SAND2014-19554C

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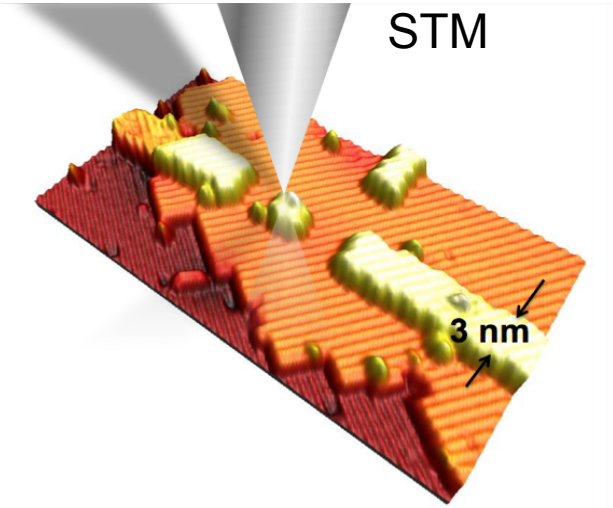

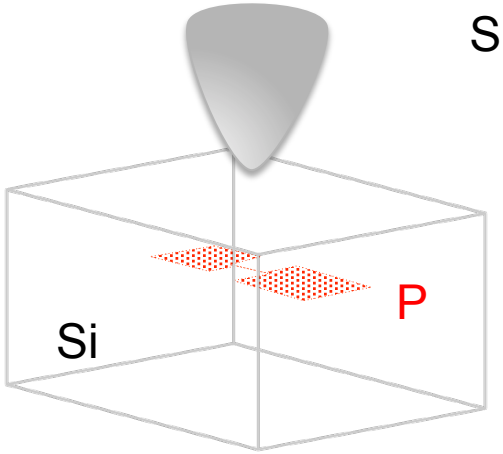

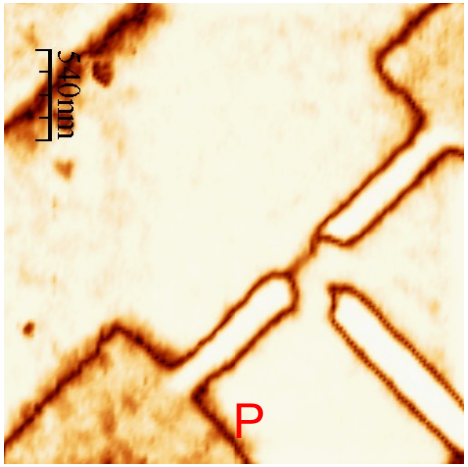

Scanning Capacitance Microscopy Imaging and Registration of 2-D Donor Devices Fabricated via Scanning Tunneling Microscopy

Ezra Bussmann (ebussma@sandia.gov), S. Misra, M. Rudolph, S.M. Carr, J. Dominguez, G. Subramania, G. Ten Eyck, M. P. Lilly, M. S. Carroll

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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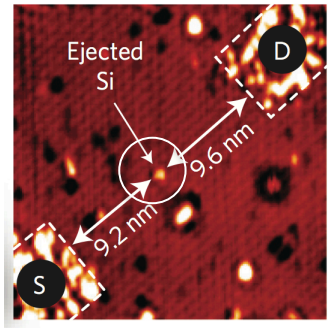
Motivations

- Atomic-precision engineering of nanostructures
  - Example: Single-donor electron and nuclear spin qubits
  - At present, devices fab'd via conventional techniques (ion implant, 10-nm-scale precision)
  - Atomic-precision placement essential to reproduce numerous identical devices
  - Michelle Simmons (UNSW, Australia) demonstrated atomic precision donor devices via STM

    - A single atom transistor **(M.Y Simmons, UNSW, Australia)**

Fuechsle, Nature Nano. (2012)



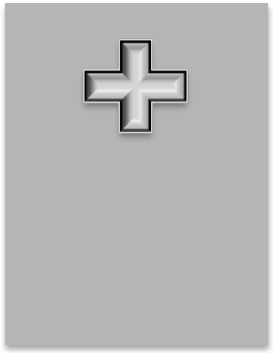
- **Challenge: Integration of STM fab'd devices with conventional fab to place ohmics, gates, ESR lines**
- **Problem: nanoscale registration of buried donor layer**
- **We developed a scanning capacitance microscopy technique to image & register donor structures for 100-nm precision placement of ohmics (and gates, ESR lines etc)**

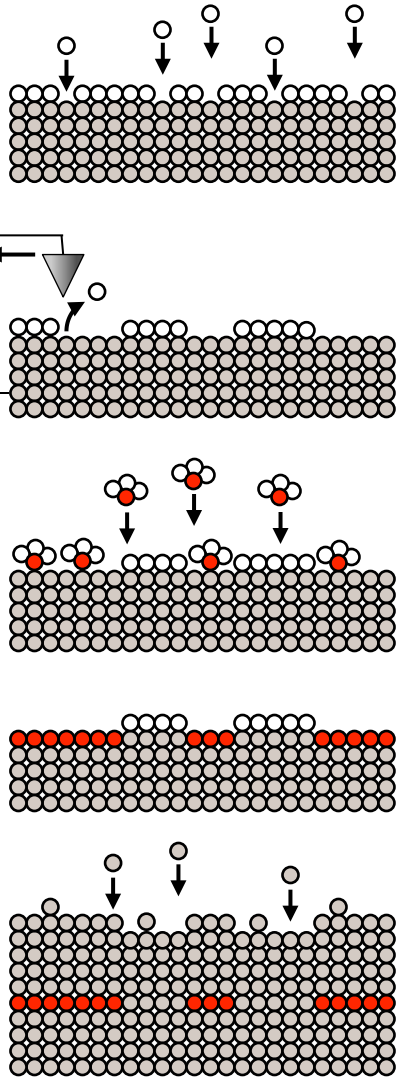
Atomic-precision fabrication via STM

- Technique developed by Lyding, Tucker, Shen (UIUC) & by M.Y. Simmons et al (UNSW) (2004)

Si microfab

Prepare Si chips with registration marks





Passivate Si (100) with H

Selectively desorb H with atomic precision by STM

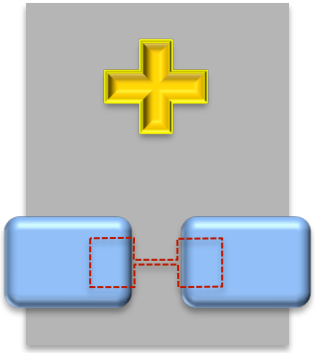
Introduce PH_3 gas

Incorporation anneal

Grow epitaxial Si capping layer

Si microfab

fab metal contacts to buried dopant

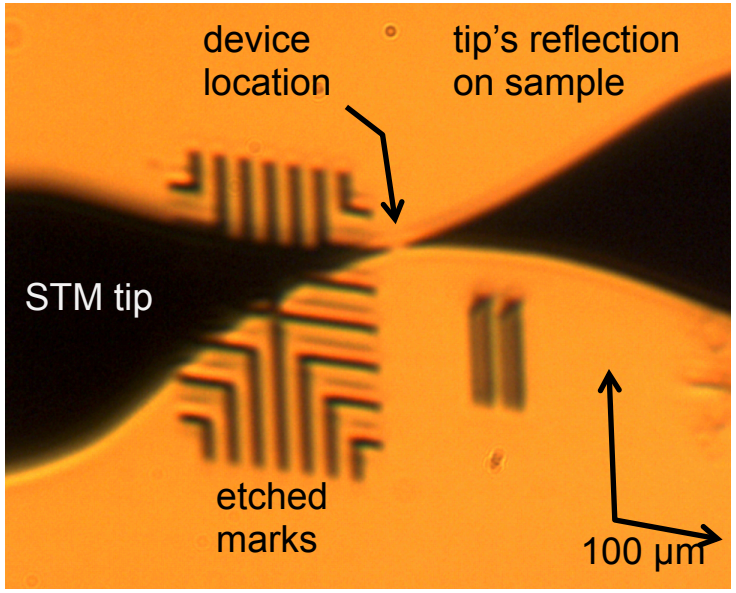


Challenge: locating donor device accurately

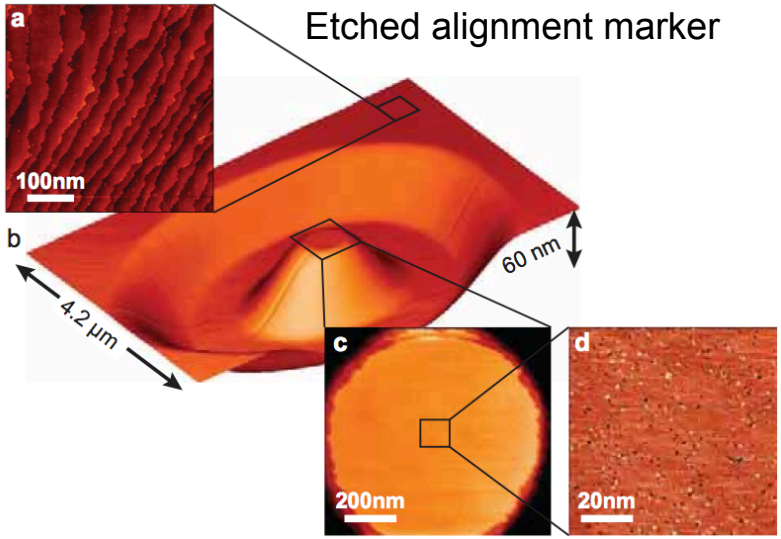
- Simmons Method: 1. coarse location via microscope 2.precision registration to an etched mark using STM imaging

- Challenges: time consuming to locate etch feature, requires scanning over large topo features--shortens tip lifetime, requires fine-tuned X-Y-Z coarse motion

1. Coarse optical positioning



2. STM registration to nanoscale features



Flat central terrace for device Simmons et al. JVST B (2007)

- **Is there some way we could do away with step 2, allowing devices to be fab'd anywhere** ?

Scanning capacitance microscopy of buried donor structures

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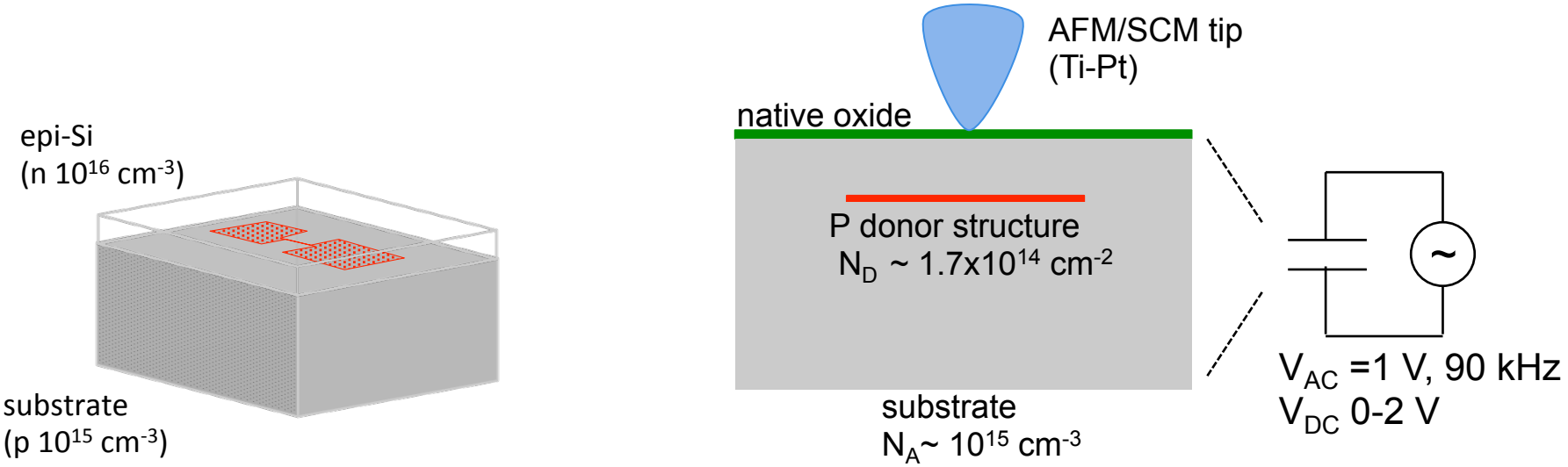
- End product from STM process
  - All-epitaxial planar buried delta doped nanostructure
  - Atomically abrupt in X Y and Z
  - Donor & e- density 1.7x10^{14} cm^{-2} (metallic) (~10^{21} cm^{-3})



- SCM measures MOS CV response of the tip-oxide-Si
- SCM detected by lock-in → dC/dV (90 kHz), SCM phase
- Magnitude ~ doping level, phase ~ doping type

Scanning capacitance microscopy of buried donor structures

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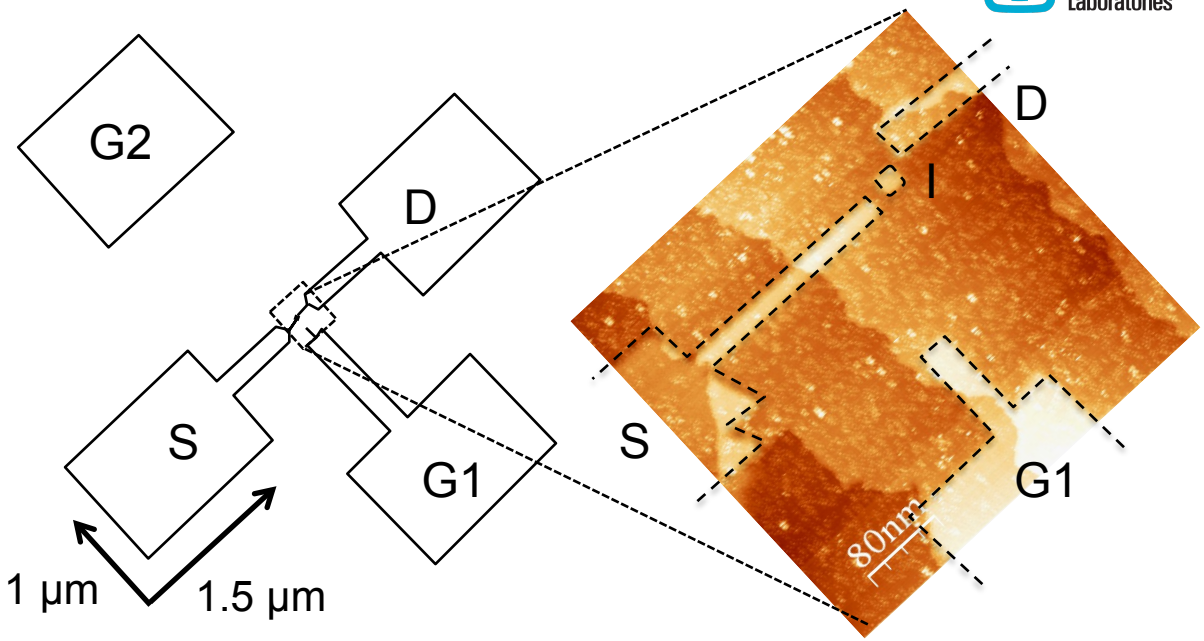
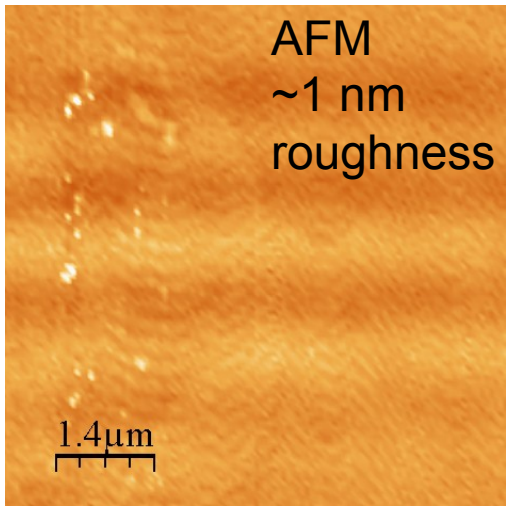
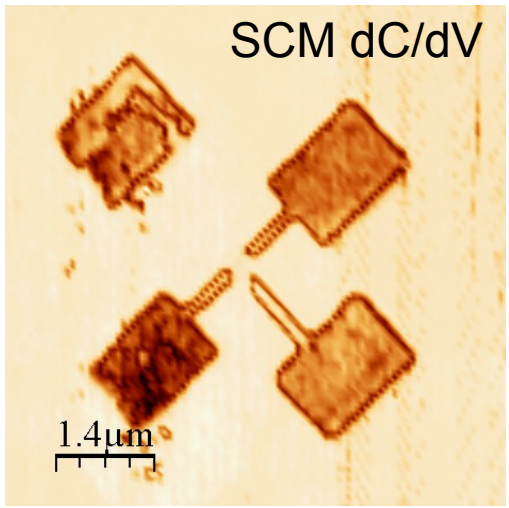
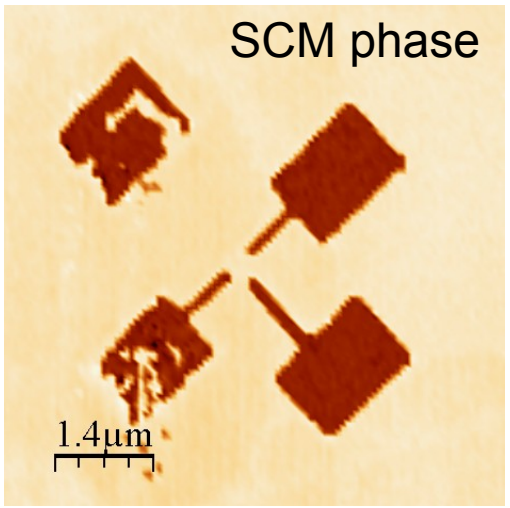
- H-litho and STM



- AFM/SCM

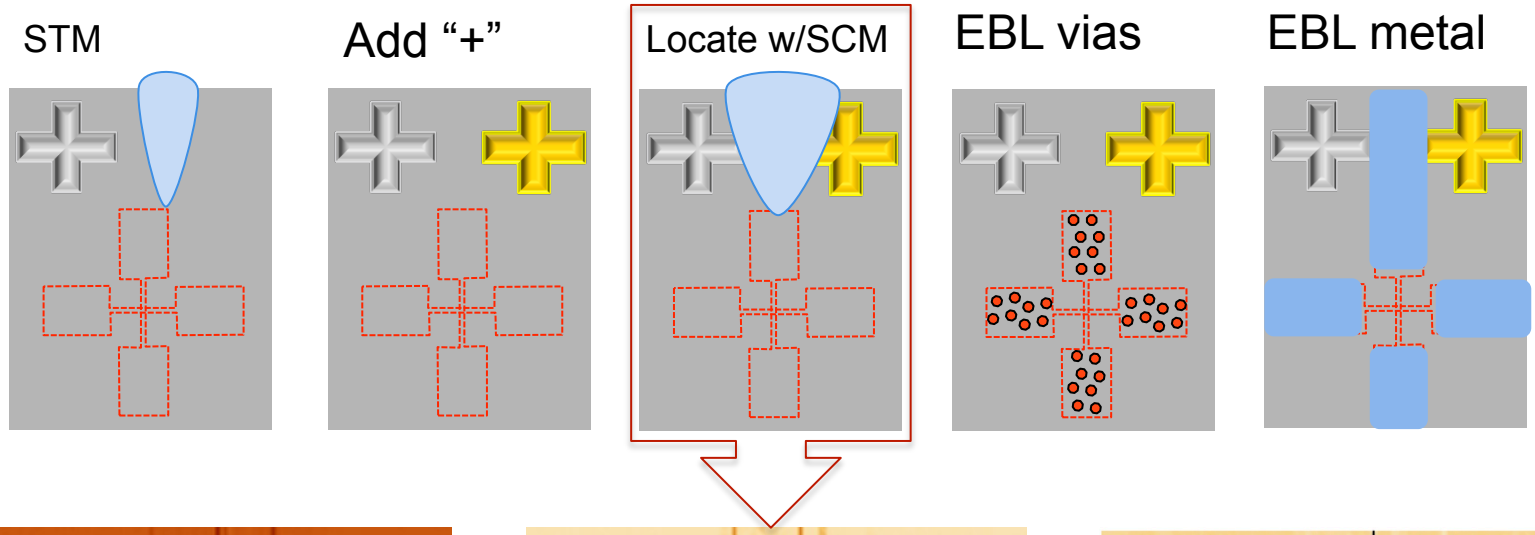


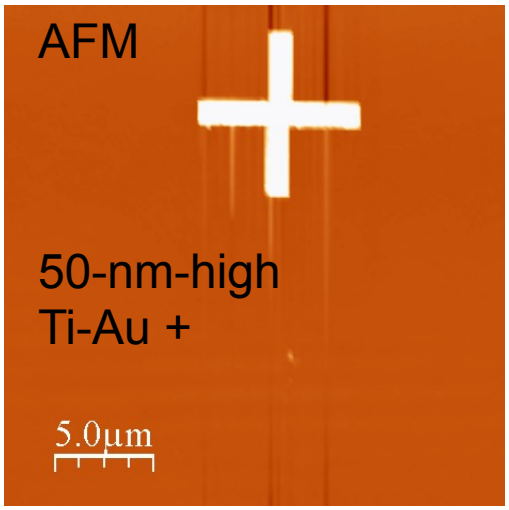


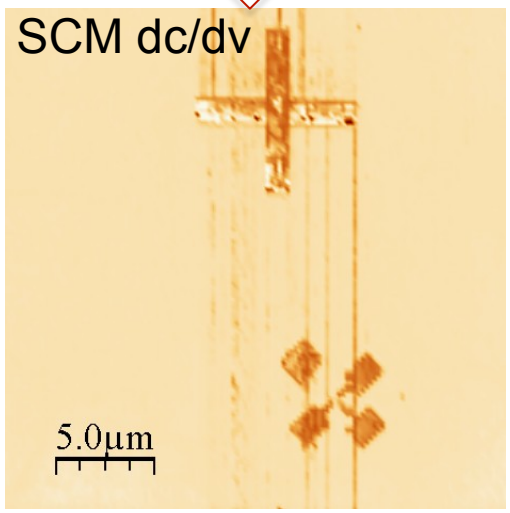


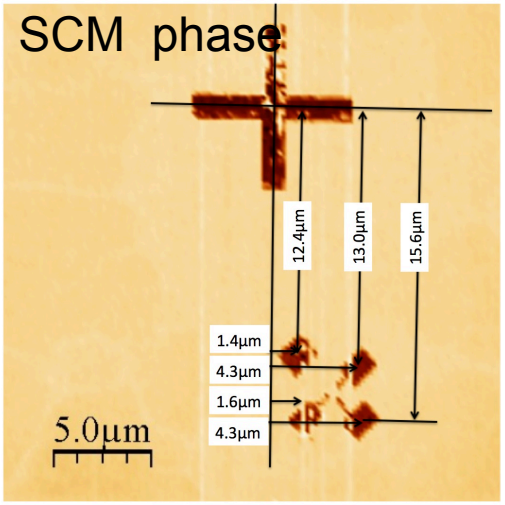
Registering & contacting donor structure

- process flow for contacting device









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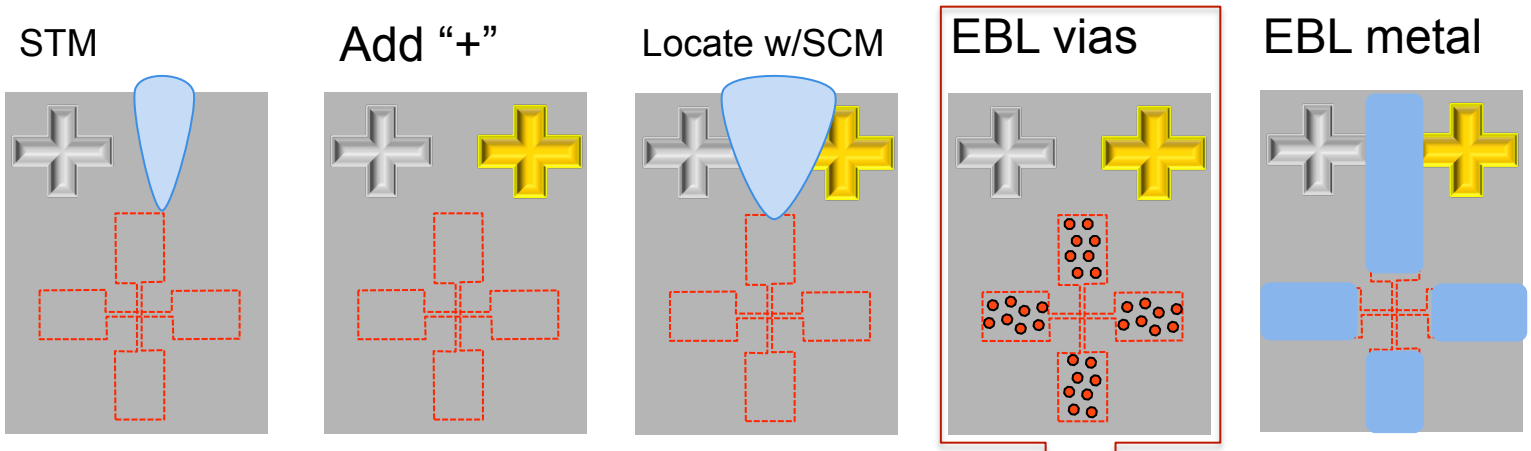
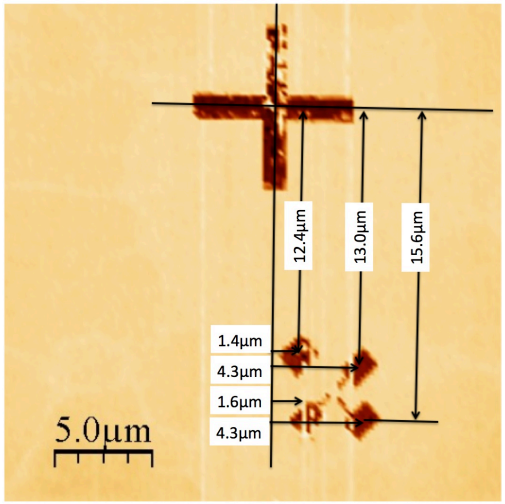
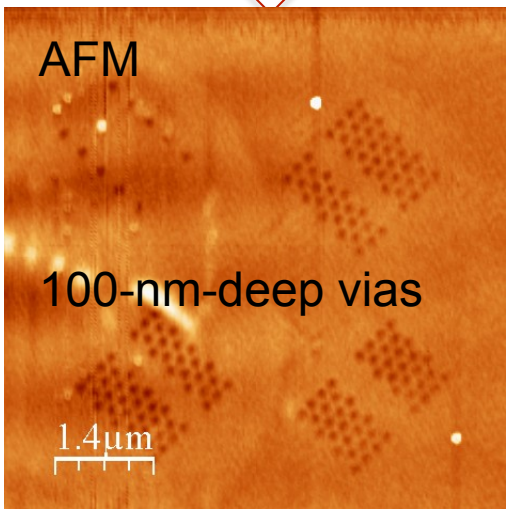
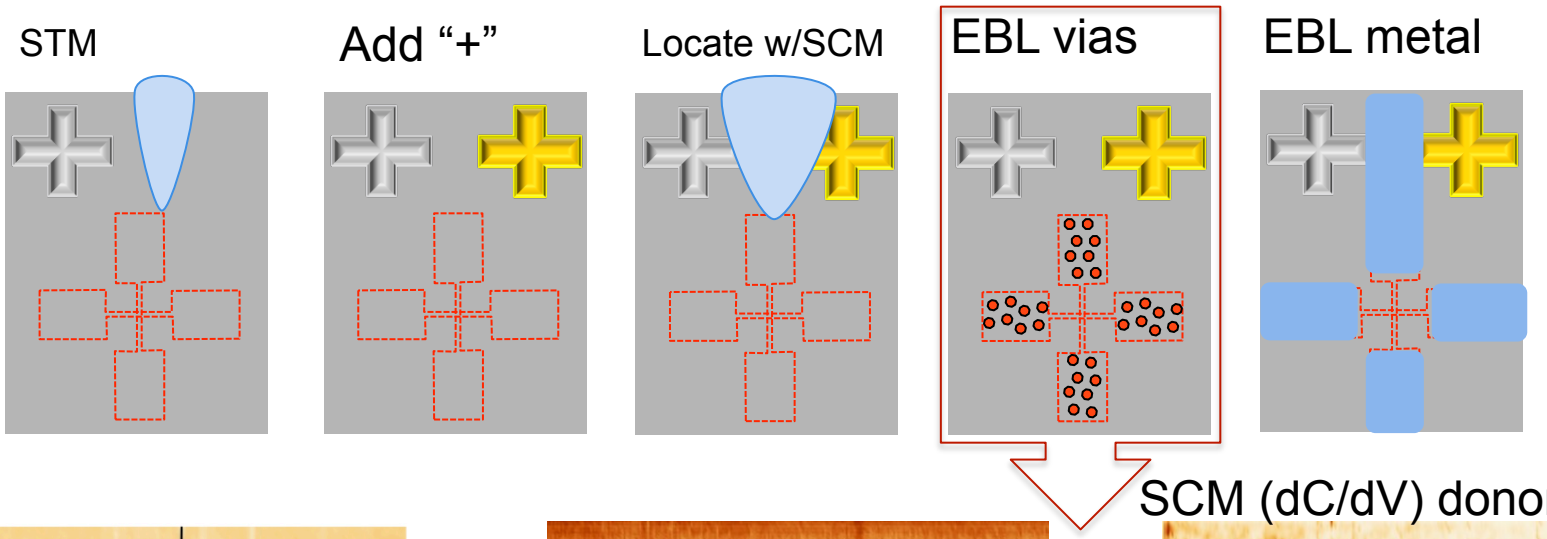


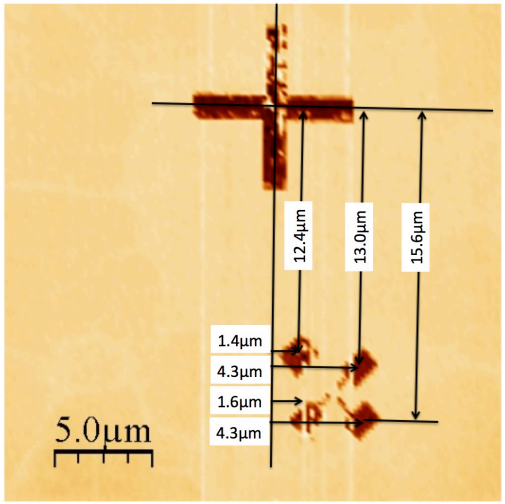


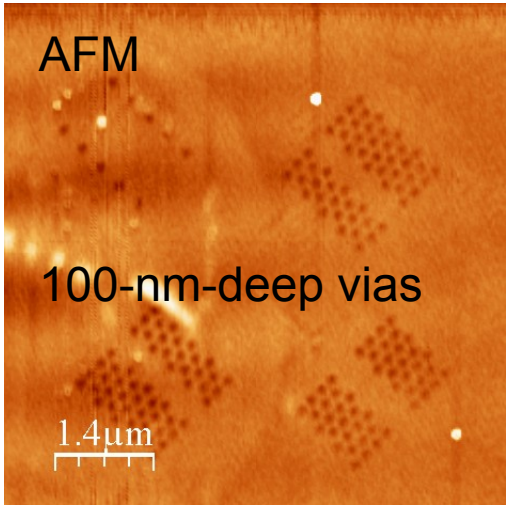


Registering & contacting donor structure

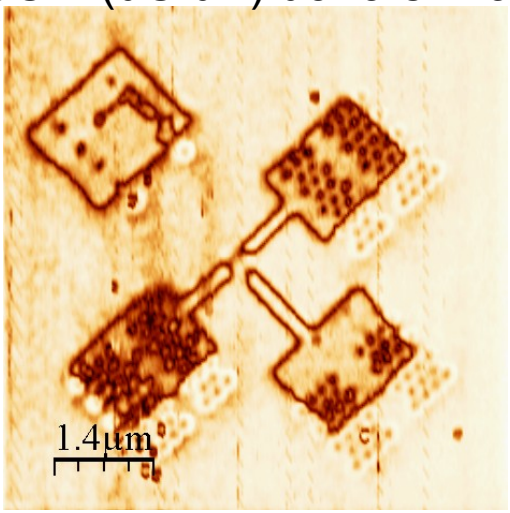
- process flow for contacting device





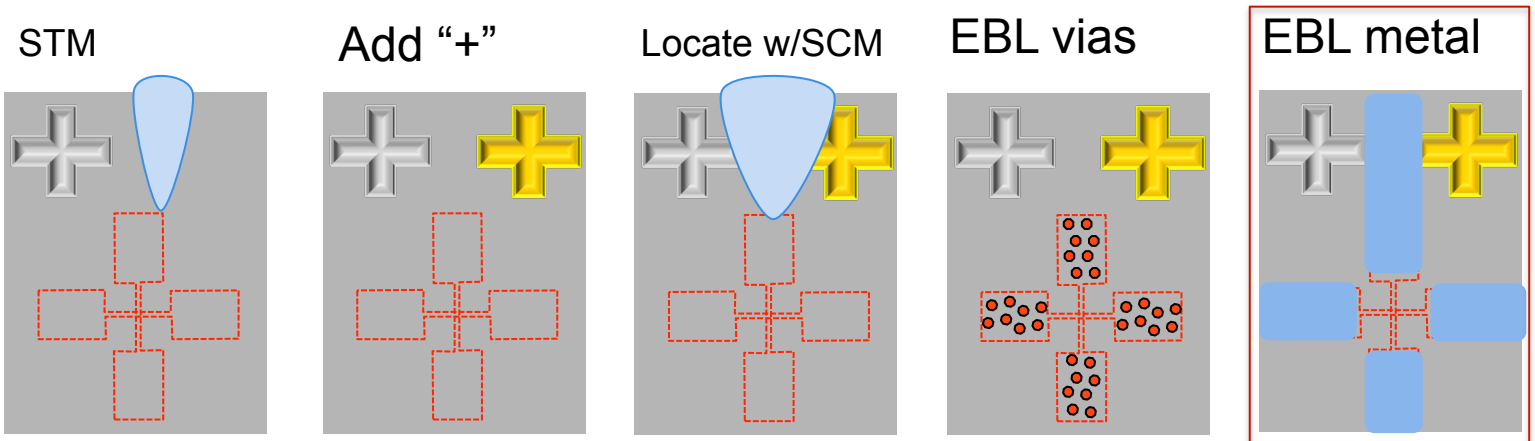


SCM (dC/dV) donors+vias

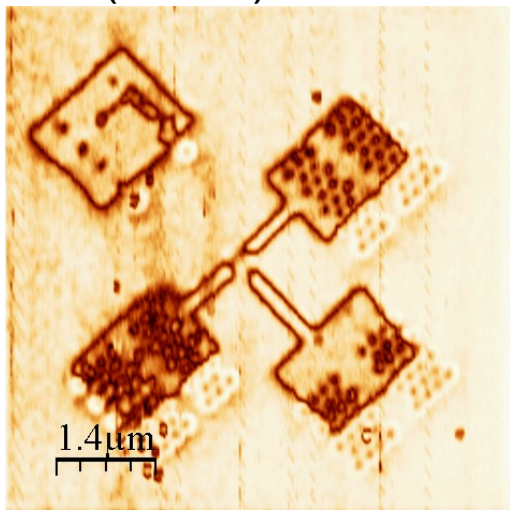


Registering & contacting donor structure

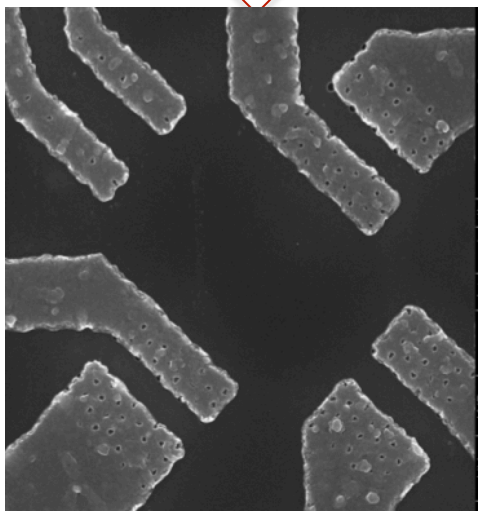
- process flow for contacting device



SCM (dC/dV) donors+vias



SEM 100-nm-Al



Registering & contacting donor structure

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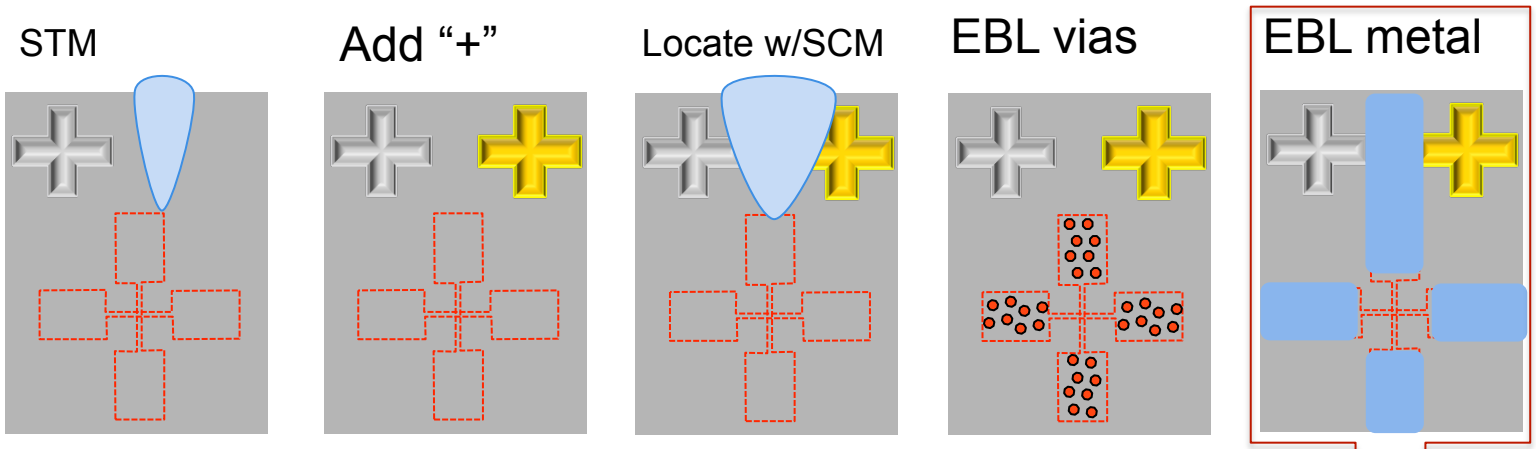
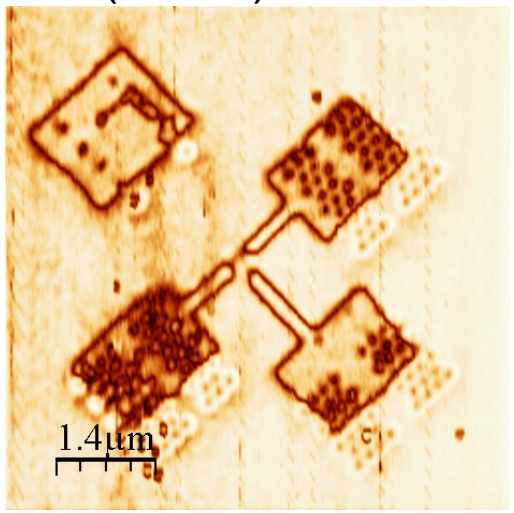
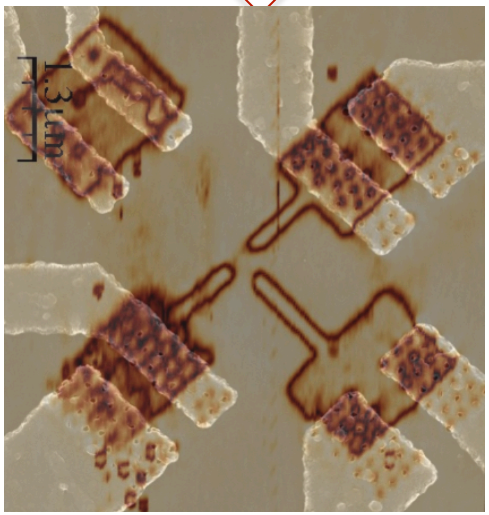


SCM (dC/dV) donors+vias



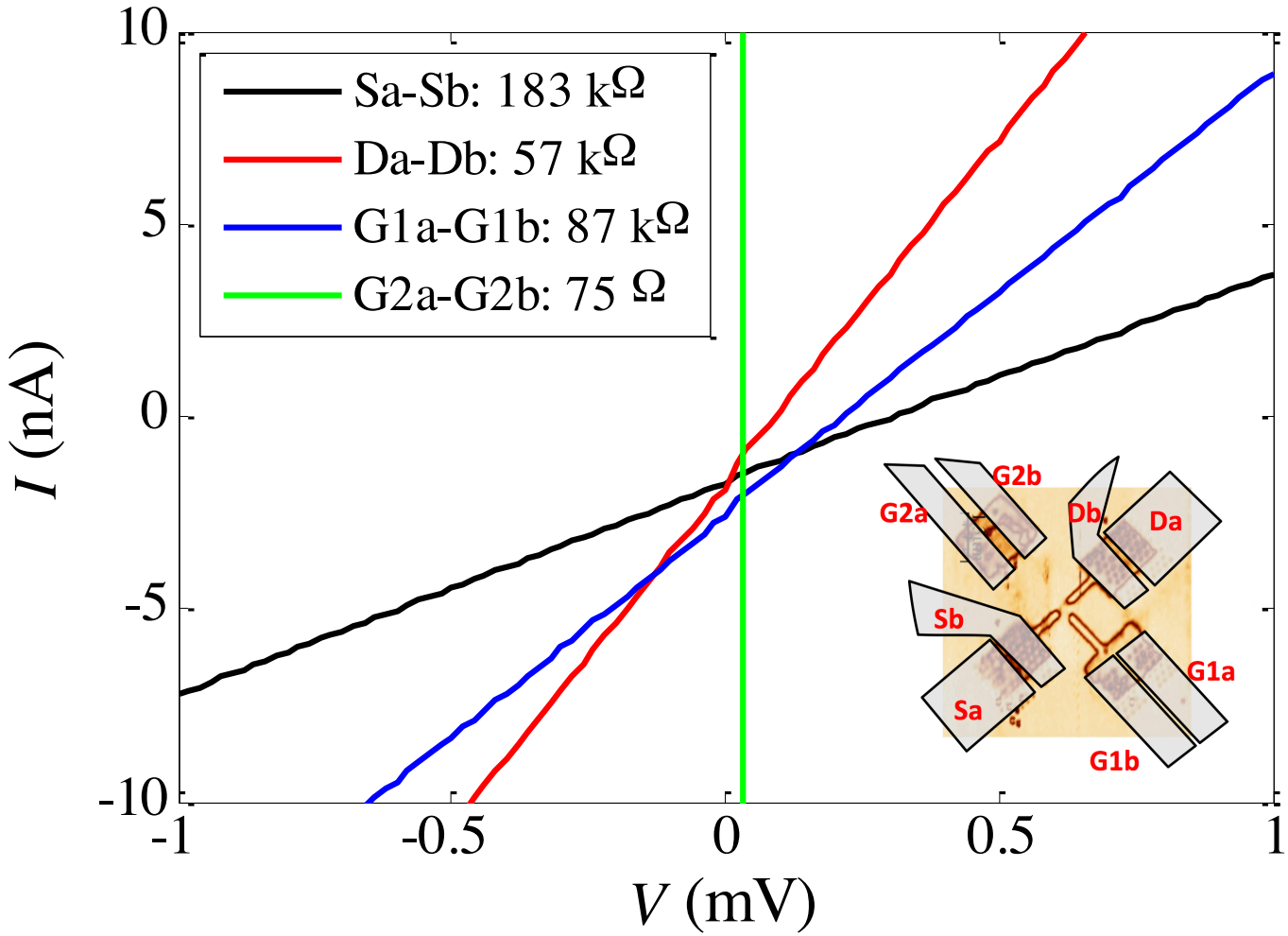
- **Metal+vias successfully hit the buried donor target**

SCM+SEM



Testing contact placement (Martin Rudolph)

- T=4K transport measurements show successful ohmic contact to buried device layer



Summary

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- SCM : first technique for direct visualization of the carrier/dopant distribution of buried donor structures

- SCM provides useful nanoscale metrology for each step of fab process

  -lets us know we are actually making the structures that we think we are

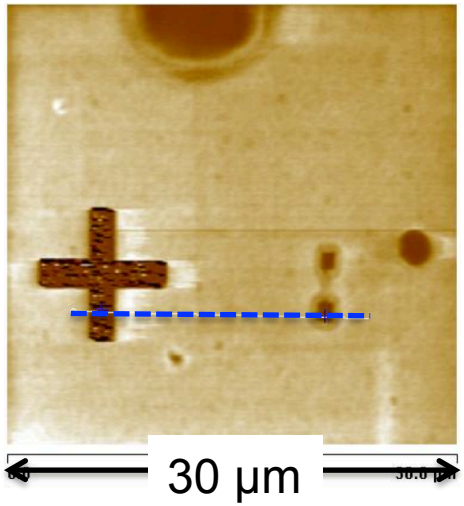
- We demonstrated 100-nm-scale accuracy technique to contact buried donor structures in order to complete device

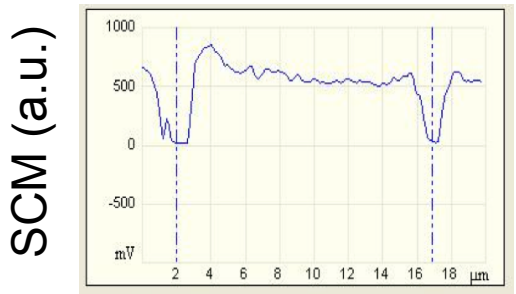
- SCM registration technique may ultimately achieve higher accuracy than other methods of metal placement for critical features like ESR lines

Metrology for atomic precision devices

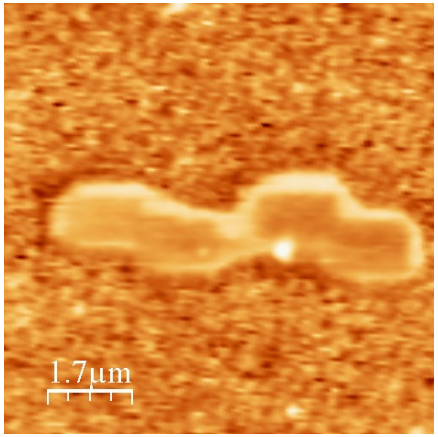
- SCM provides an additional new means of structural characterization
- To date: STM of buried structure, transport measurements, and SIMS…
- SCM provides direct view to the donor distribution, allowing diagnosis of litho problems

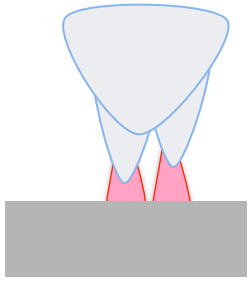
- SCM response (dC/dV) on donor layer is comparable to metal



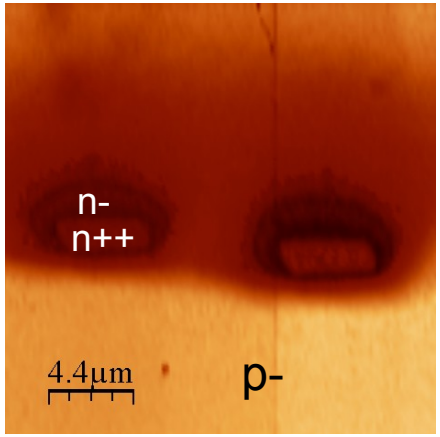


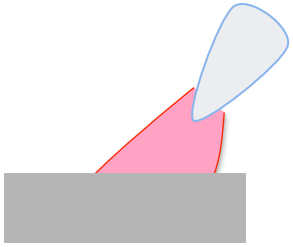
- Diagnosing problems: double asperity tip writing





- Diagnosing problems: adventitious depassivation in field emission





Front end process

- Greg Ten Eyck
- Tammy Pluym
- …unidentified SiFab techs

STM lithography and measurement

- **Ezra: STM Litho**
- Bob Butera
- Esmeralda Yitamben
- Shashank Misra
- Troy Gourley, Jon Rivera

Backend process

- Eric Langlois
- **Ganesh Subramania**
- **Martin Rudolph**
- Steve Carr
- **Bev Silva**
- **Jason Dominguez**

Measurement

- **Martin Rudolph**
- Mike Lilly

collaborations and guidance

- Michelle Simmons (UNSW)
- Rick Silver (NIST)
- Josh Ballard, John Randall (Zyvex)
- Brian Swartzentruber (CINT)