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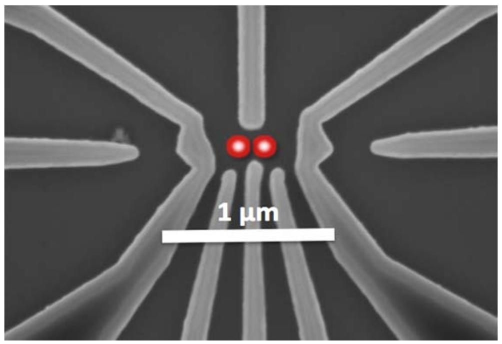

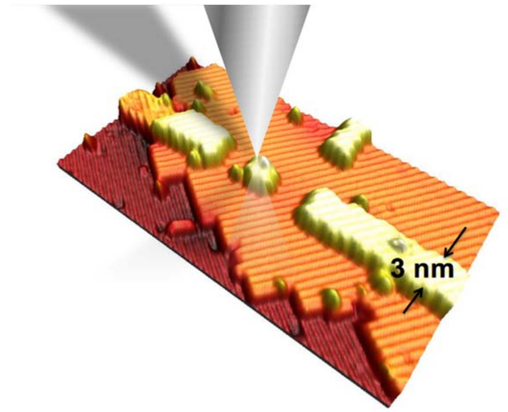

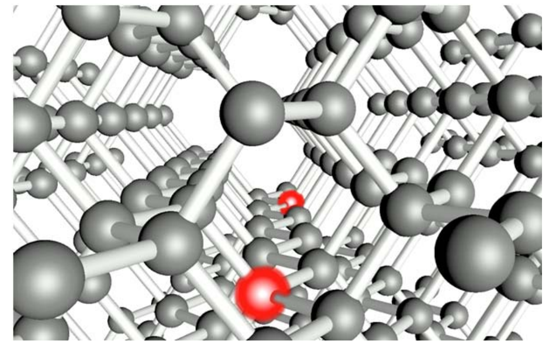

Donor charge qubits via scanning tunneling microscopy (STM) assisted fabrication

Ezra Bussmann (ebussma@sandia.gov), J. Rivera,
J. Dominguez, S.Carr, T.-M. Lu, E. Nielsen, T. Jacobson, W. Witzel,
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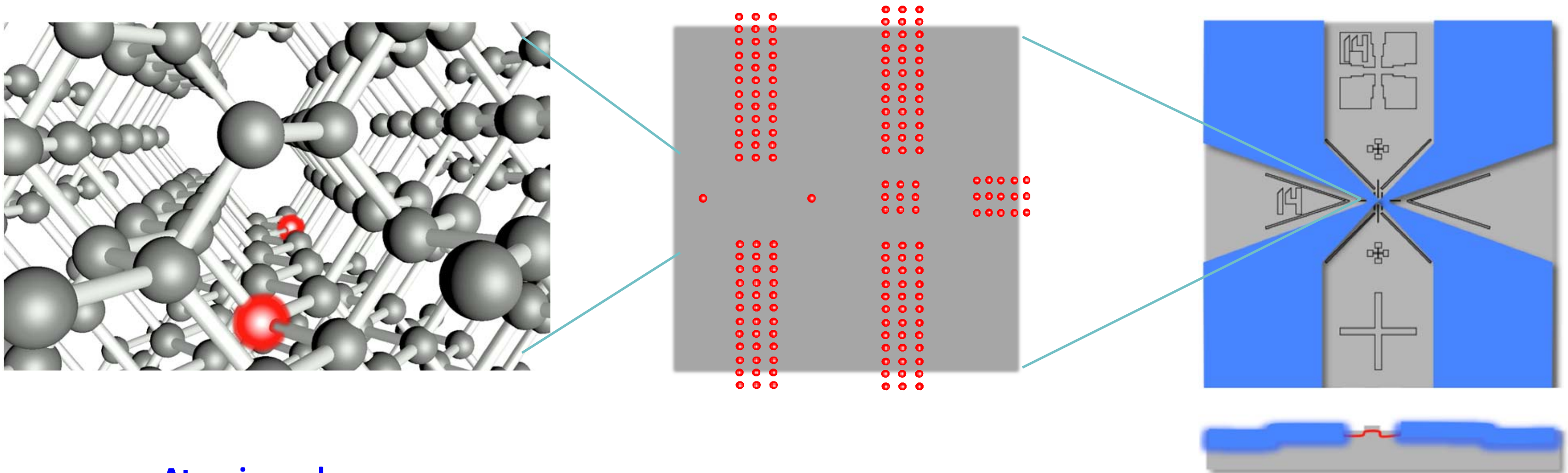
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

LDRD Laboratory Directed Research & Development

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Goal: Establish a Sandia capability to fabricate atomic precision devices in silicon



Atomic-scale circuit elements
-individual dopants positioned with atomic precision

Integrated in nanoscale electronics
-gates,
charge sensors

Integrated in conventional electronics
-wires,contacts

- **Over about 12 years, Michelle Simmons (UNSW CQC2T Australia) has demonstrated the atomic-precision fabrication techniques and device elements**
- **Method: ultrahigh vacuum scanning tunneling microscopy (STM) lithography and conventional Si fabrication techniques**

Talk overview

I. Review of Scanning Tunneling Microscopy (STM) assisted fabrication

I. Review of progress report at 3rd EAB (June 2012)

II. Progress on milestones since the 3rd EAB

-Demonstrated several STM patterned donor devices

-Developed e-beam litho technique for contacts (move from photolitho)

-refined measurement techniques and sample handling

-Began work on our final product :

an STM patterned double-quantum dot qubit

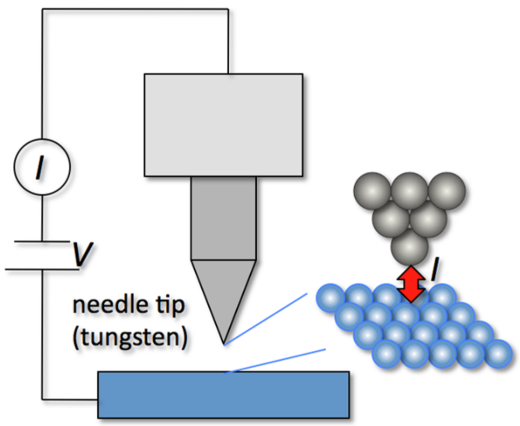
-Improved STM electronic/acoustic shielding

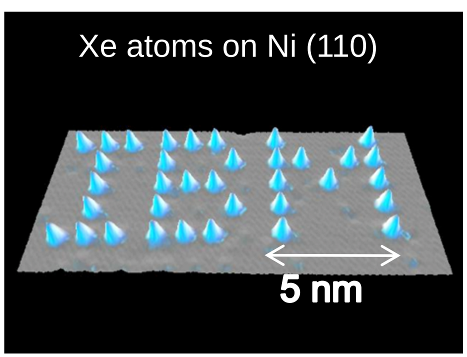
to reduce noise, increase speed and image quality

IV. Present work: demonstrate a working charge sensed double quantum dot qubit

STM assisted fab overview

- STM : an atomic resolution surface imaging and manipulation tool

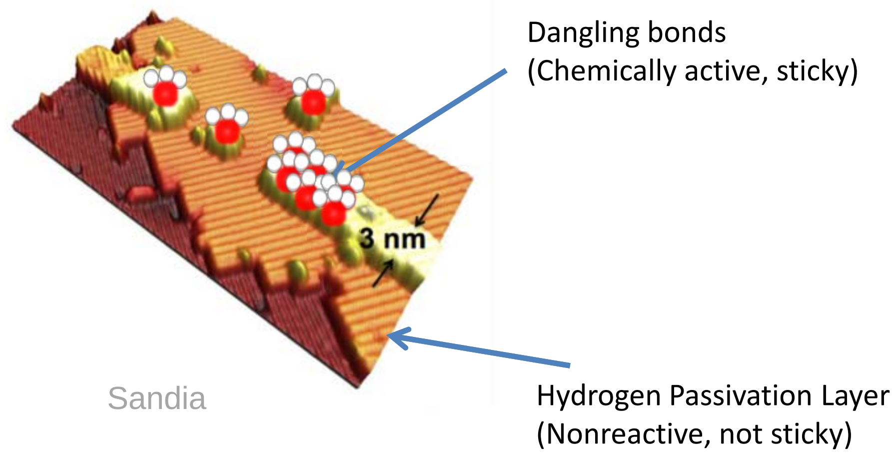




D.M. Eigler et al. *Nature* (1990)

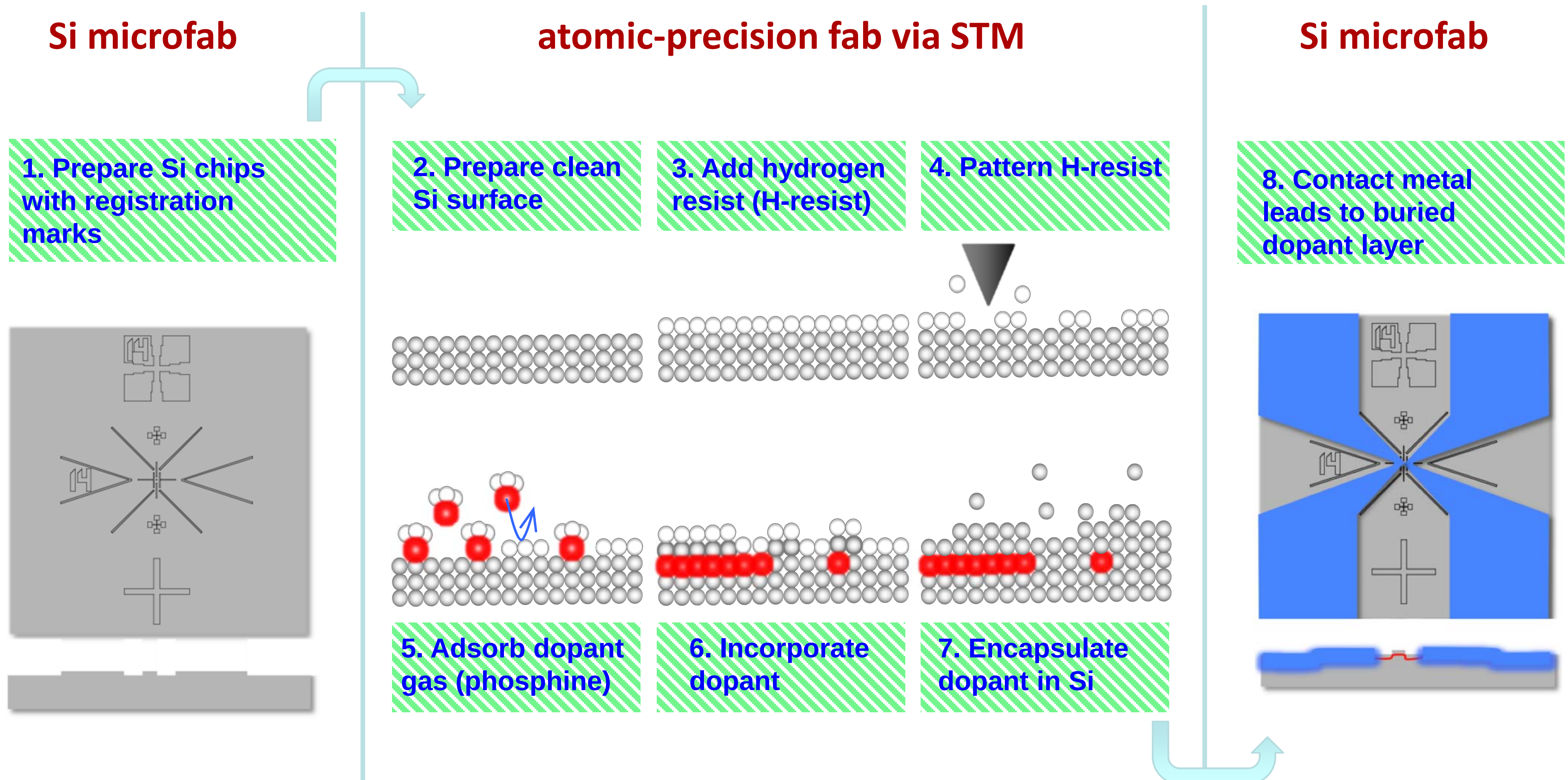
Alternate approach: STM as an atomic-precision lithography stylus

Si dangling bonds in a layer of Hydrogen passivation on Si (100)

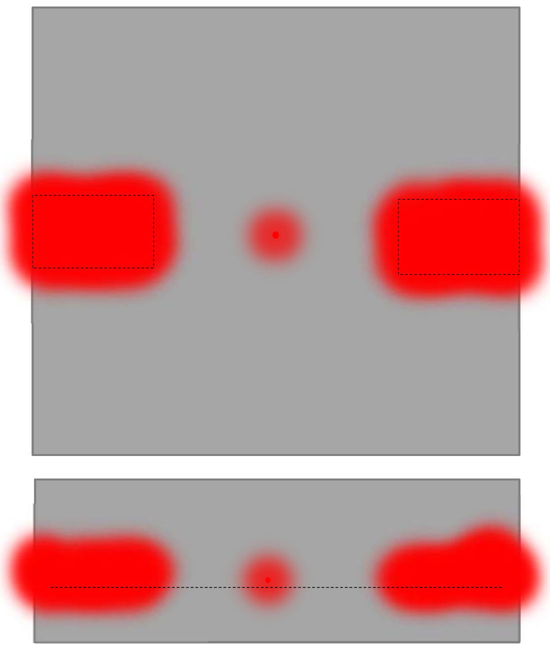


Atomic-precision fabrication process

- Method developed by Michelle Simmons CQC2T UNSW Australia
- & also by T.C. Shen et al. U of Illinois and Utah State U.



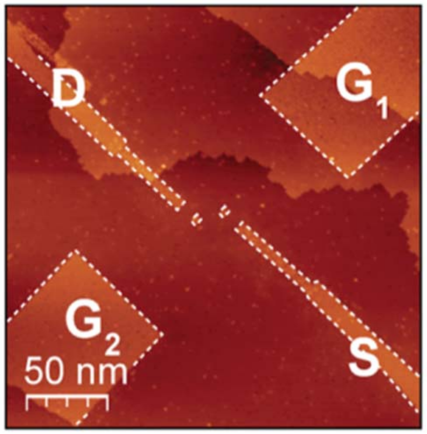
Some unique characteristics of material & devices produced via STM fab



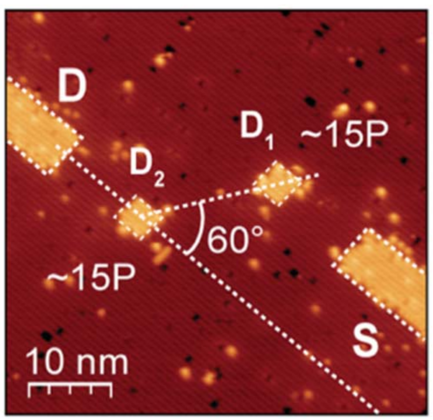
- Experiment shows
  - P incorporates within a few atomic sites of litho patterning
  - P constrained to a few atomic layers vertically
- 2-D dopant density N ~$10^{14}/cm^2$ (1/4 atoms)
  - > Si metal-insulator transition, sample is metallic in the doped regions, remains conductive as T → 0 K
- At T~300K, electrons are detached from the donor nuclei
- Must cool to T ≤ 10K! then e- is within ~2.5 nm of donor
- At low T, doped regions act effectively as tiny ideal conductors → device simple to model (no semiconducting parts, less bad interfaces)

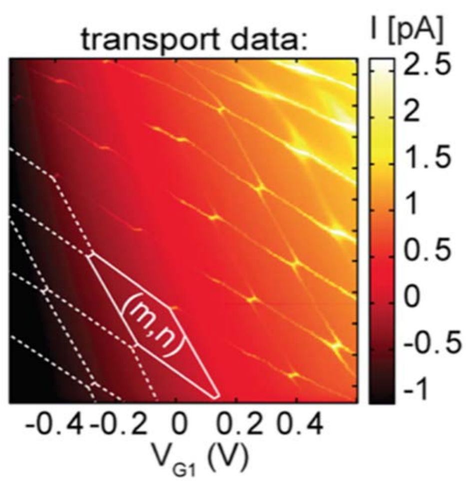
Atomic-precision devices have been demonstrated

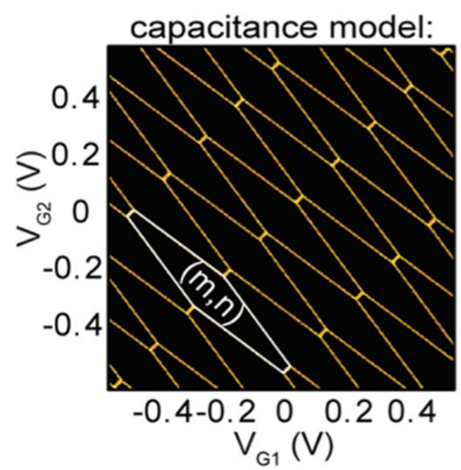
- **Example: transport double quantum dot** M. Y. Simmons et al. Nano Lett. (2012)



- Tunable double quantum dot showing clear transport resonances indicating single-electron charging (Coulomb blockade) on dots
- semiquantitative/predictive modeling of dot charge occupation vs applied gate voltage







Images: CQC2T UNSW

STM fab milestones at previous EAB

- Year 1
  - -Recover old STM chamber outside of clean room for non-toxic gas experiments
  - -Design clean room STM (includes phosphine capability)
  - -Build clean room STM
  - -Show clean hydrogen terminated surface and local removal with STM tip
- Year 2
  - -Establish capability to pattern large areas (long tip lifetime)
  - -Connection to large area contacts (n+ or Al spike)
  - -Silicon encapsulation of phosphorus
  - -*Incorporation of phosphorus on surface*
  - **-Demonstrate initial transport test devices (Macroscopic Hall effect devices)**
- Year 3
  - -Demonstrate double quantum dot structure
  - -Develop charge sensor for double quantum dot
  - -Demonstrate qubit operations on DQD

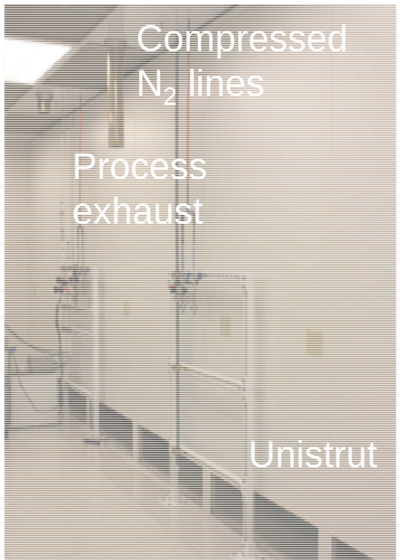
STM fab milestones at present

- Year 1
  - -Recover old STM chamber outside of clean room for non-toxic gas experiments
  - -Design clean room STM (includes phosphine capability)
  - -Build clean room STM
  - -Show clean hydrogen terminated surface and local removal with STM tip
- Year 2
  - -Establish capability to pattern large areas (long tip lifetime)
  - -Connection to large area contacts (n+ or Al spike)
  - -Silicon encapsulation of phosphorus
  - -Incorporation of phosphorus on surface
  - ✓Demonstrate initial transport test devices (microscopic STM patterned wires)
- Year 3
  - -Demonstrate double quantum dot structure
  - -Develop charge sensor for double quantum dot
  - -Demonstrate qubit operations on DQD

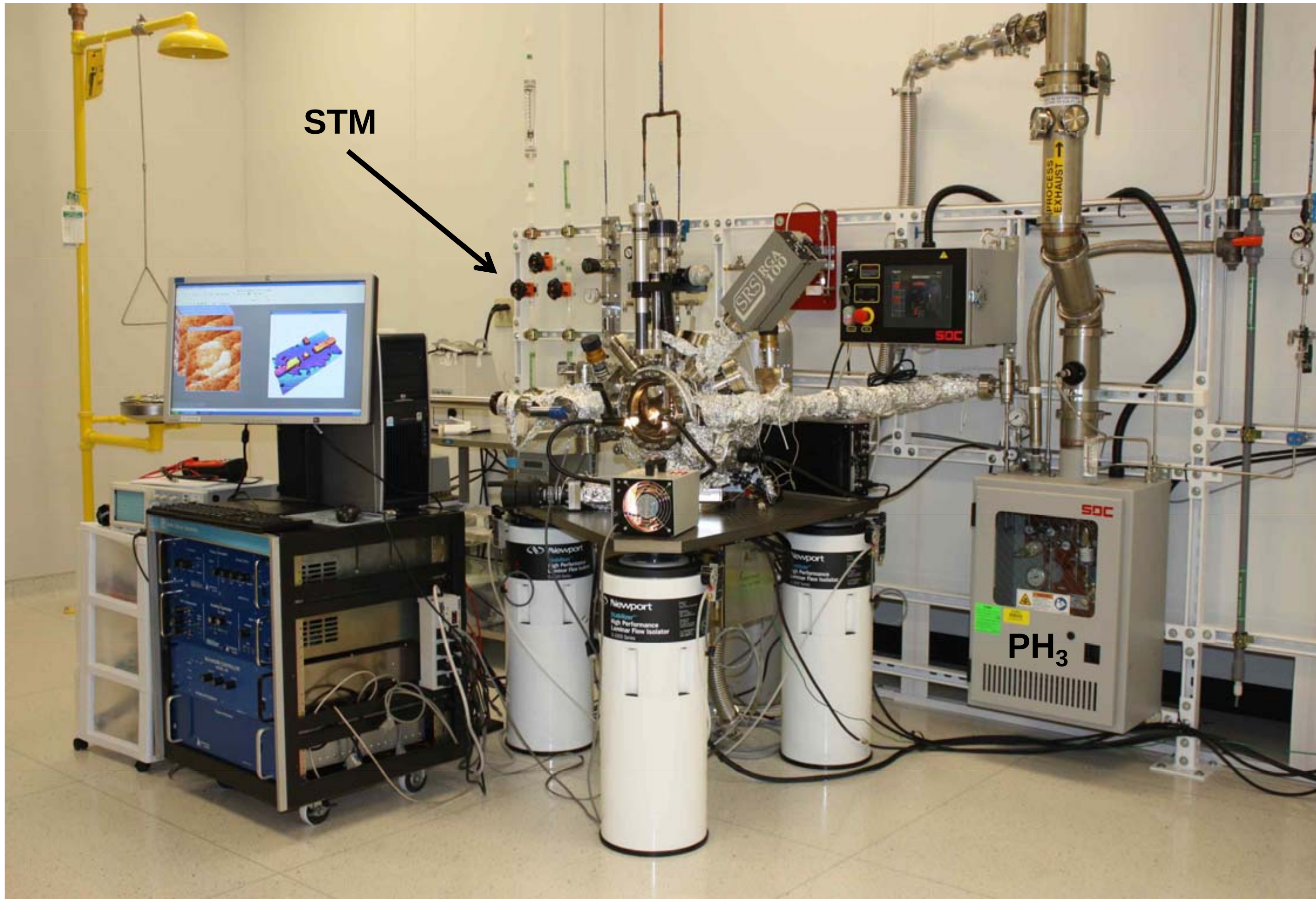
Summary of progress at previous EAB

- Completion of a new cleanroom laboratory & STM for device processing
- Demonstration of each step of Simmons recipe
- Fabrication and T=4 K measurements of our first donor devices (did not include STM patterning, just donor doping)

Completed new lab in cleanroom



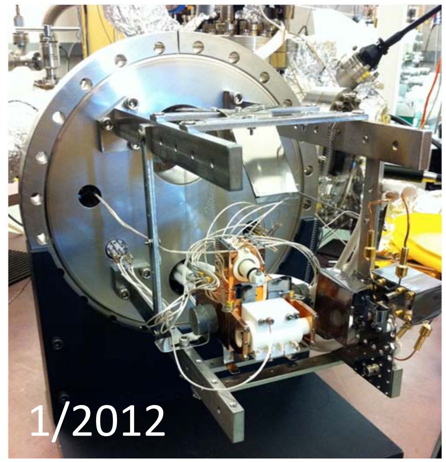
8/2011



5/2012

- We now have 2 labs/ 2 STMs for donor device fab-related work

Completed new STM for Si fab process



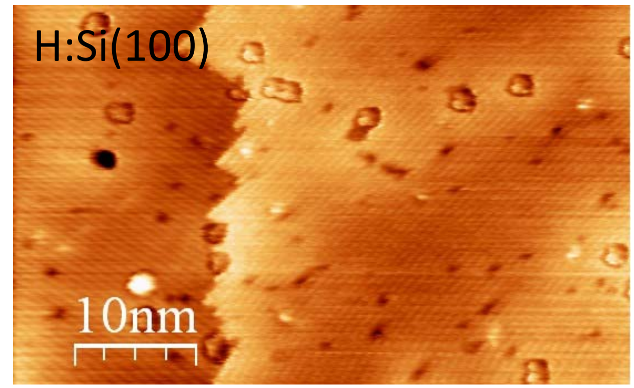
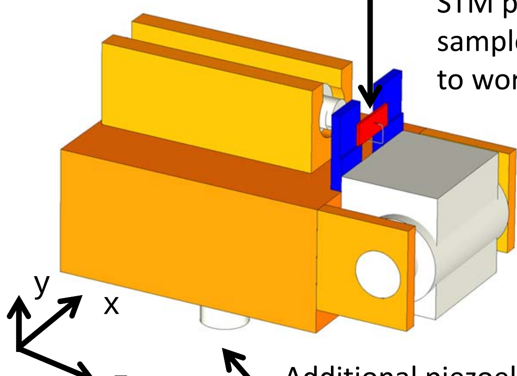


Image obtained with new STM near-atomic resolution (3/2013)

New STM head w/ X-Y-Z motion and line-of-sight to sample



STM probe wraps around sample (red) allowing line-of-sight to work surface

Additional piezoelectric actuator for 3-axis motion

- **Accessible scan range 4.5µm x 4.5µm (allows for larger scale litho) than our first STM (1.6µm x 1.6 µm)**
- **Line of sight to sample (Essential to be able to view the tip/sample surface)**

(mid-2011-3/2012)

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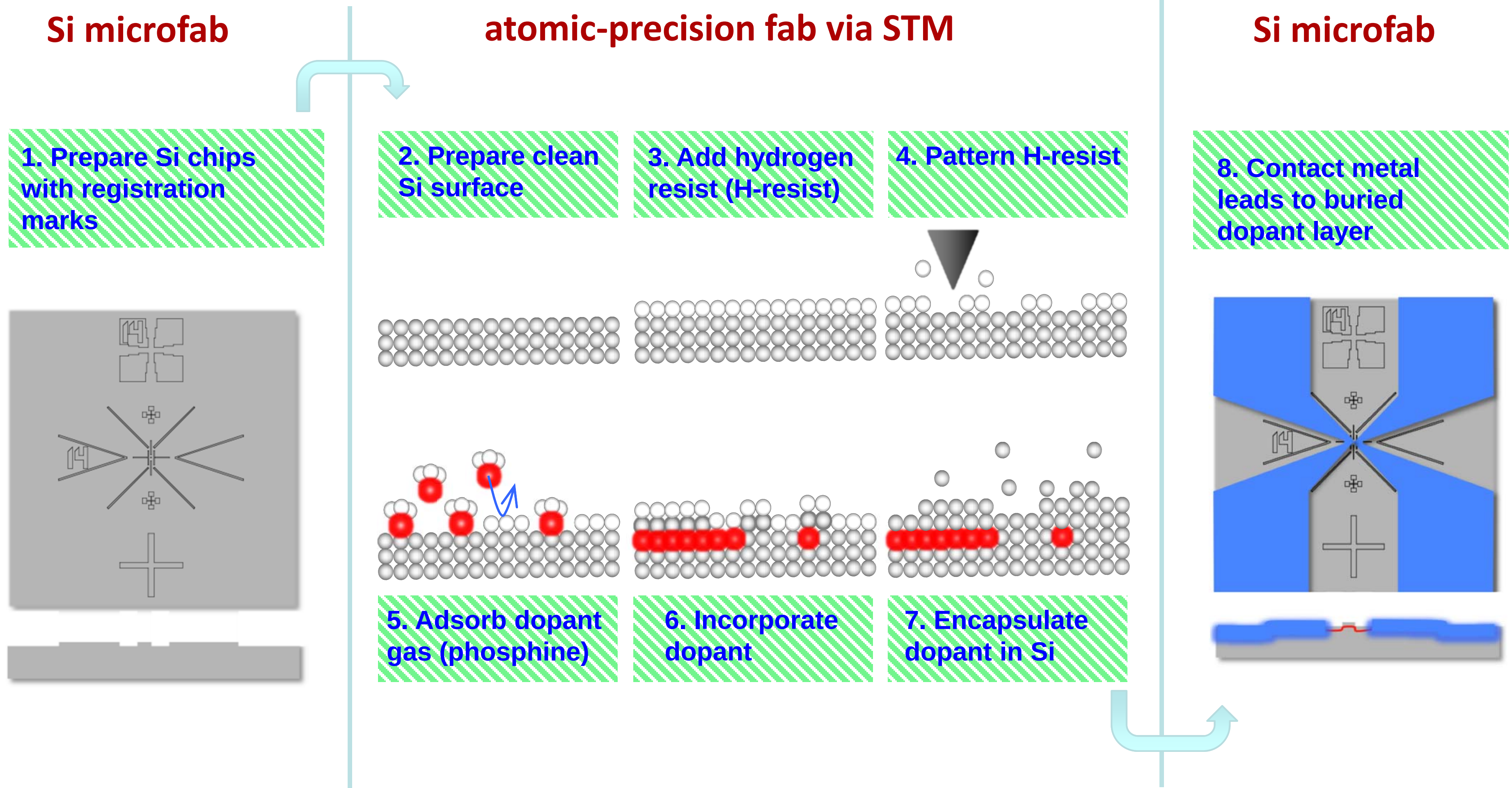
Demonstrated all fabrication steps

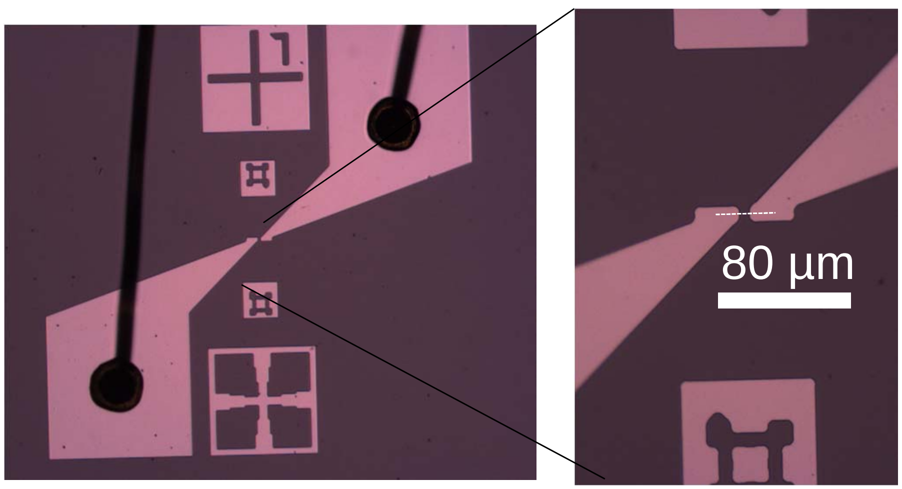


Fabricated macroscopic test devices

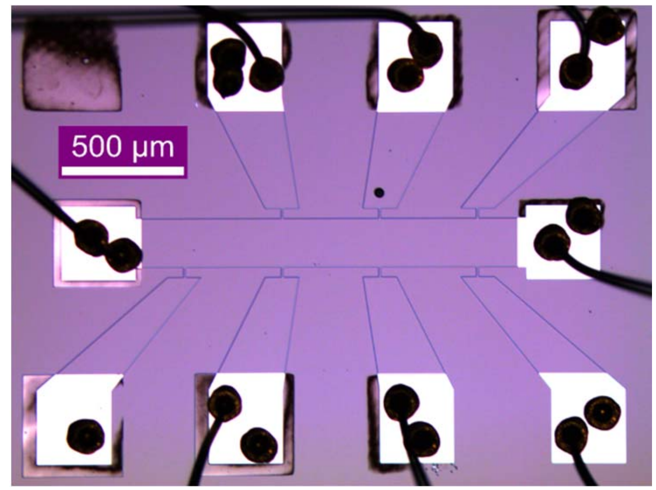
(3/2012 - 5/2012)

- Fabricated and measured (T=4K) two types of diagnostic devices verifying successful incorporation, encapsulation, and connection to highly doped P donor layer

Two-contact device



Trench isolated Hall device



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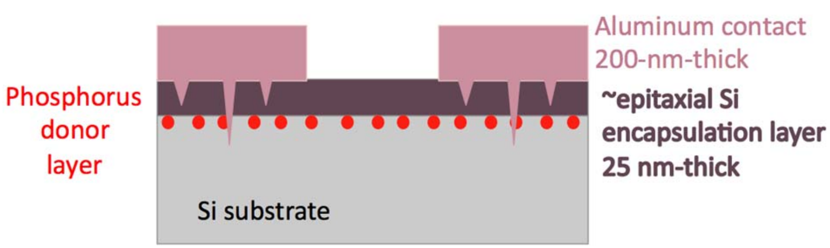
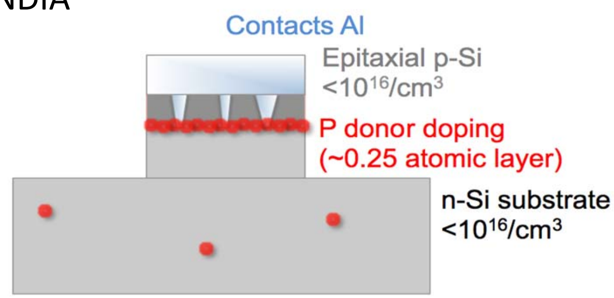


Device cross section schematic



Device cross section schematic

Fab'd & measured test devices

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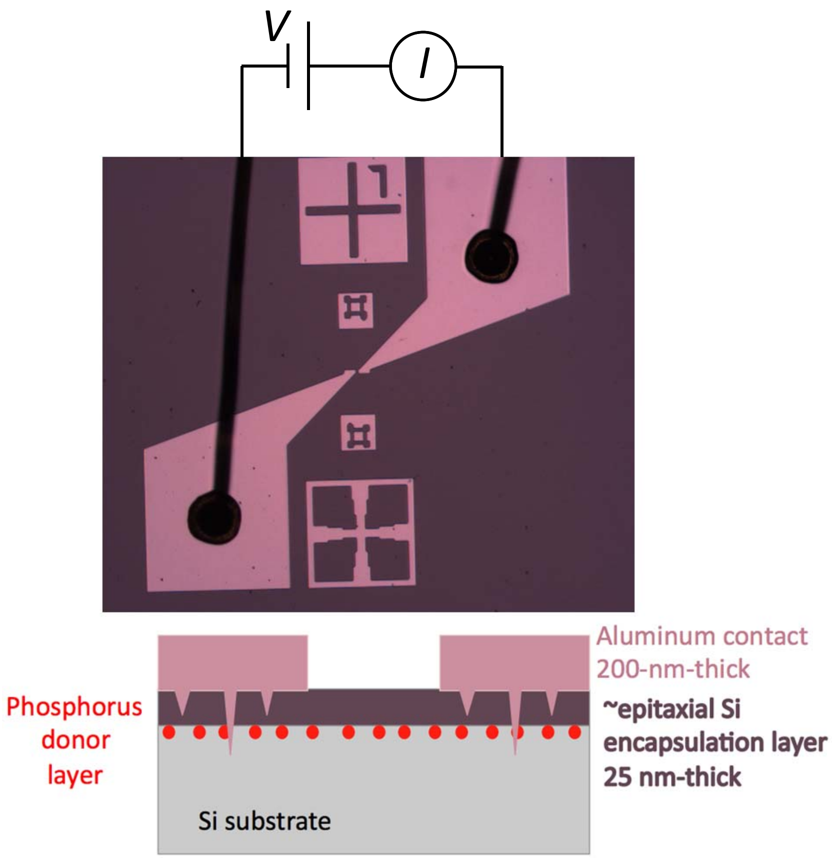
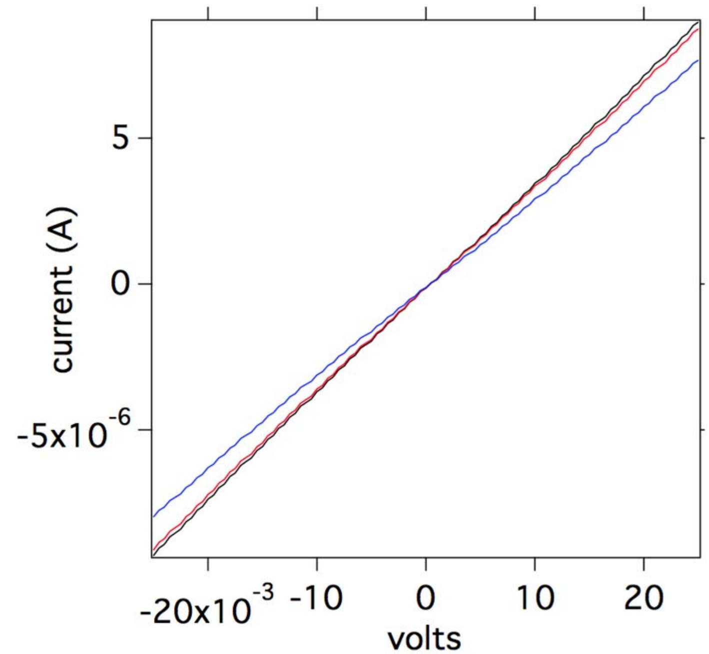
(3/2012 - 5/2012)



Device cross section schematic

Current vs voltage measurements for three devices at T=4K

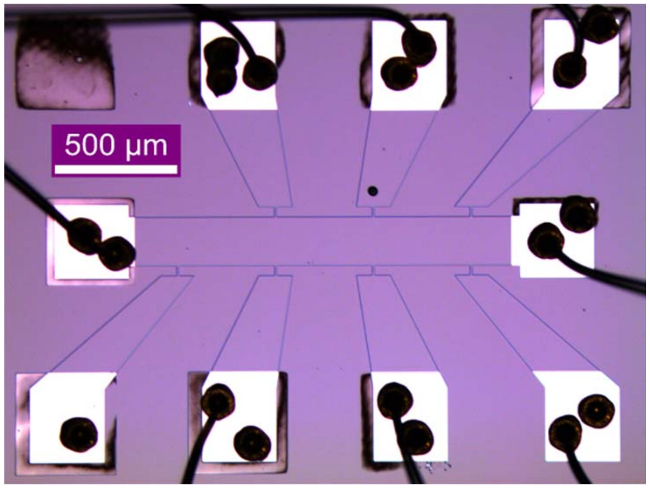


- **Ohmic conduction at 4K shows successful fab & connection to highly doped donor layer**
- **Typical resistances of 2-6 kΩ are similar to Simmons results (Nano Lett. 2004)**

Fab'd & measured test devices

(4/2012 - 5/2012)

Trench isolated Hall device



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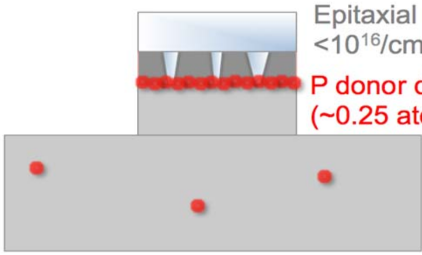


- **Extract e- density & mobility from longitudinal R_{xx} and transverse R_{xy} Hall resistance**

Electron density and mobility at T=4K

Device	e^- density n_e 10^{14} /cm^2	e^- mobility cm^2/Vs
1	0.7	127
2	0.7	143
3	1.2	122

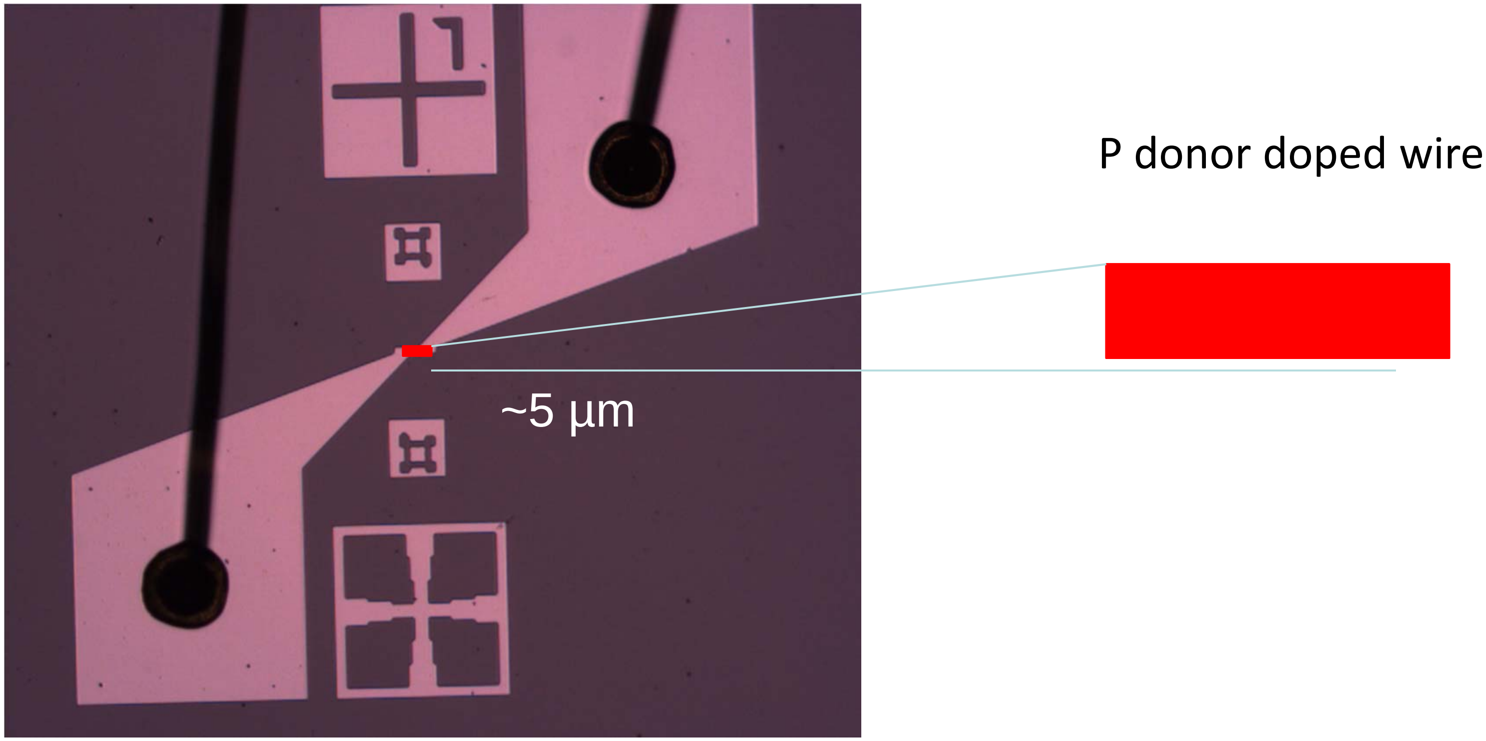
- **Similar Hall effect devices from Simmons yielded n = 1.2-1.7x10^{14}/cm^2 mobility<100 cm^2/Vs**

****Since previous EAB, we have reached the 1.7x10^{14}/cm^2 value doping saturation reported by Simmons (SEE Steve Carr's POSTER)**

- **Donor and electron density sufficient for atomic precision devices**
- **Next step: implement complete atomic-precision fab technique**

As of previous EAB we had started work on devices that include STM patterning step

- Do all fab steps sequentially to produce STM patterened wires



- **These simple structures serve as practice/test of our device contact process (e-beam litho), prove that the complete process flow is working, and allow us to practice the wire-up and measurement of STM devices**

Work since previous EAB

Milestone progress

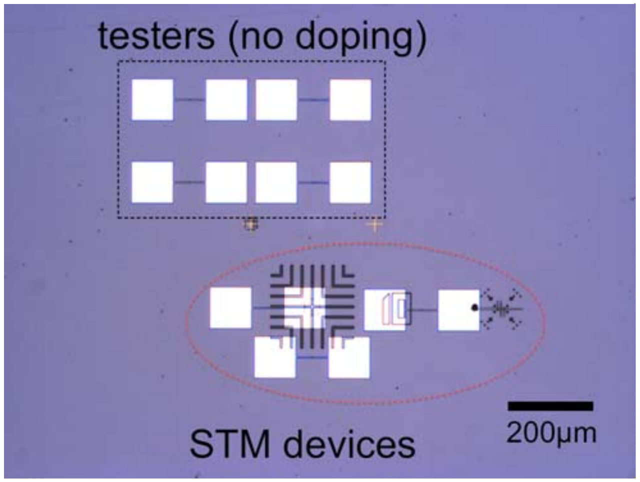
- Fabricated & measured Sandia's first STM patterned devices (7/2012-2/2013) (Year 2 milestone)
- Now working on charge sensed double quantum dot (2/2013-) (Final milestone, Year 3)

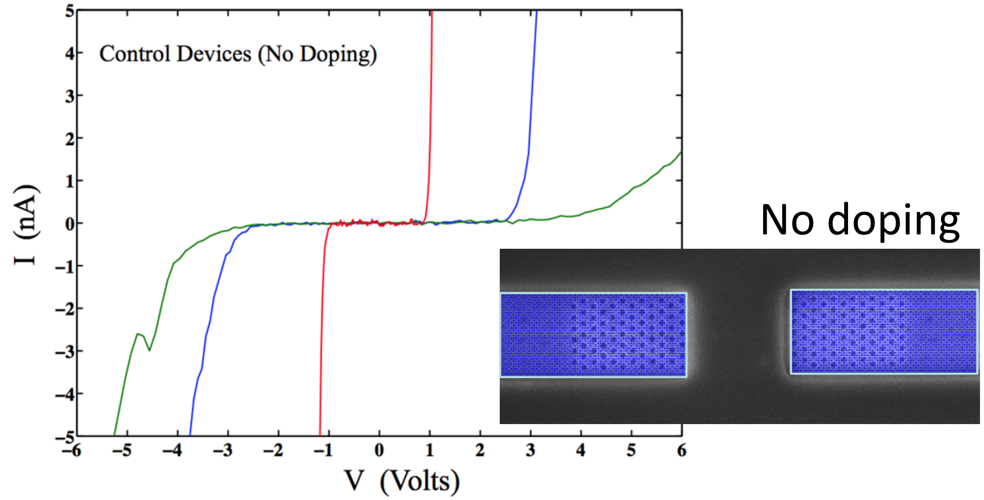
Important background work completed in support of the milestones

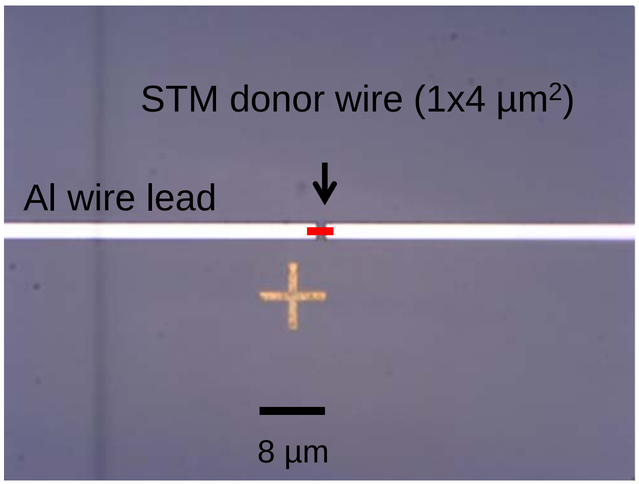
- Move to electron beam lithography process for macroscopic metal contacts (improved lithographic precision from micron to few-hundred-nm scale, allows more flexibility in contact design)
- Refined sample handling and measurement capabilities for STM devices

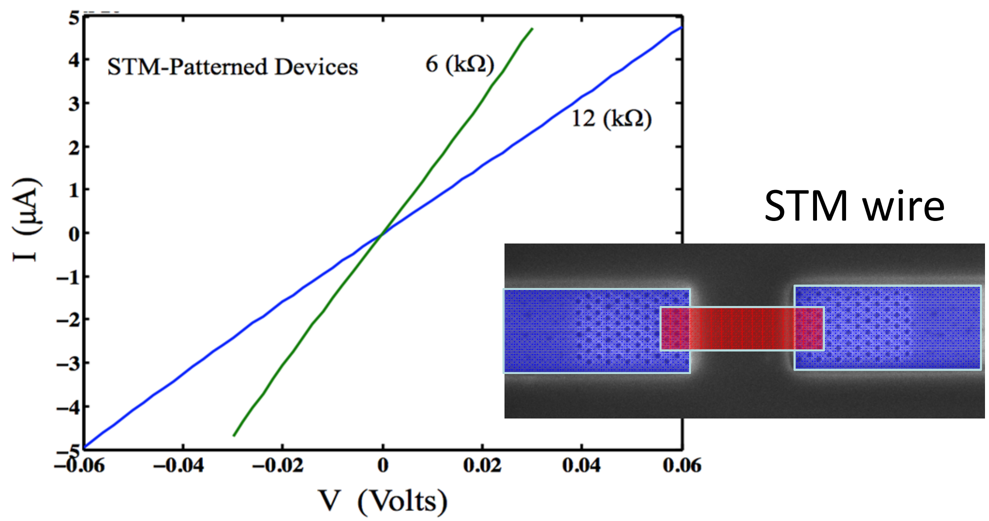
Sandia's first STM patterned devices

- **1x4 µm buried donor wires patterned via STM litho**





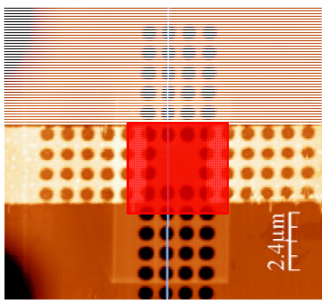


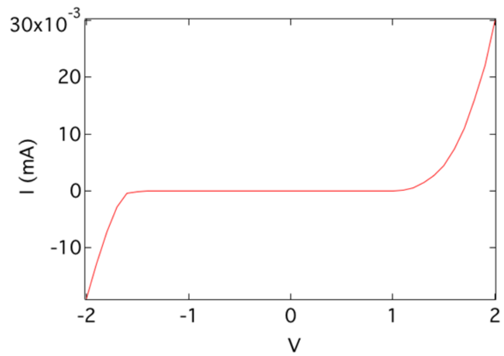


- Fab'd & T=4K tested 6 total devices, with final yield of 5/6
- limited by e- beam litho accuracy & contact quality (improving w/each try)

Background: process development

- (10/2012-2/2013) Moved from optical lithography (~1 µm accuracy) to e-beam litho (few hundred nanometer accuracy)

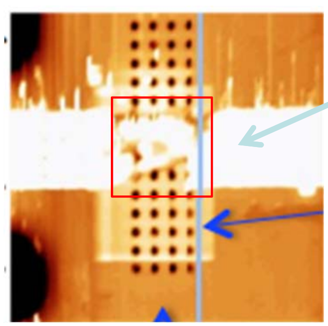




Diode-like
Behavior at 4K due to
Poor metal-dopant
contact

Reworked/improved
Sample cleaning,
Contact designs
Alignment marks

- Refined sample handling and measurement capability - see Steve Carr's poster



Loss of device
Melted by
Electrostatic
Discharge (ESD)

ESD ground straps
And Anti-static lab coats
At all times when handling
Devices

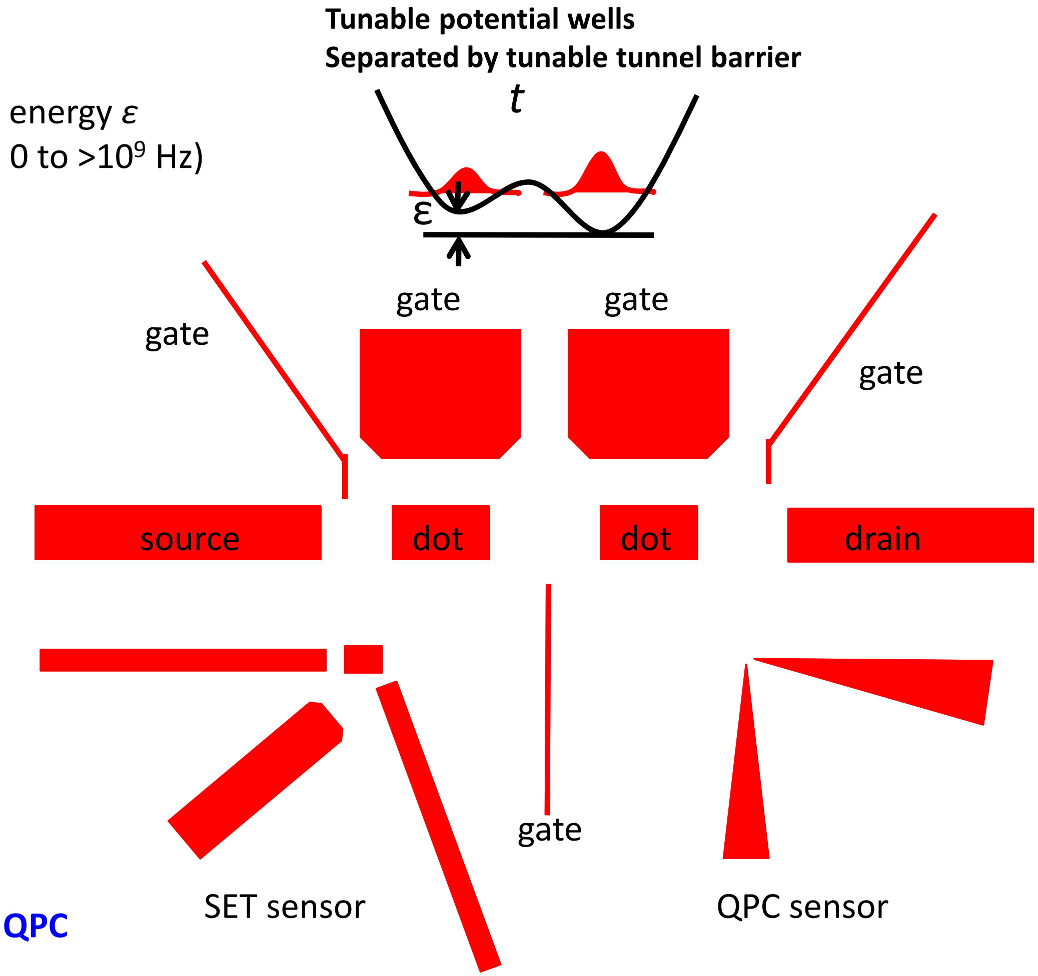
Now, we are working on DQD charge qubit

Brainstorm on what we need for qubit

1. Tunable e- occupation (few electron) and relative energy ε
2. Tunable tunnel barriers (ideally tunnel rates from 0 to >10^9 Hz)
3. A charge sensor

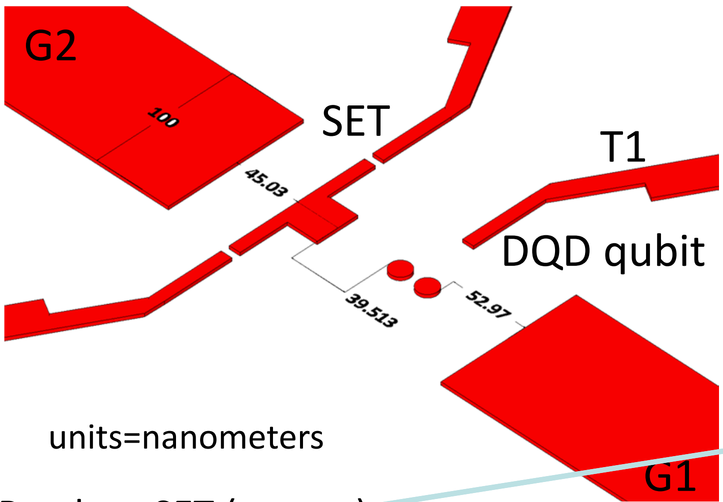
Charge qubit components

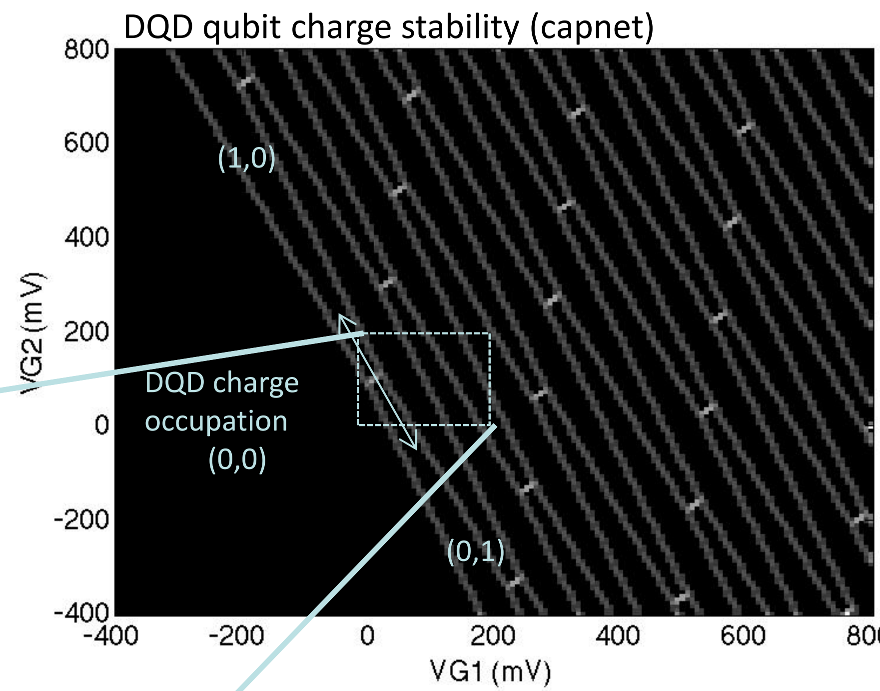
1. **Quantum dots**
2. **Source/drain leads**
3. **Tunneling gaps**
4. **Gates**
- Plungers to tune chemical potentials (definitely)
- Barrier gates to tune tunnel barriers/rates
5. **A passive charge-state readout circuit e.g. SET or QPC**



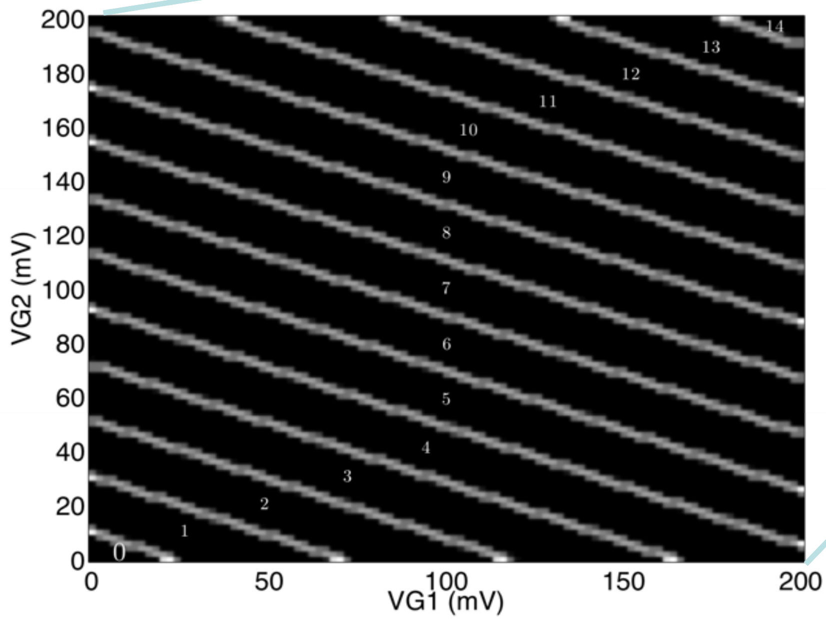
All elements are coplanar → crowding limits number of device elements

DQD charge qubit design





Readout SET (capnet)



Charge transfer signals 3 – 6% (ΔVG2=0.6-1.2 mV)

- Many DQD charge states accessible in a realistic range of VG1 & VG2
- The SET has many more charge states in the same VG1 & VG2 range
- Charge transfer signals of 3-6% suggest SET will be sensitive electrometer of qubit state

Attempt at DQD qubit patterning

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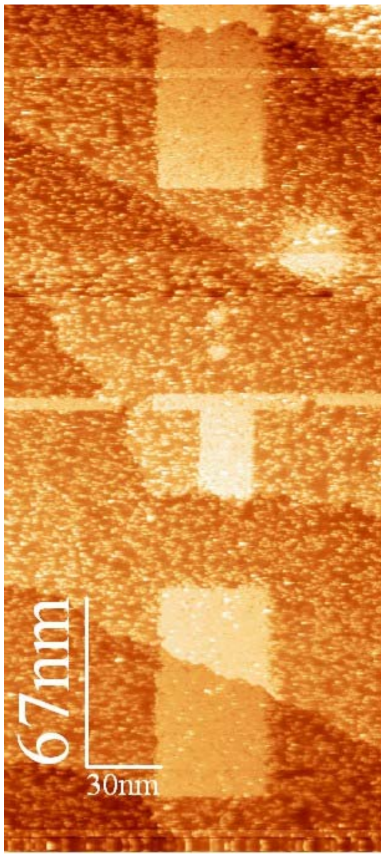
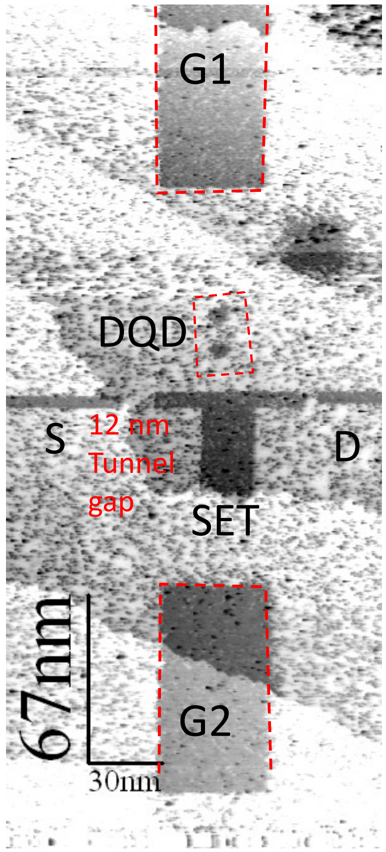
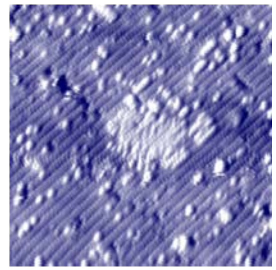
Hydrogen litho for device body



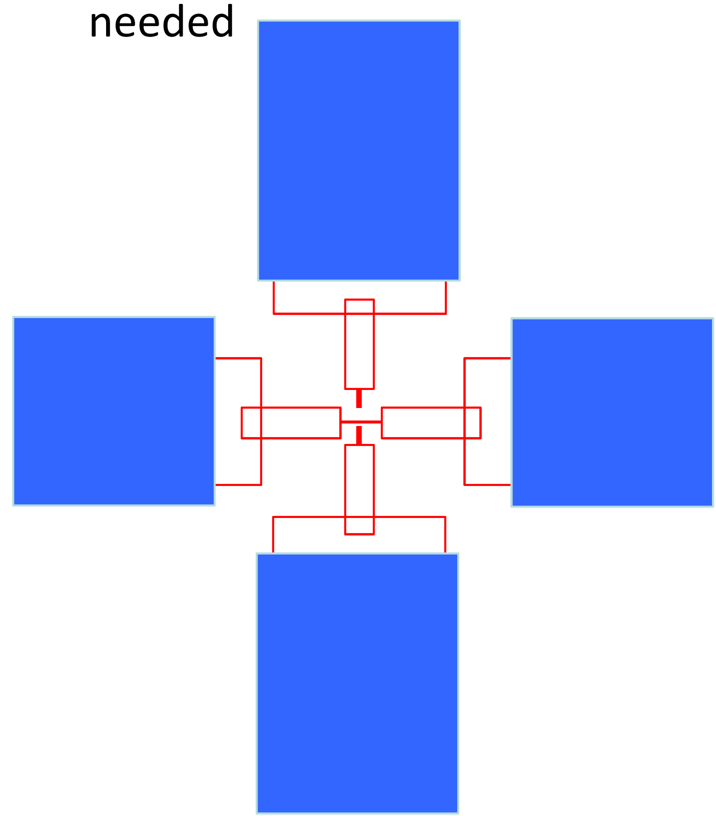




~30 donor dots for DQD

Process required 5 hours
2 tip reconditions to keep atomic resolution

Contact pads (STM litho) and metallization (e-beam litho) are needed



This would require about 8 hours of additional STM Litho+1 day for the e-beam process

Summary of work

- Developed a hundred-nanometer-precision e-beam lithography contact process
- Refined sample processing to get high donor incorporation/activation up to level reported by Simmons (See Poster by Steve Carr)
- Learned sample handling and low-T measurement methods
- Fabricated and measured several working STM-patterned wire devices
- Began working to write/contact our final target device, a charge-sensed DQD structure
- Demonstrated pattern for DQD+SET allowing us to gauge difficulty & identify challenges