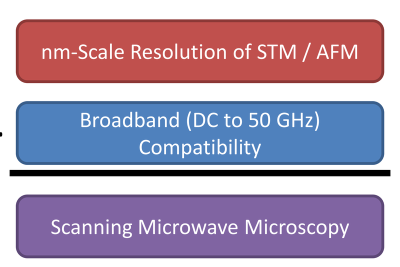
Spatially-Resolved Dopant Characterization with a Scanning Microwave Microscope

T. Mitch Wallis, Atif Imtiaz, Alexandra Curtin, Pavel Kabos, Matt Brubaker, Norman Sanford, and Kris Bertness

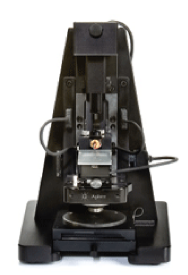
NIST, Boulder, Colorado

Scanning Microwave Microscopy



The scanning microwave microscope (SMM) is a tool for spatially-resolved characterization of nanoelectronic materials and devices. SMM combines the nanometer-scale spatial resolution of scanning probe microscopes with broadband compatibility The microscope incorporates a sharp, near-field probe, which measures local changes in reflected microwave signals from a device under test. With proper calibration and modeling, a variety of parameters can be extracted from the measurements, including impedance, absolute capacitance, and dopant concentration.

Commercial RF-AFM 100 MHz – 20 GHz



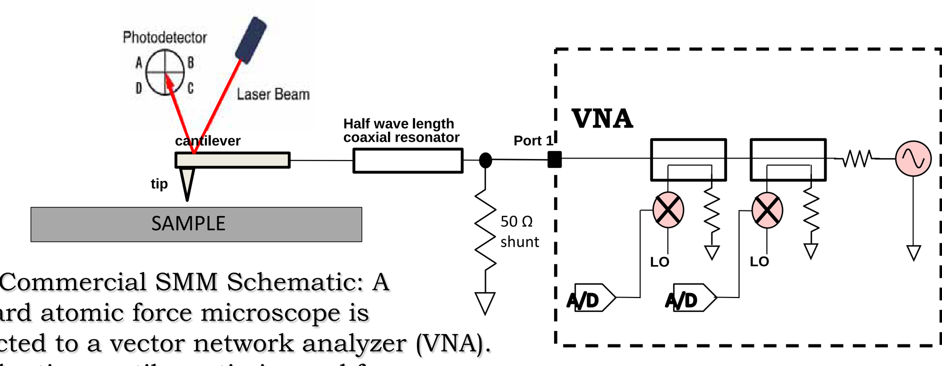


Fig. 1 Commercial SMM Schematic: A standard atomic force microscope is connected to a vector network analyzer (VNA). A conductive cantilever tip is used for transmitting an incident microwave signal to the sample.

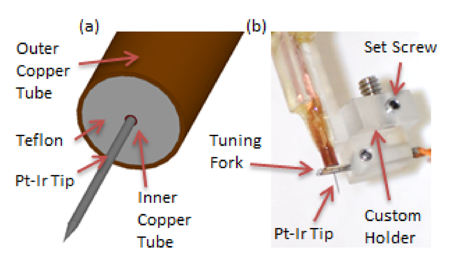


Fig. 2 (a) Schematic of probe tip construction (b) Photo of tuning fork holder

NIST built system: STM/AFM DC – 50 GHz

Our home-built system incorporates a Pt-Ir tip inserted into an open-ended coaxial cable to form a weakly coupled resonator. Tuning fork feedback enables simultaneous, non-contact measurement of topography and reflected microwave signal (S_{11}).

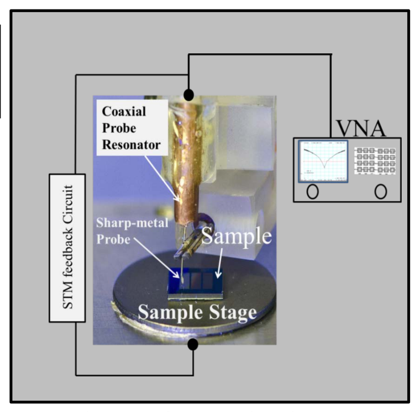


Fig. 3 Photo of NIST-built SMM

[1] J. C. Weber, et. al. *Rev. Sci. Instrum.* **83**, art. no. 083702 (2012).

Calibrated Nanoscale Dopant Profiling

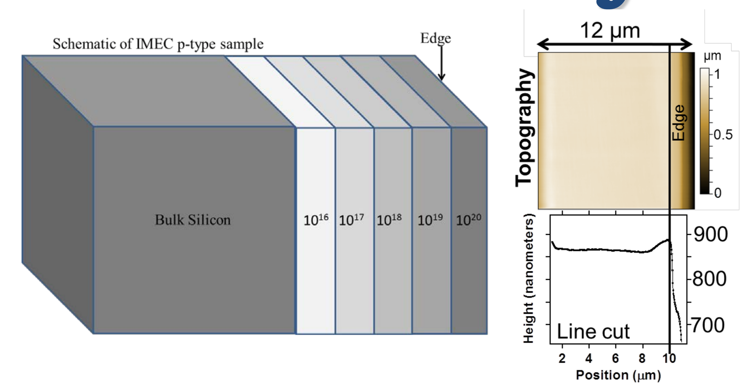


Fig. 4 Calibration samples for dopant profiling.

- Topography free
- Variably-doped p-type Si
- Dopant concentrations in "stripes" are 10^{16} cm^{-3}, 10^{17} cm^{-3}, 10^{18} cm^{-3}, 10^{19} cm^{-3}, and 10^{20} cm^{-3}

dC/dV: Measurement and Simulation

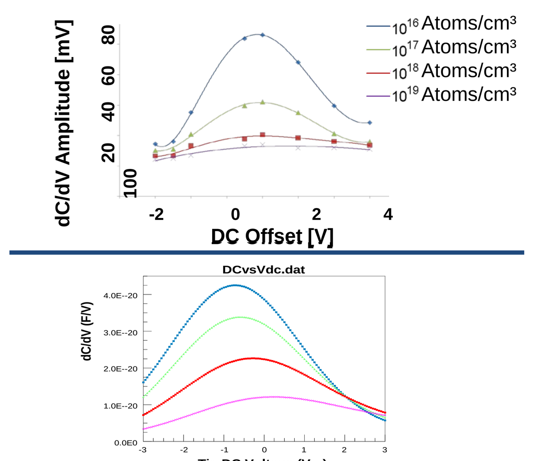
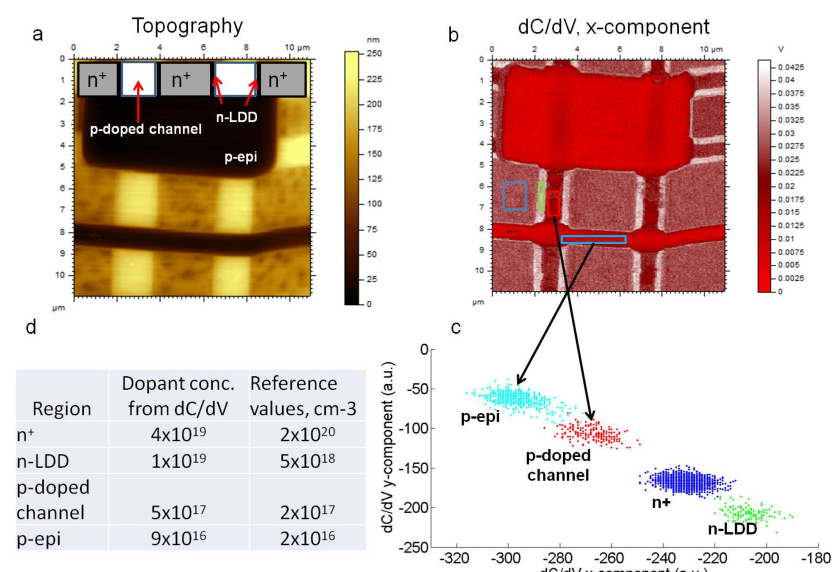


Fig. 6 Comparison of measurement (top) to simulation (bottom) used to extract calibration parameters with NIST FastC2D [3].

Bipolar p-n SRAM: Materials Contrast



Region	Dopant conc. from dC/dV	Reference values, cm-3
n^+	4×10^{19}	2×10^{20}
n-LDD	1×10^{19}	5×10^{18}
p-doped channel	5×10^{17}	2×10^{17}
p-epi	9×10^{16}	2×10^{16}

[3] H. P. Huber, et. al. *J. Appl. Phys.* **111**, art. no. 014301 (2012).
[4] J. Kopanski, et. al. *J. Vaccuum Sci. & Tech. B* **22**, p399 (2004).

Imaging P-N Junctions in GaN Nanowires

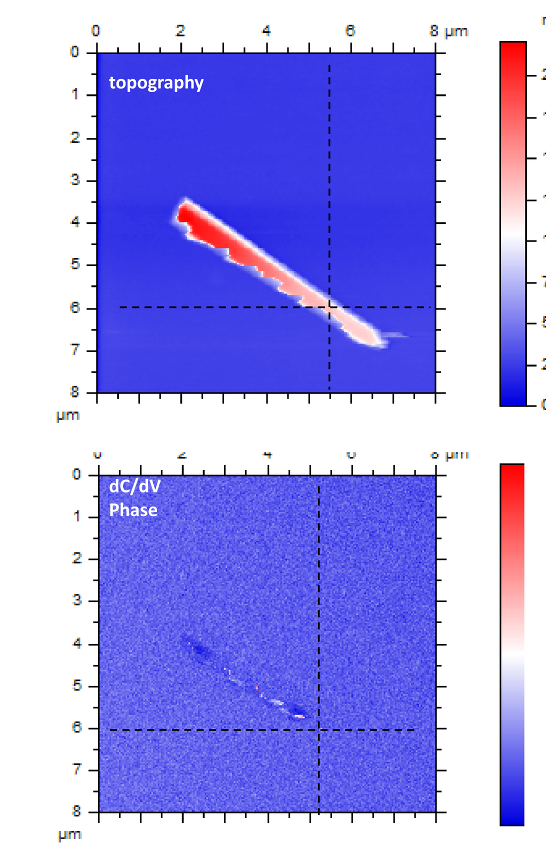


Fig. 15 (Top) Contact AFM topography of GaN NW (12 µm X 12 µm). (Bottom) *dC/dV* phase image, operating frequency 18.5 GHz. The apparent topographic length of the structure is about 6 µm. However, the apparent length decreases to about 4 µm in simultaneously acquired *dC/dV* amplitude and phase images (phase image shown). In other words, only the n-type segment of the NW shows a response in the *dC/dV* images.

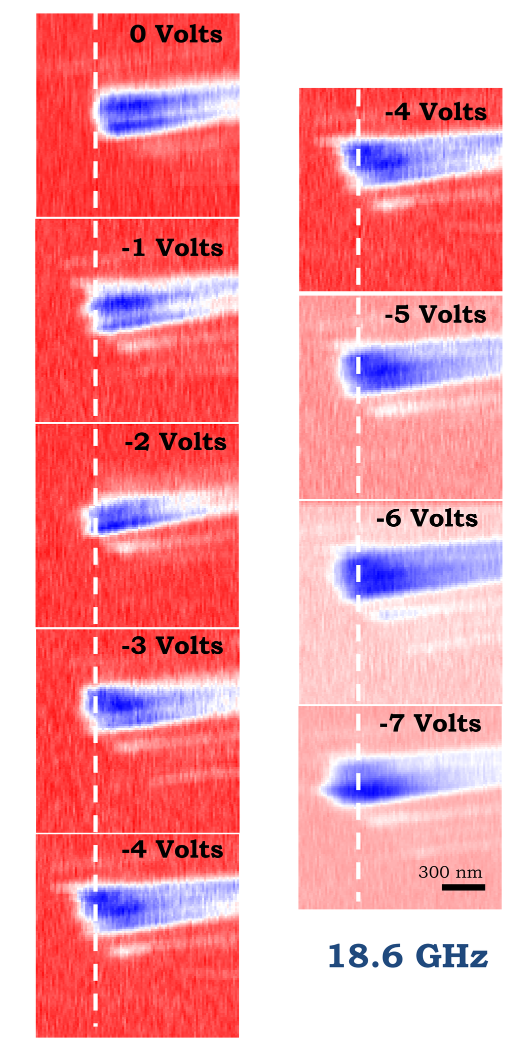


Fig. 16 As the DC tip bias is changed from 0 volts to -7 volts, the location of the P-N junction shifts by about 300 nm, as seen in dC/dV amplitude images.

Absolute Capacitance Calibration

Samples

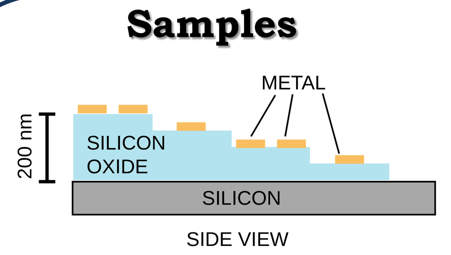


Fig. 11 Schematic of calibration samples for absolute capacitance calibration.

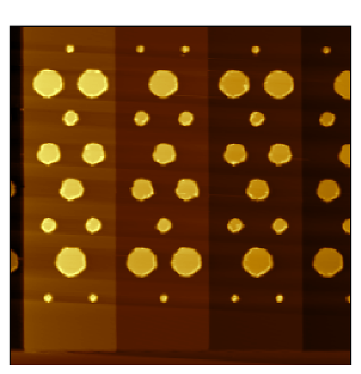


Fig. 12 AFM topography of calibration samples for absolute capacitance calibration.

Model

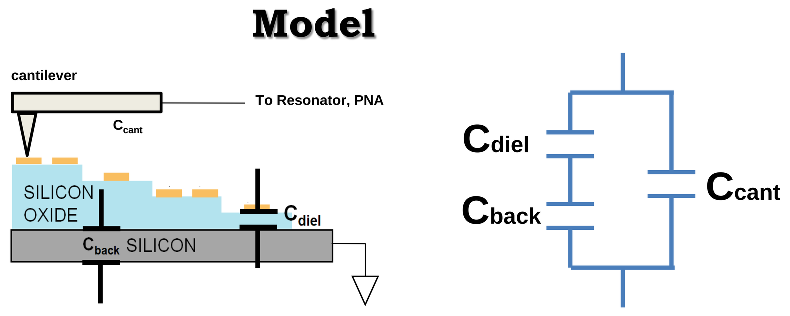


Fig. 13 Circuit model for absolute capacitance calibration.

- Reflection amplitude with probe on Au pad: S_{11}^{Au}
- Reflection amplitude with probe on dielectric step: S_{11}^{step}
- Relative signal: $\Delta S_{11} = S_{11}^{Au} - S_{11}^{step}$

→ exclude effects of stray (parasitic) capacitance C_{cant}

$$C_{tot} = \alpha\ \Delta S_{11}$$

$$\frac{1}{C_{tot}} = \frac{1}{C_{diel}} + \frac{1}{C_{back}}$$

Find calibration constants α, C_{back}

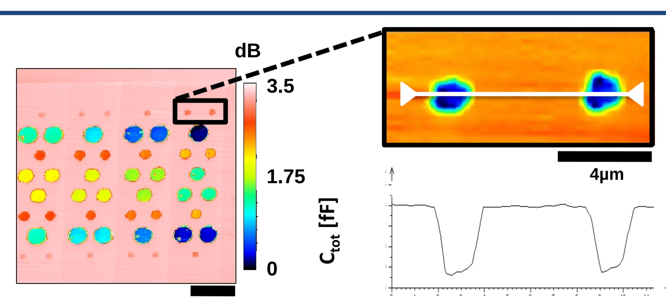


Fig. 14 SMM Image of calibration sample with detail and cross-section.

Sensitivity

Smallest gold pad (1 µm) on 50 nm dielectric
- resolve capacitance difference of 0.15 fF
- variation across pad ~0.02 fF

[2] H. P. Huber, et. al. *Rev. Sci. Instrum.* **81**, art. no. 113701 (2010).

Frequency-Dependent Sensitivity

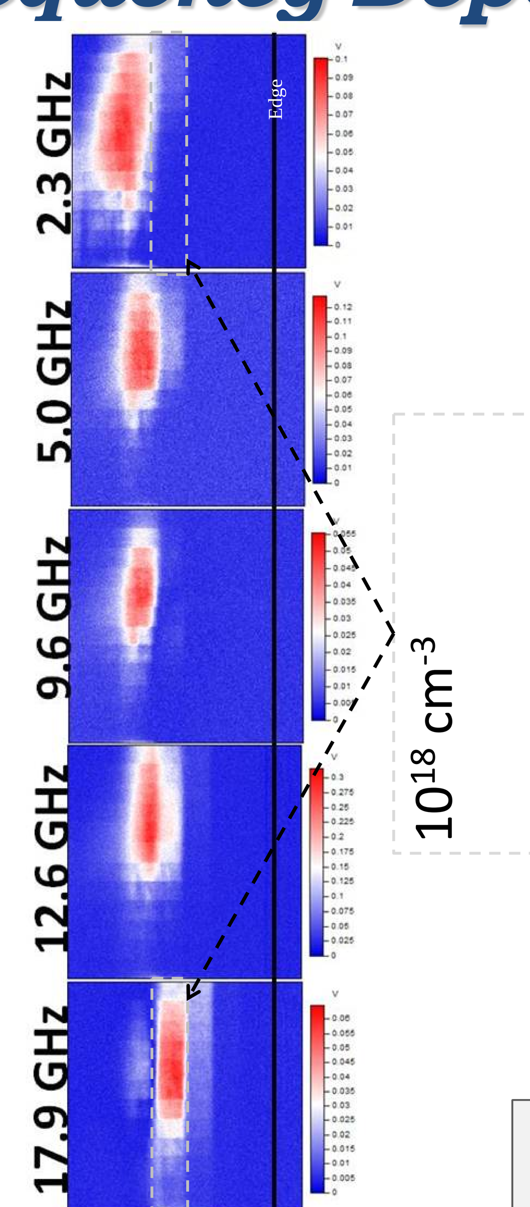


Fig. 8 SMM images of dopant profile samples at five different frequencies.

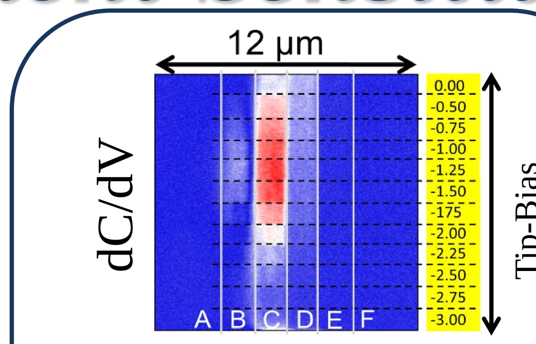


Fig. 7 Imaging approach for exploring the frequency-dependent sensitivity of SMM. The same calibration sample is used as in the calibrated dopant profiling experiment. . The DC SMM bias was adjusted from 0.00 V to -3.00 V during image acquisition. Beginning at the topmost horizontal scan lines, the data was acquired with a bias of 0.00 V. Throughout the scan, the bias was adjusted sequentially until the bias was -3.00 V in the bottommost scan lines.

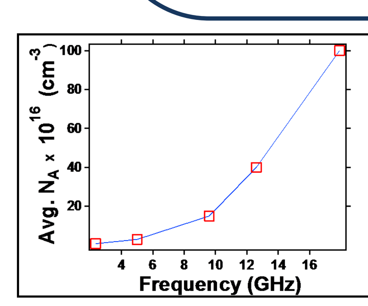


Fig. 9 Graph showing which concentration (stripe) shows the most contrast as a function of frequency.

$$Selection-Frequency = \frac{1}{\xi(R_s + R_x)C_{total}}$$

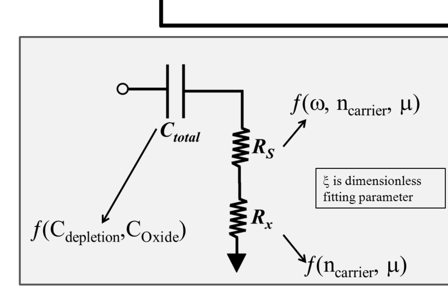
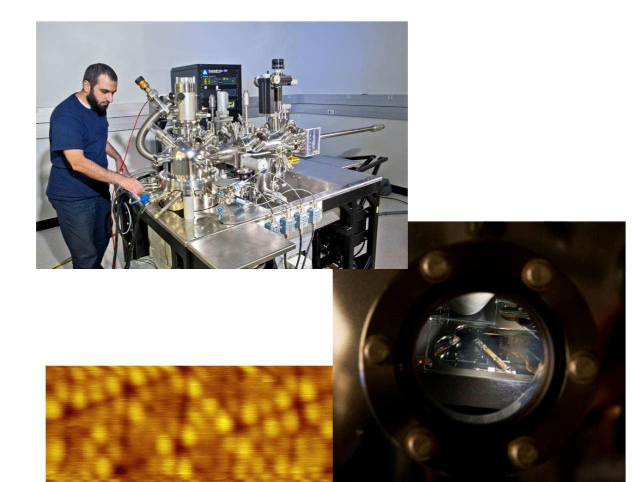


Fig. 10 Simple circuit model of the tip-sample interaction in the junction between the SMM sample and the Si dopant profile sample.

[5] A. Imtiaz, et. al. *J. Appl. Phys.* **111**, art. no. 093727 (2012).

SMM at the Atomic Scale



The ongoing goal of our work is to take calibrated, broadband scanning microwave microscopy to the atomic scale. Our new multiprobe radio frequency STM was installed in January, 2013 and features:

(i) Four Scanning Tunneling Microscope (STM) probes
(ii) Each STM probe has is broadband: from DC to 40 GHz
(iii) Integrated Scanning Electron Microscope (SEM) enables positioning of probe tips relative to each other and devices
(iv) Ultrahigh Vacuum, Variable Temperature: 10K – 300K
(v) Can apply in-plane magnetic field up to 40kA/m (500 Oe)

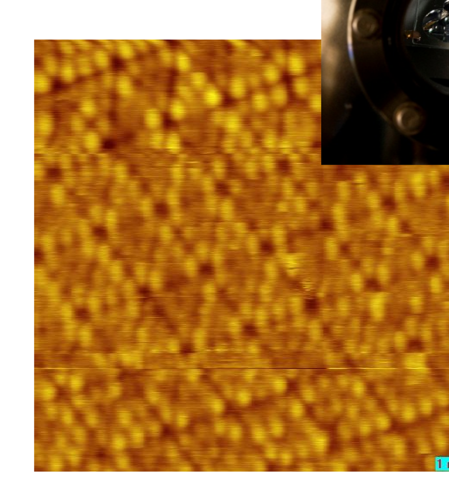


Fig. 17 Image of Si(111) 7x7 surface taken with new multi-probe system.

Future directions of the research include broadband transport measurements, sub-surface imaging, FMR of nanoscale objects, as well as extension of our established dopant profiling and capacitance calibration capabilities to the atomic scale.

Acknowledgements

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