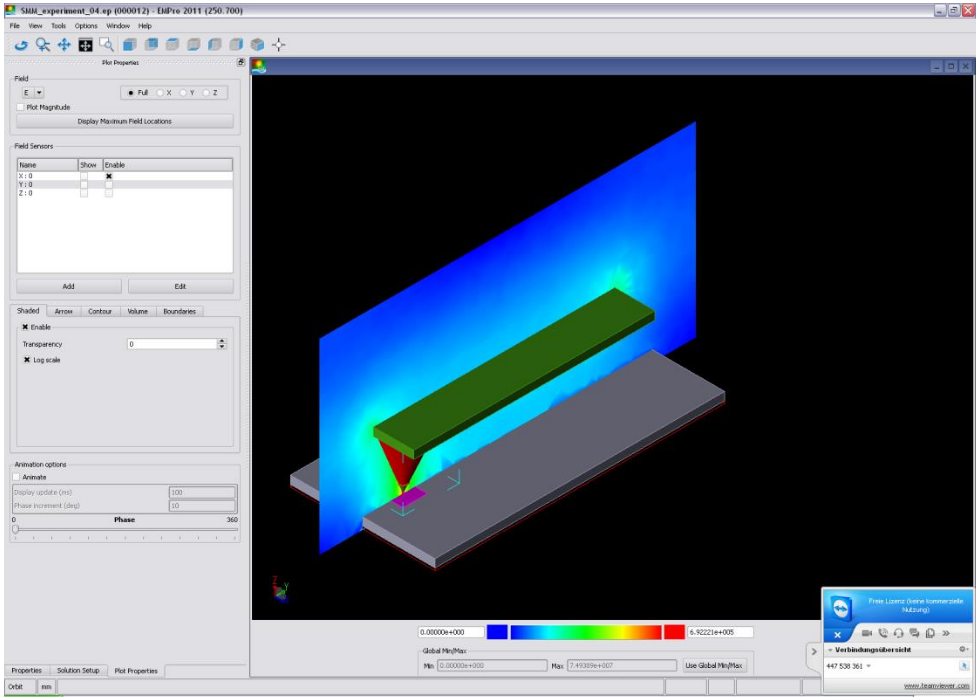
Numerical results include E-field and complex impedance

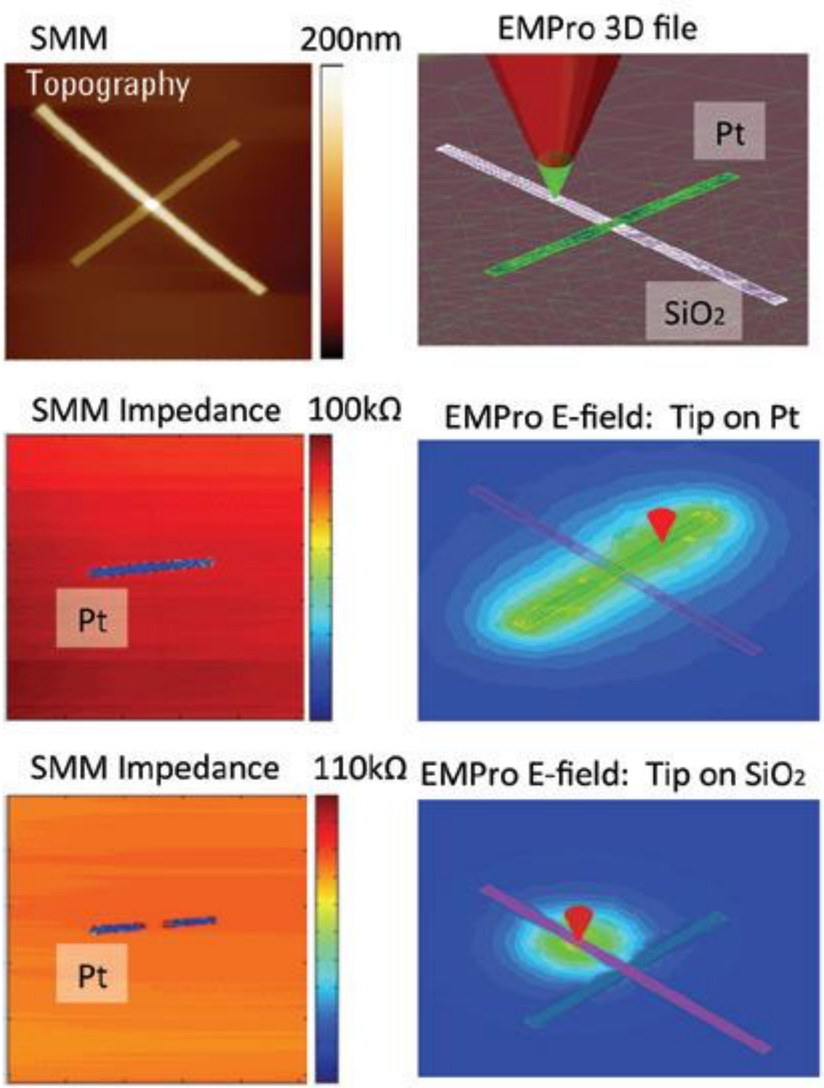


SMM project included in EMPro

KEYSIGHT TECHNOLOGIES

EMPro Modeling and SMM direct comparison





Kasper et al., Keysight AppNote 2013, 5991-2907
Oladipo et al., APL 103 (2013) 213106
Oladipo et al., APL 105 (2014) 133112

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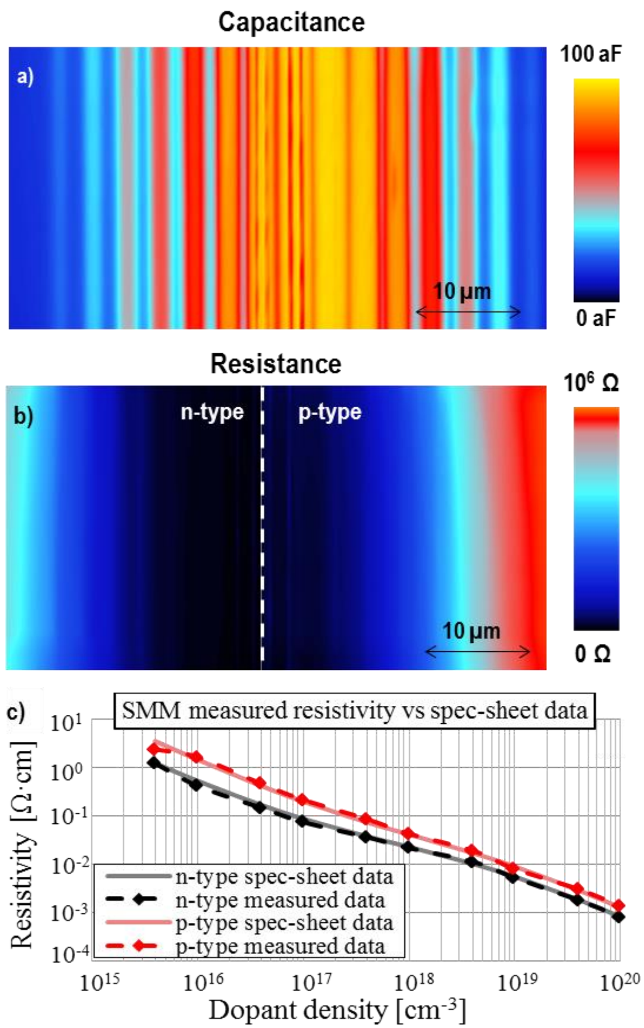
Application III: Resistivity from resistance



Brinciotti et al, Nanoscale Oct 2015

The SMM calibrated resistance R_m is converted into resistivity ρ using an analytical model:

$$R_m = \frac{\rho}{\delta} + \frac{\rho W_{DL}}{\pi r^2}$$

Where:

$$W_{DL} = \sqrt{2\varepsilon\mu\rho \cdot \left(\frac{\Box_{Pt} - \Box_{Si} + qV_t \cdot ln\left[\frac{N_C}{n}\right]}{q}\right)}$$

Depletion layer width

$$\delta = \left(\frac{1}{\omega}\right)\left\{\left(\frac{\mu\varepsilon}{2}\right)\left[\left(1 + \left(\frac{1}{\rho\omega\varepsilon}\right)^2\right)^{1/2} - 1\right]\right\}^{-1/2}$$

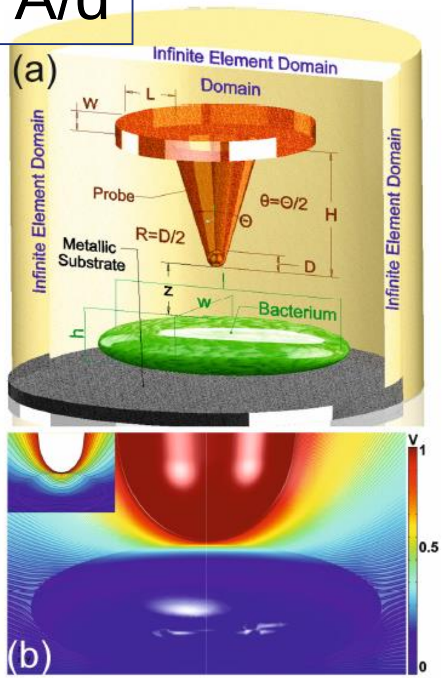
Skin depth

At 19GHz the depletion width ranges from 4 nm (heavily doped) to 574 nm (low doped), and the skin depth from 10 µm to 0.7 mm, respectively.

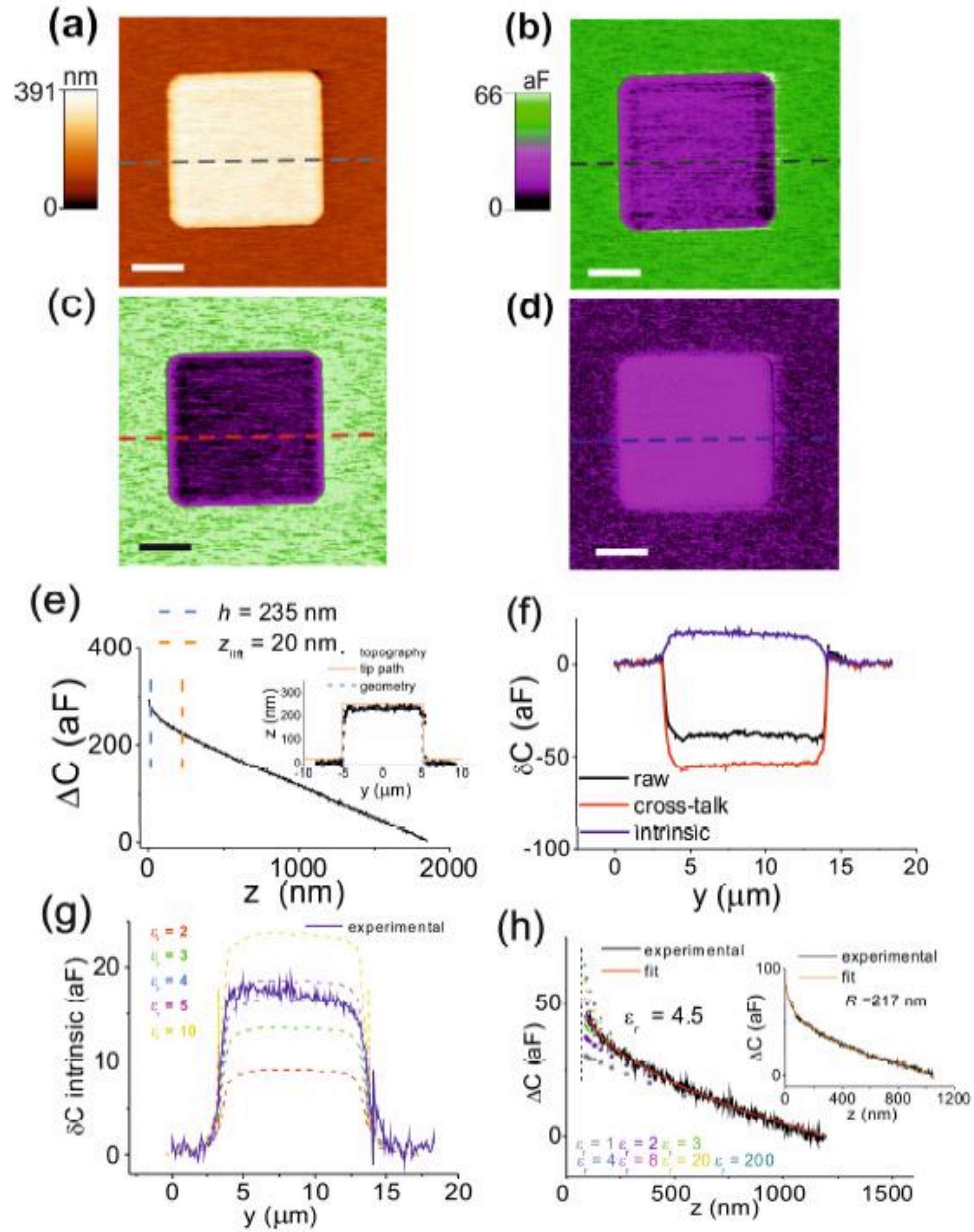
-> changing the SMM frequency modulates the values of the skin depth allowing to adjust the SMM vertical resolution for sub-surface imaging.

Application IV: Accurate dielectric quantification

$C = e*A/d$



Prof. Gabriel Gomilla & Maria-Chiara Biagi et al, IBEC Barcelona
ACS Nano Jan 2016, 10, 280 (8p)



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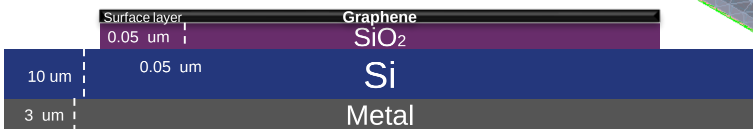
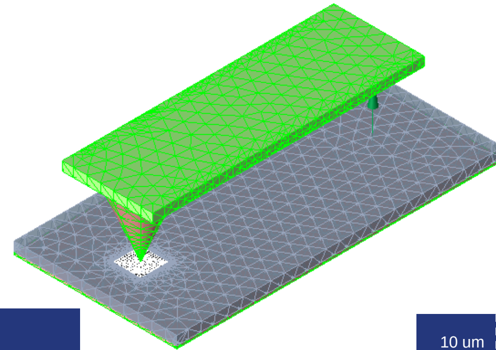
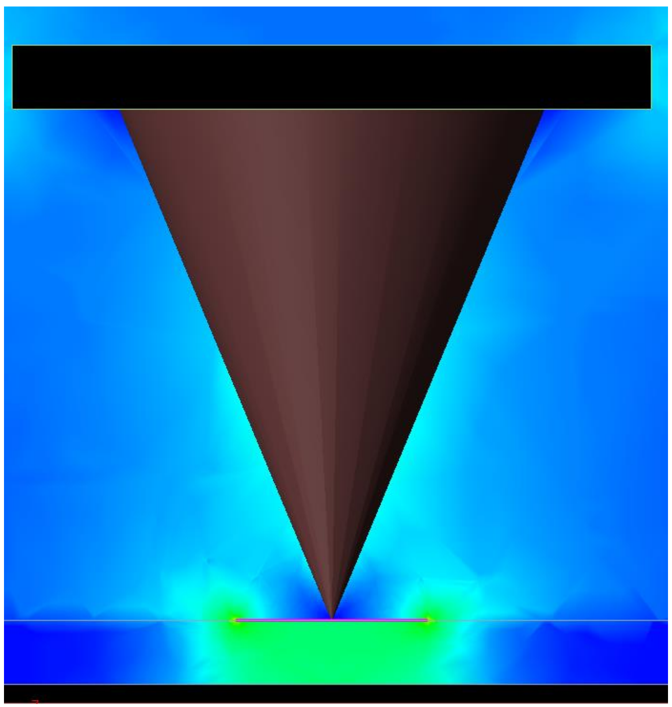
Application to single layer graphene:

Graphene layer included





Graphene layer not included



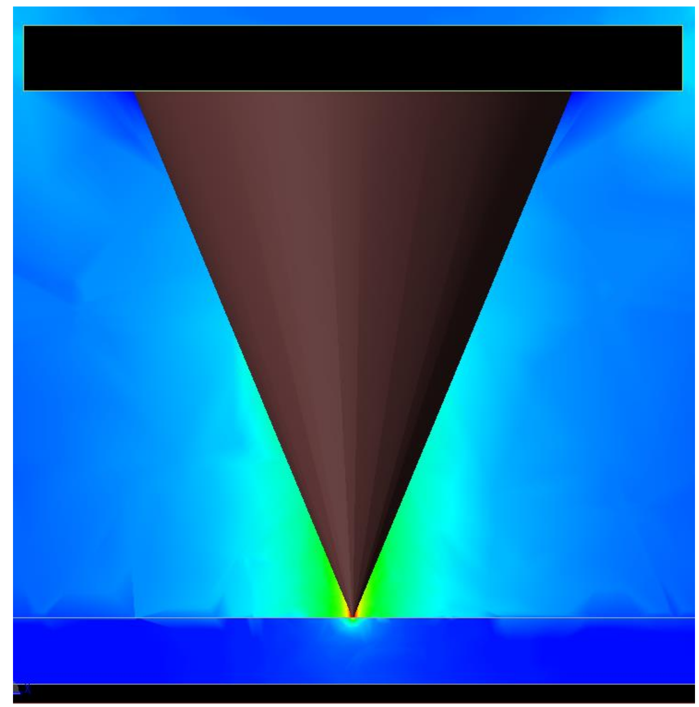
Simulated Frequency
10 GHz

Graphene model

S-Parameters	-0.022 dB
Re(S11)	0.9779
Im(S11)	-0.1968
| S11 |	0.9975
Phase(S...	-11.381 °

Non Graphene model

S-Parameters	-0.011 dB
Re(S11)	0.9933
Im(S11)	-0.1039
| S11 |	0.9987
Phase(S11)	-5.969 °



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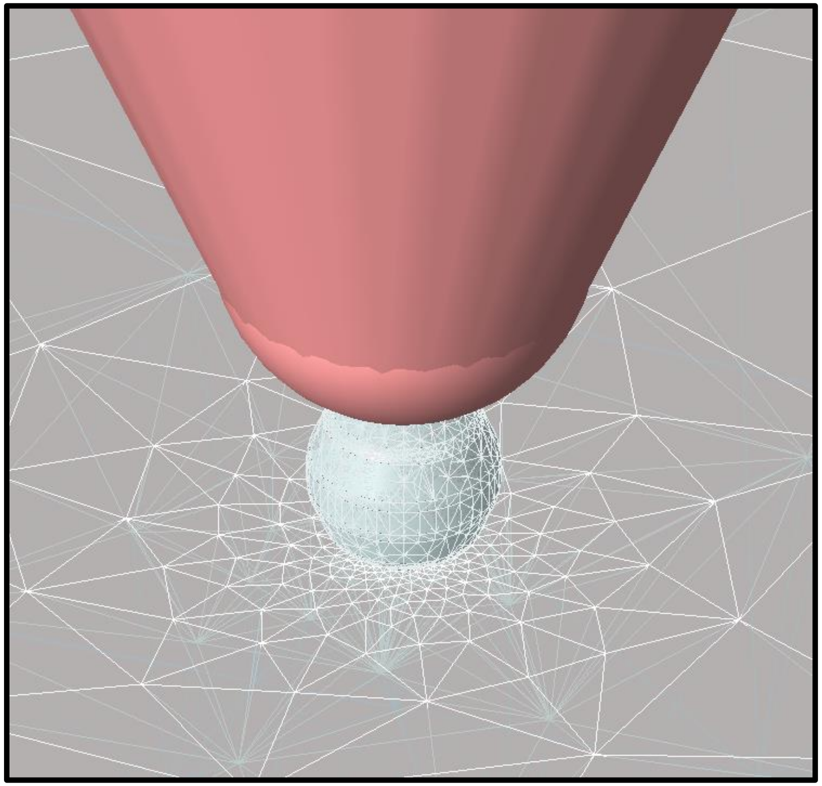
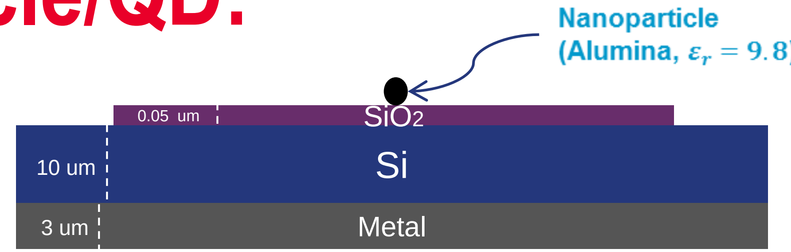
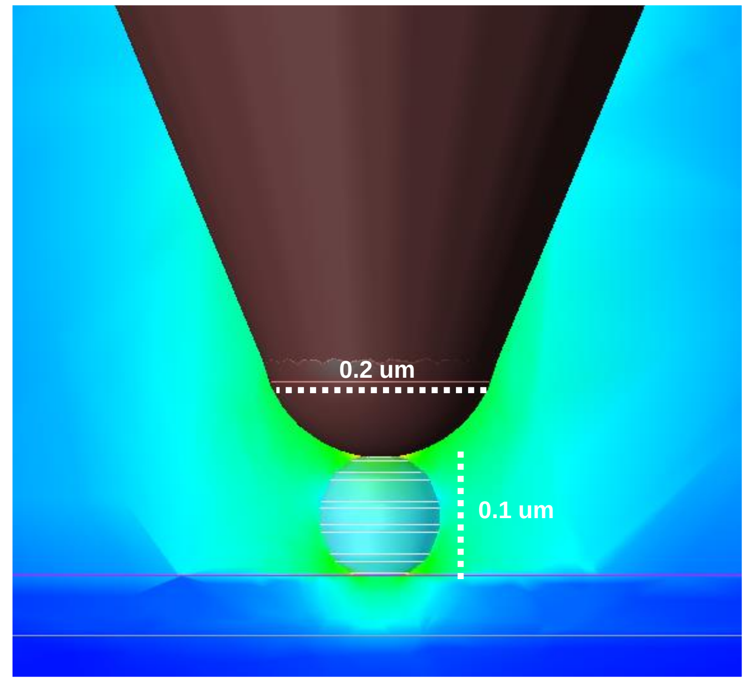
Keysight Labs Linz, unpublished

Application to nanoparticle/QD:



Nanoparticle EMpro Meshing





Simulated Frequency: 10 GHz

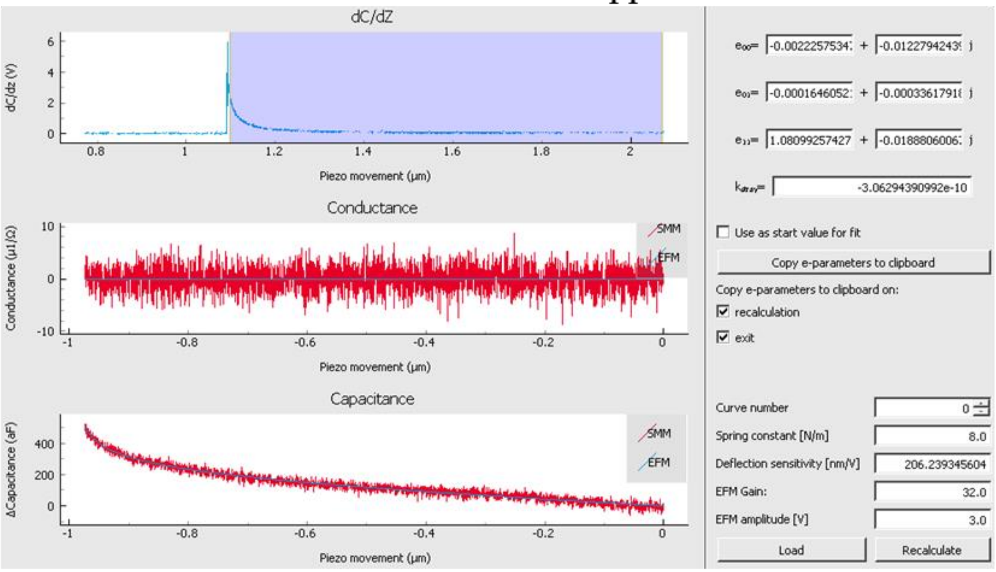
S-Parameters	-0.011 dB
Re(S11)	0.9933
Im(S11)	-0.1036
| S11 |	0.9987
Phase(S11)	-5.955 °

KEYSIGHT TECHNOLOGIES

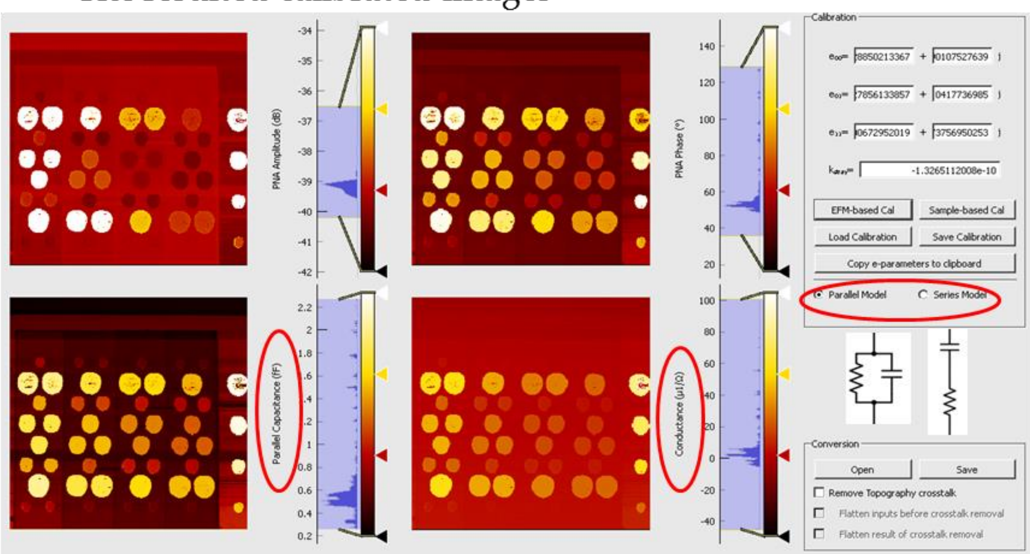
Keysight Labs Linz, unpublished

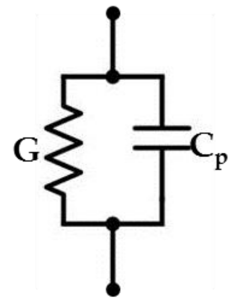
Software implementation in PicoView & script:

EFM-based calibration of an EFM/SMM approach curve on Si substrate



The resulted calibrated images



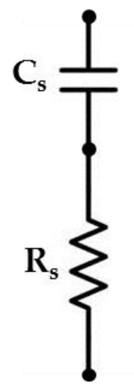


Admittance of parallel RC equivalent circuit:

$Y = G + j*B = G + j*\omega*C_{parallel}$;

$G = Real(Y)$;

$C_{parallel} = Imaginary(Y) / \omega$;



Impedance of series RC equivalent circuit:

$Z_{series} = R_{series} + j*X = R_{series} + 1/(j*\omega*C_{series})$;

$R_{series} = Real(Z)$;

$C_{series} = (-1)/(\omega*Imaginary(Z))$;

$\omega = 2*\pi*frequency$; $Z = 1/Y$;

B susceptance; X reactance;

EFM- based calibration, described in Gramse G. et al, "*Calibrated complex impedance and permittivity measurements with SMM*," Nanotechnology, 2014, vol. 25, no. 14, pp. 8

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- Complex impedance for materials science
  - Calibration
  - Subsurface imaging
  - Resistivity from resistance
  - Dielectric quantification
  - 2D materials (graphene)
- **Multi-modal SMM solutions**
  - **Augmented SMM (SMM plus add-ons)**
  - **New modes: transmission, magnetic, and QuBits**
- Bio-SMM & liquid imaging
- Summary

Multi-modal Keysight solutions: from products to solutions

Source meter unit SMU B2900 for advanced voltage spectroscopy

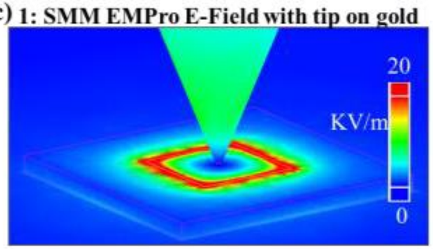
3

ECal unit for advanced SMM impedance calibration in air and liquid

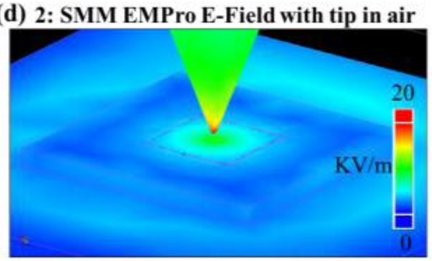
2

EMPro/ADS Modeling

(c) 1: SMM EMPro E-Field with tip on gold



(d) 2: SMM EMPro E-Field with tip in air



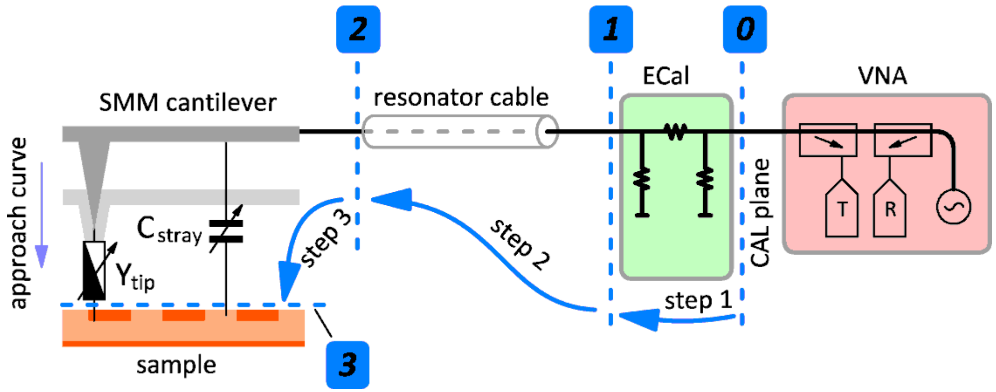
4

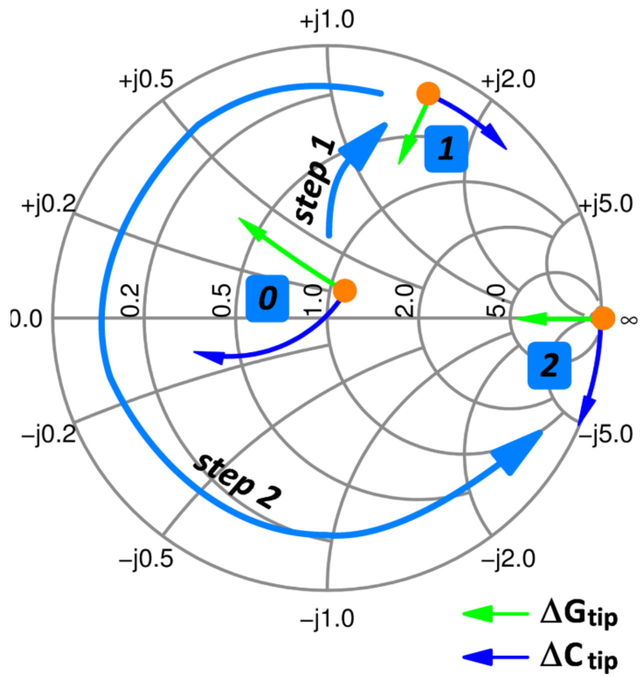
Dielectric probe kit for liquid measurements & complex permittivity at GHz

1

1. SMM+Ecal: advanced impedance calibration using time-gating, network analysis and de-embedding

Applications for advanced RF/electrical engineer labs





SMM + ECal

$$A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}} \qquad B = Z_0\frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}}$$

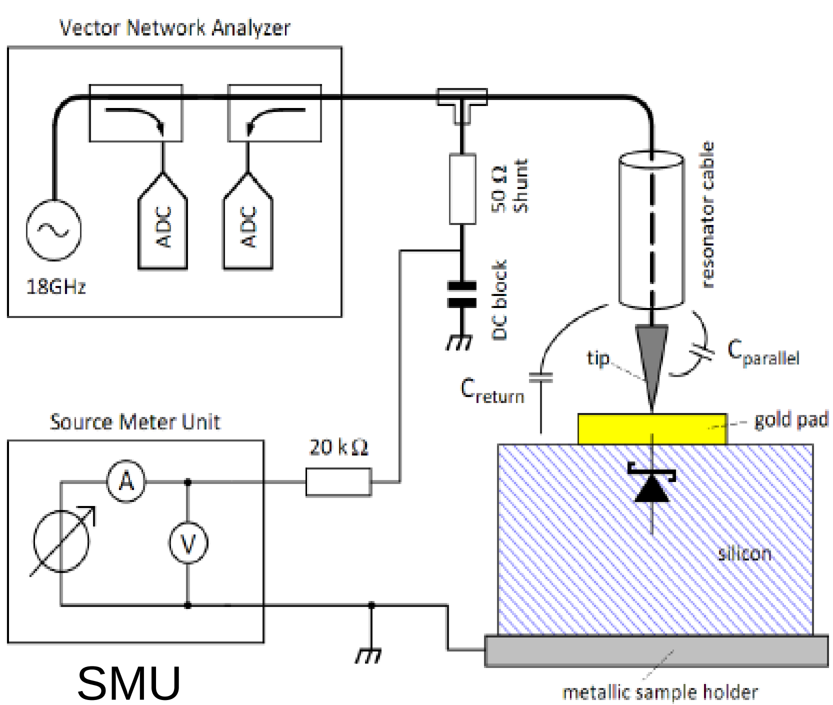
$$C = \frac{1}{Z_0}\frac{(1-S_{11})(1-S_{22})-S_{12}S_{21}}{2S_{21}} \qquad D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}} . \quad (2)$$

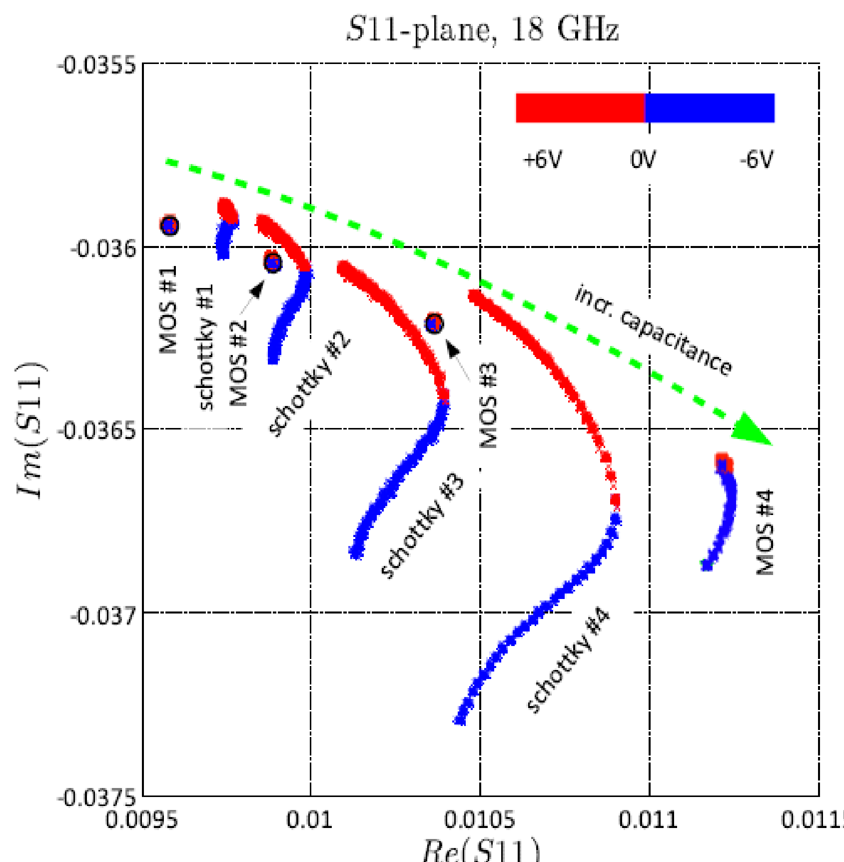
Kasper et al, May 2016 at IEEE IMS, San Francisco,
4 page paper conference proceeding

2. SMM + SMU for advanced voltage spectroscopy

Applications on electronic devices (eg MOS capacitors) and eg varactors from STMicroelectronics France

Measurement schematics (left) and SMM results (right)

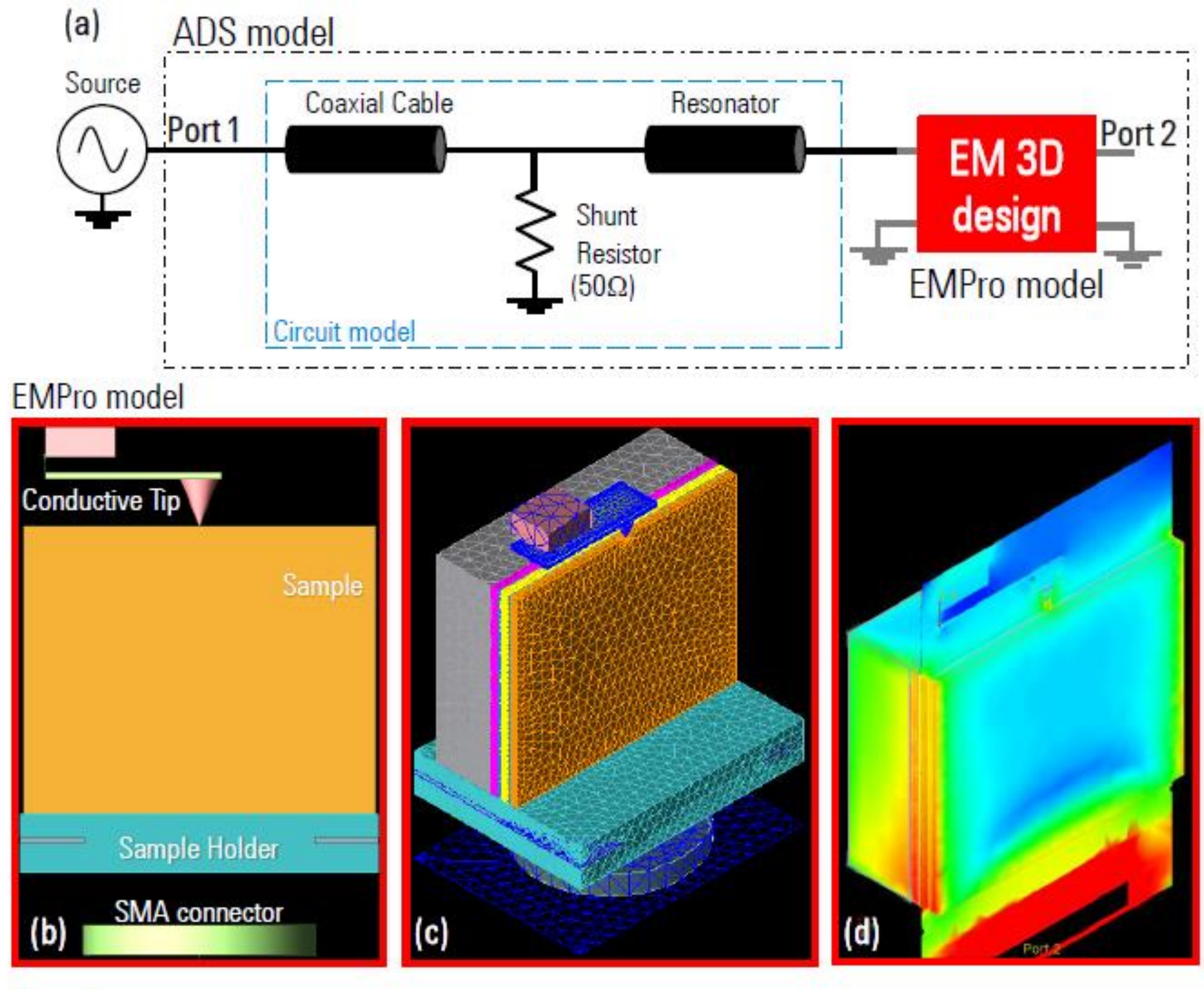




SMU

Kasper et al., JAP 2014, 116, 184301 (8 pages)

3. Transmission SMM: ADS and EMPro Modeling

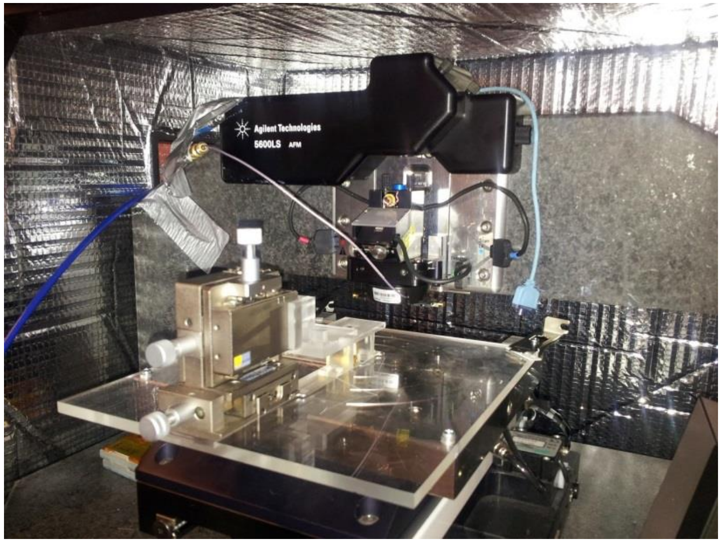


S21 transmission shown in Fernandez et al, EuMW 2015

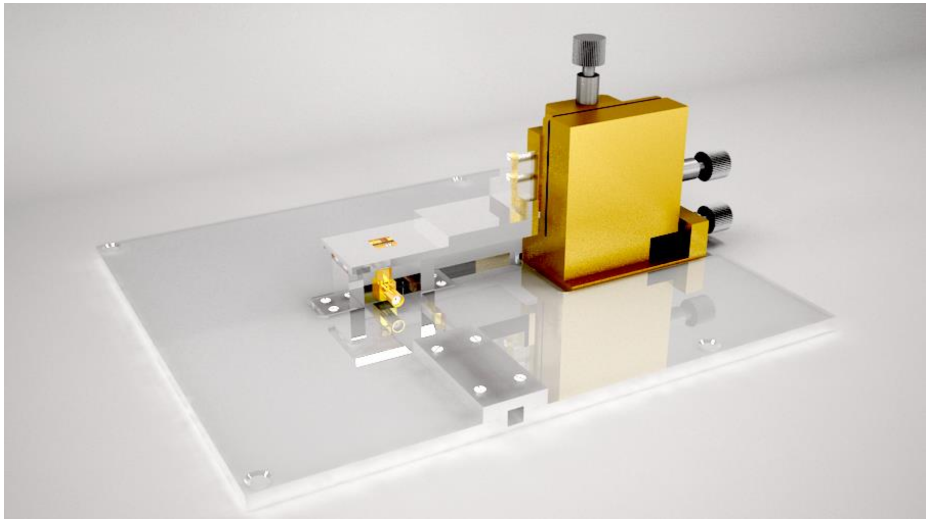
Keysight Labs Linz, Silviu Tuca & Giulio Campagnaro et al, Microscopy & Analysis July 2015, Issue 19, pp 9-12

Transmission S21 imaging: sample plate

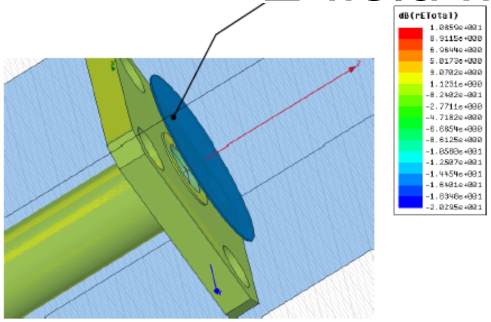
S21 sample plate integrated in 5600 SMM

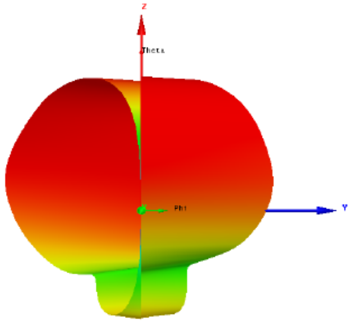


Prototype sample plate CNR-IMM



E-field modeling





KEYSIGHT TECHNOLOGIES

*Collaboration with CNR-IMM Rome, Romolo Marcelli et al, Review Scientific Instruments, April 2016, 12 pages

4. SMM for magnetic measurements

Collaboration with
CNR-IMR Rome

Applications for magnetic integrated circuits, MRAM’s, ferromagnetic resonance FMR, and multi-ferroic samples

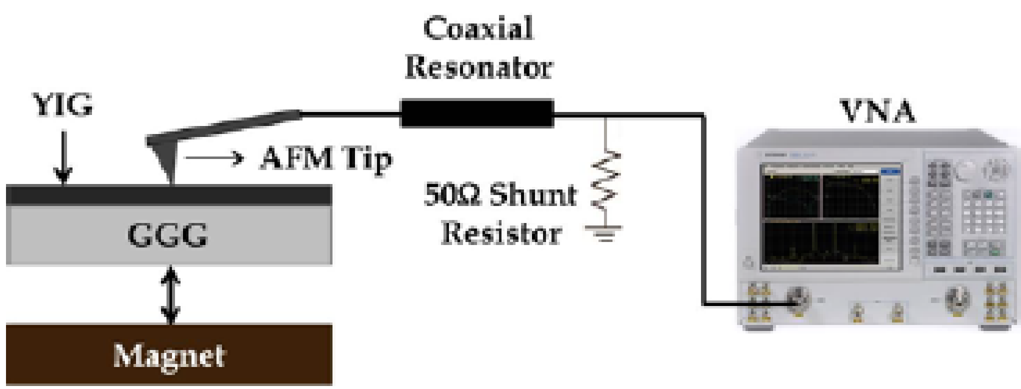


Fig. 1. Schematic of the experimental setup

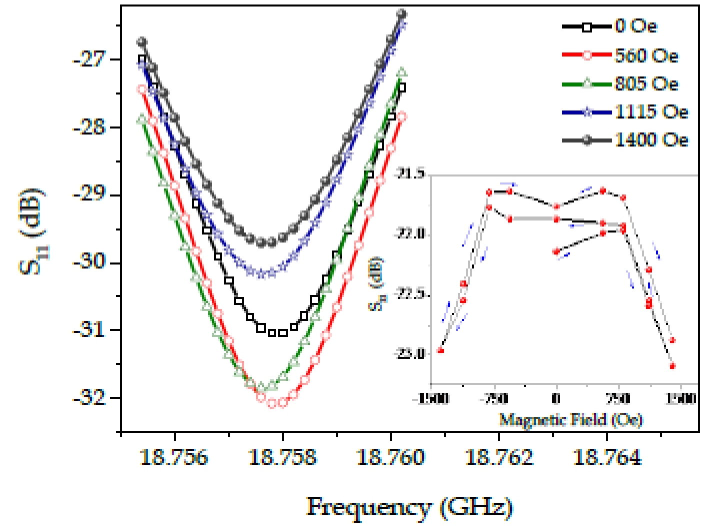
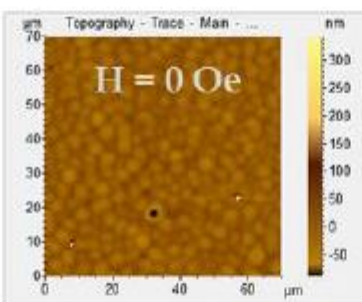


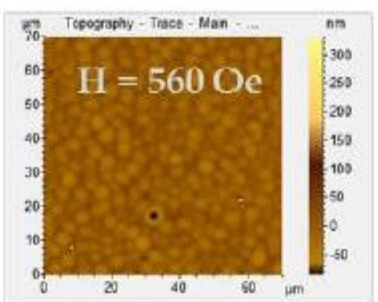
Fig. 3. The measured S_{11} for the RF sputtered YIG with respect to different external magnetic fields. Inset shows the hysteresis behavior of the sample.

$$S_{11} = \frac{Z_{total} - Z_0}{Z_{total} + Z_0} \quad (1)$$

$Z_{total} = Z_{Resonator} + Z_{Sample}$. Here, $Z_{Resonator}$ is the impedance of the $\lambda/2$ coaxial line resonator. Z_{Sample} is a bi-layer system with YIG film and GGG substrate, defined as:

$$Z_{Sample} = Z_{YIG} \frac{Z_{GGG} + iZ_{YIG} \tan(k_{YIG} t_{YIG})}{Z_{YIG} + iZ_{GGG} \tan(k_{YIG} t_{YIG})} \quad (2)$$





Magnetic EMPro modeling results

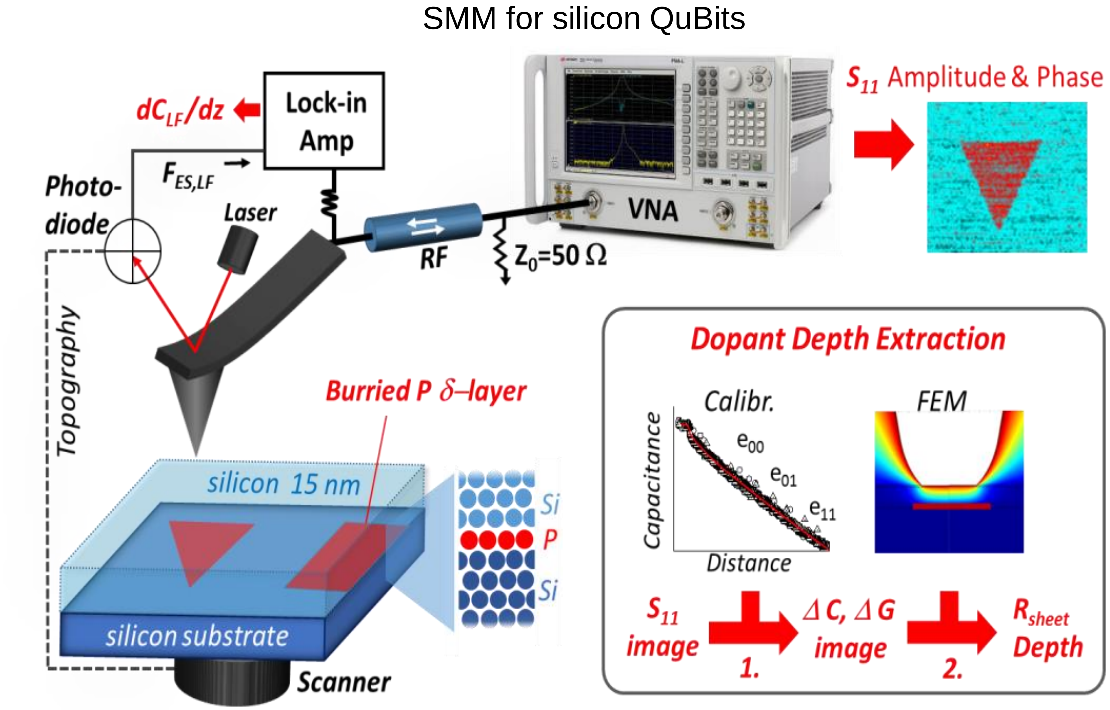
μ_r	Z_{sample} (Ω)	Conductance (fS)	Capacitance (aF)
1.0001711+j*0.9998	1.246-j*1308812.375	727.38	12.16

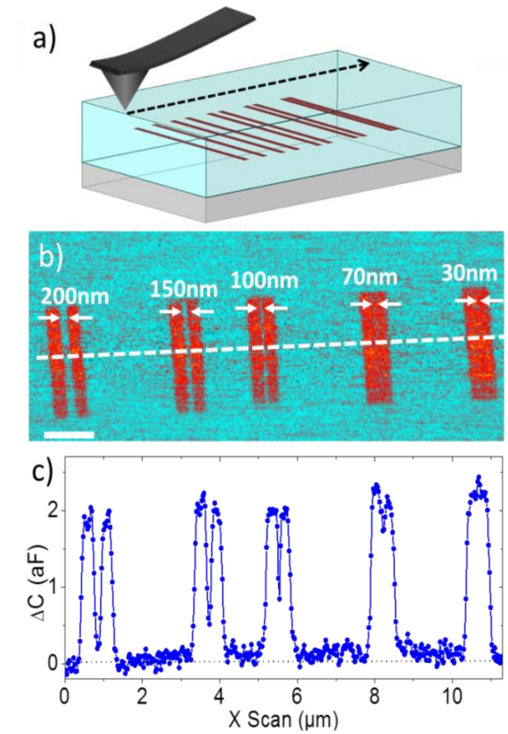
Joseph Hardly et al.,
Journal of Magnetism and Magnetic Materials, 2016, 420, 62-69

5. SMM for quantum electronic Qubits

Research collaboration with UC London (Prof Neil Curson) and London quantum technology hub

SMM for silicon QuBits





- Characterizing buried nanostructures and electrical properties of atomic thick delta dopant layers used for quantum processes.
- Talk at silicon quantum electronic workshop in June 2016.
- Gramse et al, 2018

KEYSIGHT TECHNOLOGIES

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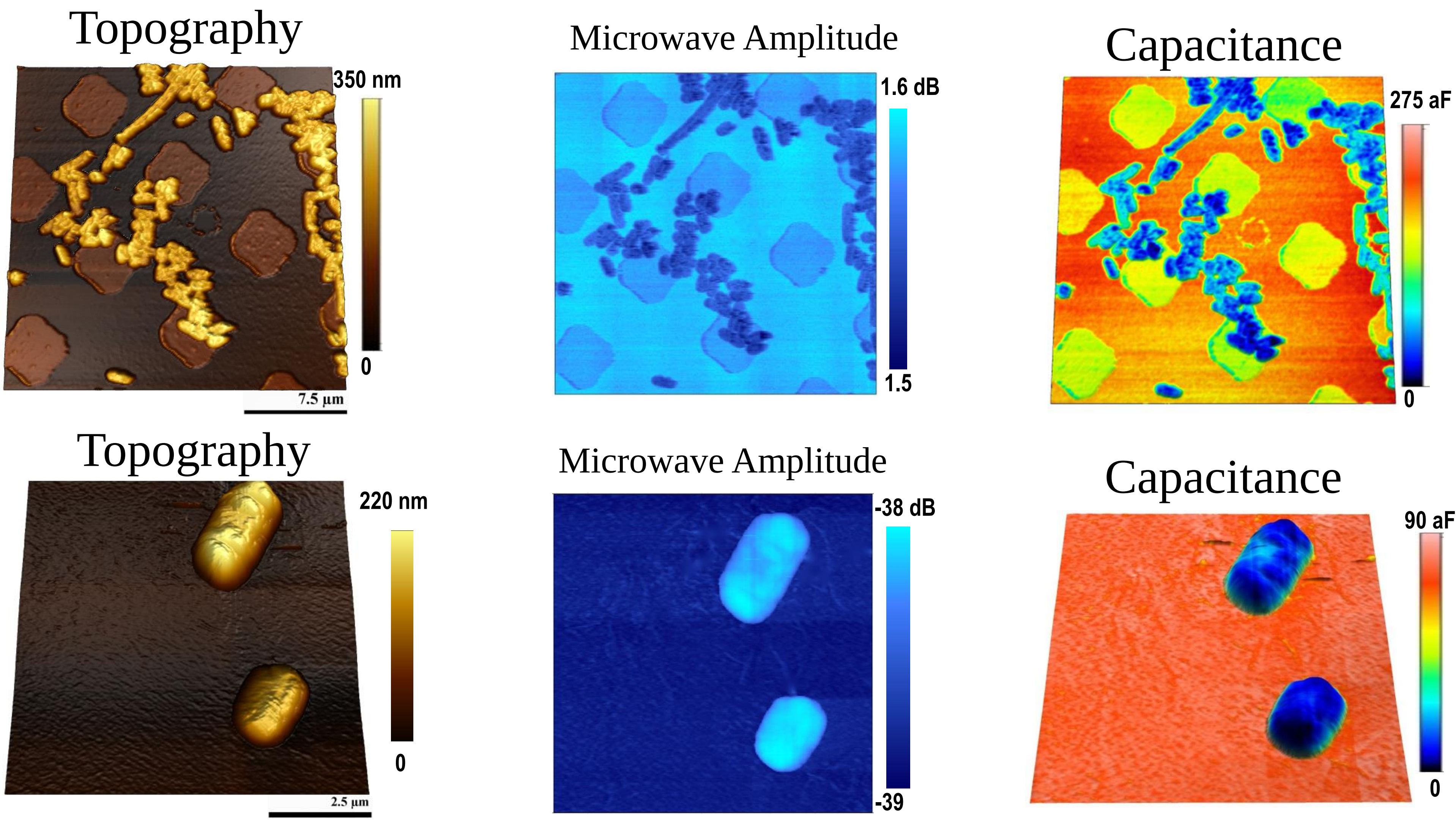
- Summary

7500 Bio-SMM in air: E. Coli bacteria over highly doped Si with SiO2 pillars

Tapping AAC mode

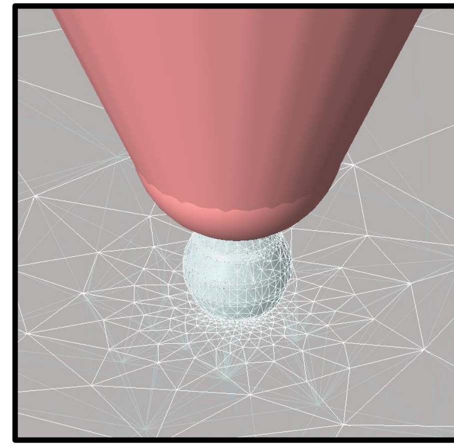


KEYSIGHT
TECHNOLOGIES

Keysight Labs Linz and JKU Linz, Tuca et al,
Microscopy & Analysis July 2015, Issue 19, pp 9-12

CHO cells in humid air (f=20 GHz)

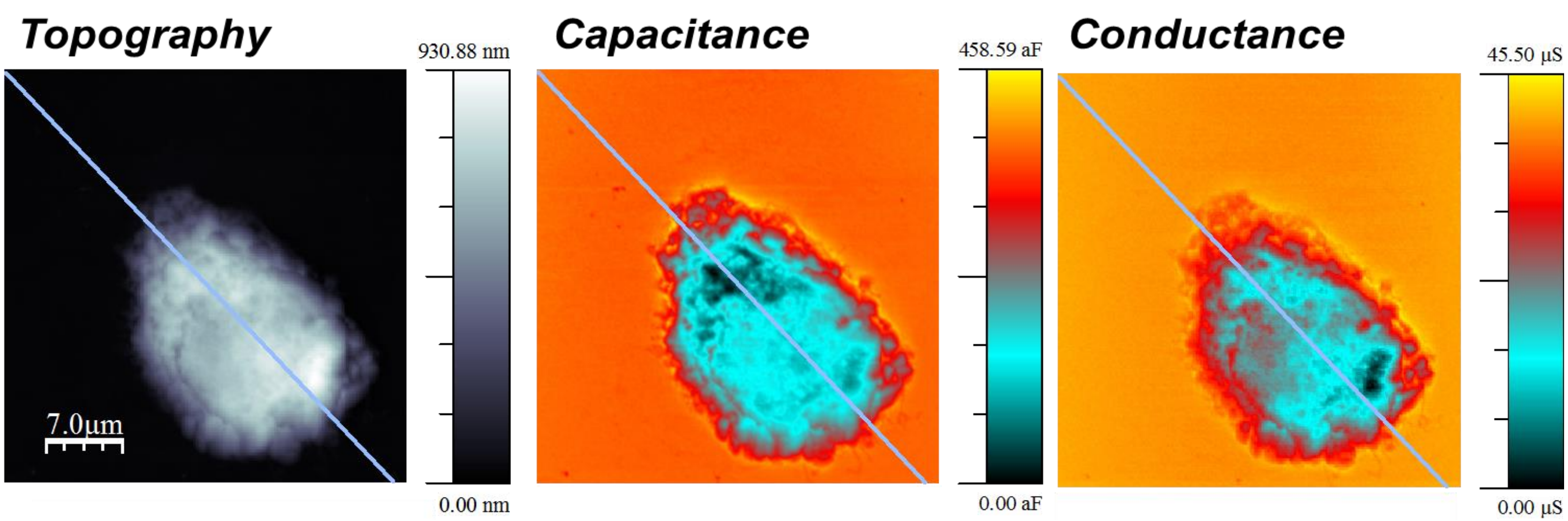
EMPro of tip-sample mashing



Single *E-coli* bacteria imaged at 20 GHz frequency using the scanning microwave microscope (SMM)

Silviu-Sorin Tuca[1], Georg Gramse[1], Manuel Kasper[2], Enrico Brinciotti[2], Yoo-Jin Oh[1], Giulio Maria Campagnaro[2], Giorgio Badino[2], Peter Hinterdorfer[1], Ferry Kienberger[2]

1 Johannes Kepler University of Linz, Institute of Biophysics, Gruberstrasse 40, A-4020, Linz, Austria
2 Keysight Technologies Austria GmbH, Measurement Research Lab, Gruberstrasse 40, A-4020, Linz, Austria

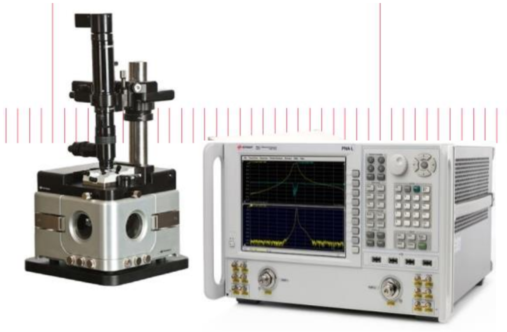


Contact & tapping mode

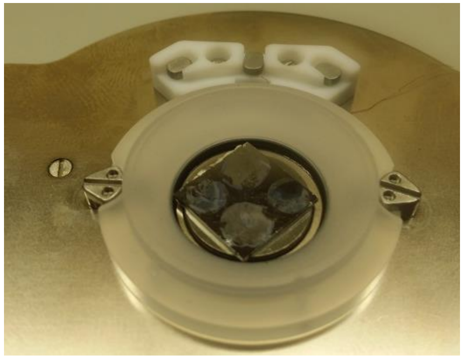
KEYSIGHT TECHNOLOGIES

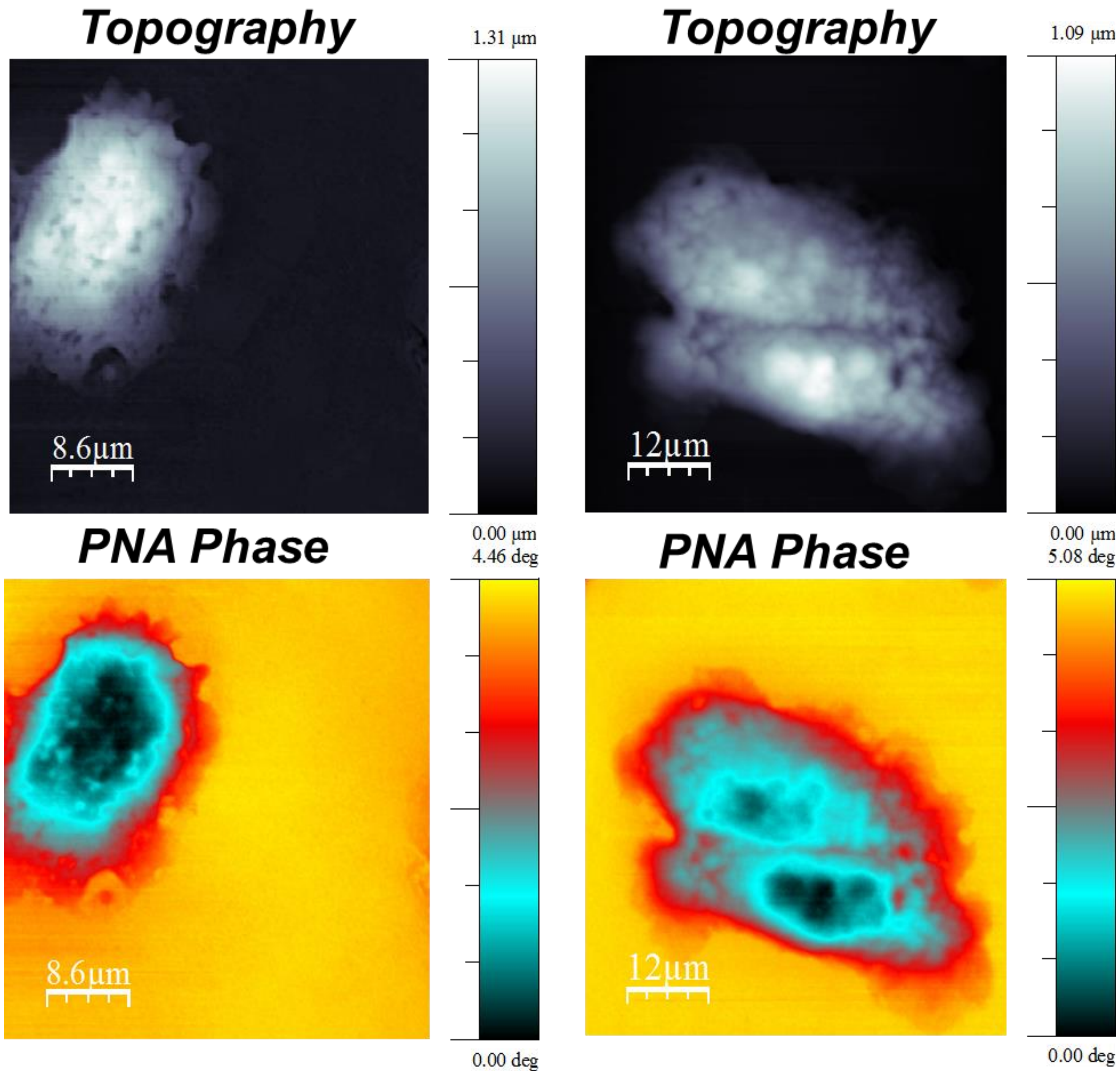
Tuca et al, Nanotechnology 2016, 27, 135702 (9p)

Bio-measurements in liquid using the 7500 SMM



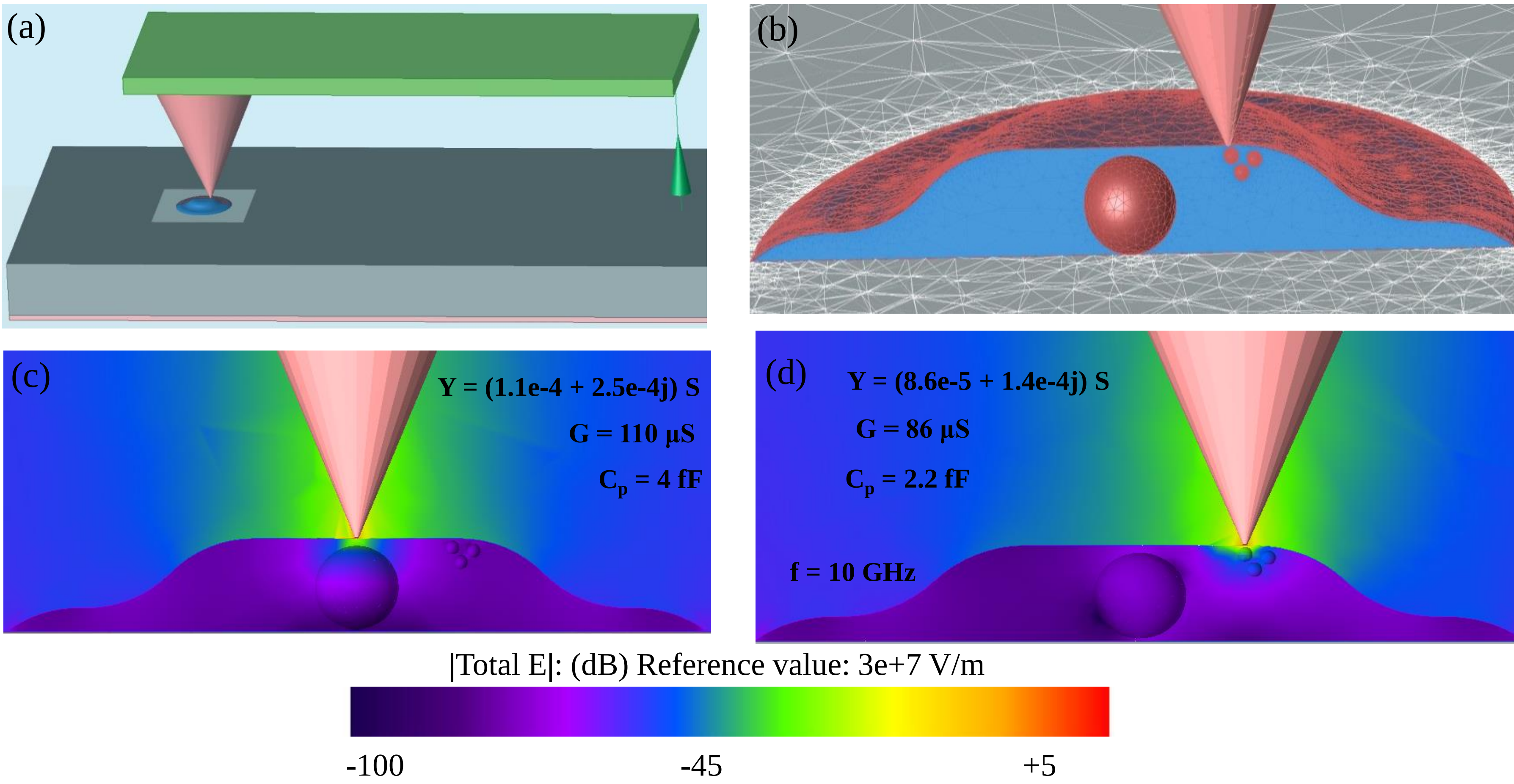
N9721B Liquid cell:





Keysight Labs Linz, Microscopy&Analysis AppNote March 2016

Application to cells in liquid: meshing, E-fields and complex impedance values



Tuca et al, Nanotechnology 2016, 27, 135702 (9p)

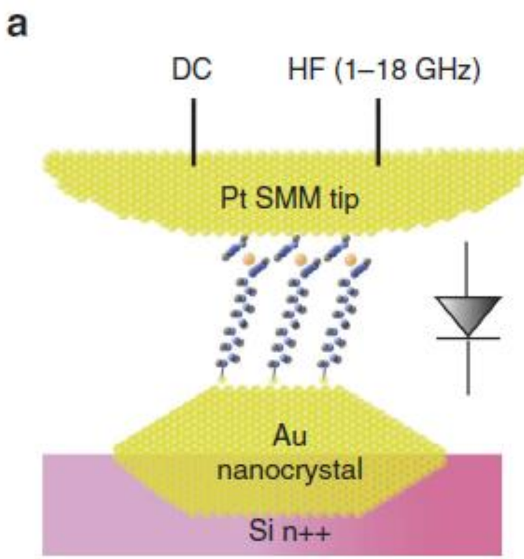
Single molecule research

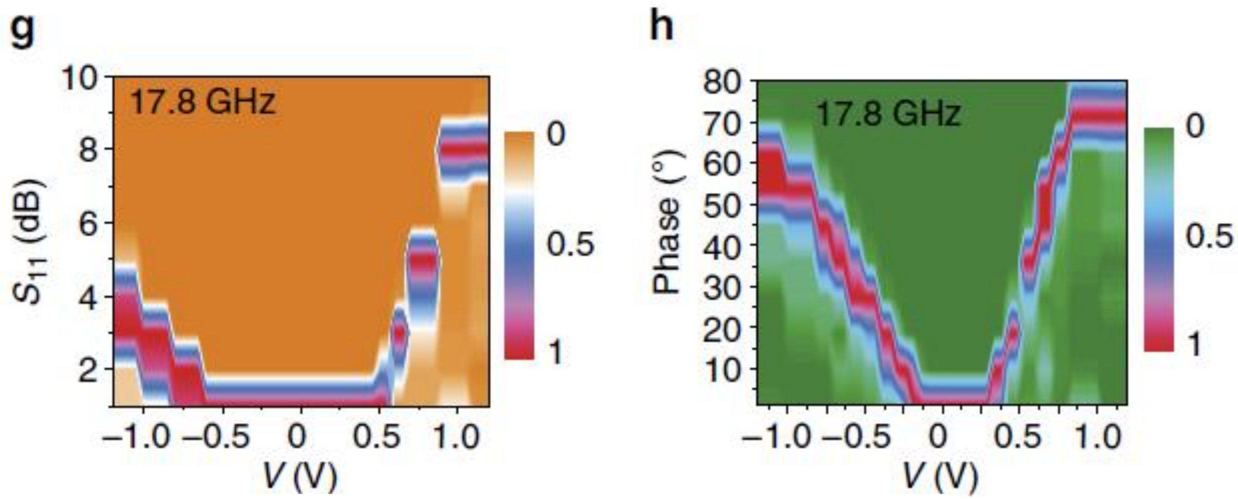
ARTICLE

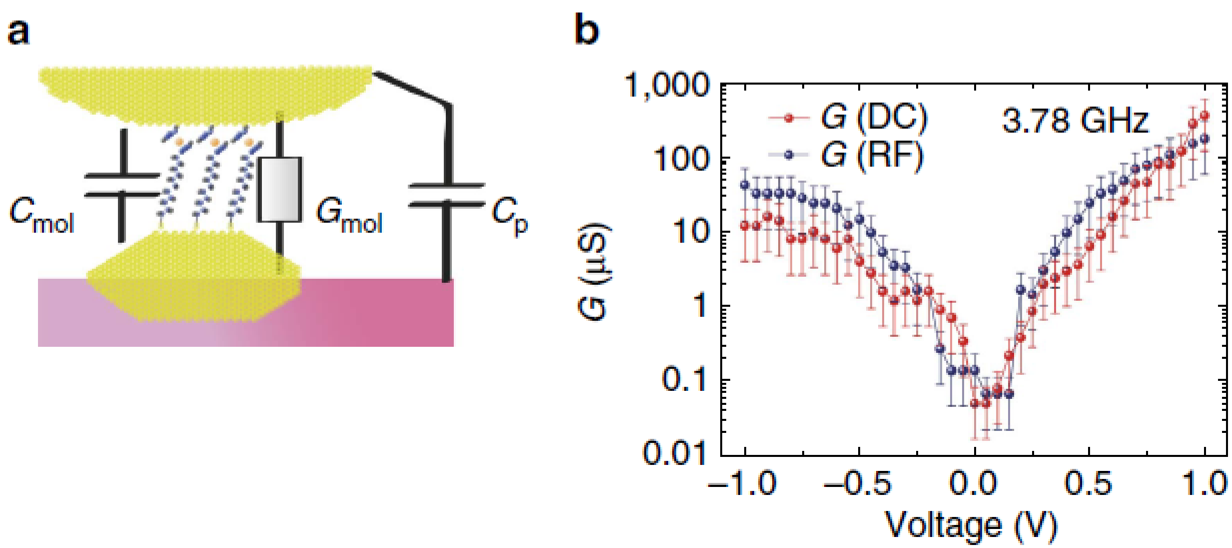
Received 12 Apr 2016 | Accepted 8 Aug 2016 | Published 3 Oct 2016

A 17 GHz molecular rectifier

J. Trasobares[1], D. Vuillaume[1], D. Théron[1] & N. Clément[1,2]



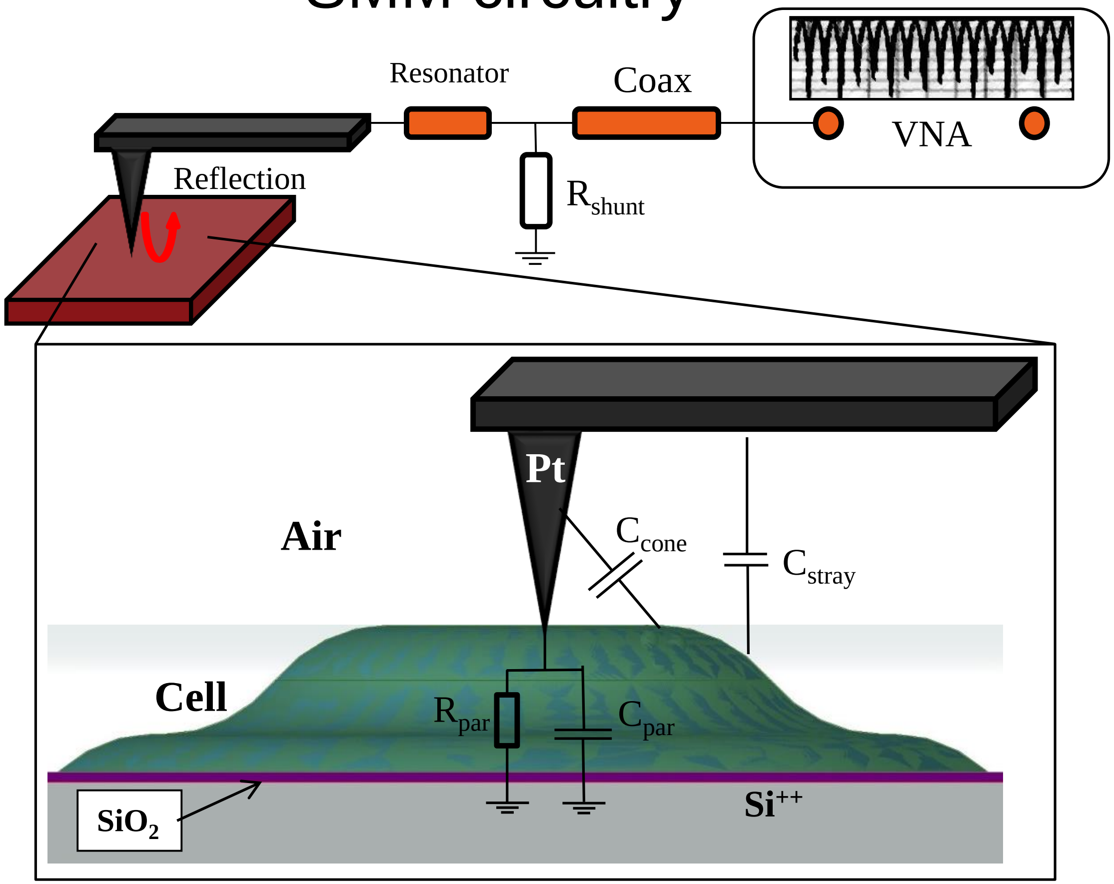


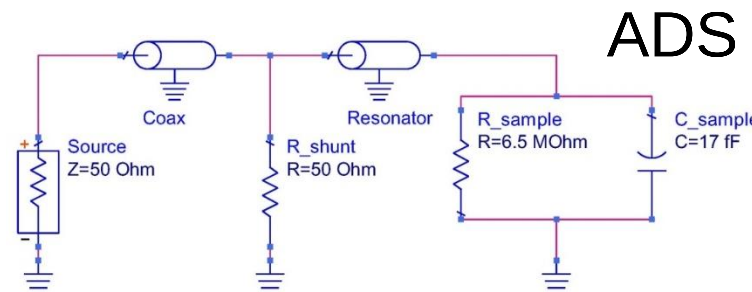


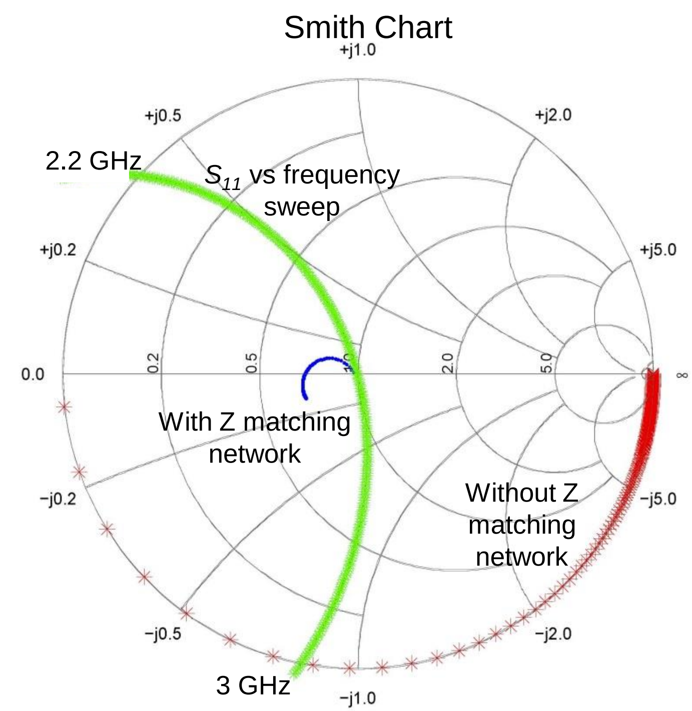
KEYSIGHT TECHNOLOGIES

Data interpretation using ADS Smith chart analysis and EMPro modeling

SMM circuitry



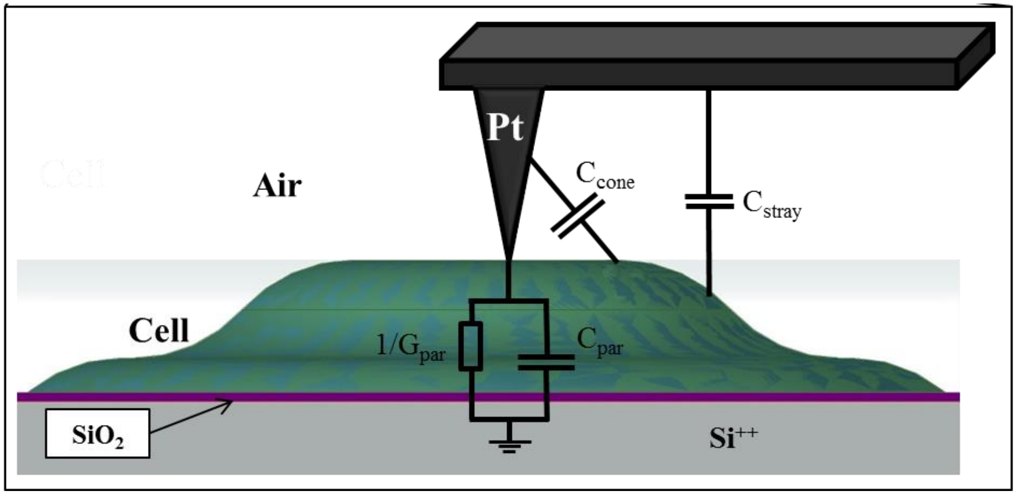


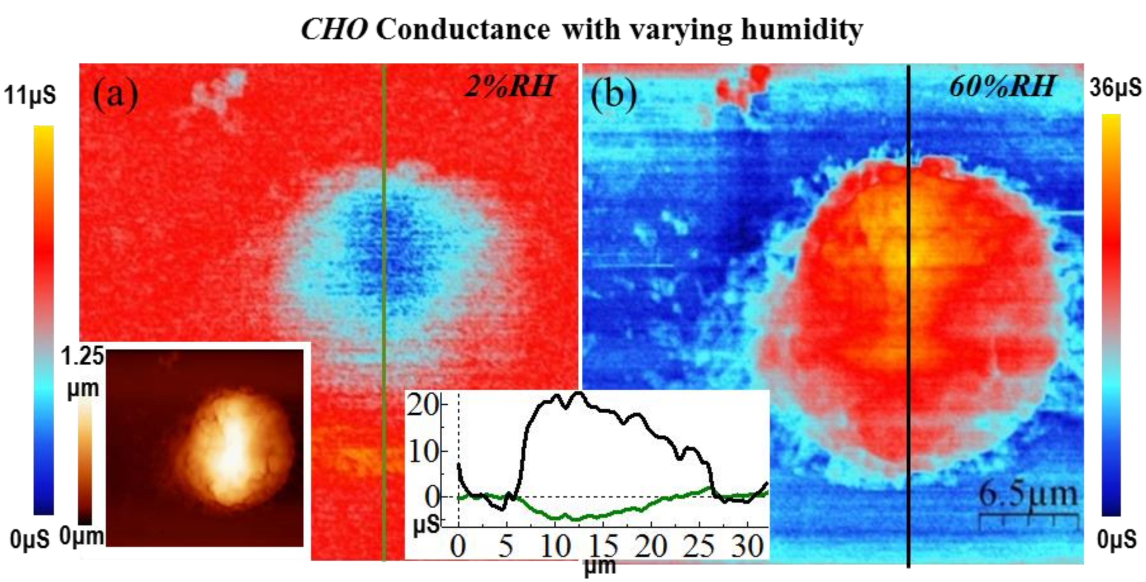


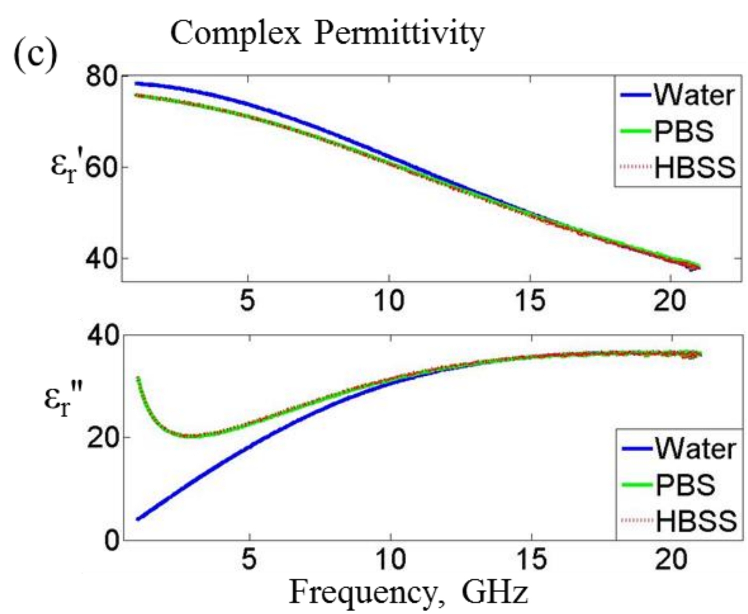
Tuca et al, Nanotechnology 2016, 27, 135702 (9p)

KEYSIGHT TECHNOLOGIES

3. SMM + dielectric probe kit for complex permittivity







KEYSIGHT TECHNOLOGIES

Tuca et al, Nanotechnology 2016, 27, 135702 (9p)

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  - Dielectric quantification
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KEYSIGHT TECHNOLOGIES

Summary general:

Ability to do **broadband** measurements, at frequencies from **1 GHz up to 20 GHz**,

- of **calibrated complex impedance** in materials science,
- of **calibrated dopant profiles** in semicon,
- of **C-V curve** spectra,
- of cells and electrochemistry in **liquid**,

and to compare the data from all these measurements with **semiquantitave 3D models** implemented in EMPro.

For all of this we **offer integrated** solutions based on several of our products: PNA-AFM, SMU, Ecal, dielectric probe kit, EMPro/ADS, ...

Various **workflows** have been implemented showing different **use cases**.

Summary details:

Differentiators

- Calibrated complex impedance
  - Capacitance and resistance: 0.5 aF sensitivity, differences of 20 Ohm can be measured up to 20 kOhm
- ***Materials properties can be determined:***
  - ***From capacitance the complex permittivity/dielectric constant (~10% accuracy)***
  - ***From resistance the resistivity (aka SSRM)***
- Calibrated dopant density for both silicon and compound semiconductors, as well as other electronic materials, large dynamic range for dopant density
- All info in one scan (topo, impedance, dopant) with high spatial resolution: ~ 10 nm
- ***Broadband frequencies (1-20 GHz) allowing for variable depth subsurface imaging and frequency selective dopant profiling***
- **The 7500 bio-SMM works in liquid**
- Technology synergy with other Keysight products: EMPro; source-meter unit SMU; Ecal calibration unit; dielectric probe kit for permittivity

KEYSIGHT TECHNOLOGIES

Thanks for your interest and your attention.

ferry_kienberger@keysight.com