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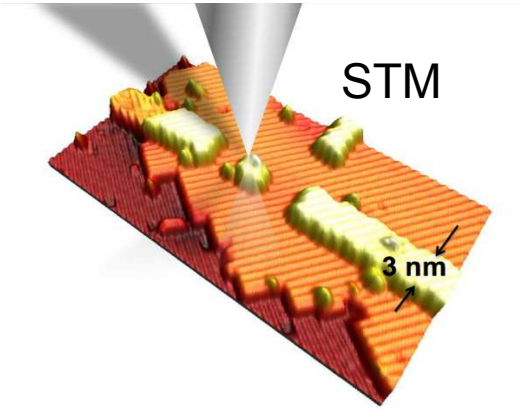
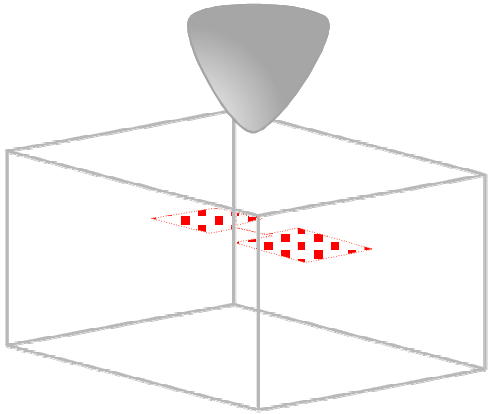
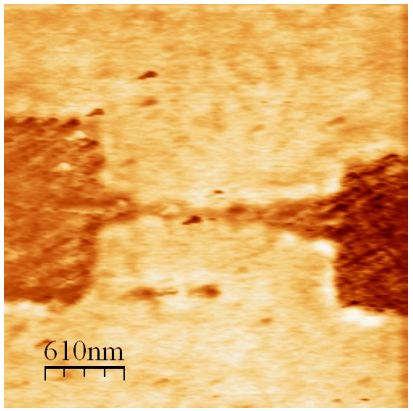




SCM



Scanning capacitance microscopy of atomic precision donor devices in Si

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

The 2014 March Meeting of the APS

U.S. DEPARTMENT OF ENERGY | NNSA

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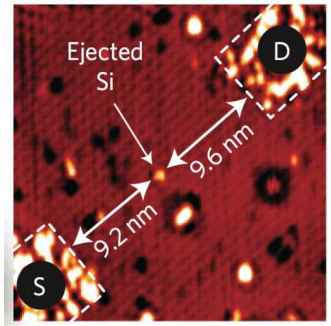
Motivations

- Good single-donor electron and nuclear spin qubits demonstrated
  - At present, devices fab'd via conventional techniques (ion implant, 10-nm-scale precision)
  - Important qubit interactions exponential in distance
  - So atom-precision placement essential to reproduce numerous identical devices
  - Simmons demonstrated fab of atomic precision donor devices via STM
    - Single atom transistor (Simmons, UNSW)

Fuechsle, Nature Nano. (2012)



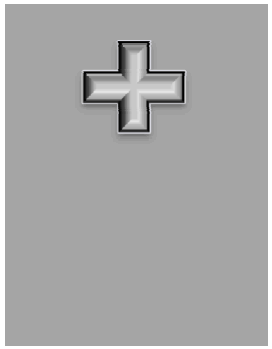
- **Challenge: Integration of STM fab'd devices with conventional fab to place ohmics, gates, ESR lines**
- **Problem: nanoscale registration of buried donor layer**
- **We show scanning capacitance microscopy technique to image & register STM donor structures for 100-nm precision placement of ohmics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

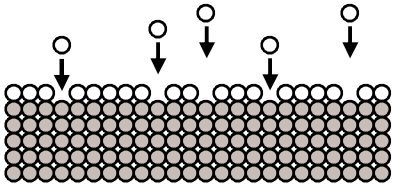
Atomic-precision fabrication via STM

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

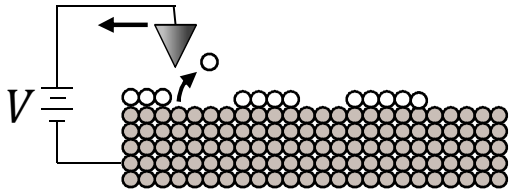
Si microfab

Prepare Si chips with registration marks

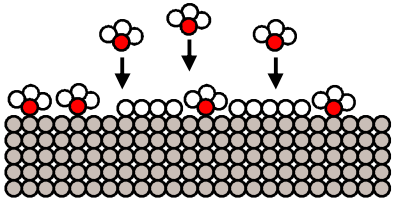




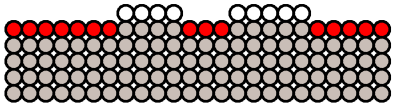
Passivate Si (100) with H



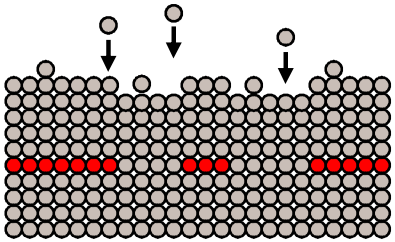
Selectively desorb H with atomic precision by STM



Introduce PH_3 gas



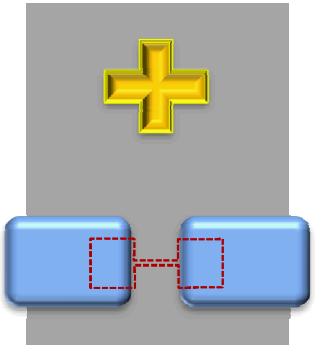
Incorporation anneal



Grow epitaxial Si capping layer

Si microfab

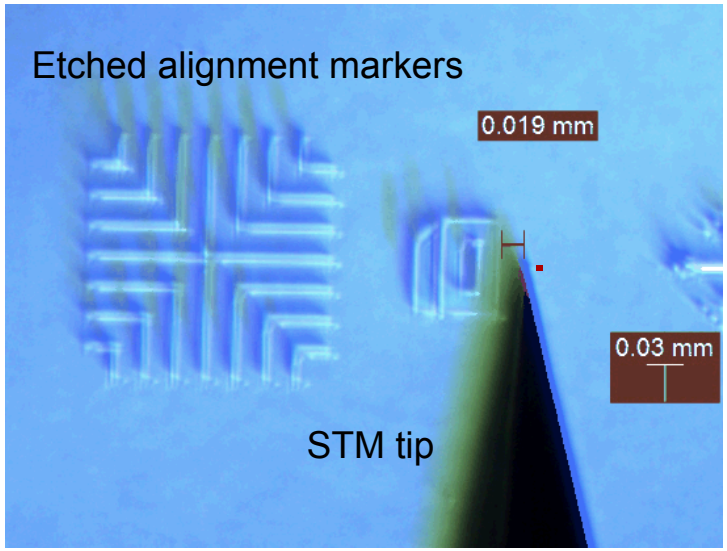
fab metal Icontacts to buried dopant



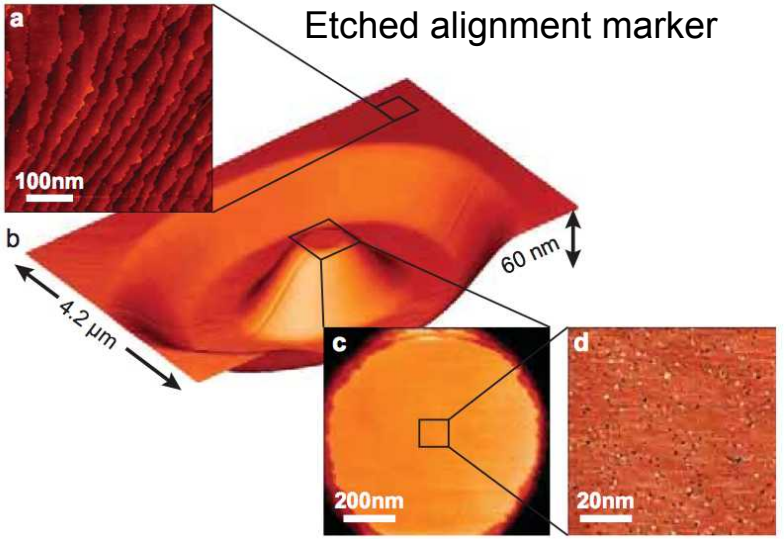
Tricky part: locating donor device accurately

- **Essential for placing subsequent device layers: Ohmics, gates, ESR lines etc.**
- Simmons Method: 1. coarse location via microscope 2.precision registration to an etched mark using STM imaging
- Drawbacks: time consuming to locate STM 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

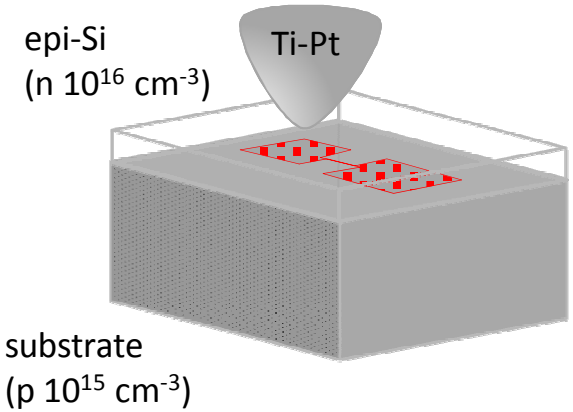


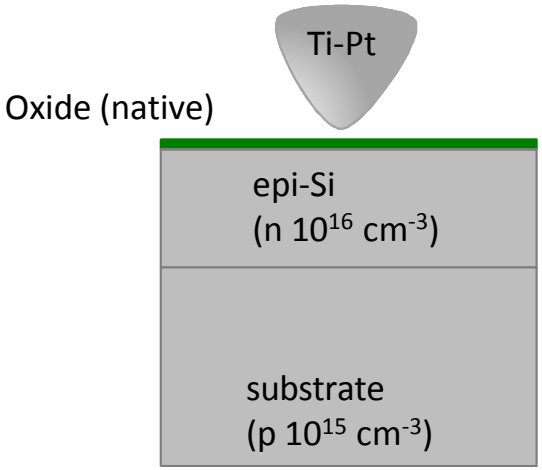
Flat central terrace for device Simmons et al. JVST B (2007)

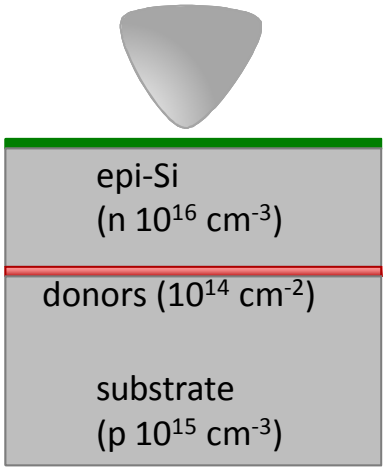
- **Is there some way we could do away with step 2, allowing devices to be fab'd anywhere** ?

Scanning capacitance microscopy of buried donor structures

- 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})







For SCM (dC/dV)

V_{AC} =1 V at 90 kHz

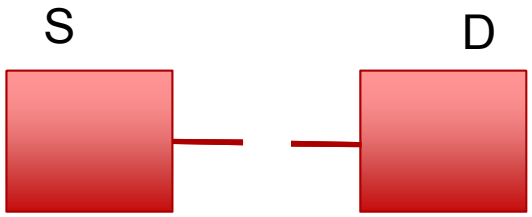
V_{DC} 0-2 V

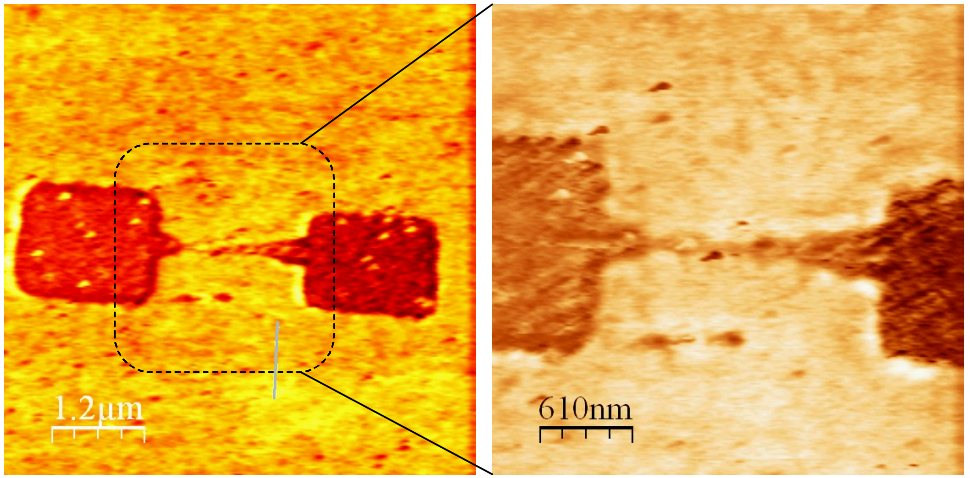
- SCM measures MOS CV response of the tip-oxide-Si
- SCM can sense buried donor structures

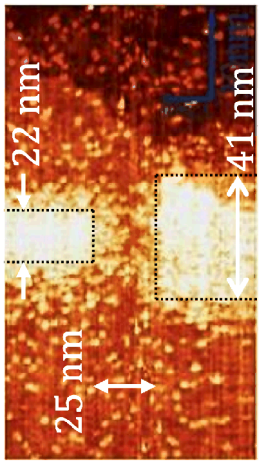
Scanning capacitance microscopy of buried donor structures

- SCM of nanoscale tunnel junction device

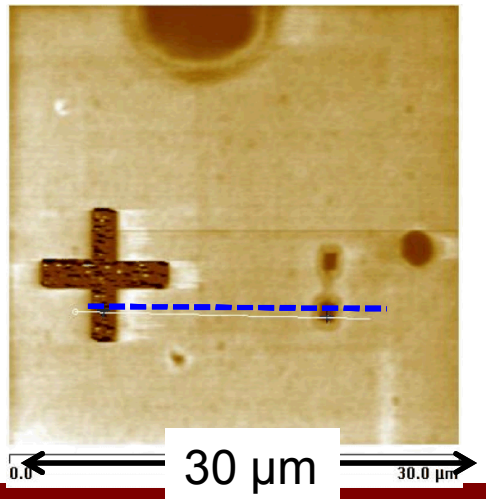
Device schematic







STM
H pattern



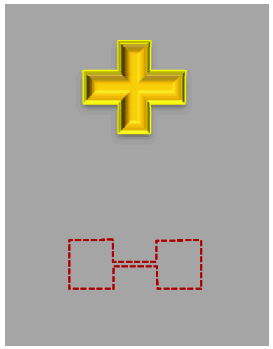
30 µm

SCM on donor layer is comparable to metal

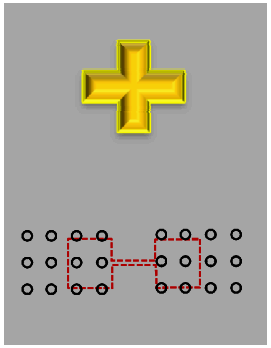
Registering & contacting donor structure

- process flow for contacting device

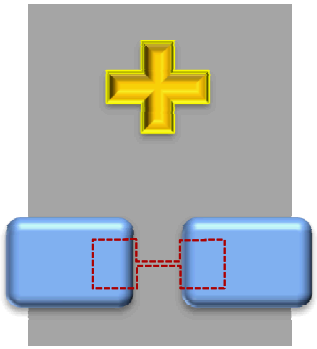
ebl 1 Ti-Au mark



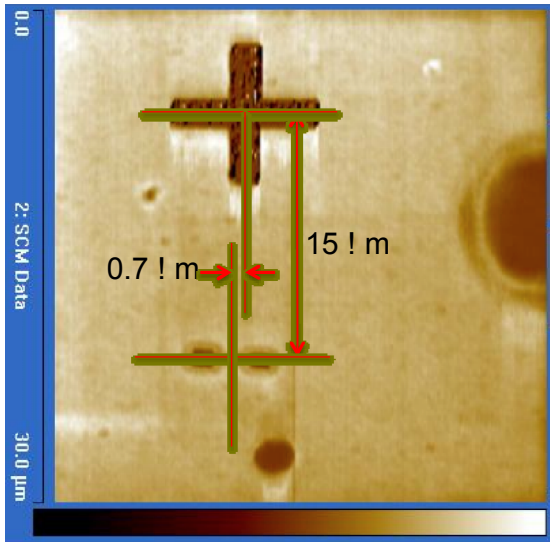
ebl 2 via holes



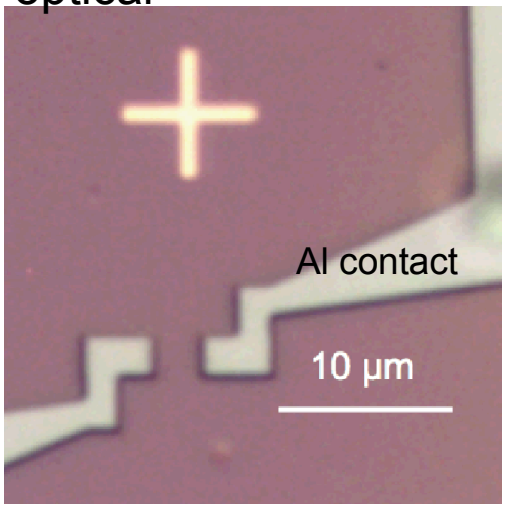
ebl 3 metal



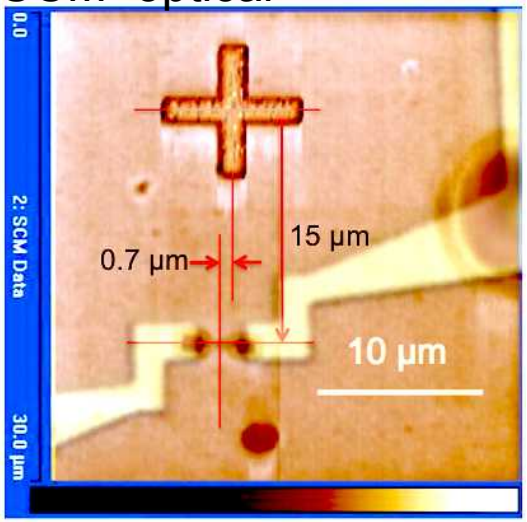
SCM



optical

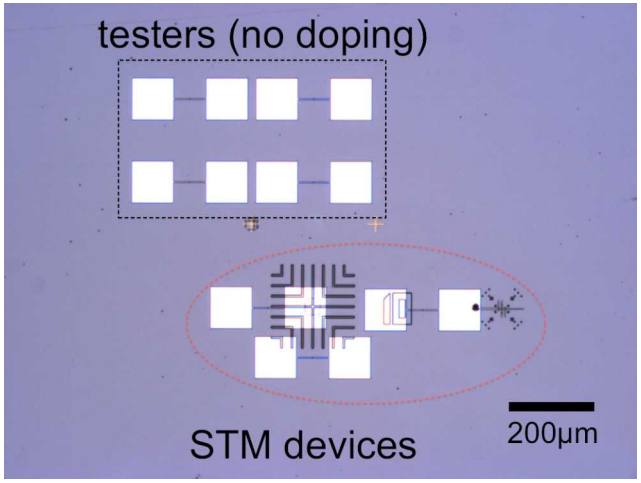


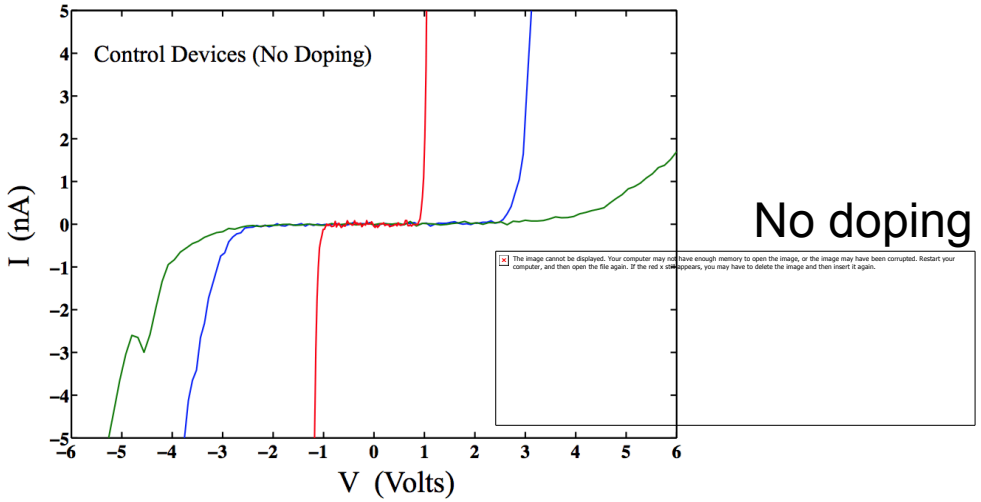
SCM+optical



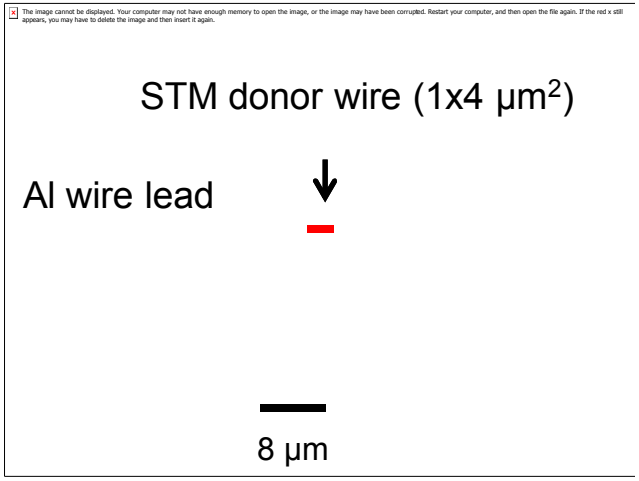
Testing contact placement

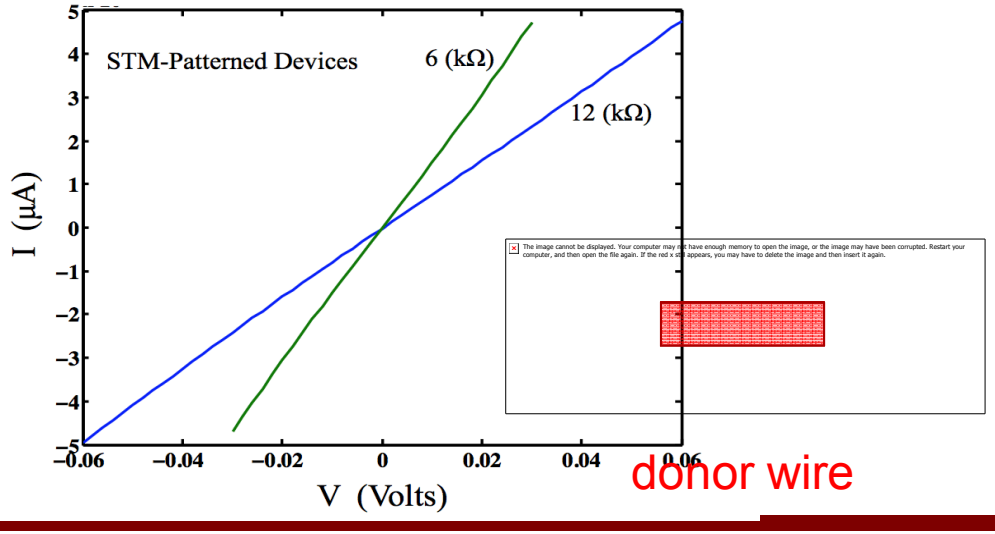
- T=4K transport measurements show successful ohmic contact to buried device layer





No doping



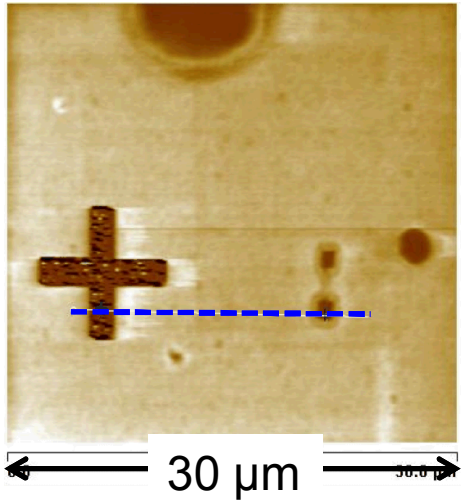


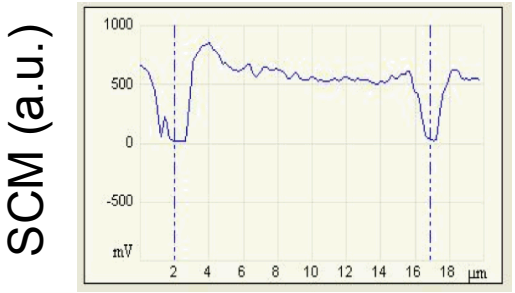
donor wire

Metrology for atomic precision devices

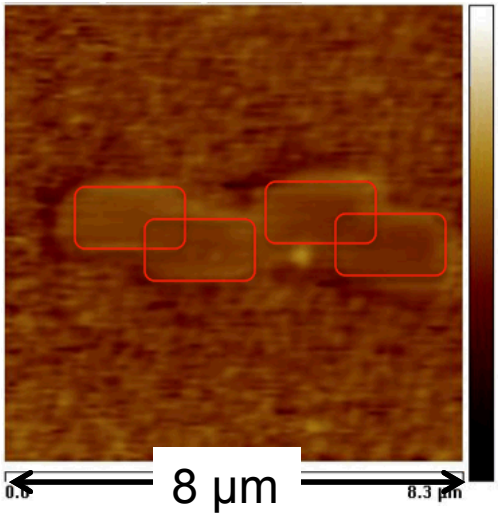
- SCM provides an additional new means of structural characterization
- To date: STM of buried structure, transport measurements, and SIMS…
- SCM provides direct view to the donor distribution, allowing diagnosis of litho problems

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

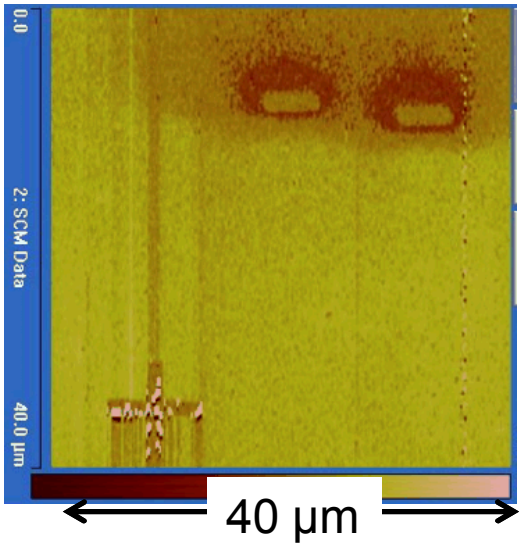




- Doubling of pattern due to two-asperity tip



- Micron-scale bleed-out from pattern due to field-emission



Summary

- Related talks

Michelle Y Simmons, **Quantum Computing in Silicon with Donor Electron Spins,**
Rm 708, Wednesday, 1:03 PM–1:39 PM

Esmeralda Yitamben, **Nanoscale Engineering of Structures and Devices on Surfaces**,
Rm 709 Tuesday 2:30 PM–3:06 PM

Martin Rudolph, **Measurement of mesoscopic Si:P delta-doped devices**,
Mile High 1,Thursday 9:24 AM–9:36 AM