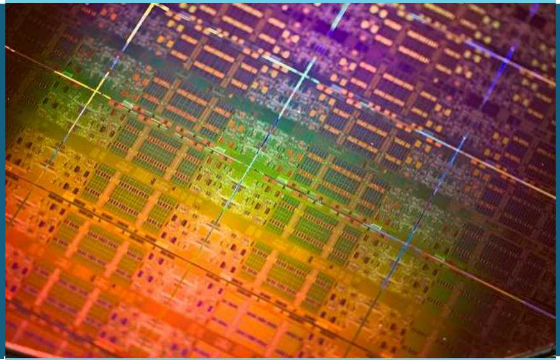
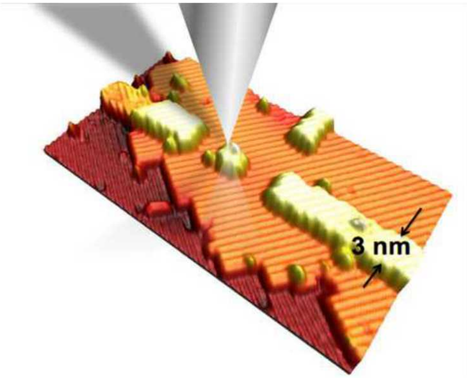
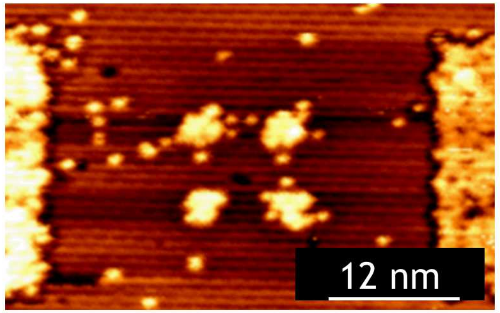
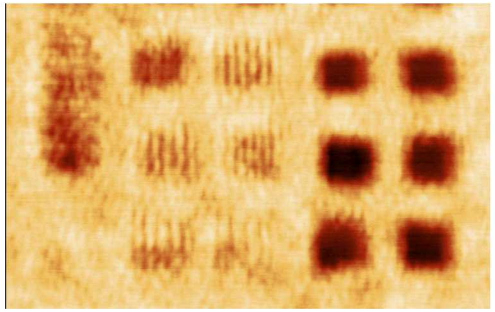
SAND2019-14595C

Scanning microwave impedance microscopy of buried dopant nanostructures in silicon







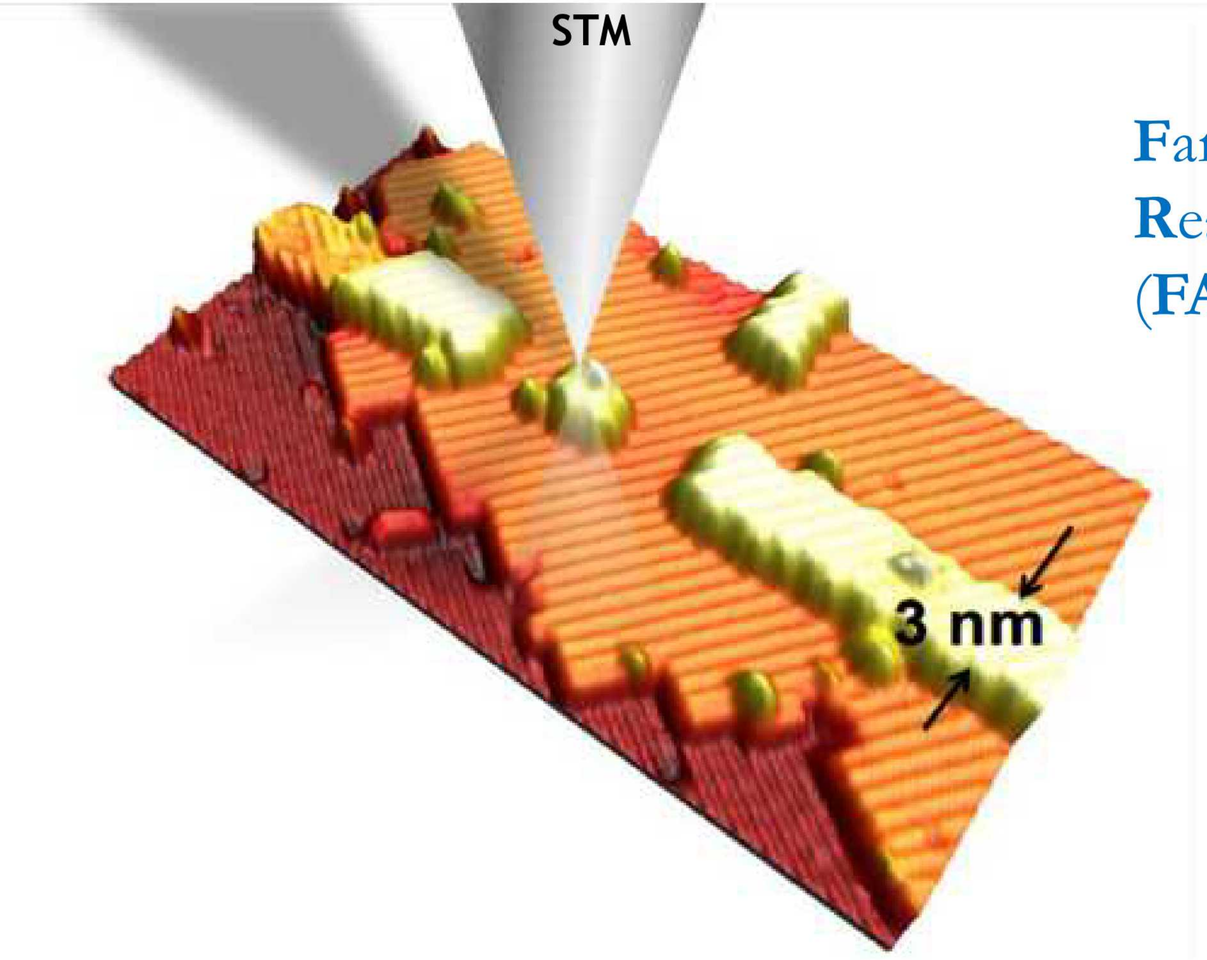


David A. Scrymgeour

Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Atomic Precision Advanced Manufacturing (APAM)

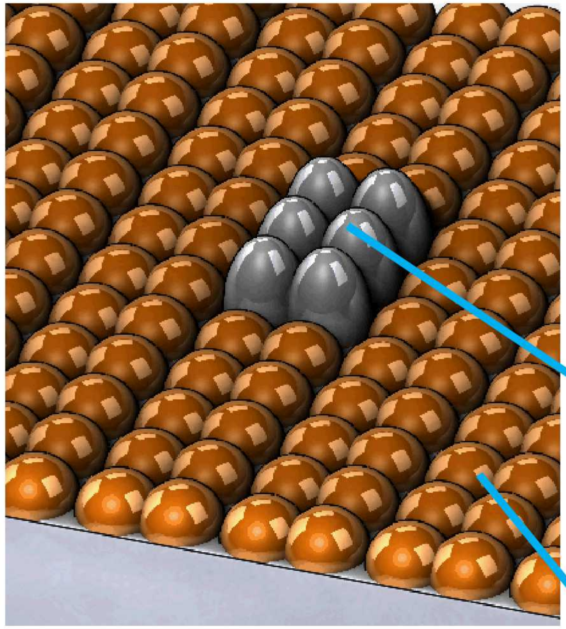


Far-reaching **A**pplications, **I**mplications, and **R**ealization of **D**igital **E**lectronics at the **A**tomic **L**imit (**FAIR-DEAL**)

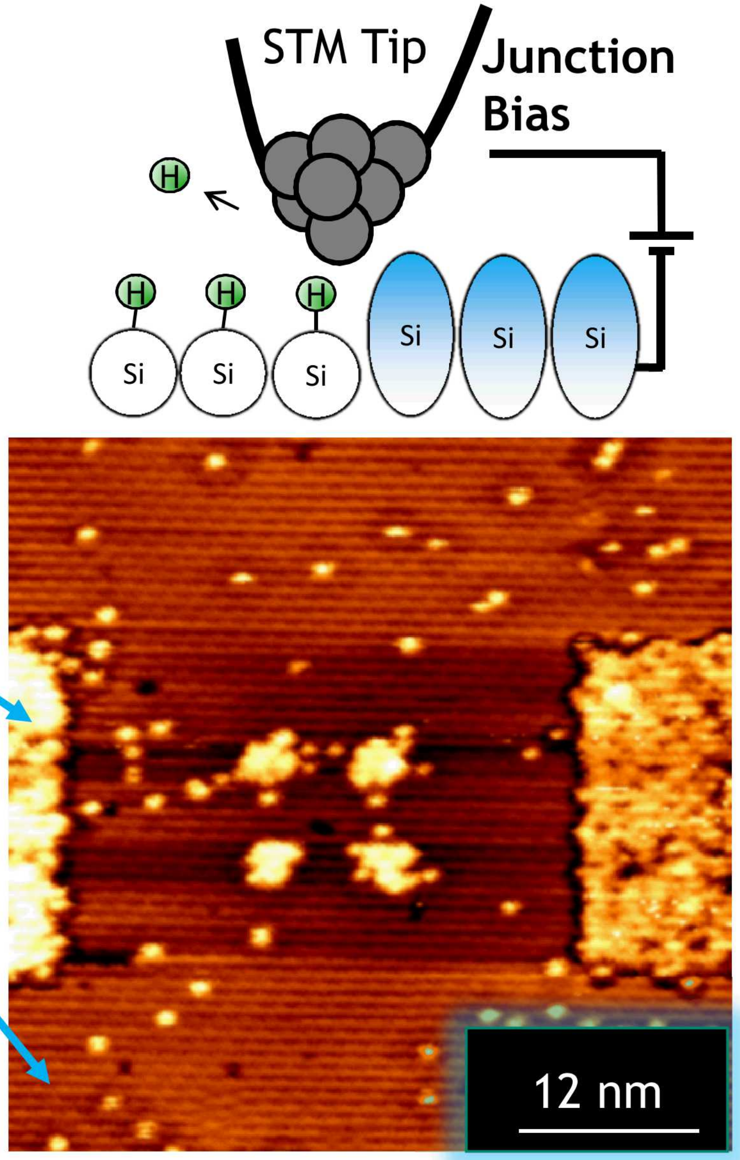
Mission: To assess the opportunities presented by APAM-enabled devices and processing for the digital microelectronics of the future

How does APAM work?

Clean Si (100): 1 unsatisfied bond/ atom

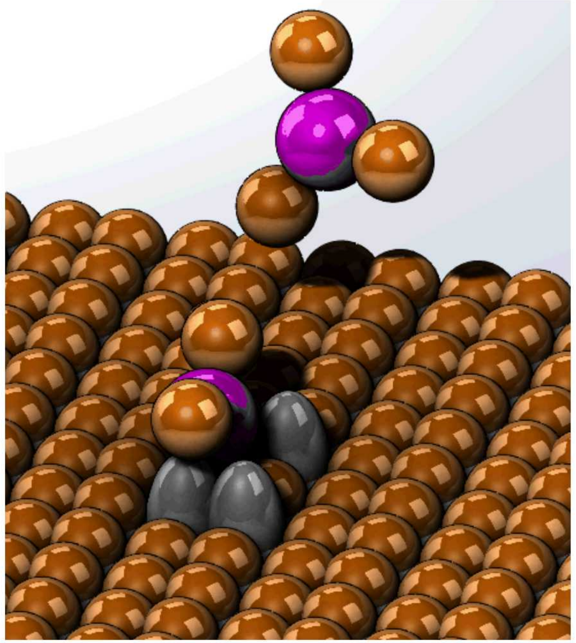


Passivate reactive bond with hydrogen

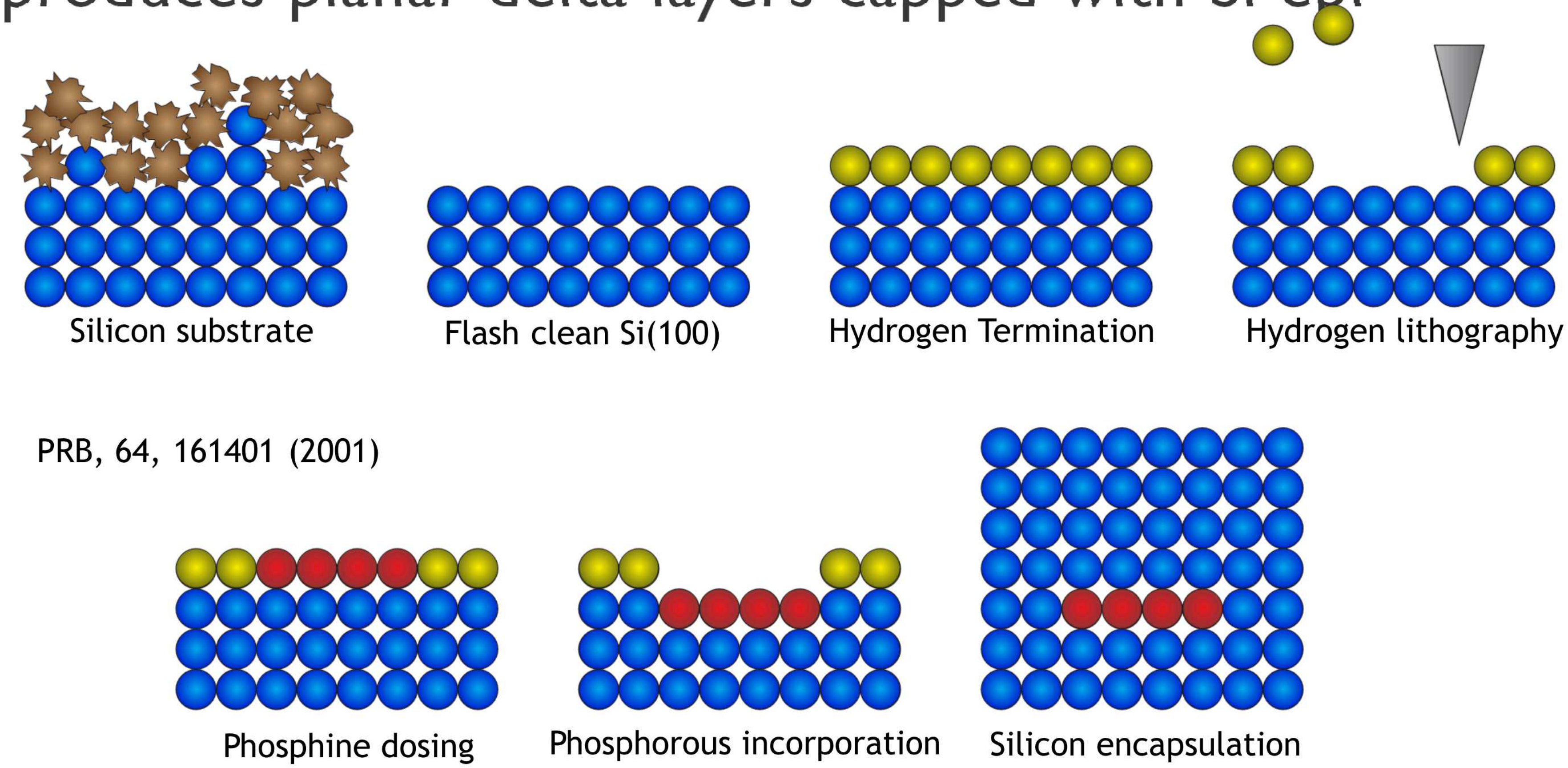


Pattern, image, and characterize with STM

React phosphine molecule in open window



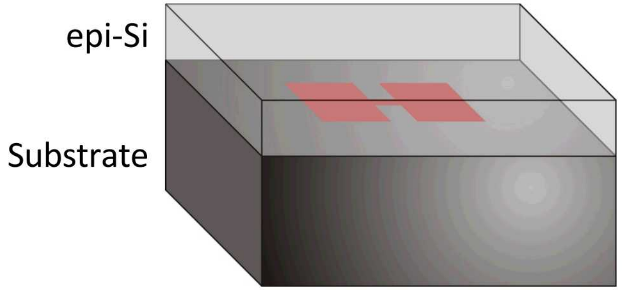
APAM produces planar delta layers capped with Si epi



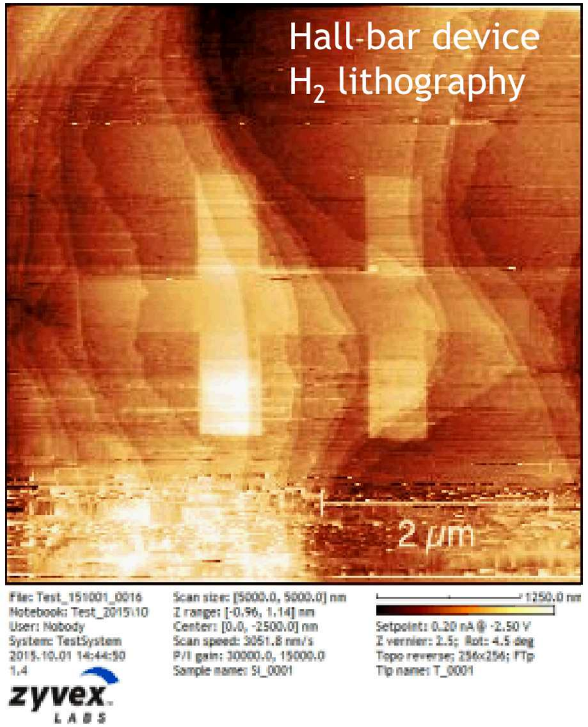
PRB, 64, 161401 (2001)

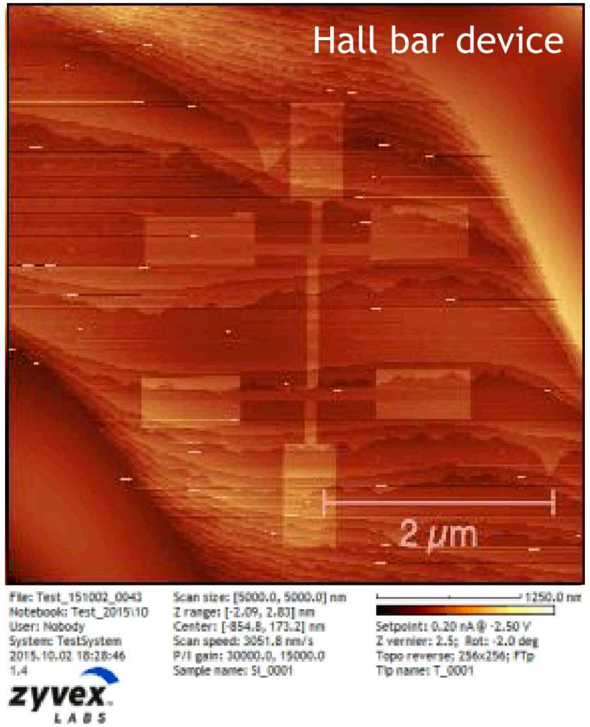
End product from STM process

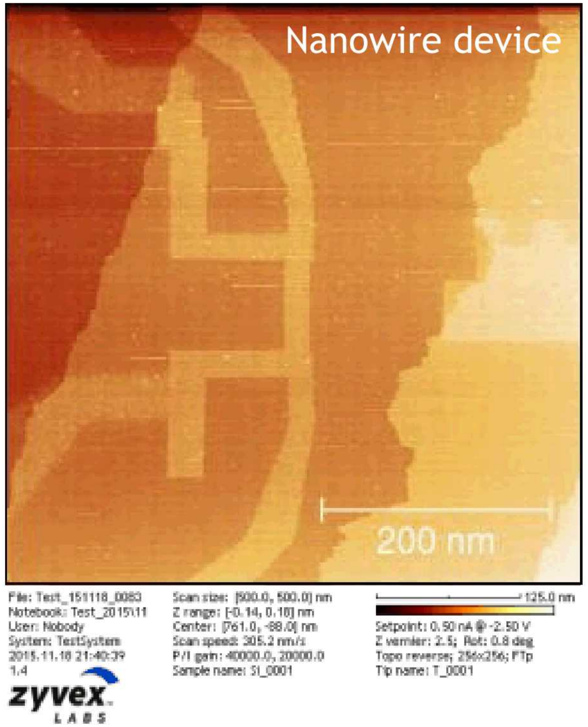
- Atomically abrupt in X Y and Z
- All-epitaxial planar buried delta doped nanostructure
- Donor & e- density 1.7x10^{14} cm^{-2} (metallic) (~10^{21} cm^{-3})



APAM produces planar delta layers capped with Si epi







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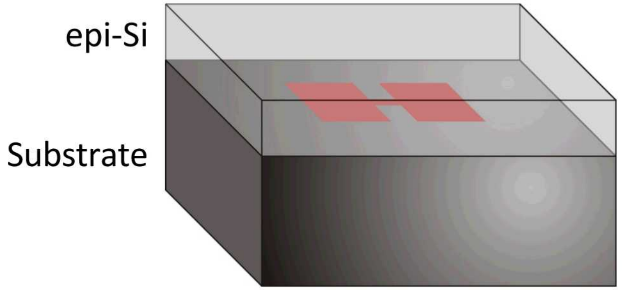
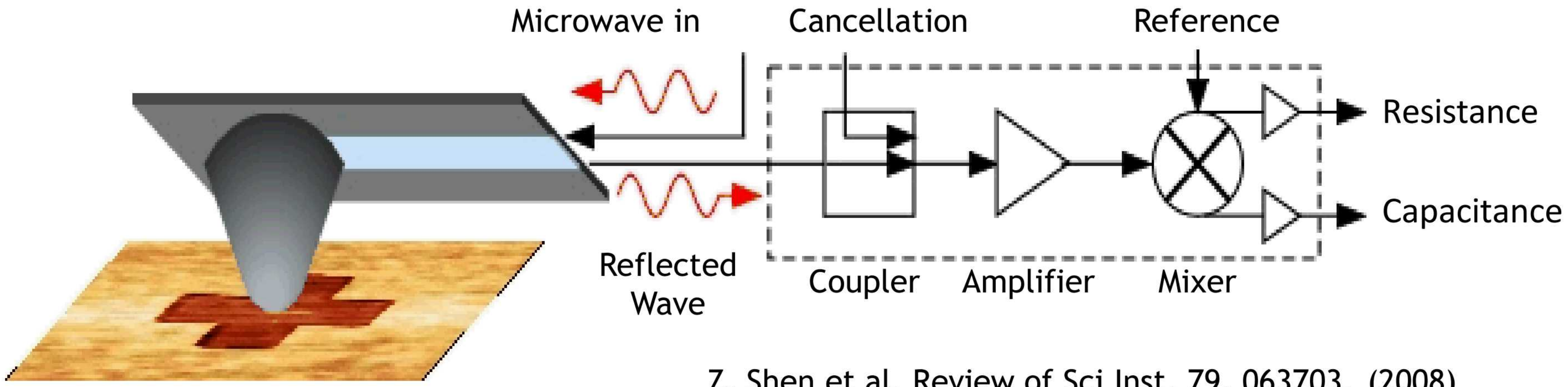


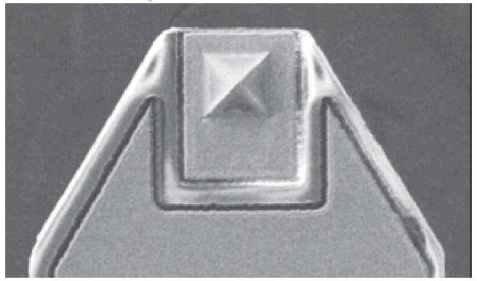
Circa 3/16

Scanning Microwave Impedance Microscopy (sMIM)



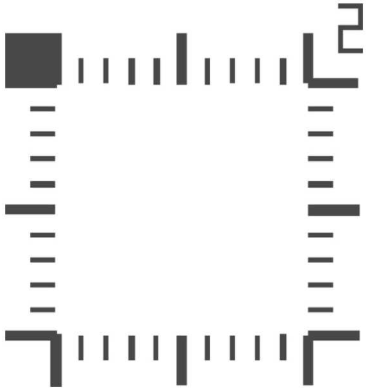
Z. Shen et al, Review of Sci Inst, 79, 063703, (2008)

- Commercialized by PrimeNano
- Shielded tip for higher SNR
- Look at variation of local impedance (electrical properties – C & R, ε & σ)

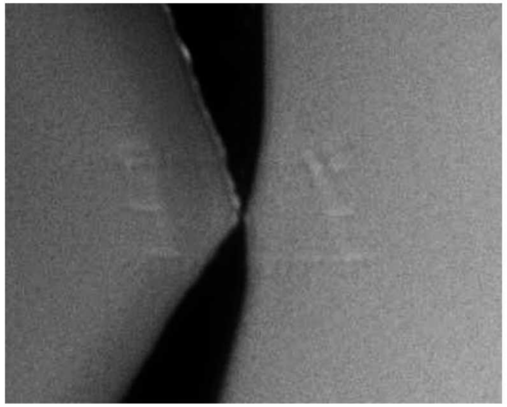


Initially used to locate device for backend fabrication

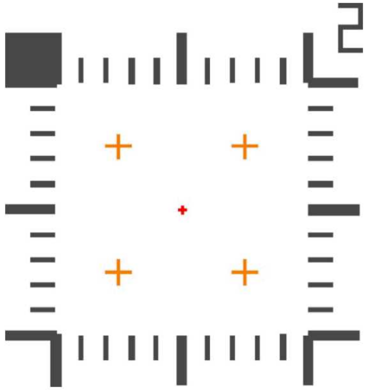
Reticle pattern on Si Chip



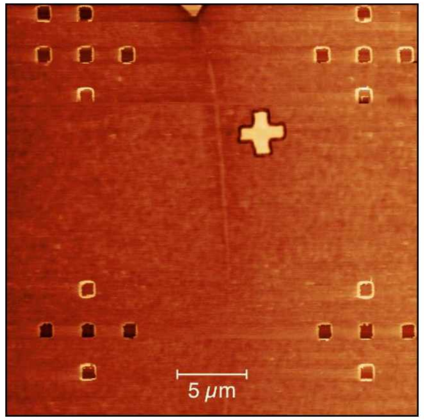
STM Pattern Part



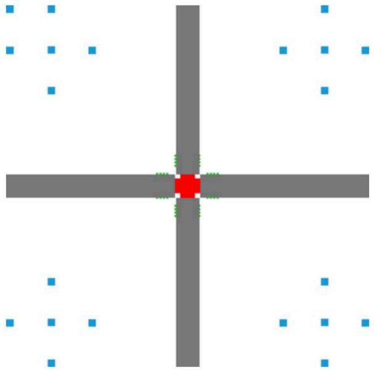
Ebeam pattern marks



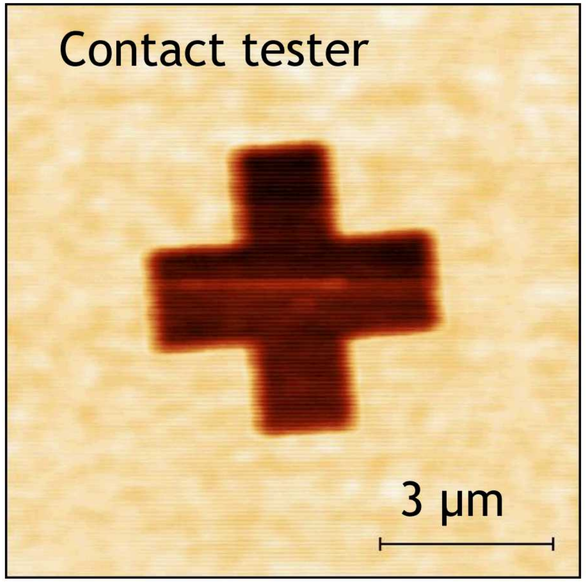
Device is located relative to gold markers

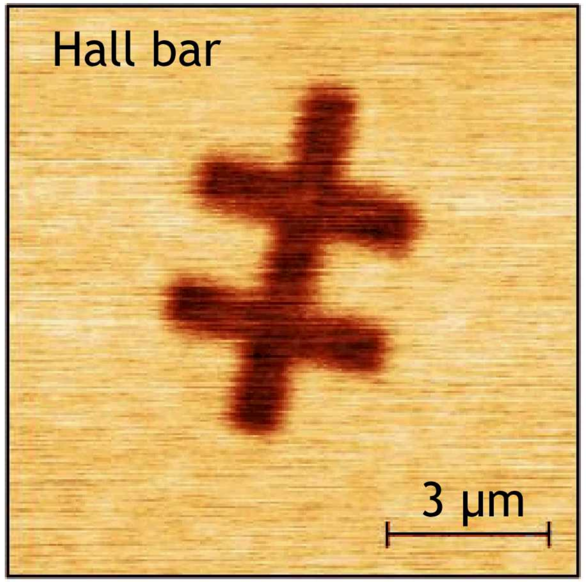


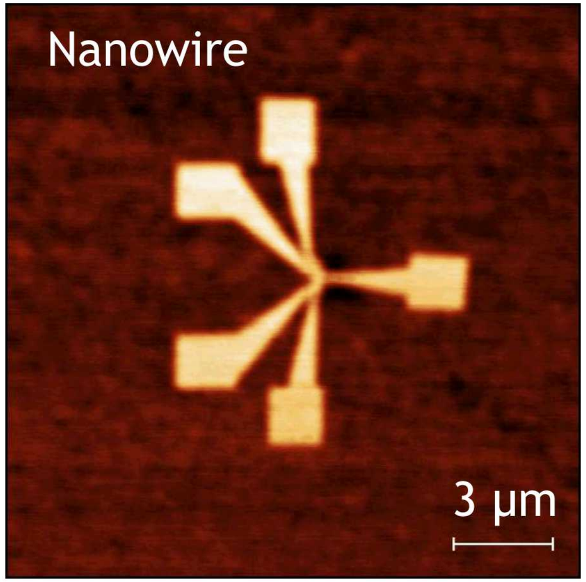
Drill vias to device, etch, and pattern



sMIM of buried P nanostructures

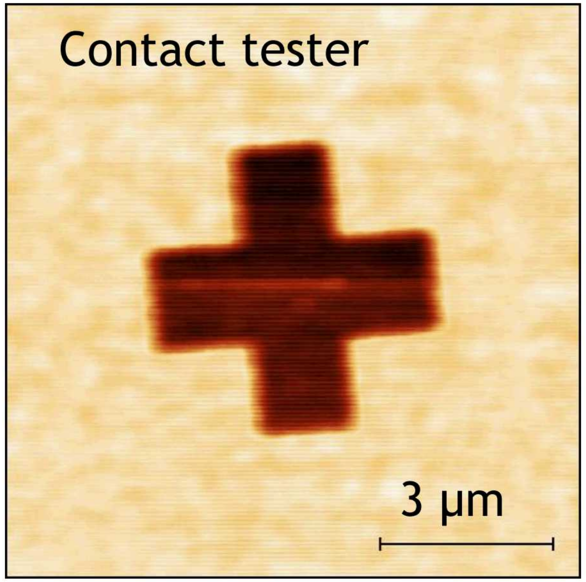


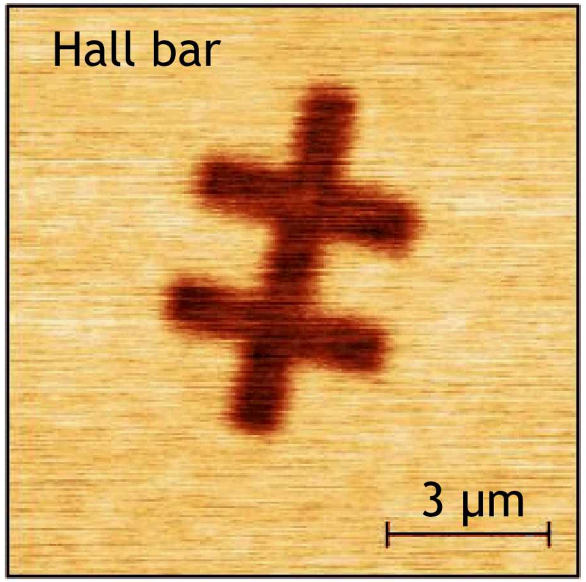


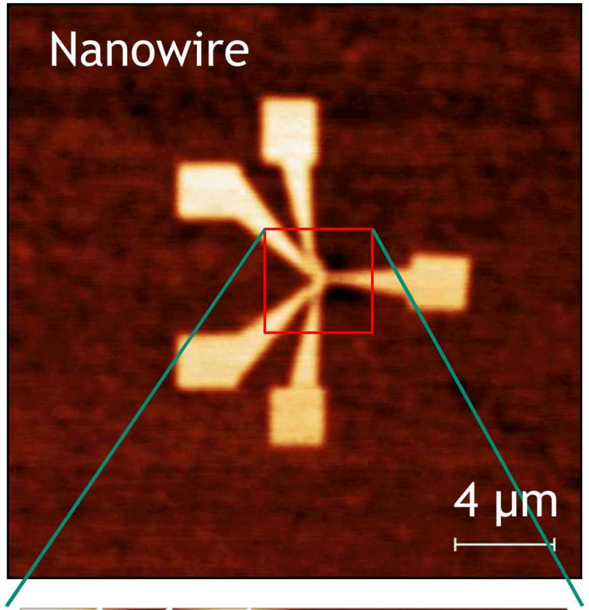


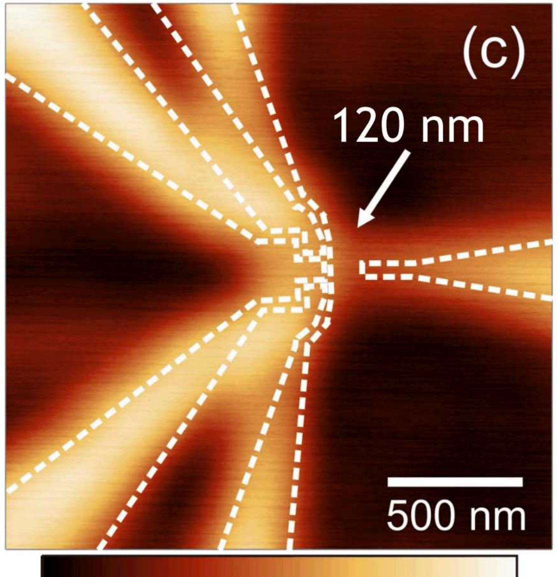
- What was limits of what we could see?
- Can we calibrate samples/tips?

sMIM of buried P nanostructures









- What was limits of what we could see?
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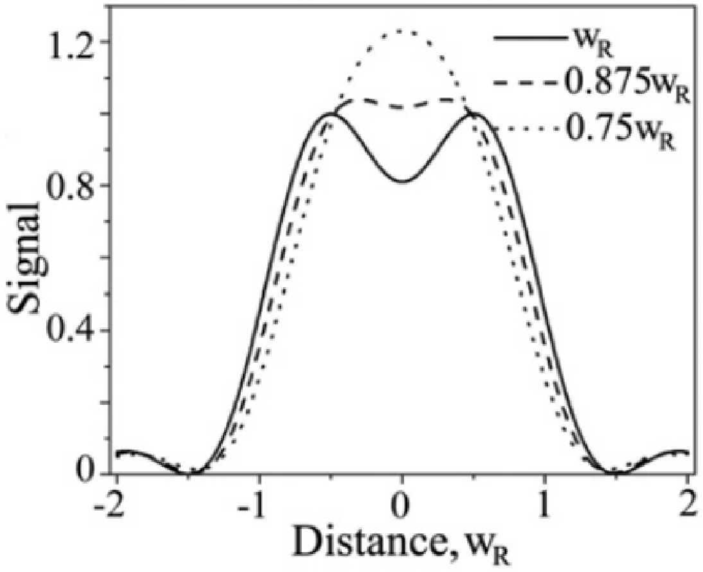
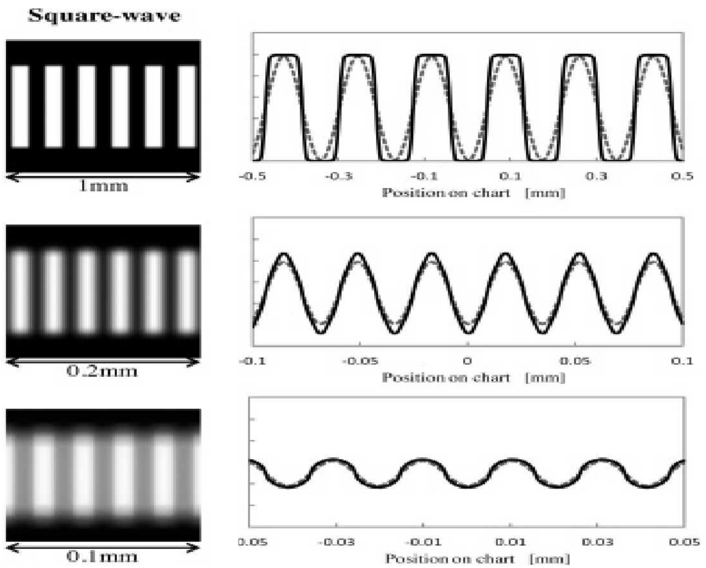
Resolution & Contrast of Line Features

Rayleigh's definition of resolution:



Nanotechnology 17, 3400-3411, (2006)

Optical definition of Contrast:

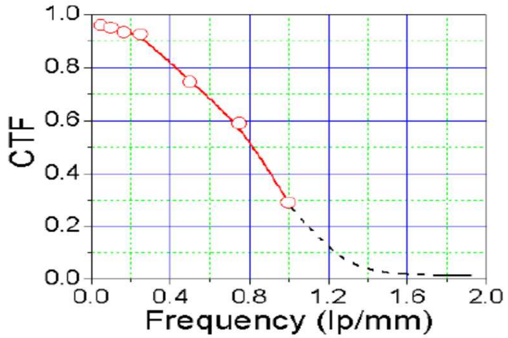


C = 1

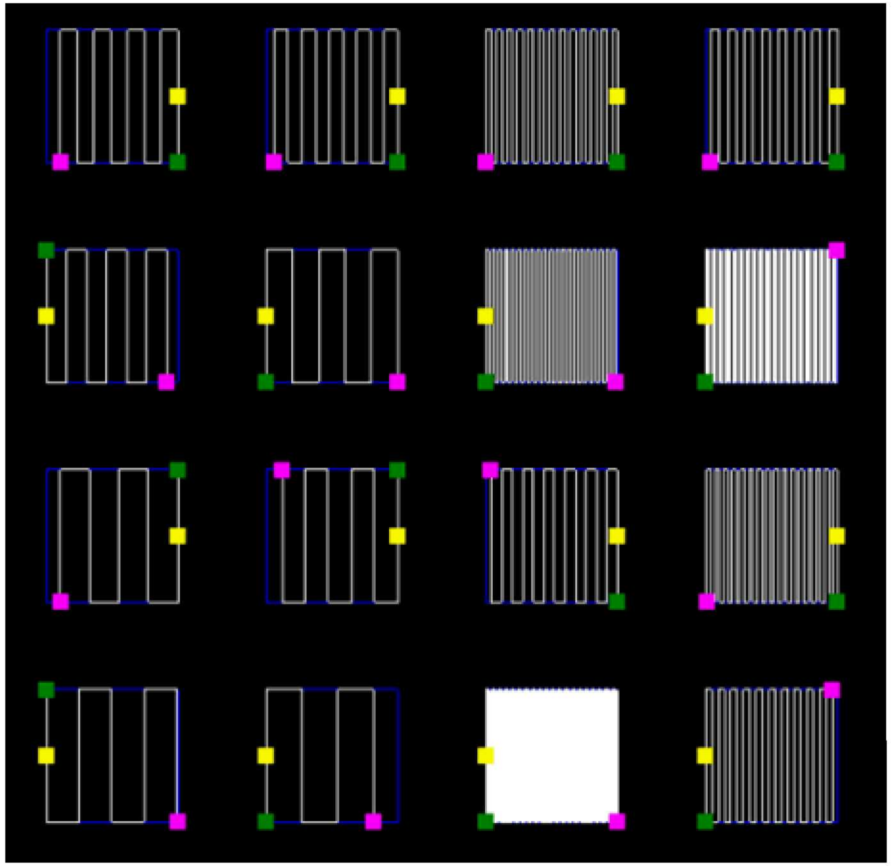
C = 0.6

C = 0.2

$$C = \frac{(S_{max} - S_{min})}{(S_{max} + S_{min})}$$



Atomically defined resolution and dose tester for sMIM characterization



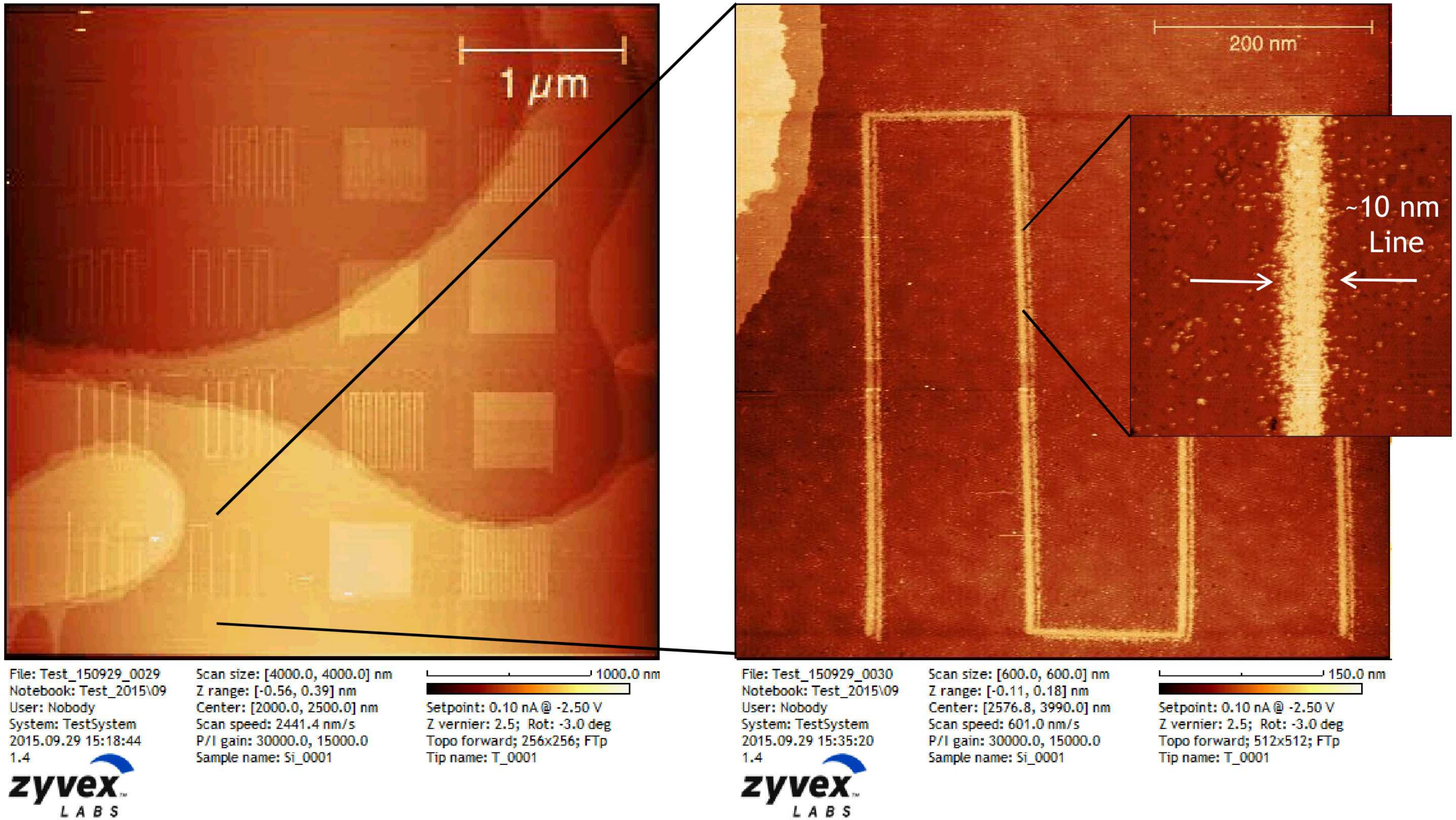
Pitch of depassivating raster line

64 nm	52 nm	24 nm	32 nm
76 nm	100 nm	12 nm	8 nm
112 nm	88 nm	40 nm	16 nm
124 nm	136 nm	4 nm	20 nm

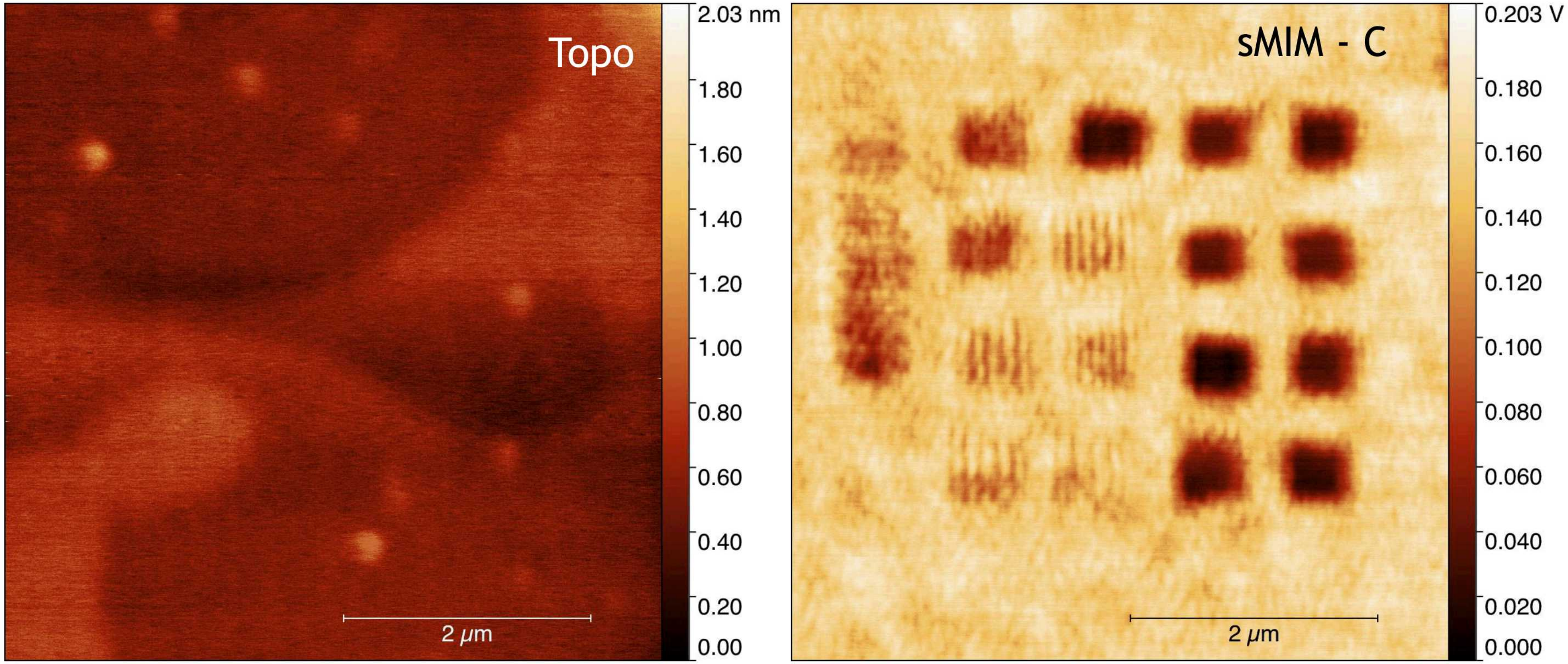
500 nm

3 μm

Atomically defined resolution and dose tester for sMIM characterization



sMIM measurements on buried dose tester

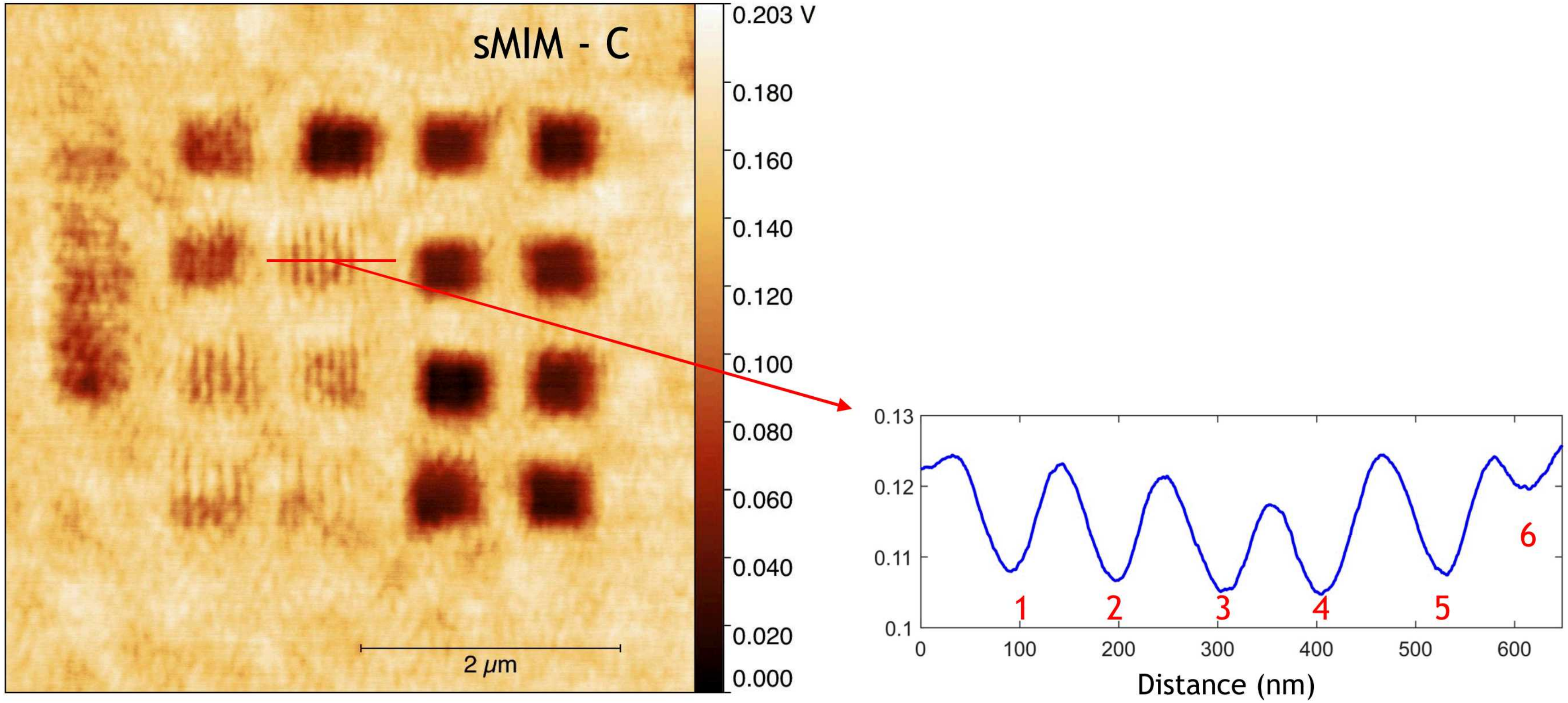


Resolve individual 10 nm buried P donor lines under <30 nm epi

sMIM measurements on buried dose tester

Gaps between lines

64 nm	52 nm	24 nm	32 nm
76 nm	100 nm	12 nm	8 nm
112 nm	88 nm	40 nm	16 nm
124 nm	125 nm	4 nm	20 nm



- Resolve line pairs > 88 nm spacing
- Convolution of tip radius and epi thickness

sMIM measurements on buried dose tester

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64 nm	52 nm	24 nm	32 nm
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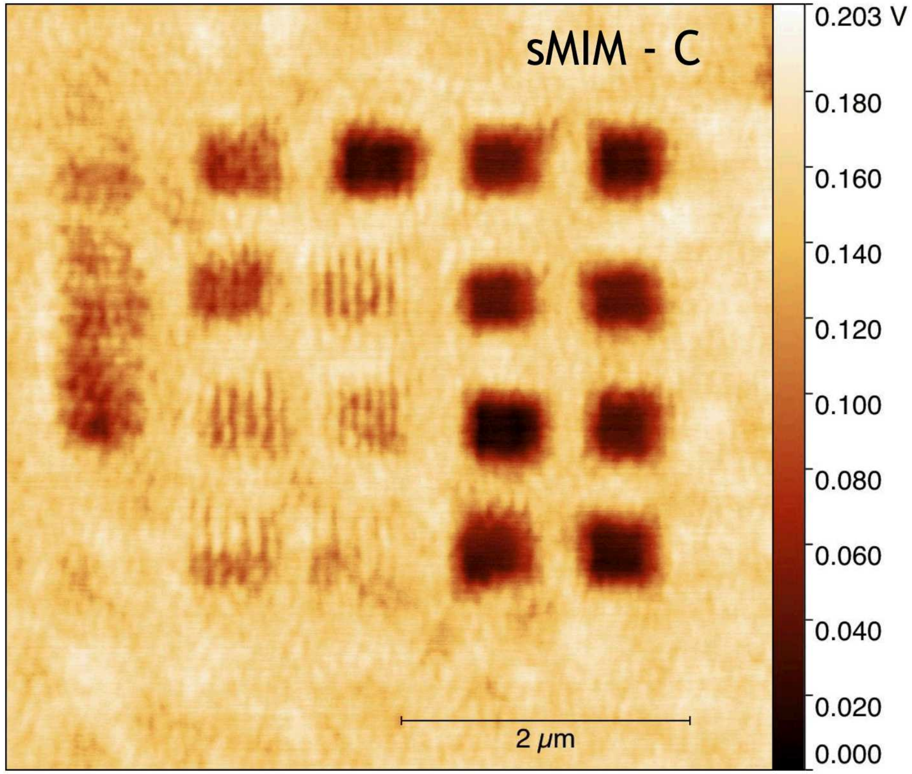
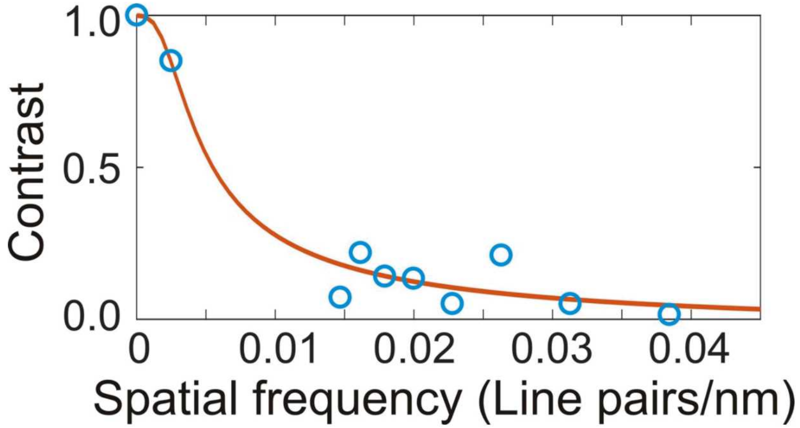
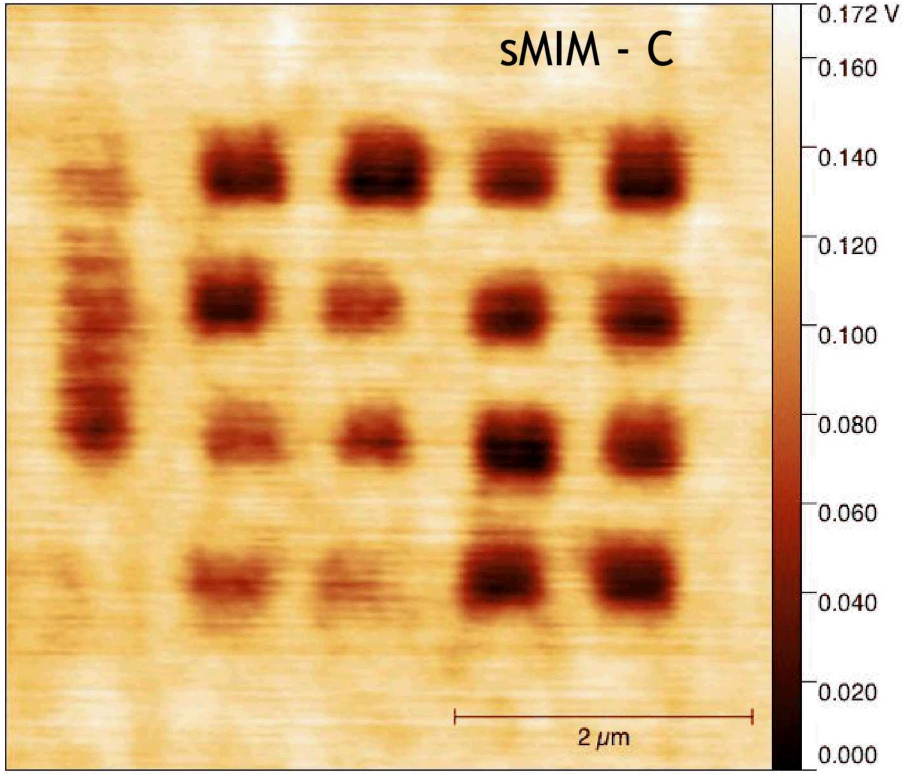


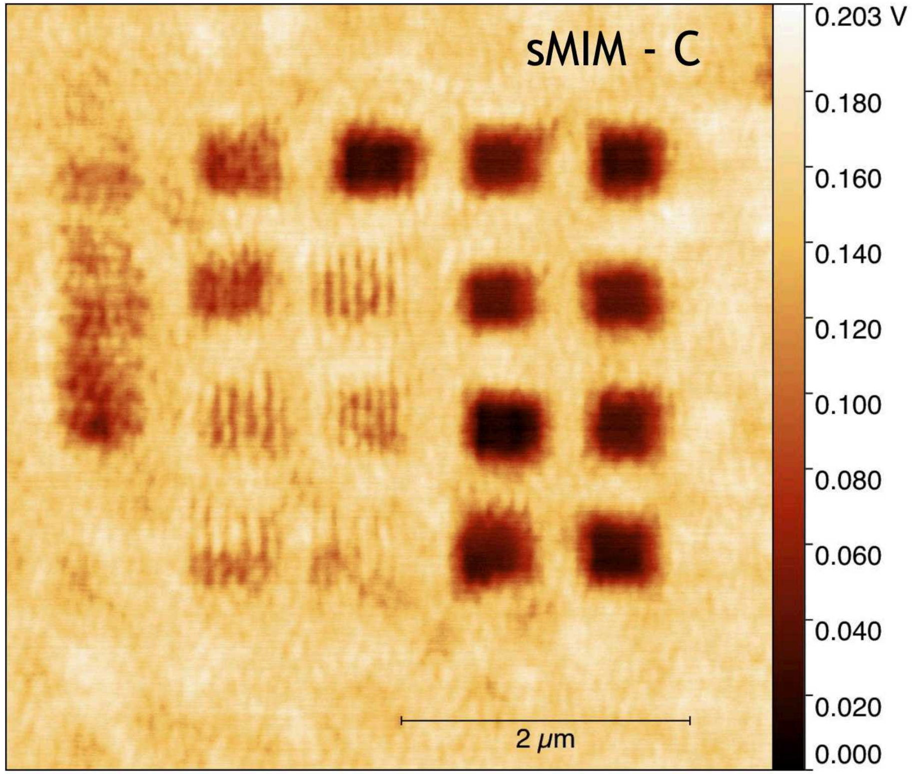


- Resolve line pairs > 88 nm spacing
- Convolution of tip radius and epi thickness

Atomically defined tester can quickly evaluate tip condition



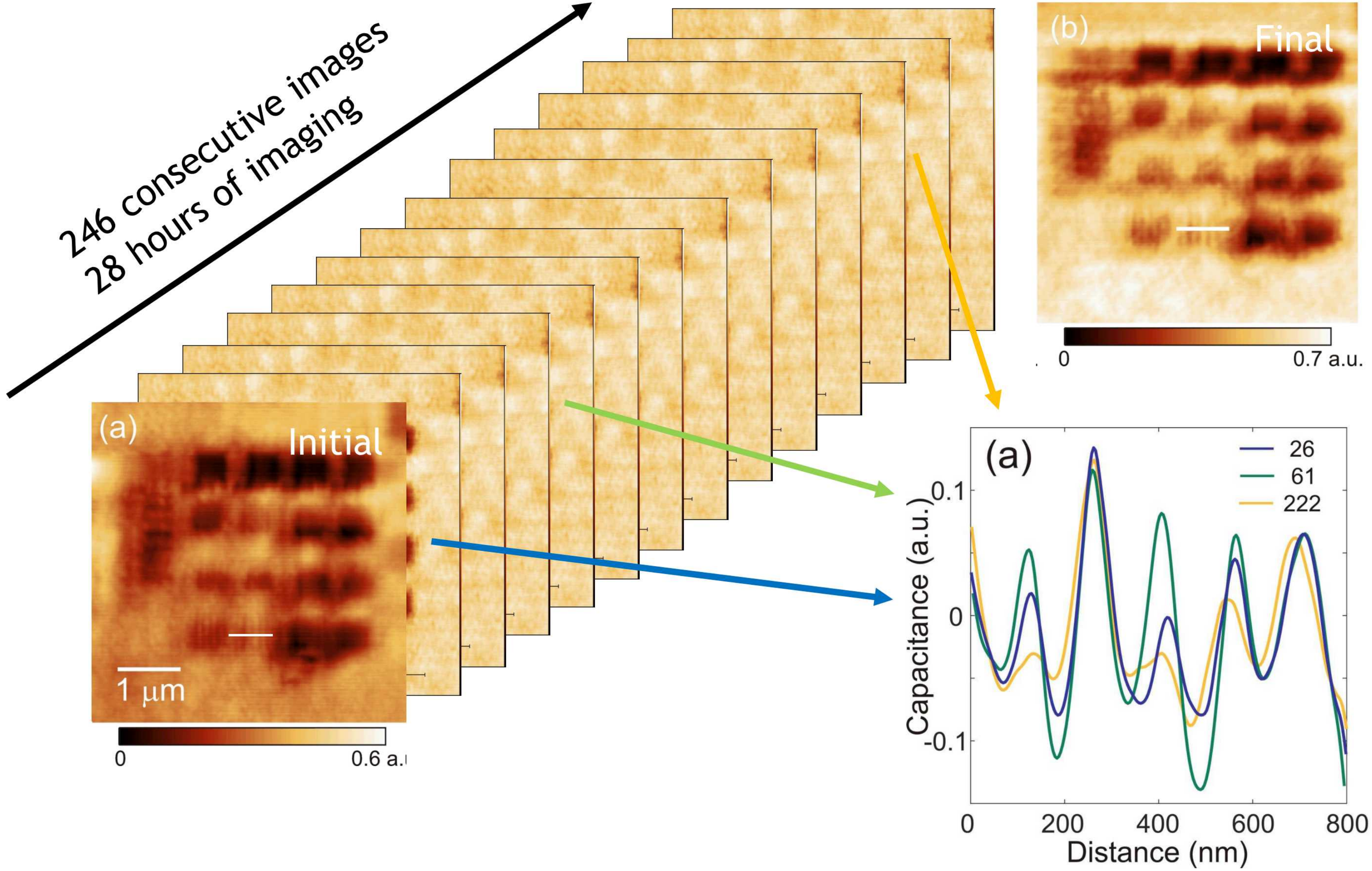
Dull Tip



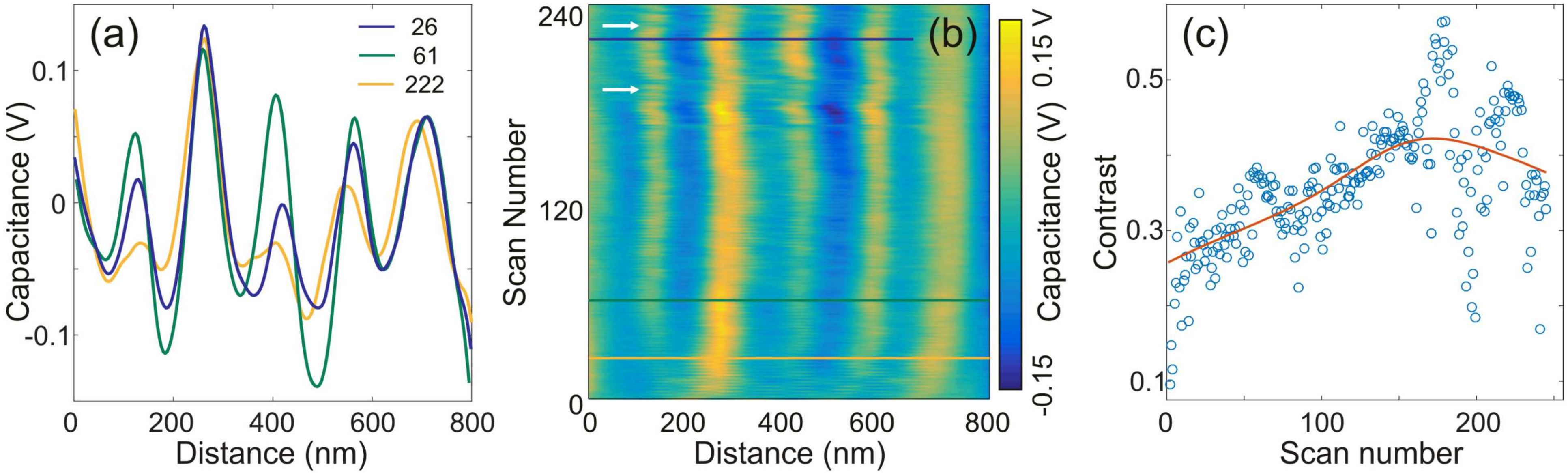
Sharp Tip

- Good tips last >50 scans, contrary to typical metal coated tips
- Tips get “better” with use

Wear test to determine change in resolution and contrast



Resolution constant for 28 hours, and contrast actually improves

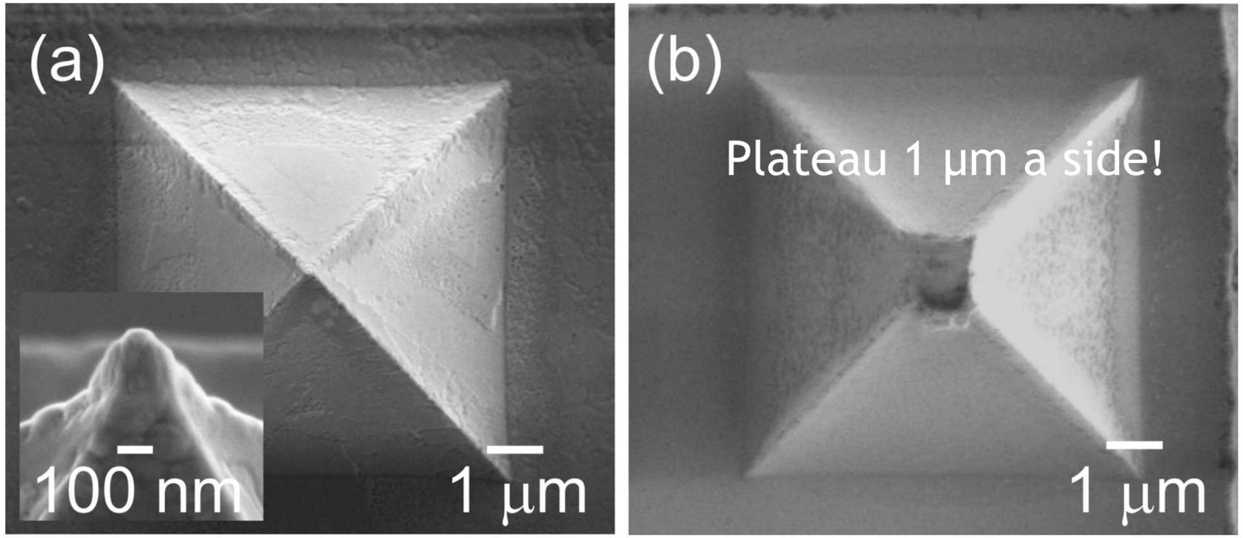


What is going on?

- Tip scanning on surface = tip wear and blunting!
- Very smooth surface (wear minimal)?
- Resolution not a function of tip apex? (Evanescent field imaging)

Resolution of sMIM not determined solely by tip apex

Before After 28 hours imaging

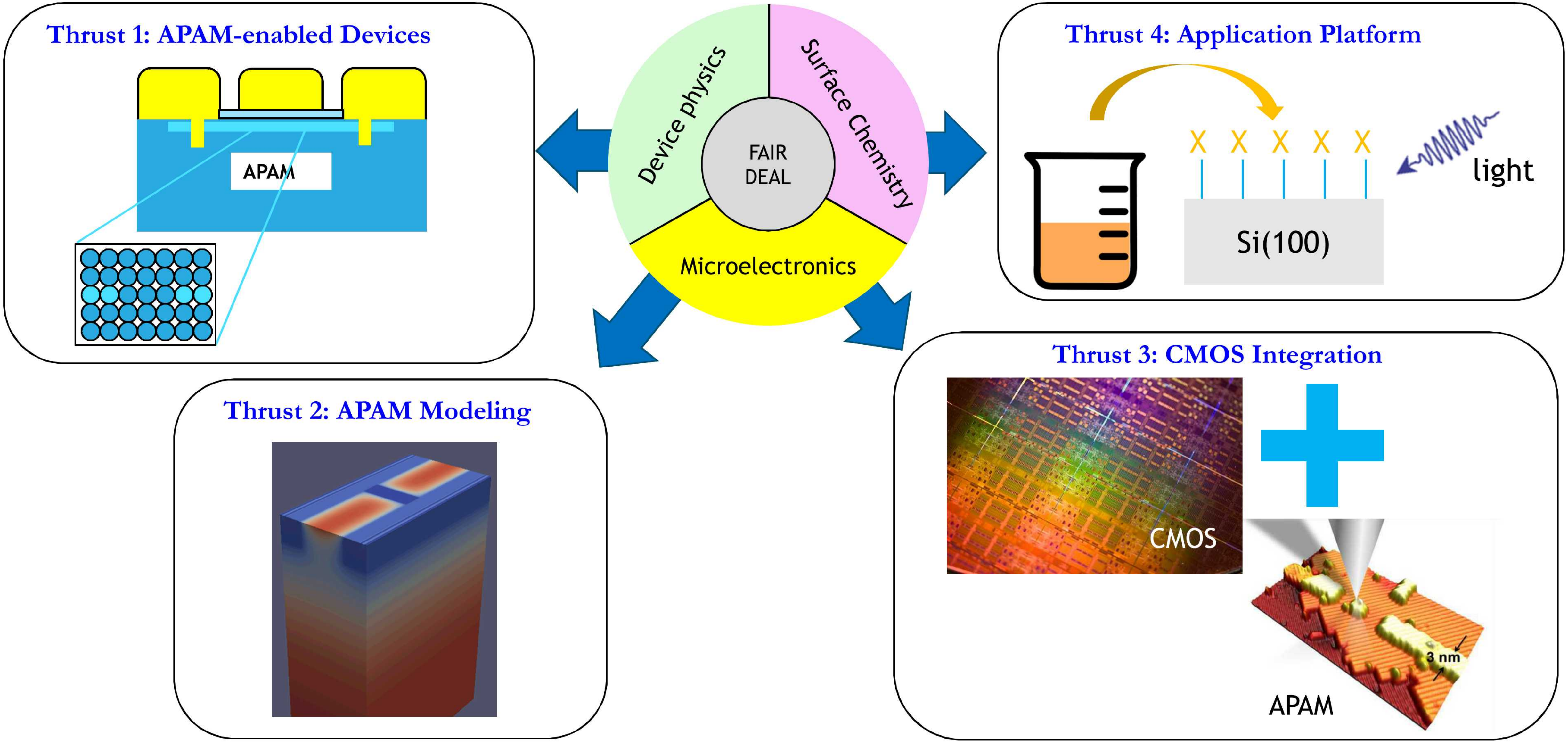


General AFM rule of thumb → resolution ∝ tip radius

Resolution <150 nm with a 1 µm tip!

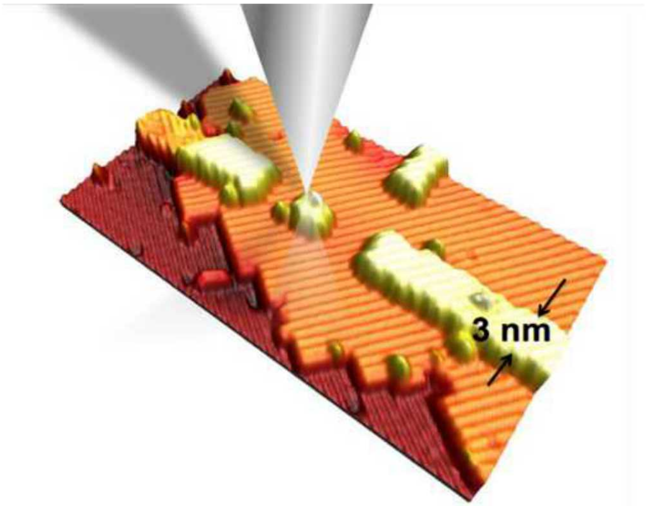
D.A. Scrymgeour et al, *Applied Surface Science* 423, 1097-1102 (2017).

Far-reaching Applications, Implications, and Realization of Digital Electronics at the Atomic Limit (FAIR-DEAL)

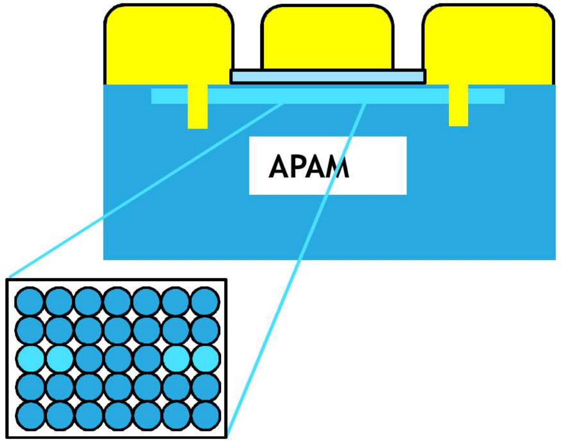


FAIR-DEAL APAM Exemplar Roadmap

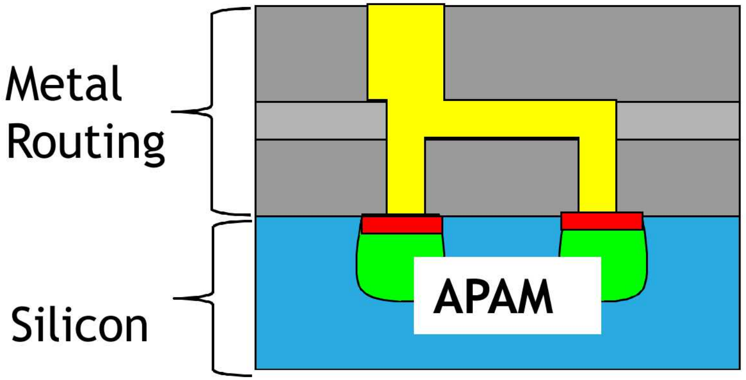
APAM



APAM – MOS transistor

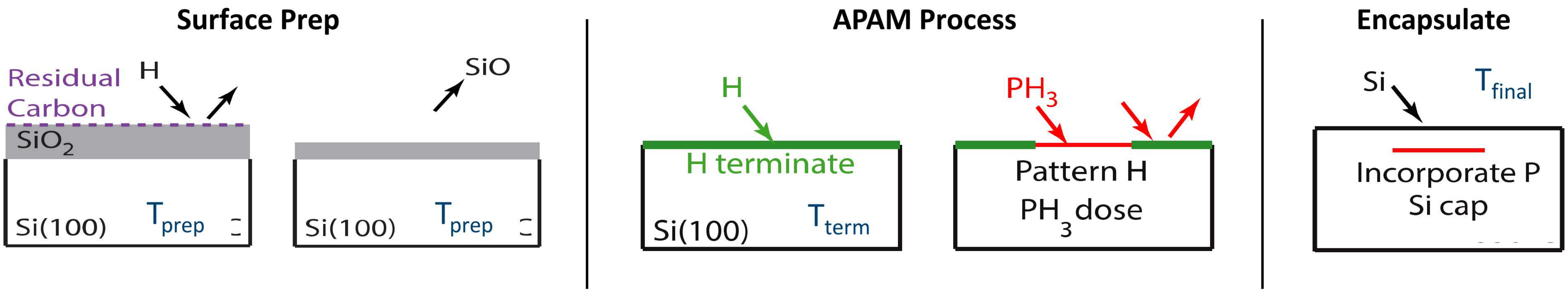


Interconnects



Fingerprint

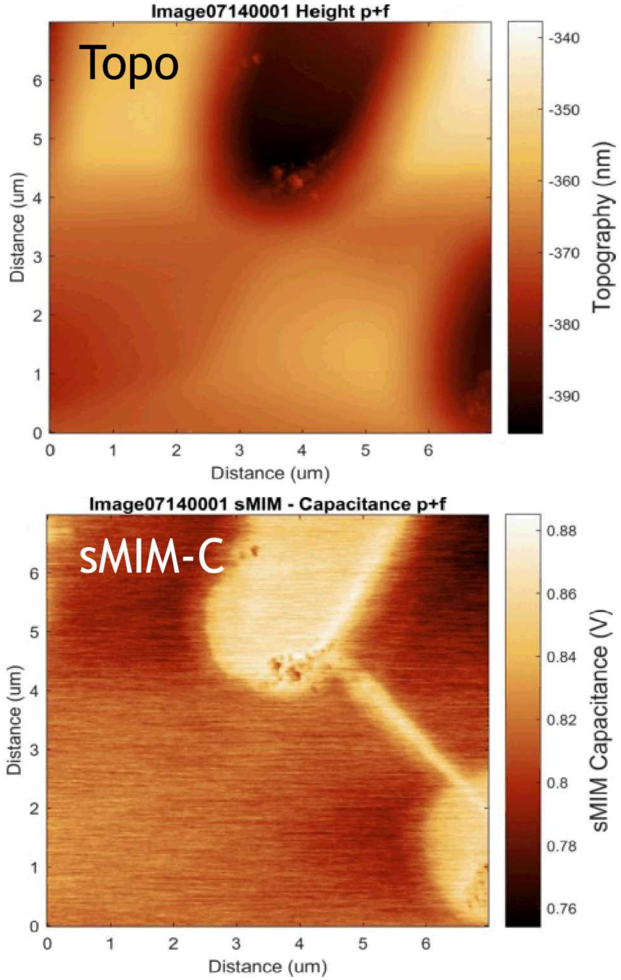
sMIM to monitoring process variation



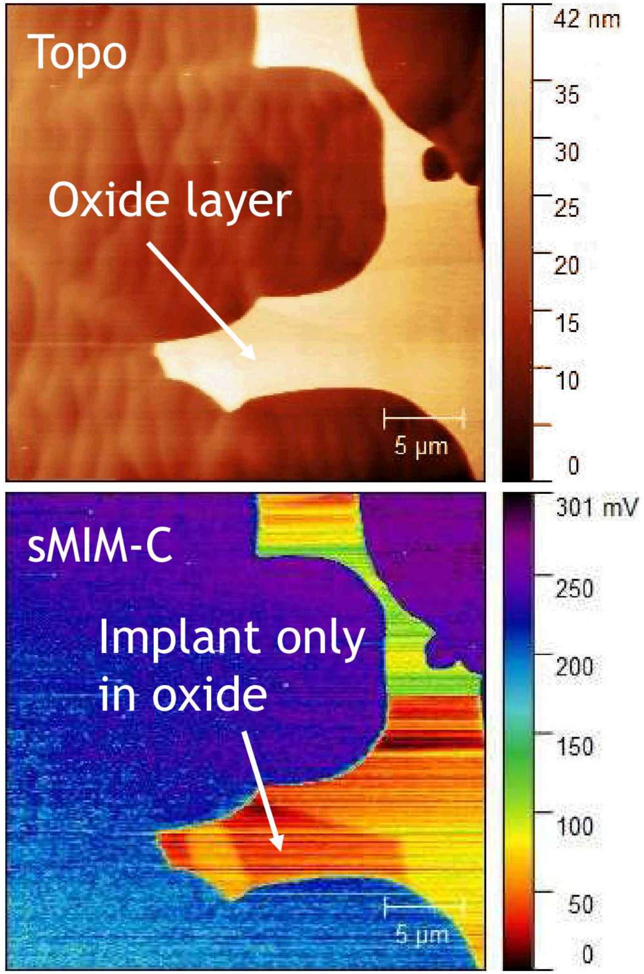
Year	Surface Prep	H Pattern & Dose	Si Top Cap
SOA FY16	T_{prep} = 1200 °C	T_{term} < 450 °C	T_{final} < 450 °C
FY19	T_{prep} = 800 °C	T_{term} = 22 °C	T_{final} = 22 °C
FY20	T_{prep} < 450 °C	T_{term} = 22 °C	T_{final} = 22 °C

D.R. Ward et al, *Applied Physics Letters* 111, 193101 (2017).

Quick evaluation of implanted samples & processing conditions



Pre-implanted starting material
STM wrote a wire between two contacts.



Ga pre-implanted starting material
Implants disappearing with processing.

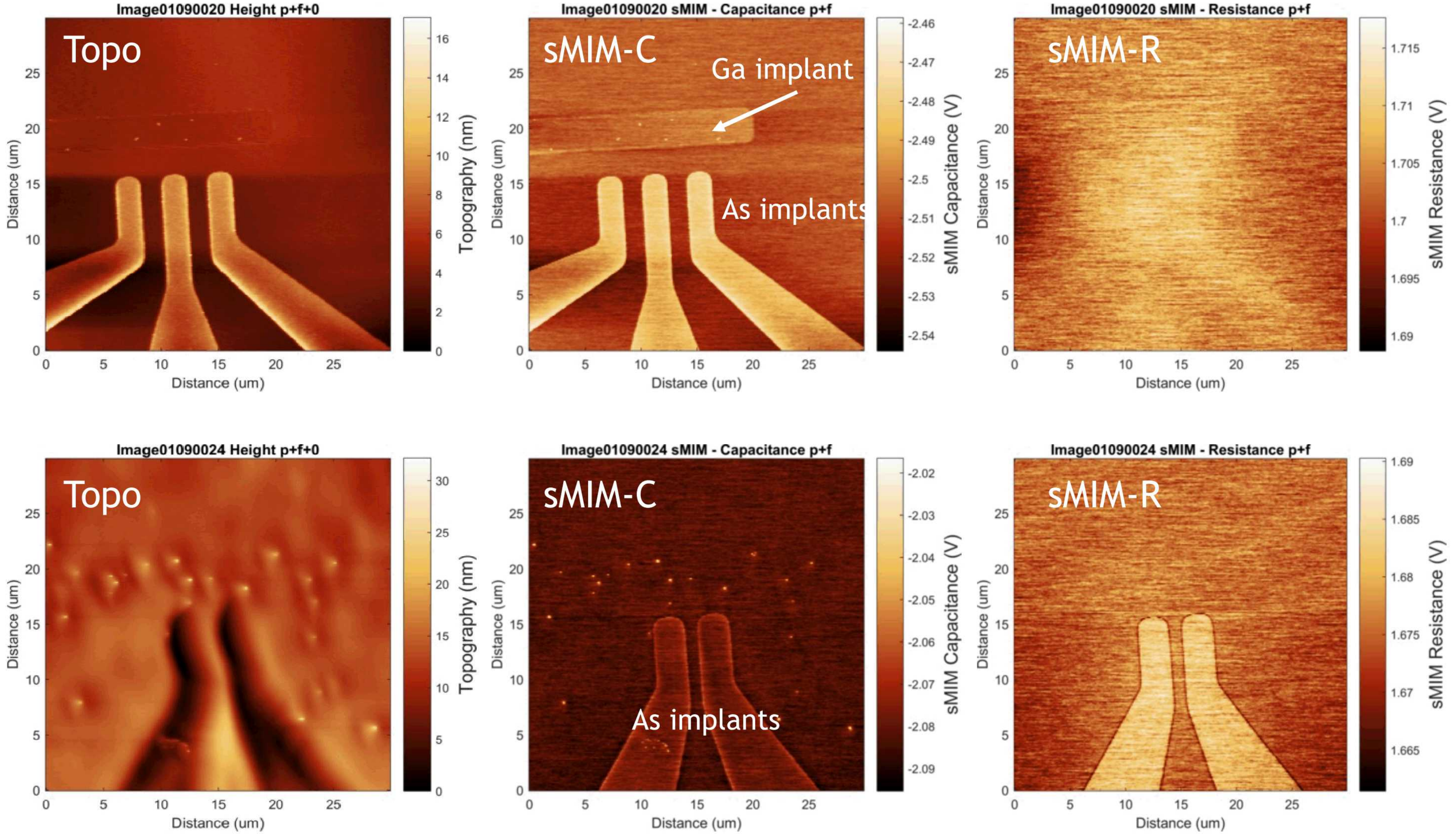
Quick evaluation of implanted samples & processing conditions

Implanted sample

As, Ga species

Implanted then flashed

Ga disappears



Conclusions/Future Work

- sMIM has imaged & registered buried P nanostructures under <30 nm Si epi
- See 10 nm lines resolved on 88 nm pitch lines
- sMIM a great tool for quick evaluation of processed samples

Current work:

- Assess epi quality with sMIM
    - epi layer thickness, donor layer doping concentration, & process temperature
- Surface sensitivity help in the novel resist & dopant strategies

Collaborators:

Microfabrication Team:

- **Dan Ward**, DeAnna Campbell, Mark Gunter, Philip Gamache, Steve Carr, Troy England, Reza Arghavani, Sean Smith

Surface Science Team:

- **Shashank Misra**, **Ezra Bussmann**, George Wang, Aaron Katzenmeyer, Evan Anderson, Scott Schmucker, Esther Frederick, Fabian Pena, Dave Wheeler, **Joe Simonson, Mike T Marshall**, David Scrymgeour

Measurement/Characterization Team:

- Lisa Tracy, Tzu-Ming Lu, David Scrymgeour, Ping Lu, Albert Grine, Aaron M. Katzenmeyer, Ting S. Luk, James. A. Ohlhausen, Paul Kotula

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The End

9:20	9:45	David Scrymgeour, Sandia	Scanning microwave impedance microscopy of buried dopant nanostructures in silicon

sMIM on buried delta layer structures

sMIM installed at Sandia ~mid 2015

- QIST work 2015-2016
- DEAL work 2017

MRS Talk from 2016
Paper from 2017

Applied Surface Science 423 (2017) 1097–1102

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journal homepage: www.elsevier.com/locate/apsusc

ELSEVIER

Full Length Article

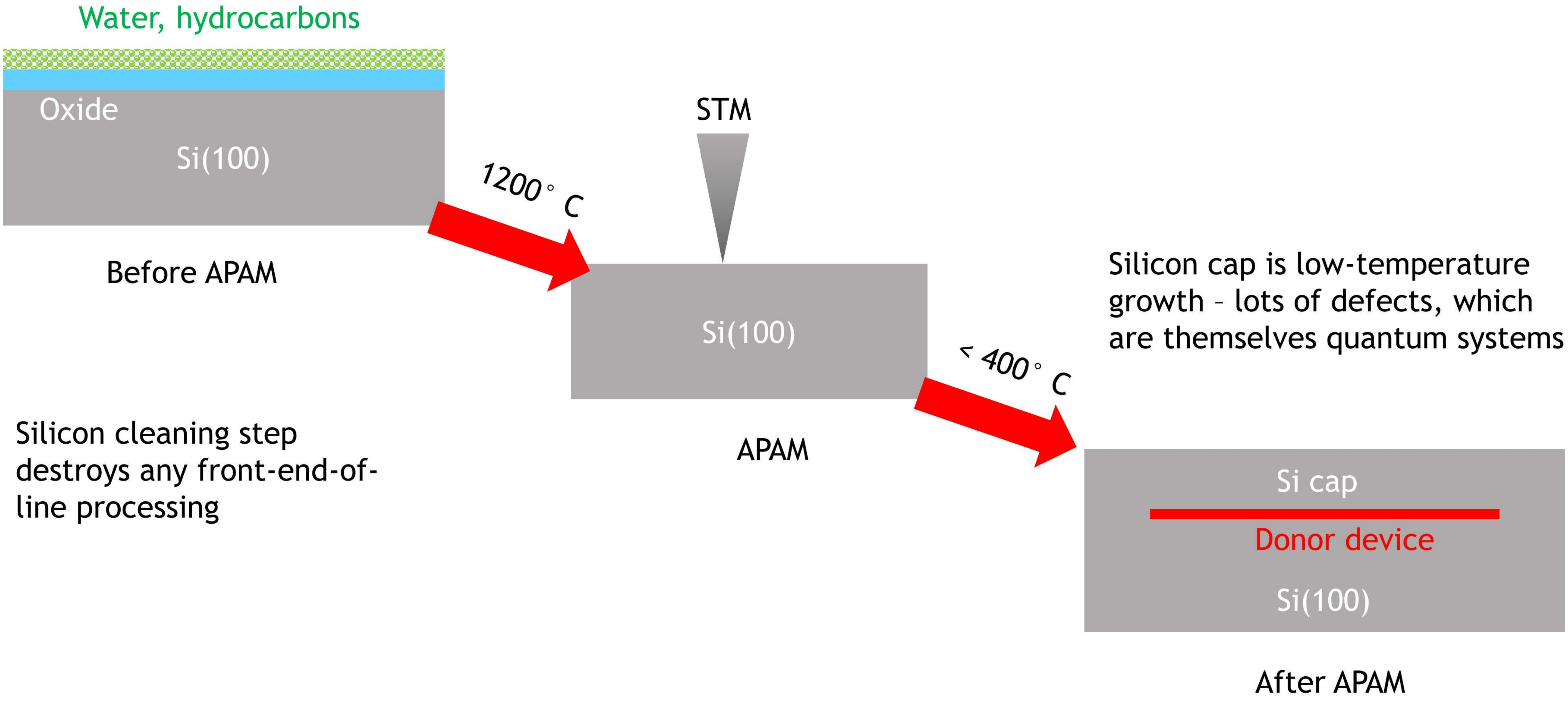
Determining the resolution of scanning microwave impedance microscopy using atomic-precision buried donor structures

D.A. Scrymgeour[a,*], A. Baca[a], K. Fishgrab[a], R.J. Simonson[a], M. Marshall[a], E. Bussmann[b], C.Y. Nakakura[a], M. Anderson[a], S. Misra[a]

[a] Sandia National Laboratories, P.O. Box 5800 Albuquerque, NM 87185, USA
[b] Center for Integrated Nanotechnologies, Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185, USA

ARTICLE INFO ABSTRACT

Using sMIM to evaluating effects of processing variation



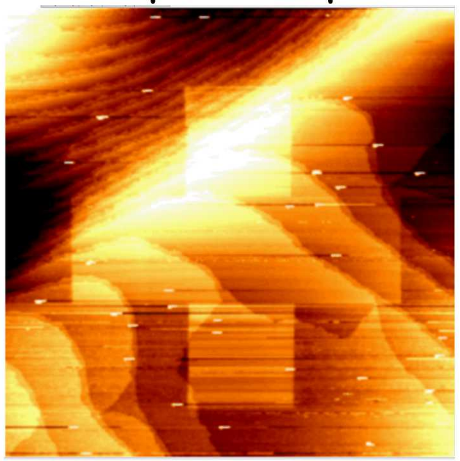
Silicon cleaning step destroys any front-end-of-line processing

Silicon cap is low-temperature growth – lots of defects, which are themselves quantum systems

Extreme surface sensitivity?

Experiment:
Cross written on H_2 terminated surface
Pulled out of vacuum, sMIM imaged within 1 hour

4 μm x 4 μm

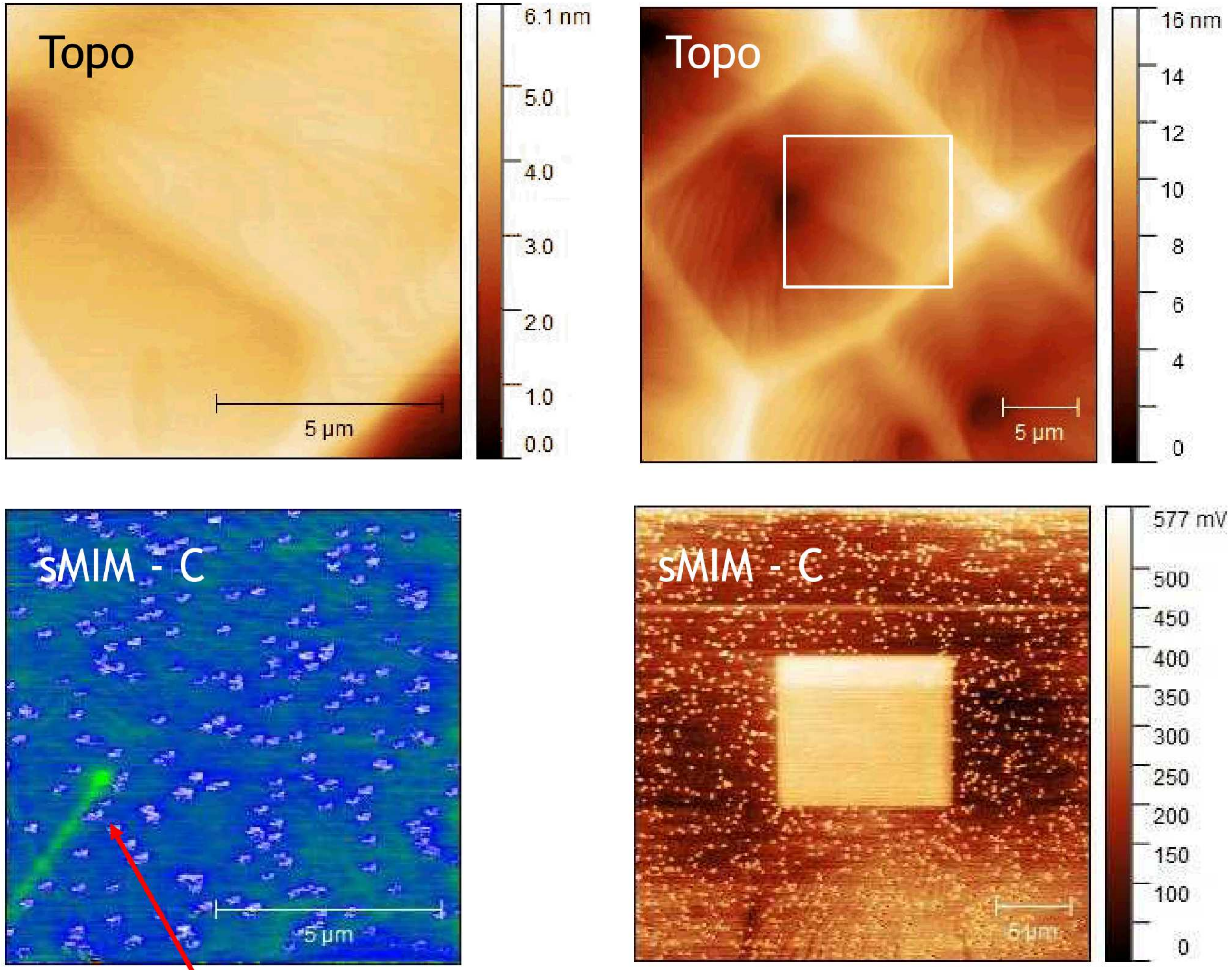


Results:
Saw patterning behavior in sMIM image
Gone by next day

Show:
sMIM sensitive to H_2/unbonded surface?
Another technique for surface resists quantification?

Small sub scan

Larger scan



AFM touch track

Extreme surface sensitivity?

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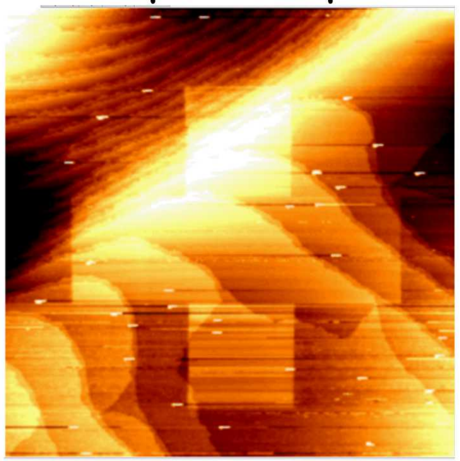

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