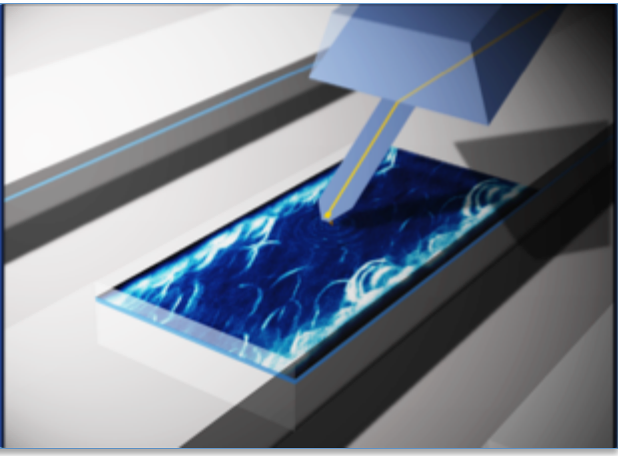
PRIMENANO

ACCELERATING THE NANO ERA

ScanWave Introduction



March 2015

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PRIMENANO

Who is PrimeNano, Inc?

- Instrument company focused on imaging and metrology for research and industry
- Founded in 2010 in Palo Alto, CA
- Patented technology spun out of Stanford University Applied Physics Dept.
- ScanWave™ is a stand alone module for commercial AFM platforms

What is sMIM? – A new mode for AFM

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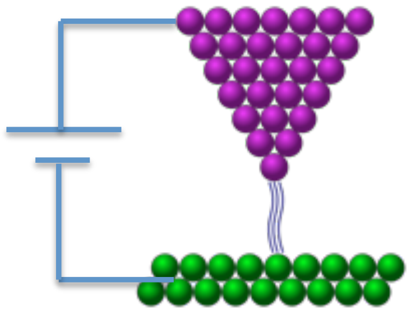
- **Direct measurement of electrical properties**
  - Image local variation of ε and σ
  - < 100 nm lateral resolution (50 nm typical, 20 nm for some modes/materials)
- **Compatible with all materials**
  - Images dielectrics, insulators, & metals
  - Measure with contact, tapping mode (resonant and non-resonant) and non-contact imaging
- **Sub-surface sensitivity**
  - Can image through ~100's nm over-layers

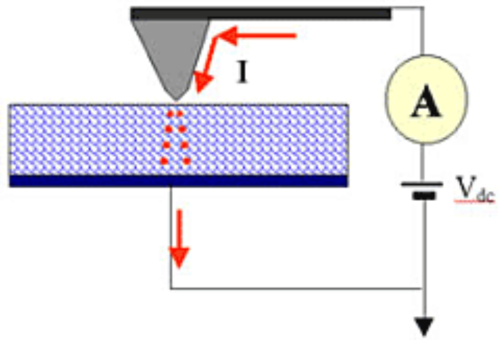
Probe the Nano Scale

STM



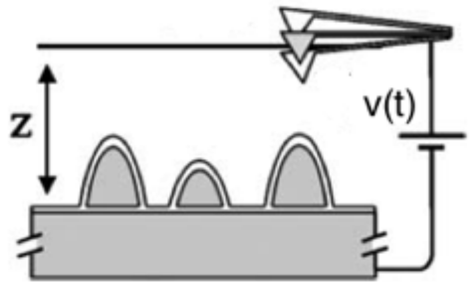
Atomic scale density of states

Conductive AFM



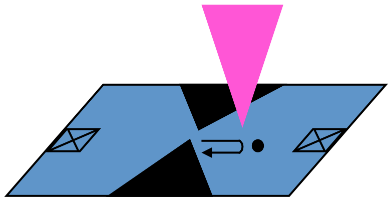
Spreading resistance

Electrostatic Force Microscope /Kelvin Probe Microscope



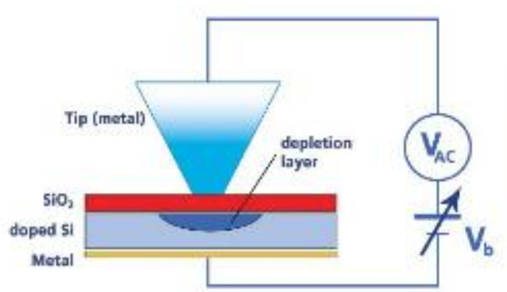
Work function / Capacitive Coupling

Scanning Gate Microscope



Current flow path

Scanning Capacitance Microscope

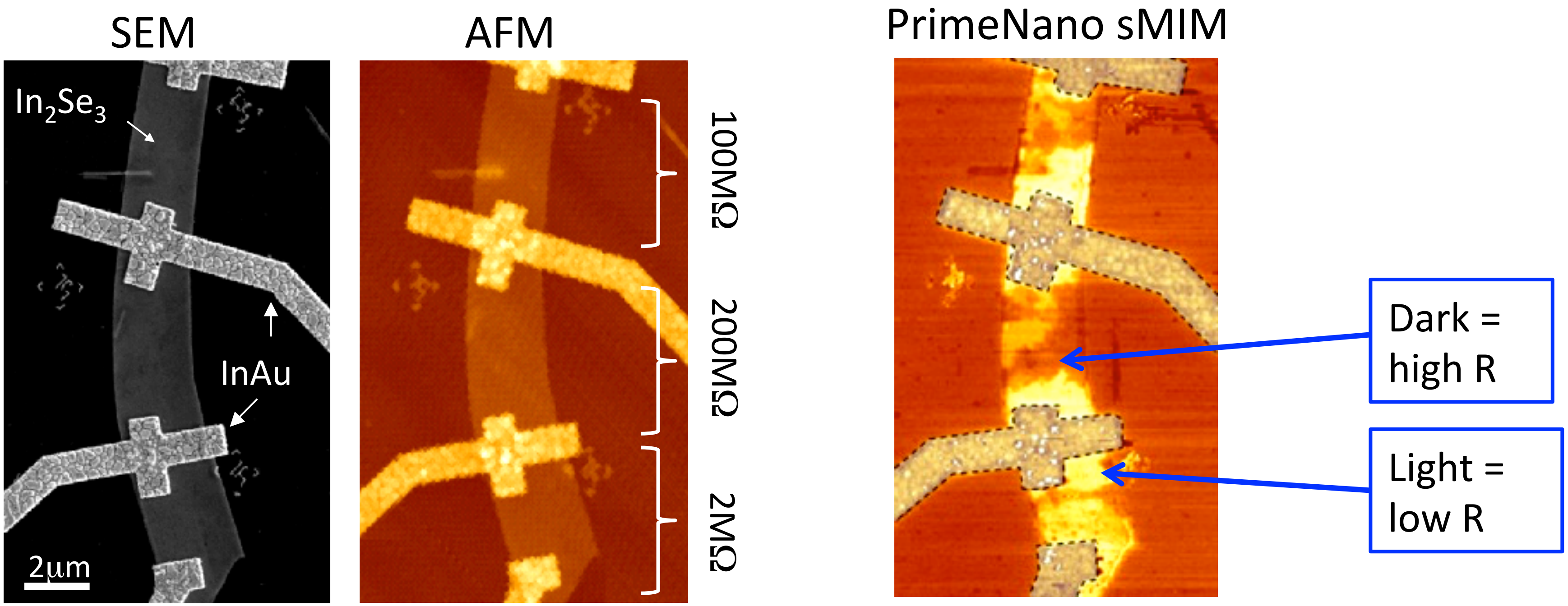


Doping level in semiconductor

Microwave Impedance Microscope

Local (σ, ε) Probe of electrical properties

Example – InSe nano ribbon



- Resistance change only seen using ScanWave system
- Clearly differentiates 2 phases of nano-ribbon material

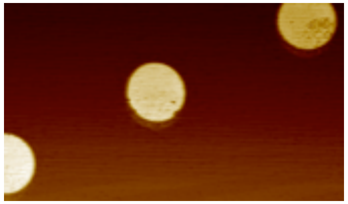
Courtesy of Prof. Yi Cui
Stanford University

Why Microwaves?

- **Optics (light) have poor contrast**
- **Microwaves have high contrast**

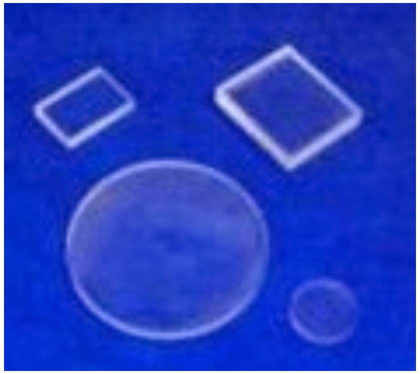
Silicon
(poor conductor, σ = 0.0016)

Aluminum
(good conductor, σ = 3.5e7)

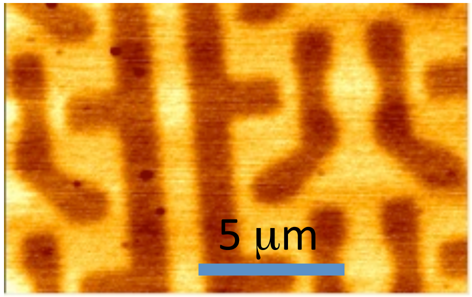


sMIM of Al dots on Si

Sapphire (Al2O3, ε ~ 9)

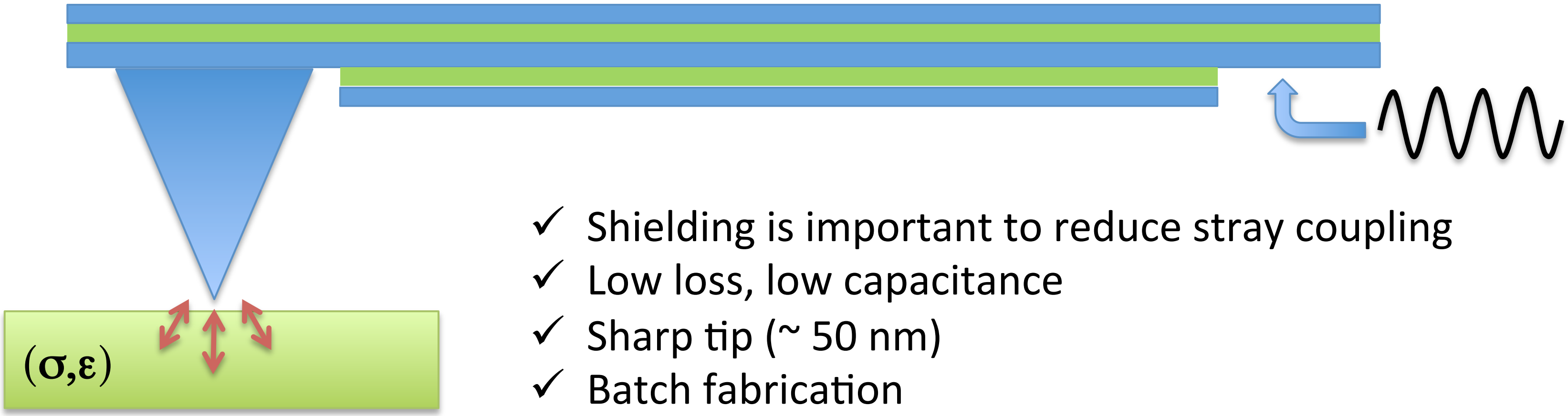


Glass(SiO2, ε ~ 4)

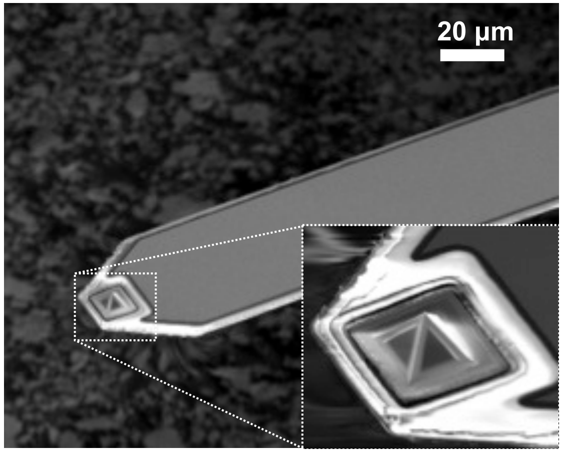


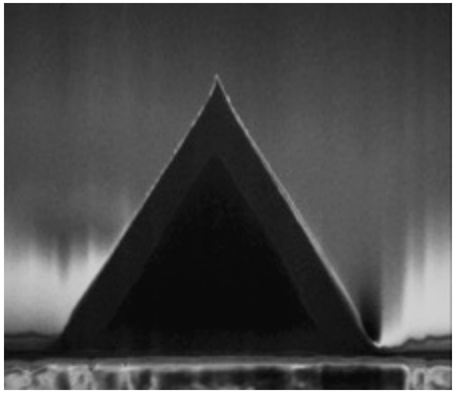
sMIM of SiO2 in Al2O3

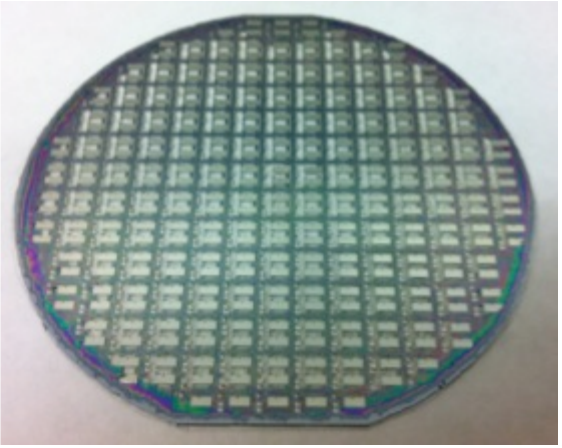
Shielded Cantilever Probe



- ✓ Shielding is important to reduce stray coupling
- ✓ Low loss, low capacitance
- ✓ Sharp tip (~ 50 nm)
- ✓ Batch fabrication







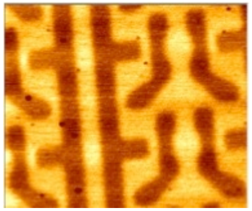
Yang, et al, J. Micromech. Microeng., (2012)

The PrimeNano Difference

- **Patented probe technology**
  - Shielded probes enhances sensitivity and reduces noise
  - Demonstrated resolution to 20nm
  - Long lasting solid metal probes
- **Specialized electronics**
  - Optimized for higher sensitivity and resolution
  - Dedicated system improves time to results
- **Compatible with existing AFM instruments**
  - Currently verified with Bruker, Asylum, & Park Systems
  - Upgrade an existing AFM Platform or integrated with a new AFM System

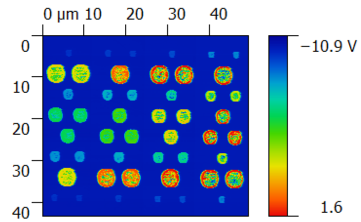
Typical Applications

Buried Structures



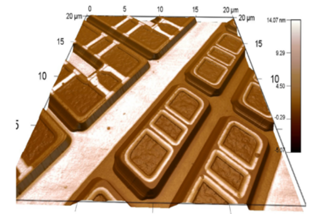
SiO_2 under 100nm of Al_2O_3

Capacitance



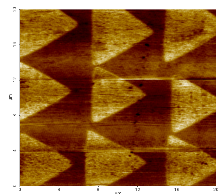
Calibration capacitance standard

Microelectronics



sMIM measurement of doped channels in SRAM structure.

Ferroelectric Domains



$LiNbO_3$ sMIM-R domain boundaries

Materials Contrast

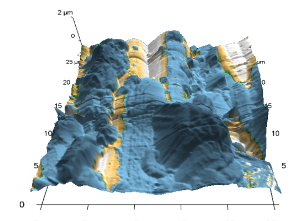
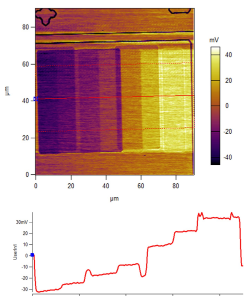


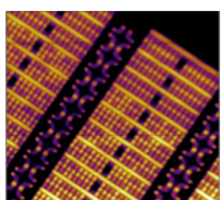
Image conductors and insulators together

Dopant Variations



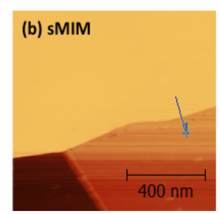
Doped Si Staircase

Semiconductors



Memory charge on floating Gate

Graphene on Si



Graphene domains

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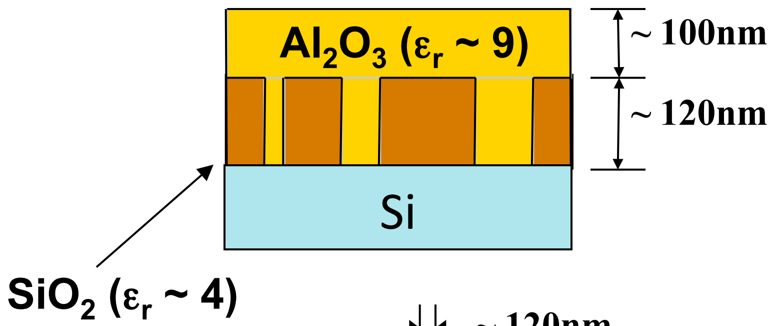
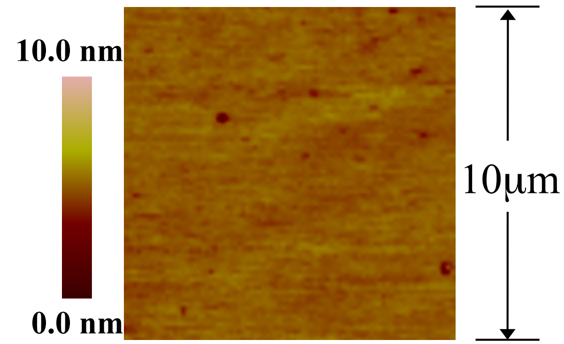
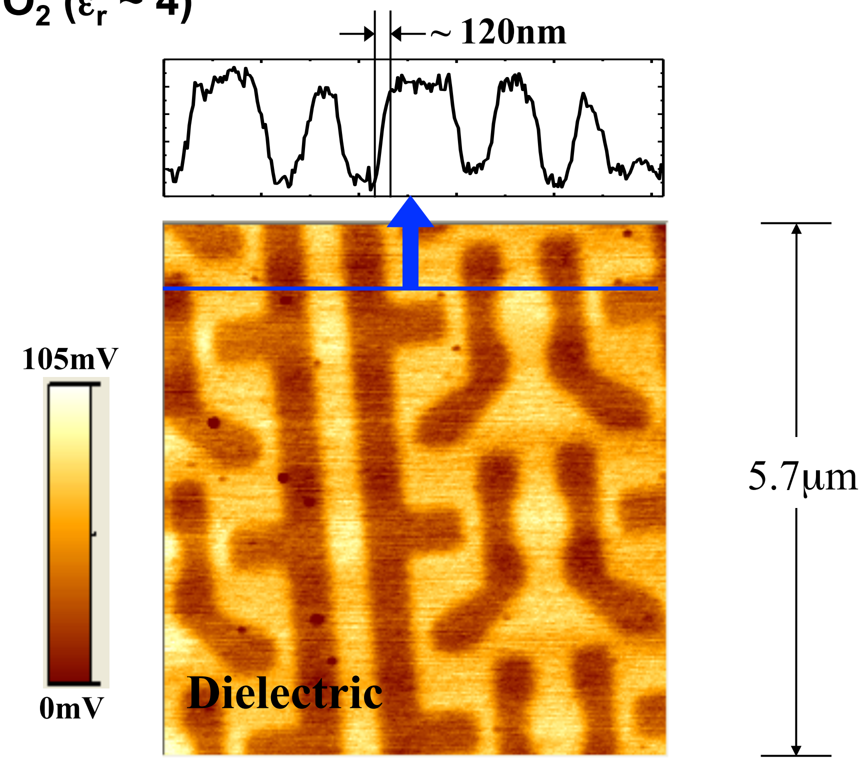
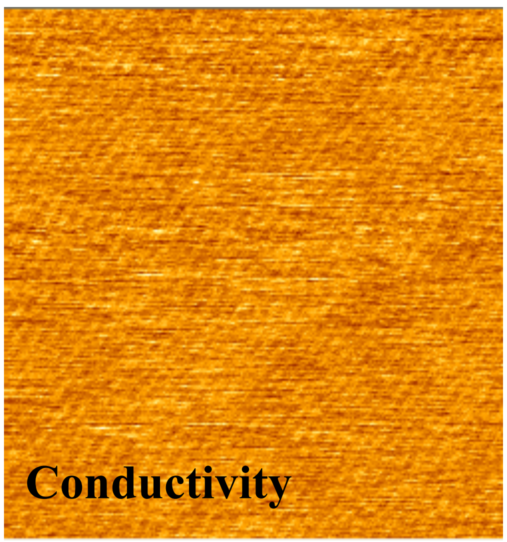
Buried Structures – Dielectric test structure









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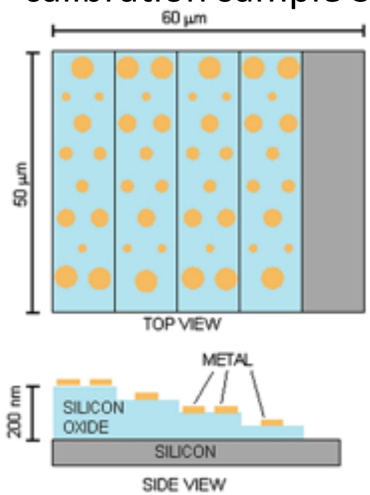
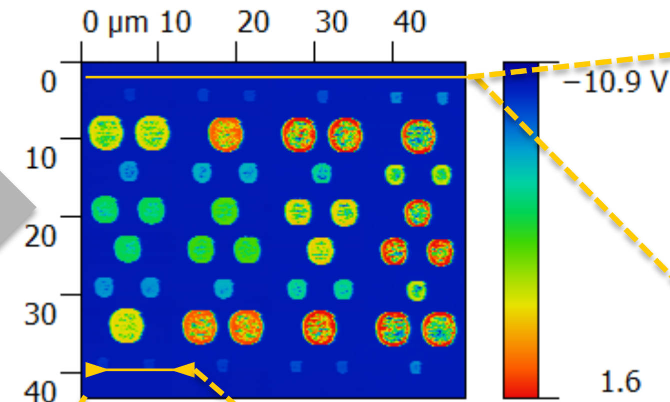
Sensitivity and Noise floor

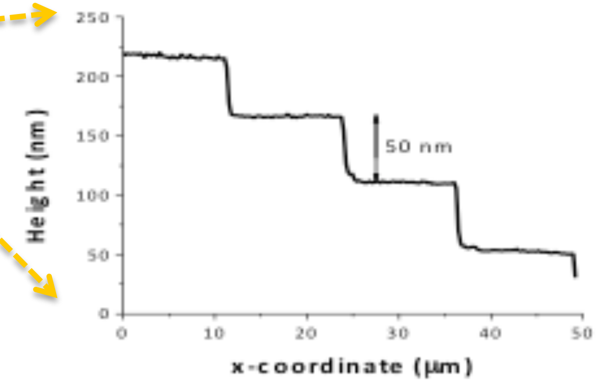
NIST developed capacitance calibration sample Schematic

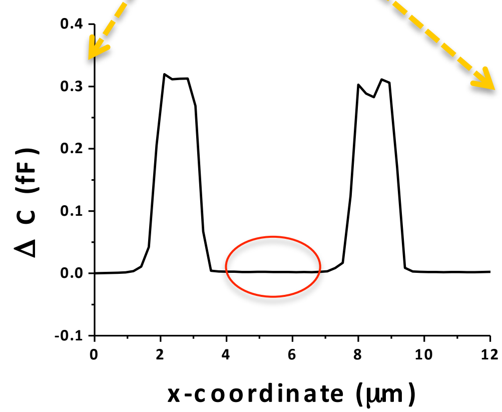


sMIM Image



Line cross-section of SiO_2 steps





Line cross-section of smallest Au gold dot cap structure

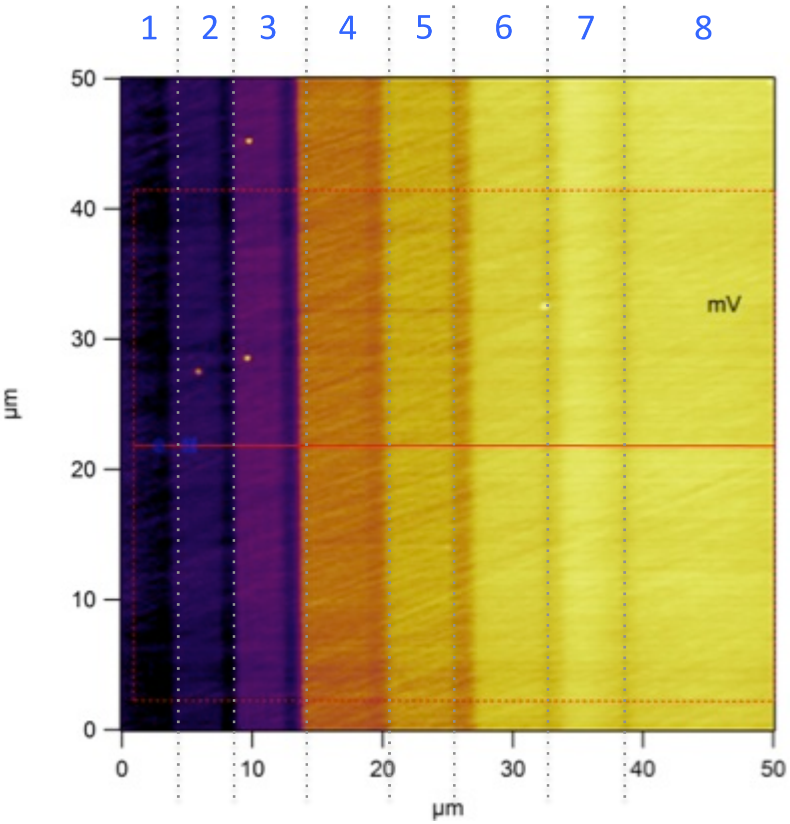
Results

1. noise level of 0.3 aF
2. Sensitivity of 0.15af/mV
3. 10x improvement over other published values

Calculated using method outlined in ref: H. P. Huber, *Rev. Sci. Instrum.* *81*(11), 113701. (2010)

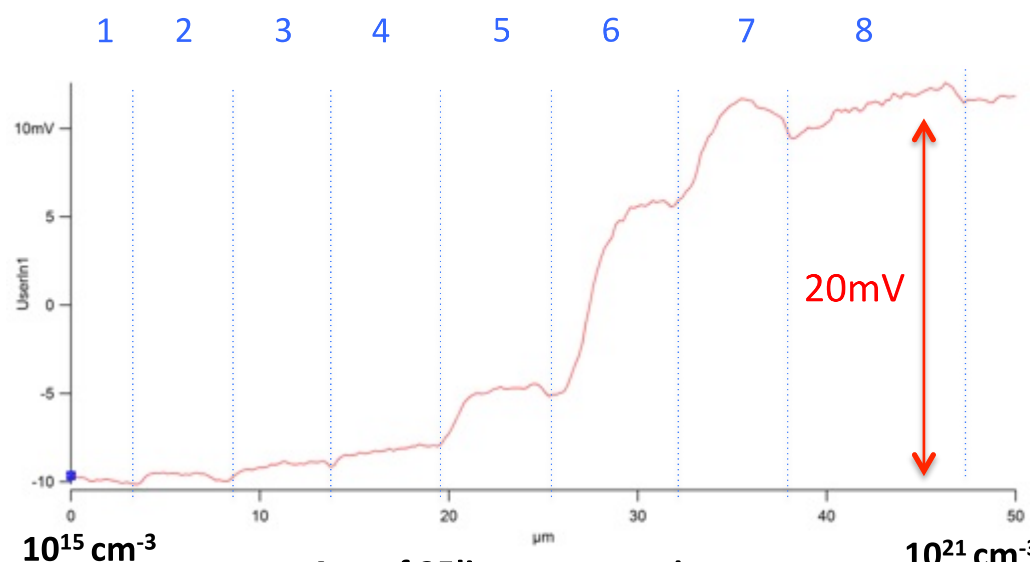
Sensitivity and Noise floor

IMEC p-type Staircase



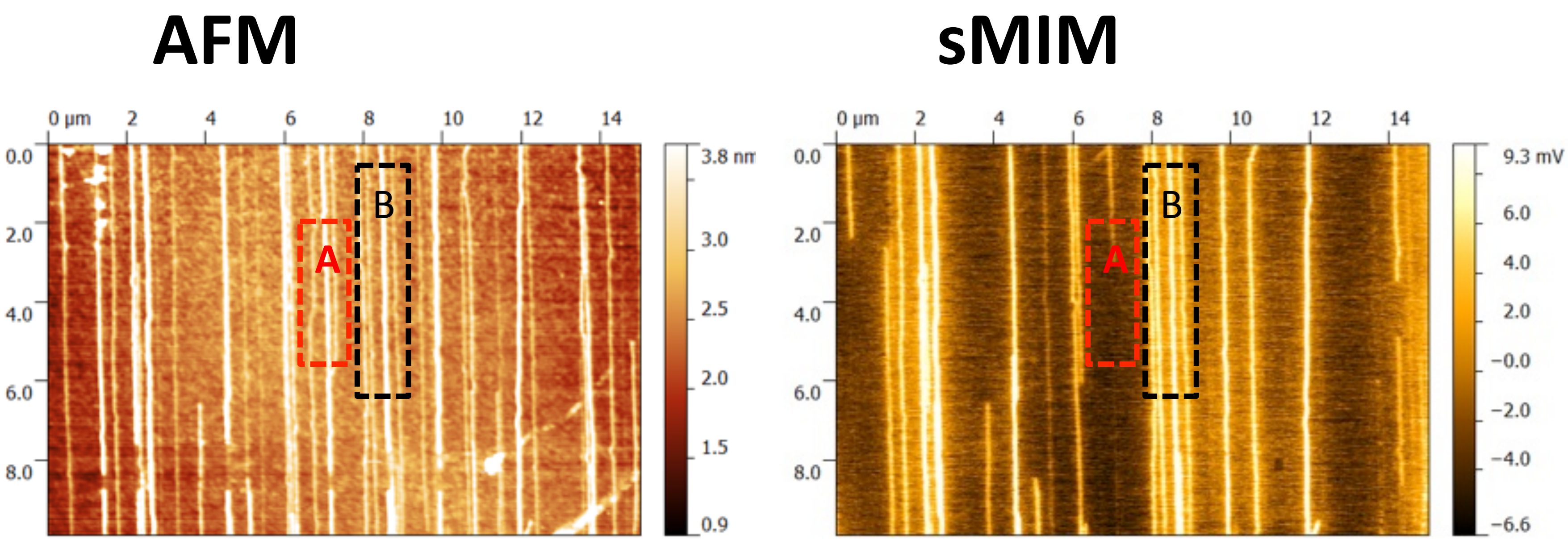
Courtesey of A. Tselev, Oak Ridge National Laboratory

Line cross-section of IMEC Staircase



Ave of 25line cross-section

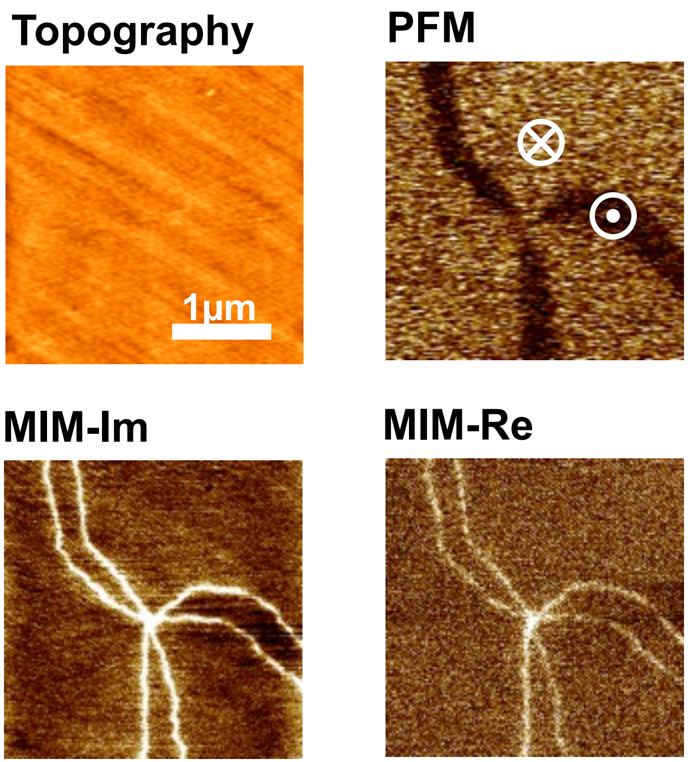
- sMIM-C is monotonic with doping concentration (linear response to change in doping concentration)
- sMIM dynamic range covers full range of sample 10^{15} to 10^{21} cm^{-3}.



Testing results on carbon nanotubes sample. (a) AFM topography. (b) sMIM image shows different CNTs have different conductivities. Courtesy Eric Seabron and Prof. William L. Wilson, Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign.

DWs on 001 surface of $ErMnO_3$

Domain Structure



- Conductive, instead of insulating DWs are observed, together with surface charging

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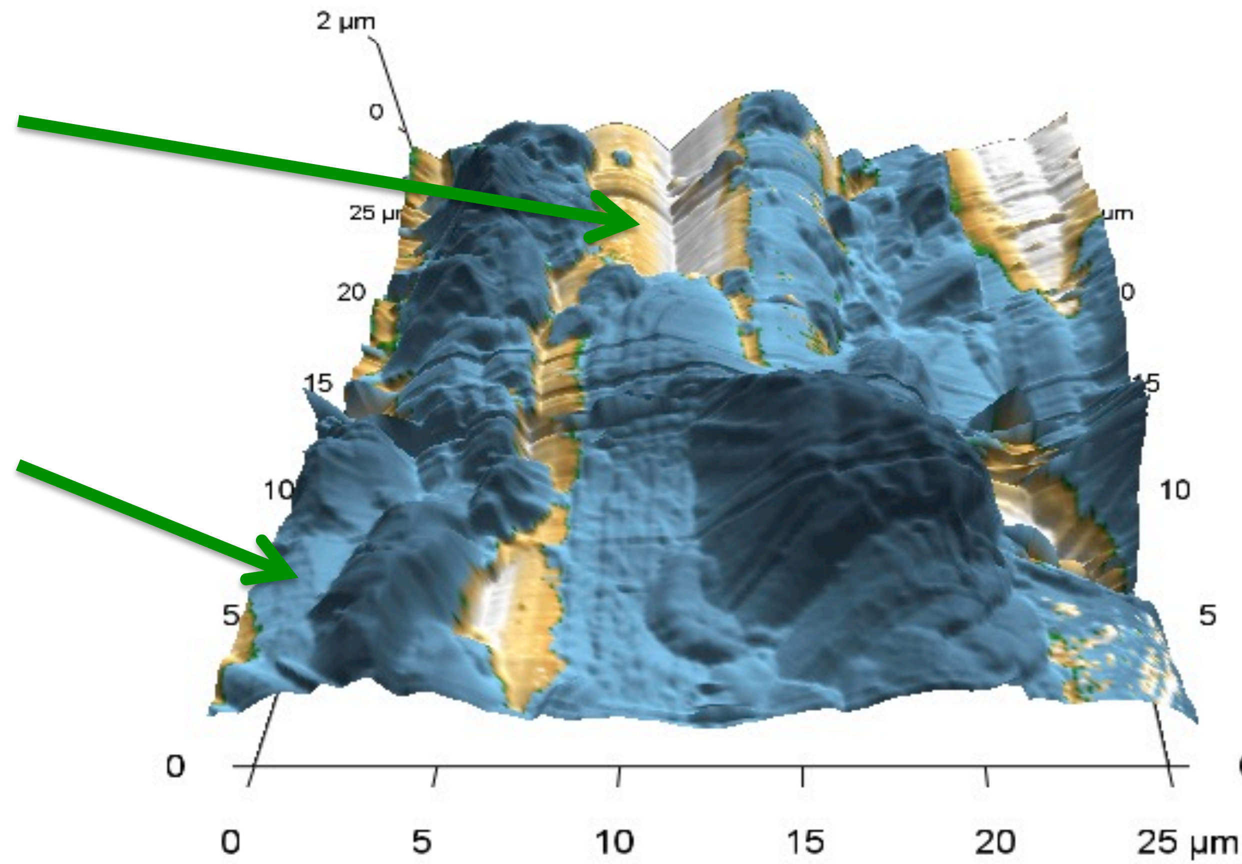
Conductive fibers in insulating matrix

Conductive Fiber
Color contrast showing very conductive region

Composite Matrix
Insulating material with uniform properties



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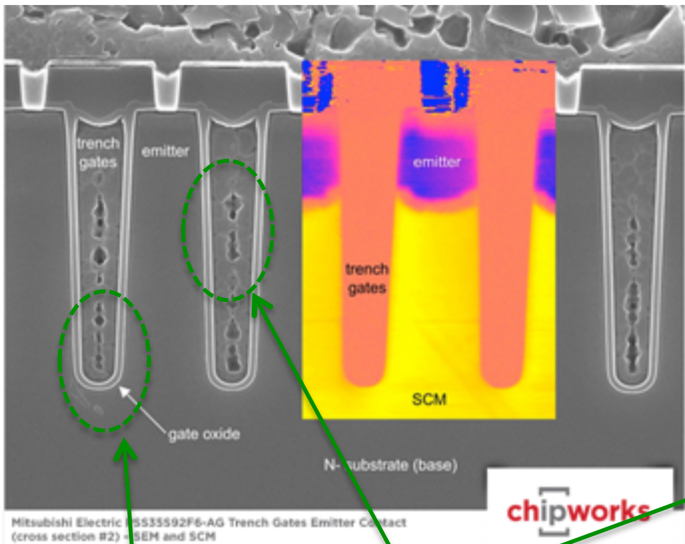
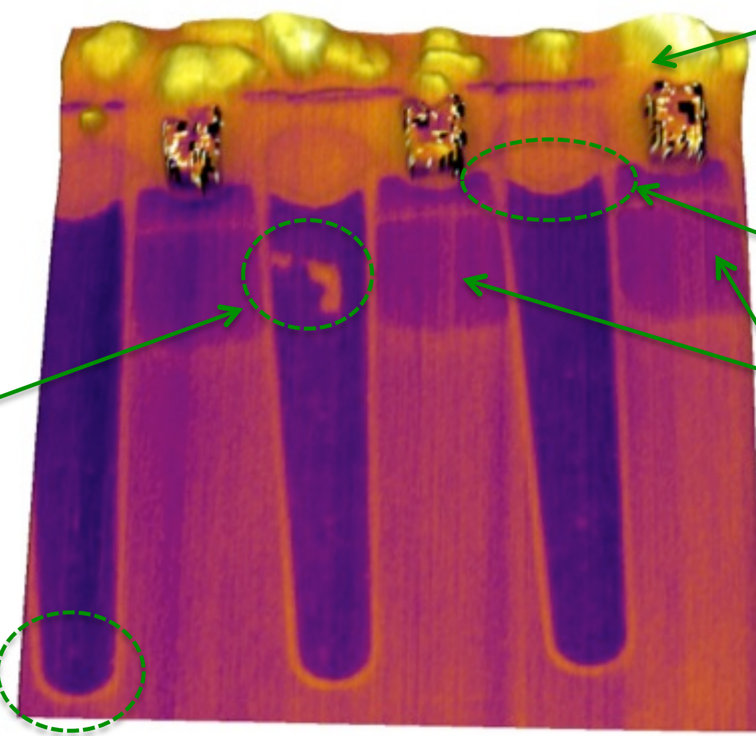
sMIM-C of IGBT Sample

SCM overlay to SEM of data



sMIM-C Image of IGBT



Common emitter/source metal

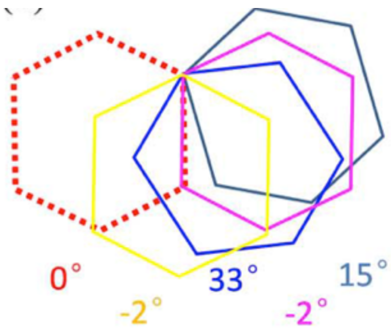
Trench gate shape sMIM matches SEM cross-section shape of feature structures

Emitter region
- sMIM shows fine structure in emitter where ε transition
- SCM does not see capture the small variations

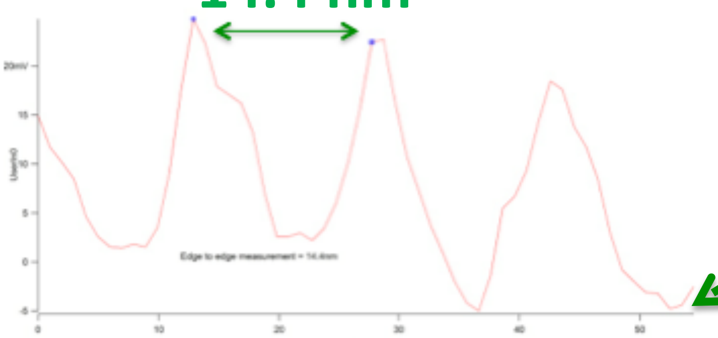
sMIM contrast from surface defect

Gate oxide
- SCM does not see oxide gate layer
- sMIM shows changes from trench to gate oxide to N-substrate base

Single layer Graphene on BN orientation effects



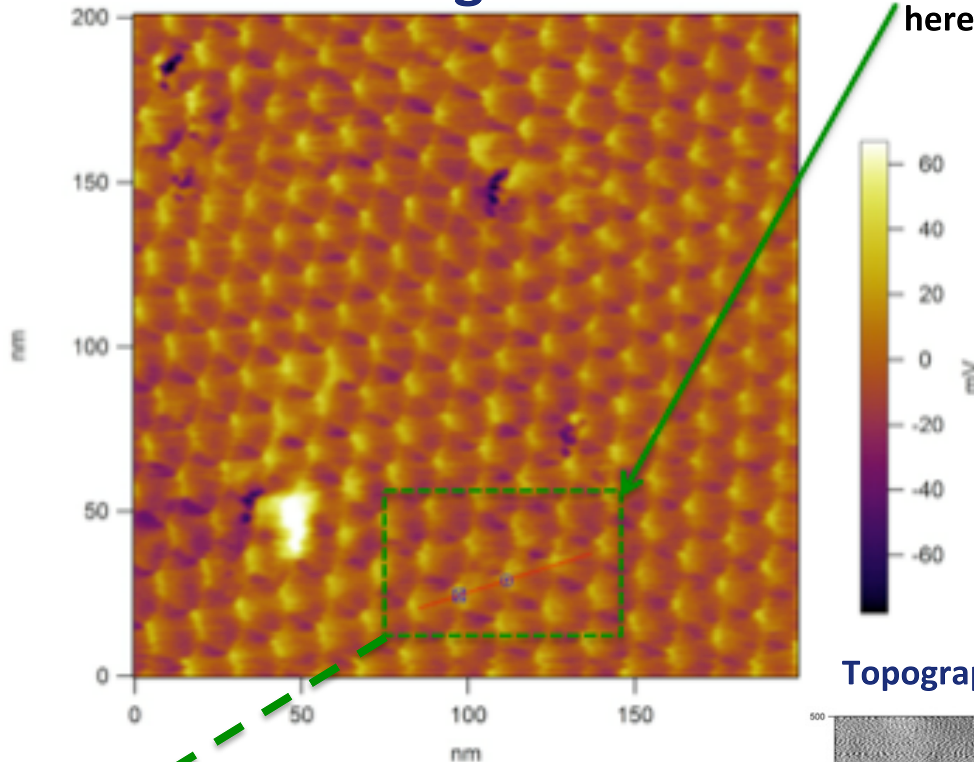
14.4 nm



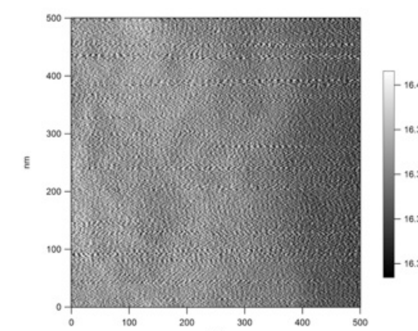
sMIM-C image

sMIM-C image

Line Profile from here



Topography image



Title: Precisely aligned graphene grown on hexagonal boron nitride by catalyst free chemical vapor deposition
Authors: Shujie Tang1, Haomin Wang1, Yu Zhang2, Ang Li1, Hong Xie1, Xiaoyu Liu1, Lianqing Liu2, Tianxin Li3, Fuqiang Huang4, Xiaoming Xie1 & Mianheng Jiang1

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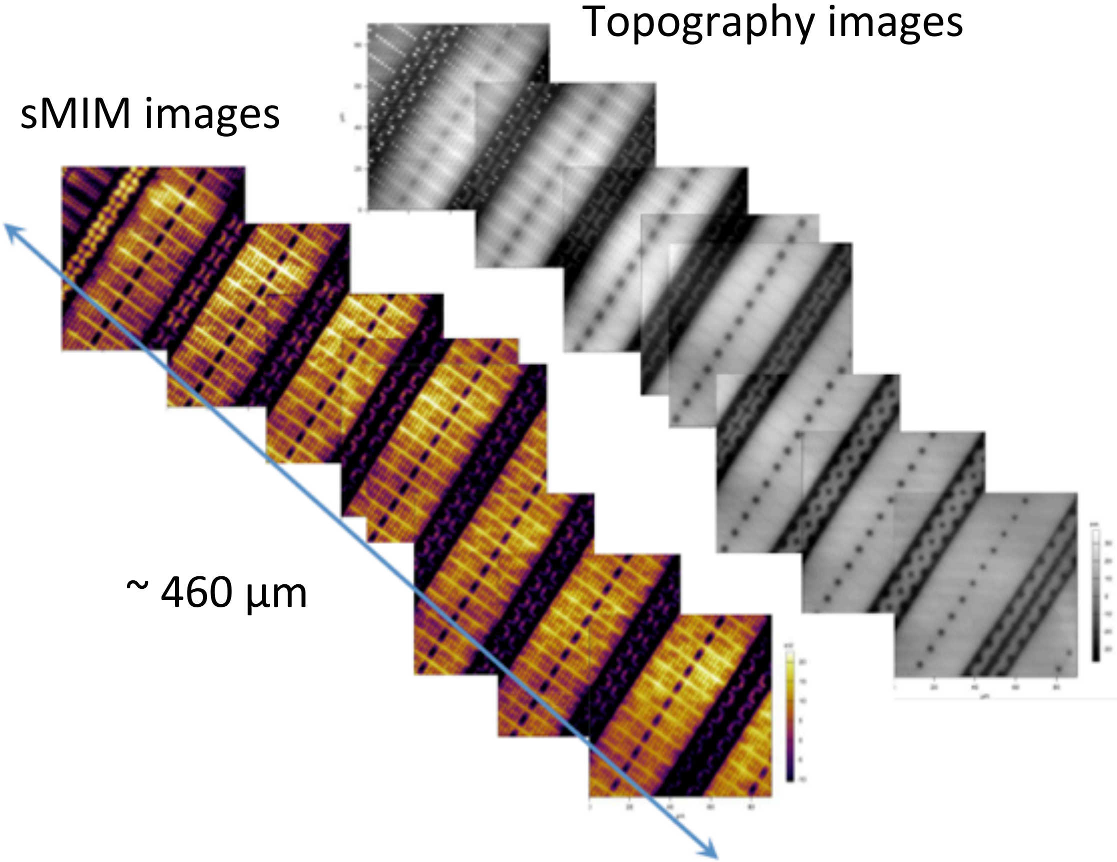
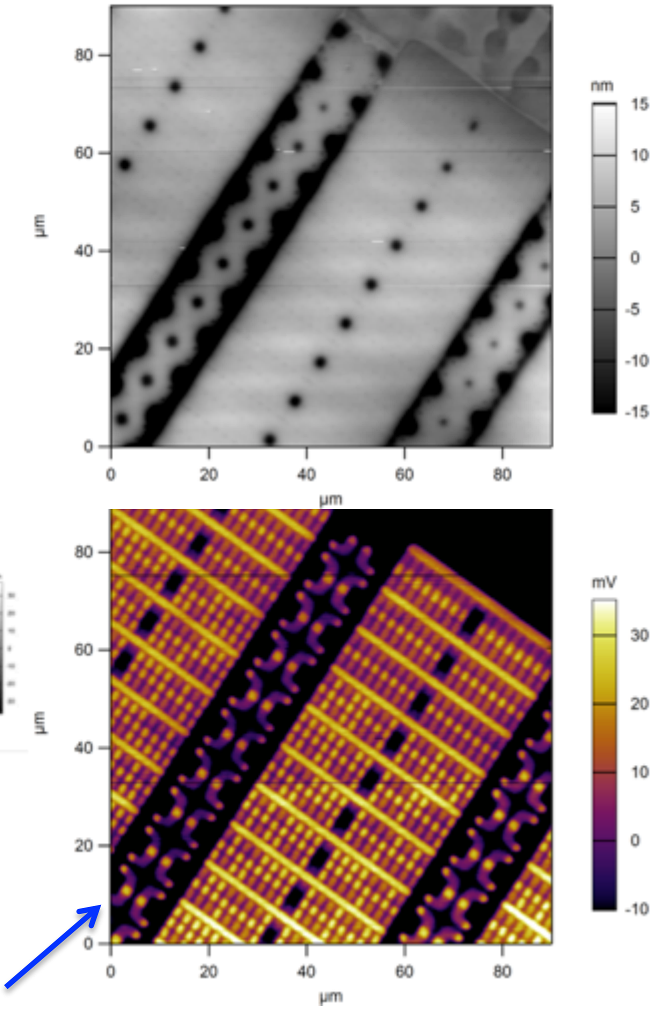
Large Stitched area of Flash Memory Array

Topography images

sMIM images



~ 460 µm



sMIM image of stored charge on floating gates

Applications

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- Materials characterization – visualize materials variations
- Microelectronics – FA analysis, performance characterization
- Nanotechnology – Extend electrical characterization to smaller dimensions and to nanostructures
- Biology – in situ electrical characterization of molecules/cells
- Physics Research – electrical properties of quantum structures
- Chemistry – material phases; concentration grouping; material distribution
- Energy related: Solar, batteries, fuel cells – material uniformity
- Material science – film characterization, grain boundaries, phases
- Biotech/medical devices – coating integrity/uniformity; constituent verification
- LED – defect and film characterization; buried defects

Journal Article References

- Unexpected surface implanted layer in static random access memory devices observed by microwave impedance microscope; Semicond. Sci. Technol. 28 (2013) 025010 (5pp)
- Imaging nanoscale electronic inhomogeneity with microwave impedance microscopy; dissertation submitted to the department of applied physics and the committee on graduate studies of Stanford university; Worasom Kundhikanjana, January 2013
- Ultrathin Topological Insulator Bi_2Se_3 Nanoribbons Exfoliated by Atomic Force Microscopy; Nano Lett. 2010, 10, 3118–3122
- Tapping mode microwave impedance microscopy; REVIEW OF SCIENTIFIC INSTRUMENTS 80, 043707 2009
- Hierarchy of Electronic Properties of Chemically Derived and Pristine Graphene Probed by Microwave Imaging; Nano Lett., Vol. 9, No. 11, 2009
- Nanoscale Electronic Inhomogeneity in In_2Se_3 Nanoribbons Revealed by Microwave Impedance Microscopy; Nano Lett., Vol. 9, No. 3, 2009
- Calibration of shielded microwave probes using bulk dielectrics; APPLIED PHYSICS LETTERS 93, 123105 2008
- Modeling and characterization of a cantilever-based near-field scanning microwave impedance microscope; REVIEW OF SCIENTIFIC INSTRUMENTS 79, 063703 2008
- Atomic-force-microscope-compatible near-field scanning microwave microscope with separated excitation and sensing probes; REVIEW OF SCIENTIFIC INSTRUMENTS 78, 063702 2007