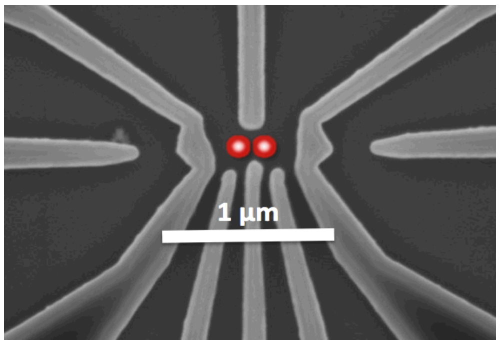
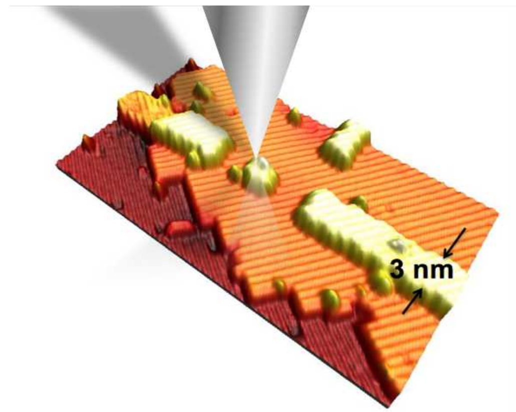
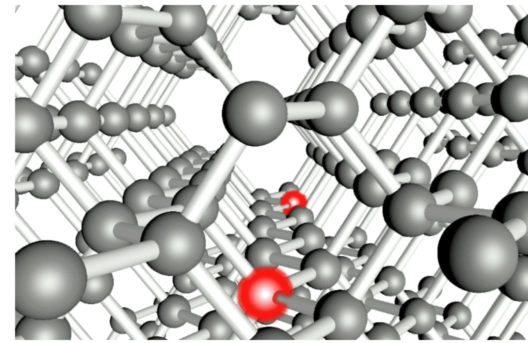






Donor charge qubits via STM assisted fabrication

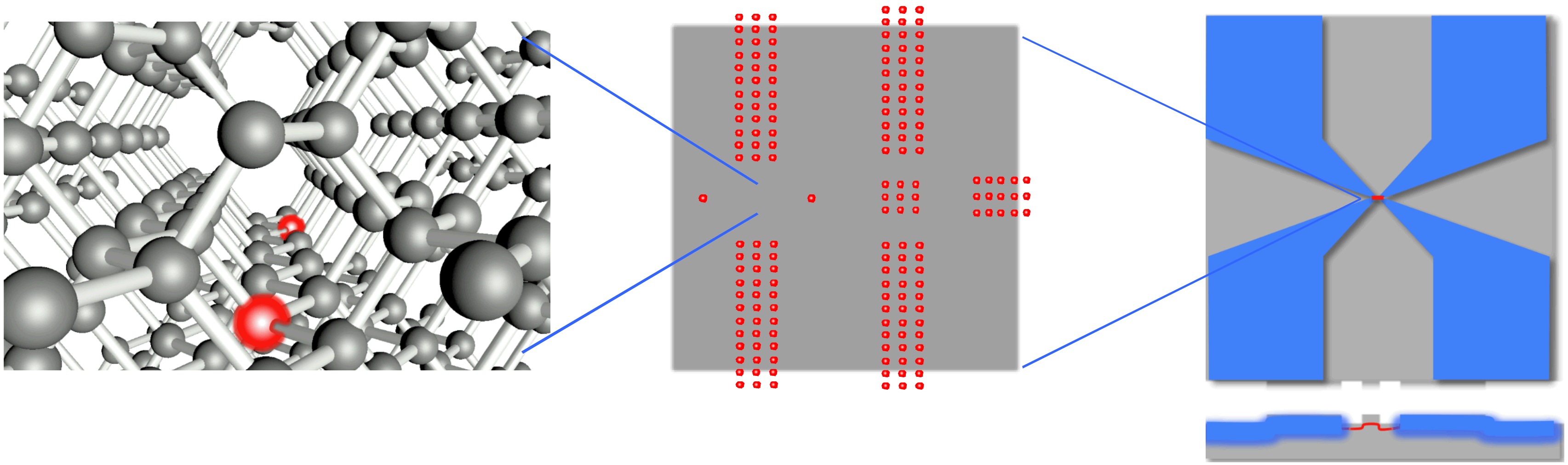
Ezra Bussmann (ebussma@sandia.gov) J. Dominguez, S.Carr, T.-M. Lu, E. Nielsen, R. Rahman, T. Jacobson, W. Witzel, G. Ten Eyck, M. P. Lilly, M. S. Carroll

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.

We want to make atomic-precision devices

Sandia National Laboratories

•Goal: A Sandia capability to fabricate atomic-precision donor qubits in Si



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**
- **Technique: Combine ultrahigh vacuum scanning tunneling microscopy (STM) lithography and conventional Si fabrication techniques**

Talk overview

Sandia National Laboratories

I. Quick review of Scanning Tunneling Microscopy (STM) Fabrication

II. Review of progress report at 2nd EAB (October 2011)

III. New results since the 2nd EAB

-Completed new cleanroom lab for STM assisted fab

-Reproduced Simmons qubit fabrication steps in lab

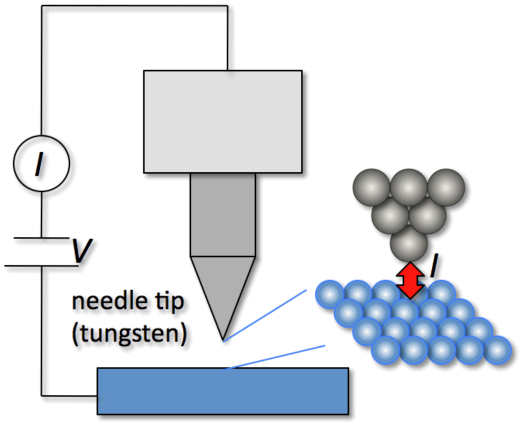
-Fabricated initial macroscopic test devices

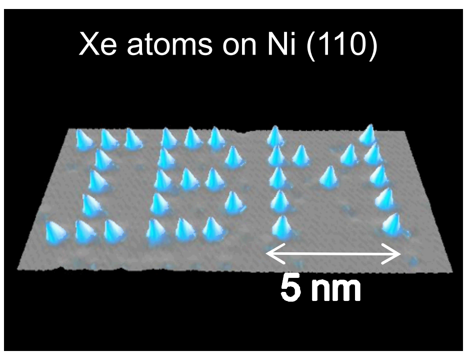
-Performed design & modeling of qubit

IV. Present work: demonstrate a working atomic-precision device

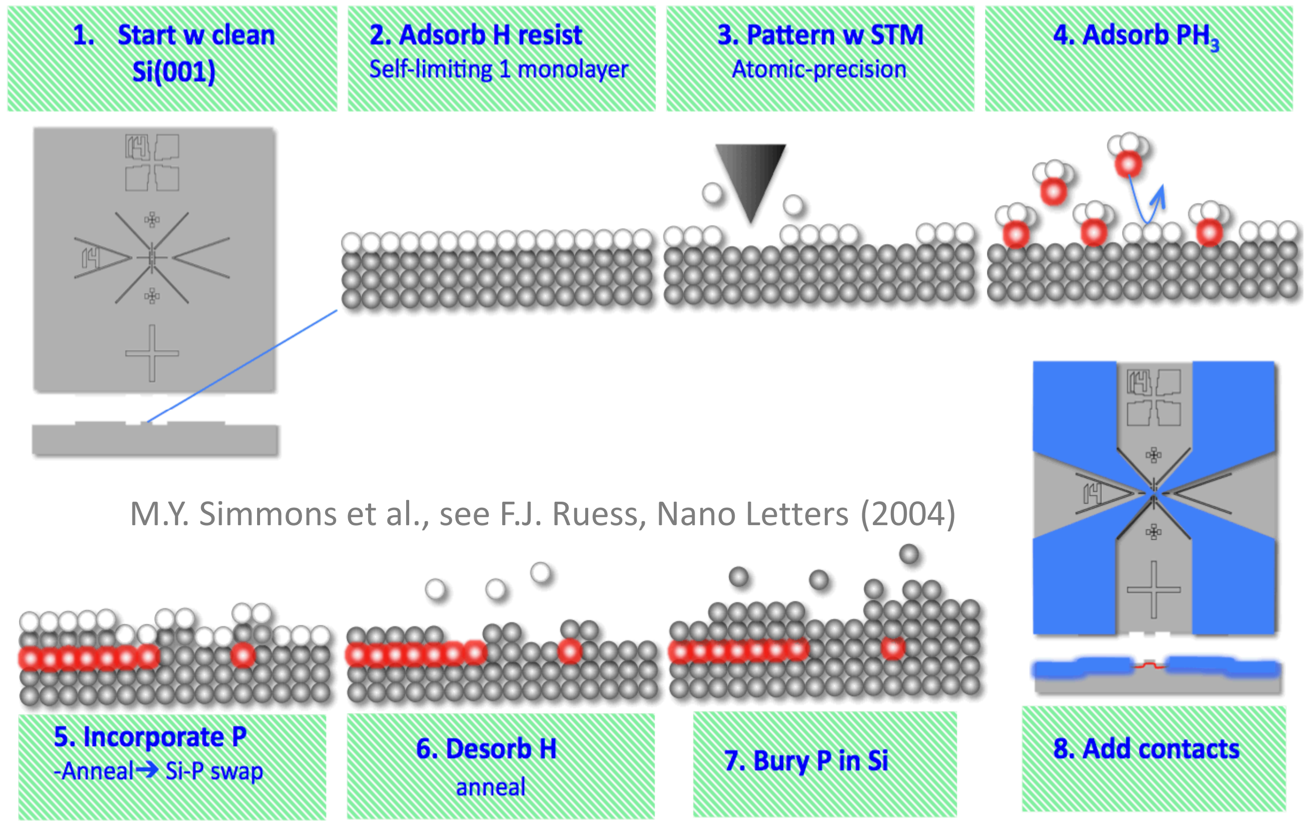
STM assisted fab overview

- STM : an atomic resolution surface imaging and manipulation tool





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



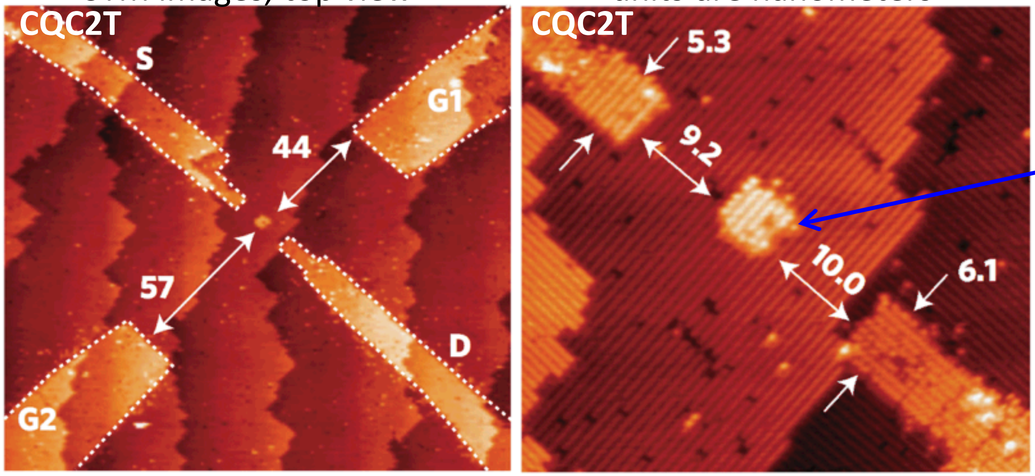
M.Y. Simmons et al., see F.J. Ruess, Nano Letters (2004)

Atomic-precision devices have been demonstrated

Sandia National Laboratories

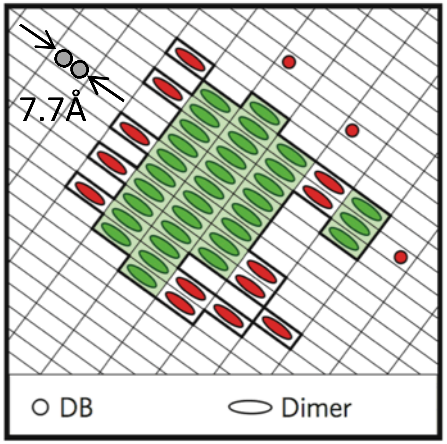
- **Example: tunable quantum dot** M. Y. Simmons et al. Nature Nano (2010)

STM images, top view — units are nanometers

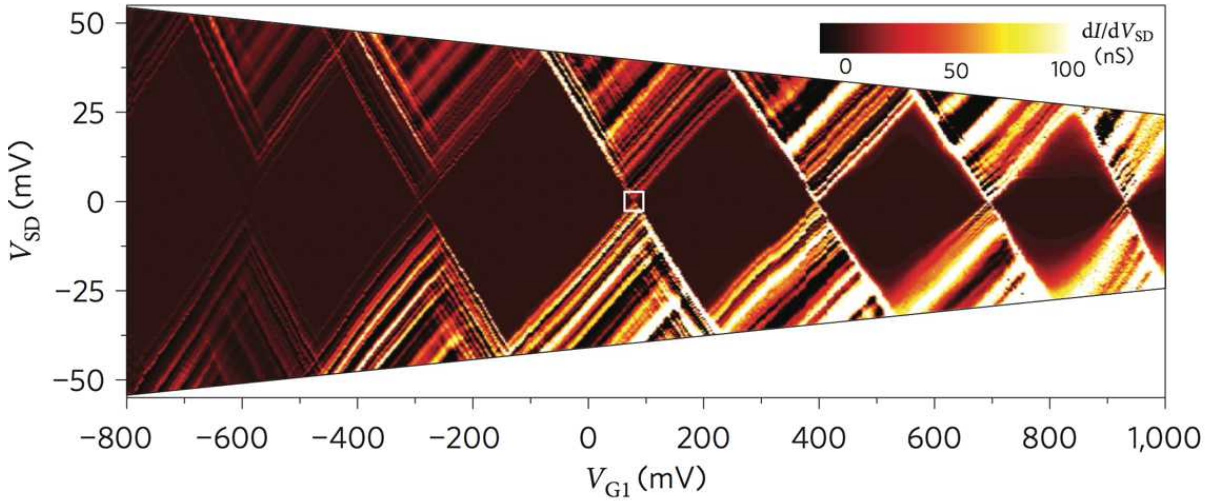


quantum dot
~6 P donors

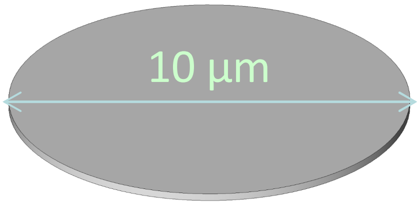
Effective window for P
surface atomic lattice



Coulomb blockade and electronic structure of the dot

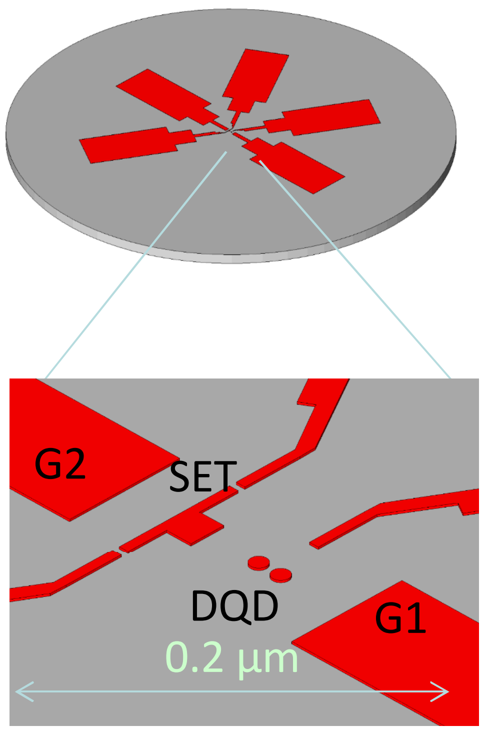


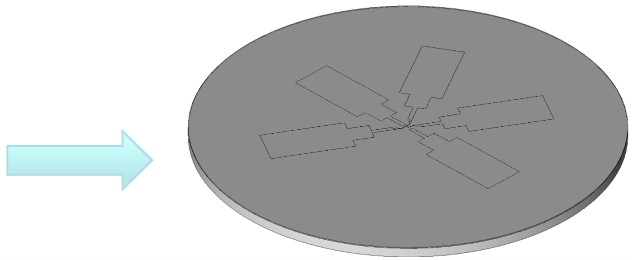
Target device: donor charge qubit



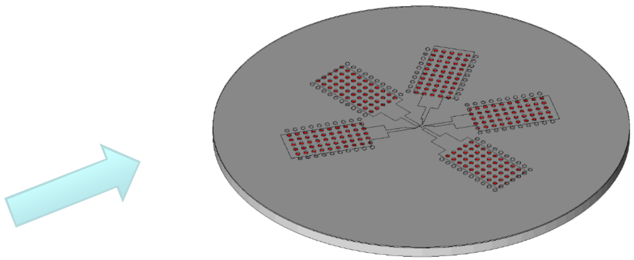
1. Clean Si w etched alignment markers (not shown)

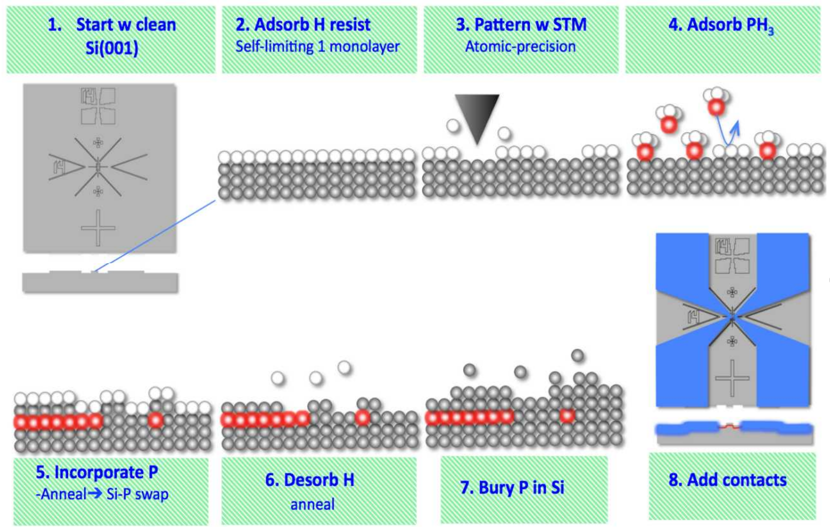
2. Perform STM process then bury device in 25-nm-thick epi-Si



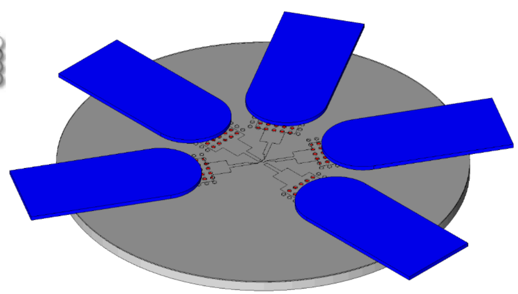


3. Align & drill vias thru epi-Si





4. Form metal contacts



- Objective: demonstrate fabrication of a donor charge qubit

Milestones for STM fab

- 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 (Including PH3, labspace, etc)
  - -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 (wires)
  - -Demonstrate single donor placement
- Year 3
  - -Demonstrate two donor placement
  - -Demonstrate transport through double donor
  - -Develop charge sensor for two donor system
  - -Demonstrate qubit

Milestones for STM fab

- 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
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- Year 2
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  - ✔Connection to large area contacts (n+ or Al spike)
  - ✔Silicon encapsulation of phosphorus
  - ✔Incorporation of phosphorus on surface
  - ✔**Demonstrate initial transport test devices (wires) (Macroscopic Hall effect devices)**
  - -Demonstrate single donor placement
- Year 3
  - -Demonstrate two donor placement
  - -Demonstrate transport through double donor
  - -Develop charge sensor for two donor system
  - -Demonstrate qubit

Completed new lab in cleanroom

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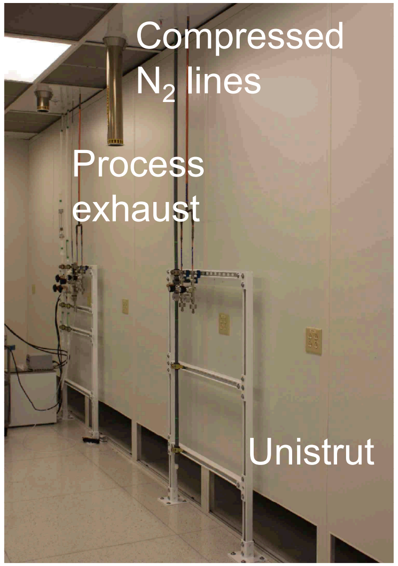
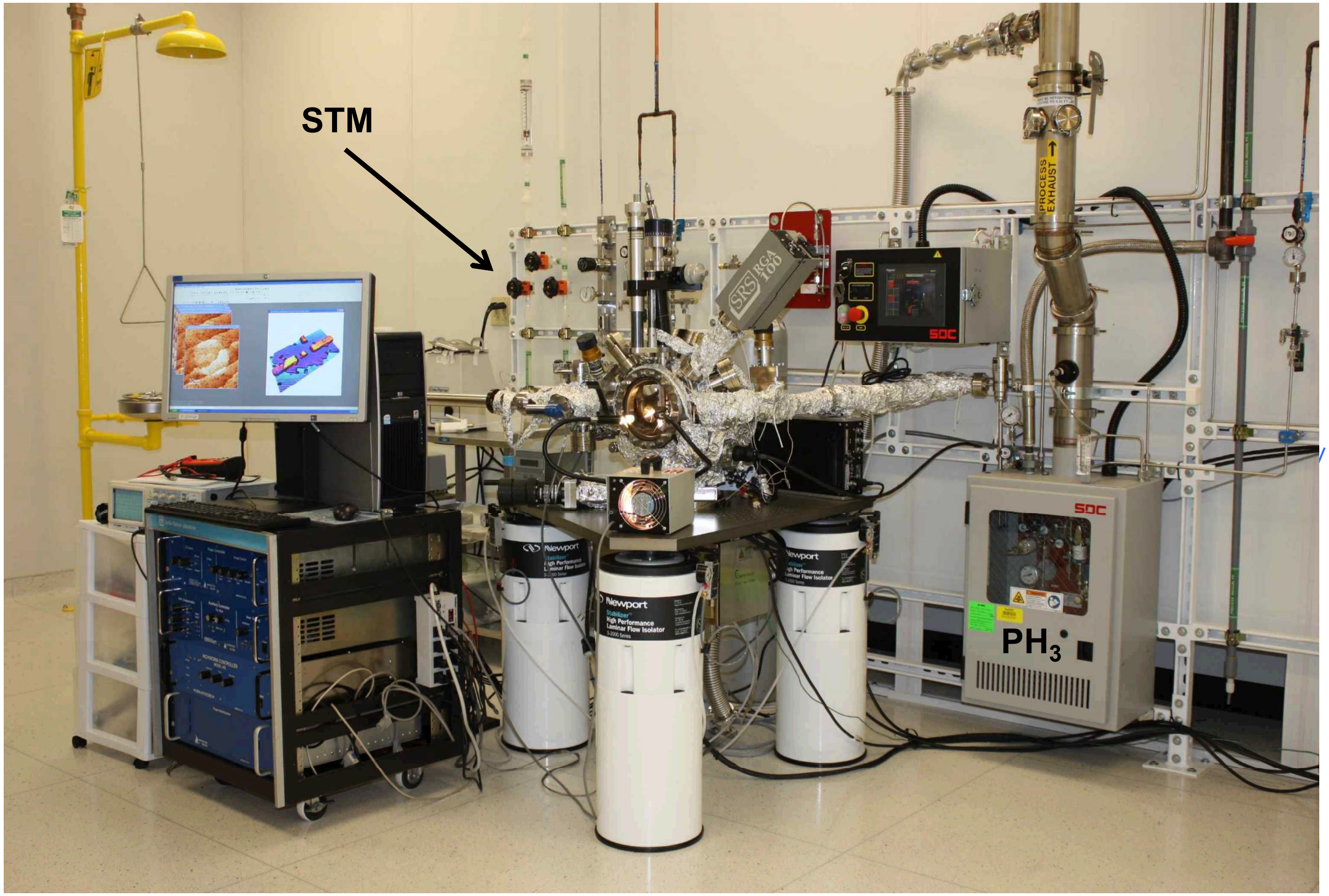


8/2011



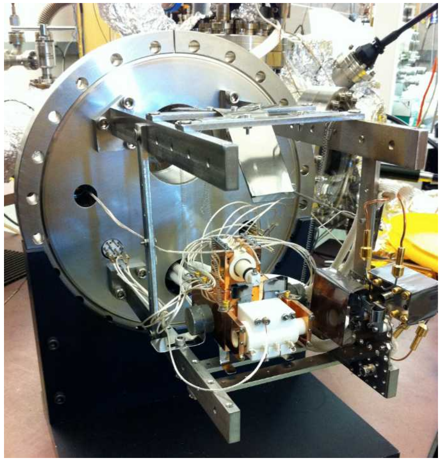
5/2012

- We now have two labs and two working STMs for donor device fabrication

Completed new STM for Si fab process

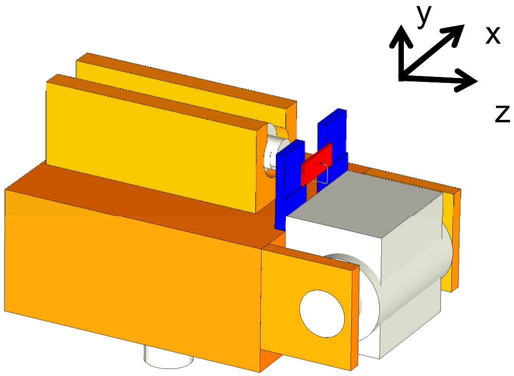
(mid-2011-3/2012)

11/2011



1/2012

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



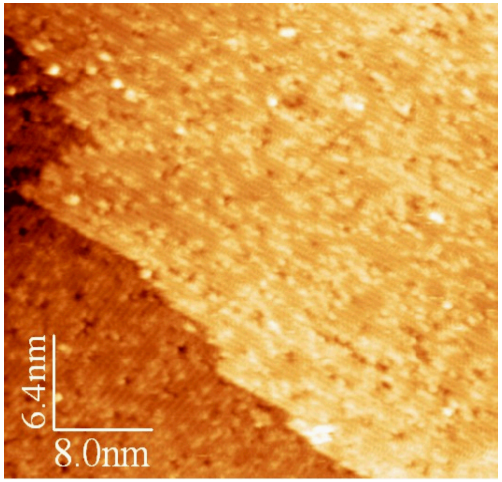
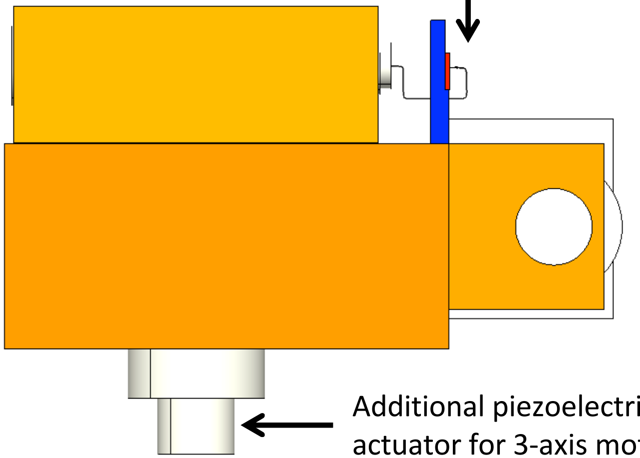


Image obtained with new STM near-atomic resolution (3/2012)

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



Additional piezoelectric actuator for 3-axis motion

Progress on fabrication steps

Sandia National Laboratories

2nd EAB

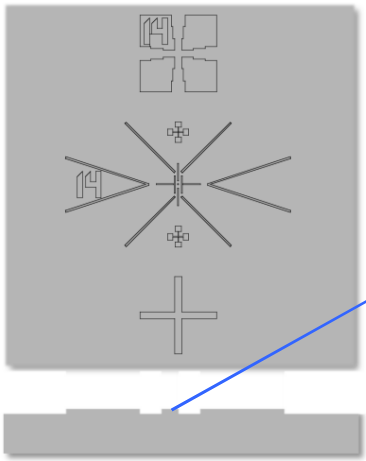
Testing PH_3 system

1. Start w clean Si(001)

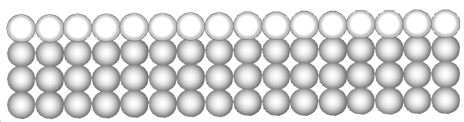
2. Adsorb H resist
Self-limiting 1 monolayer

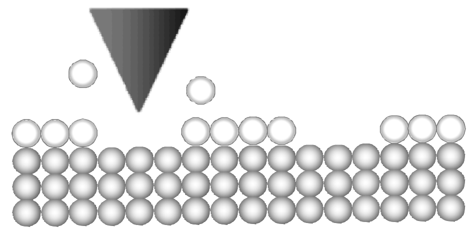
3. Pattern w STM
Atomic-precision

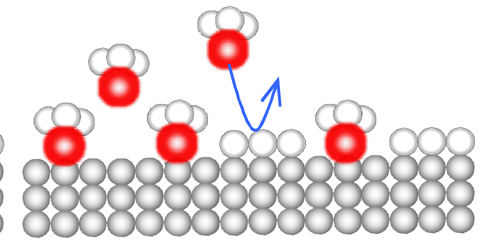
4. Adsorb PH_3



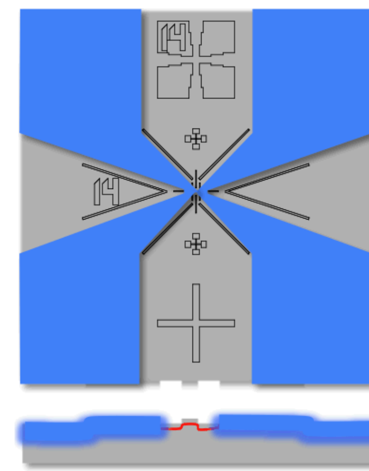
Etched alignment marks
J. Dominguez

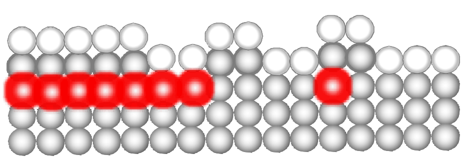


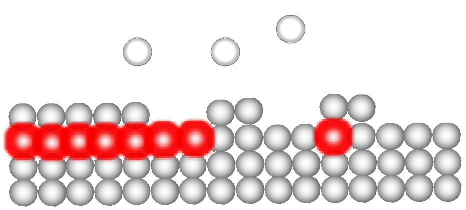


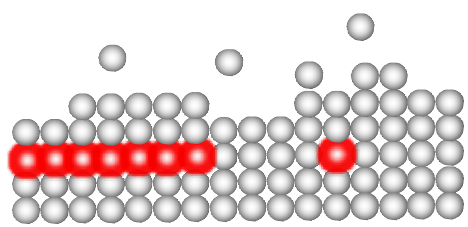


Al depo+liftoff
J. Dominguez









5. Incorporate P
-Anneal→ Si-P swap
-H resist constrains P

6. Desorb H
anneal

7. Bury P in Si

8. Add contacts

Progress on fabrication steps

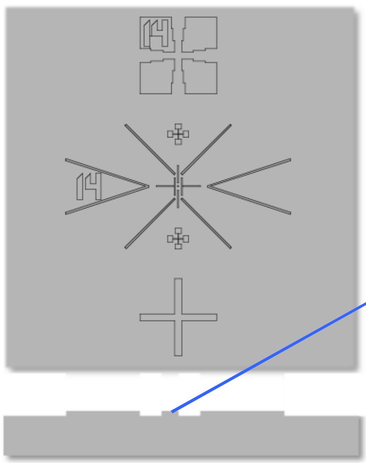
Sandia National Laboratories

1. Start w clean Si(001)

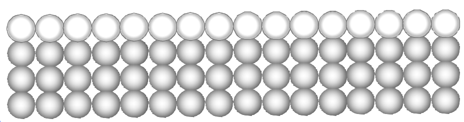
2. Adsorb H resist
Self-limiting 1 monolayer

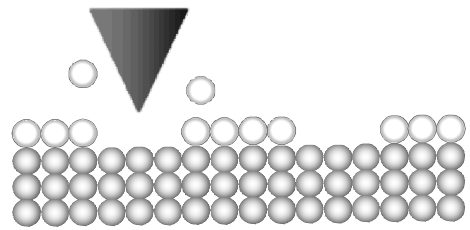
3. Pattern w STM
Atomic-precision

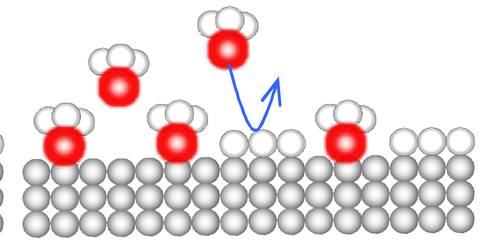
4. Adsorb PH_3



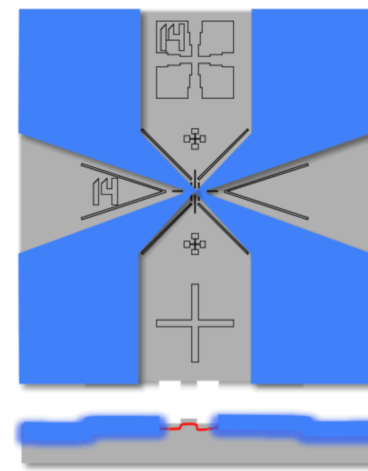
Etched alignment marks
J. Dominguez

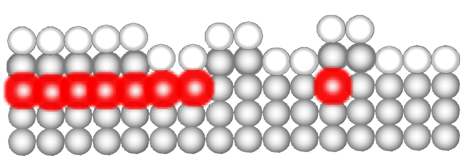


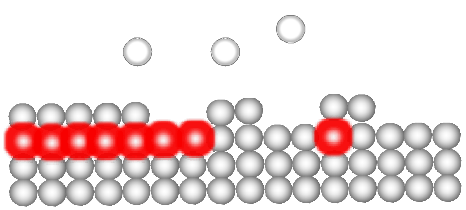


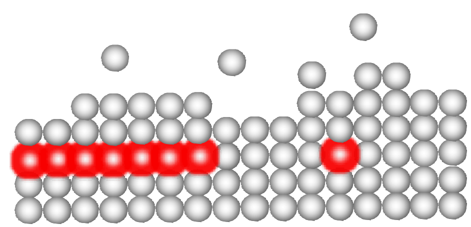


Al depo+liftoff
J. Dominguez









5. Incorporate P
-Anneal➔ Si-P swap

6. Desorb H
anneal

7. Bury P in Si

8. Add contacts

Progress on fabrication steps

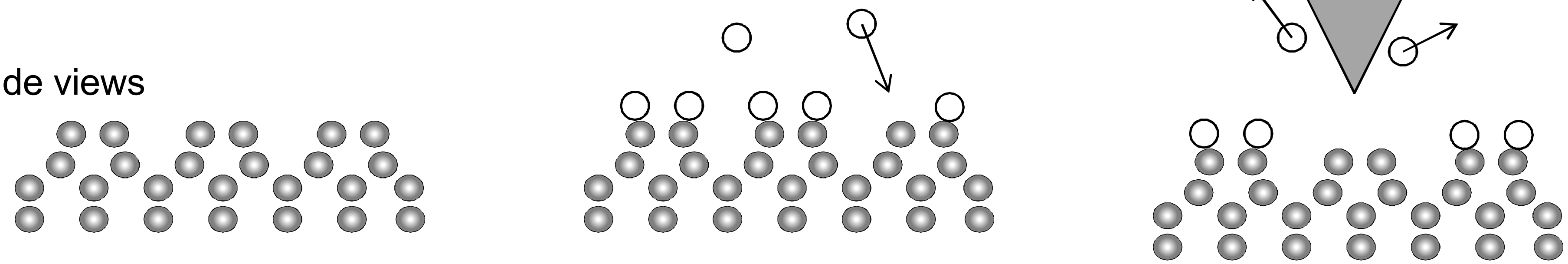
Sandia National Laboratories

1. Prepare clean Si(001) (10-11/2010)

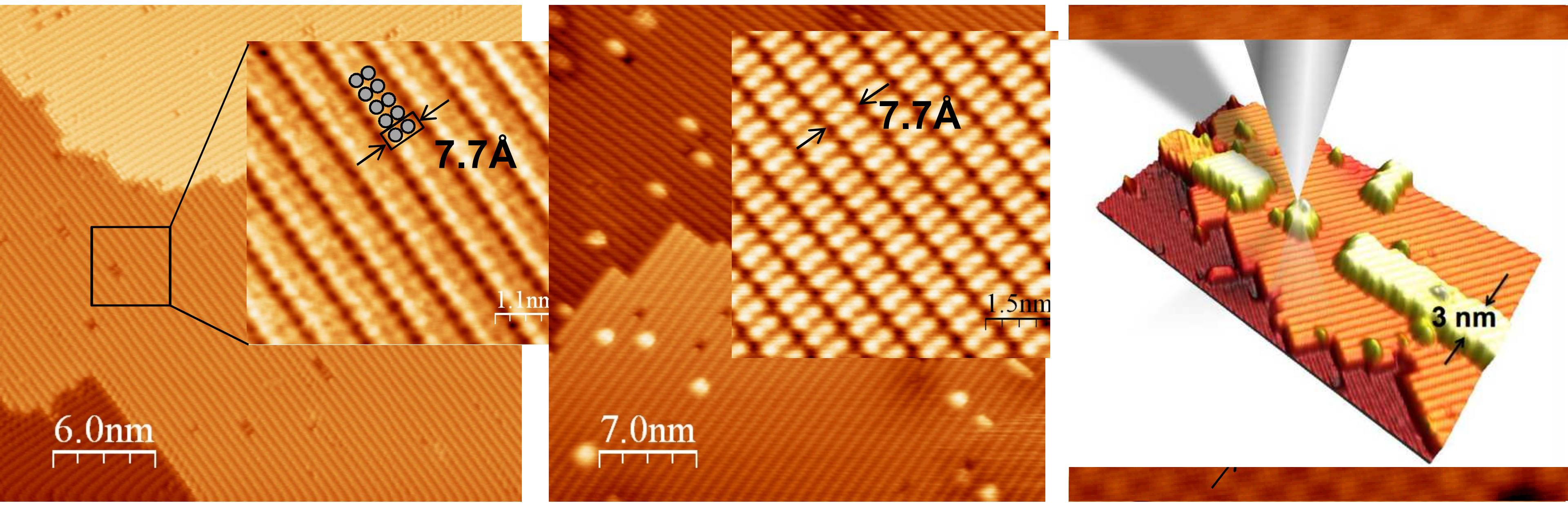
2. Low-defect H resist layers (11/2010)

3. Atomic-precision windows in resist (12/2010)

side views



top views



Si(100)-2x1

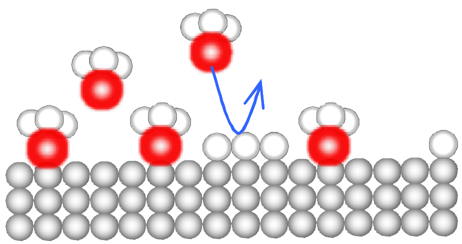
Si(100)-2x1-monohydride

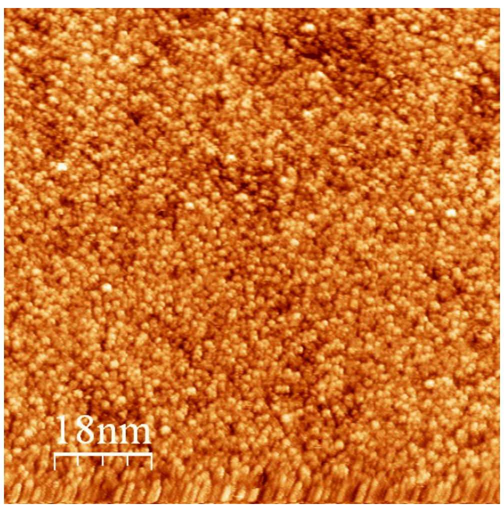
Progress on fabrication steps

Sandia National Laboratories

4. Adsorb PH_3 (1/2012)

- **Expose to PH_3 gas**

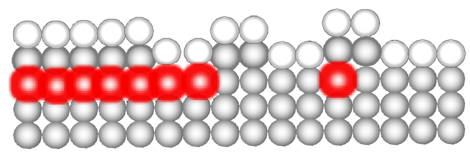


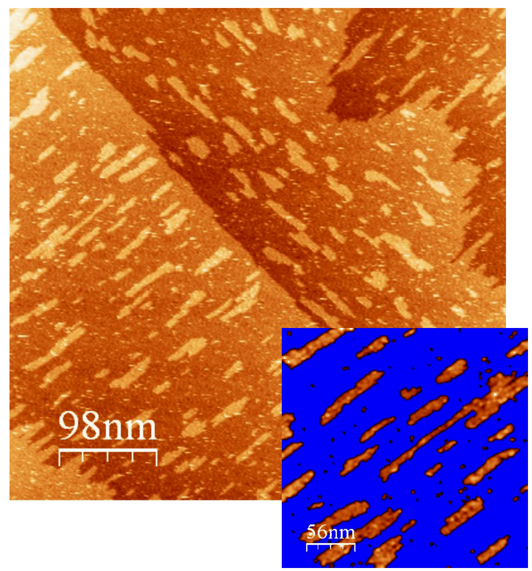


Mixed phase of H/PH_X
On Si surface

5. Incorporate P into Si (2-4/2012)

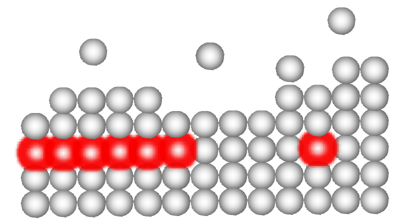
- **Anneal 350C-500C**





P incorporates into
Si→ Si ejected to surface
Forming Si islands

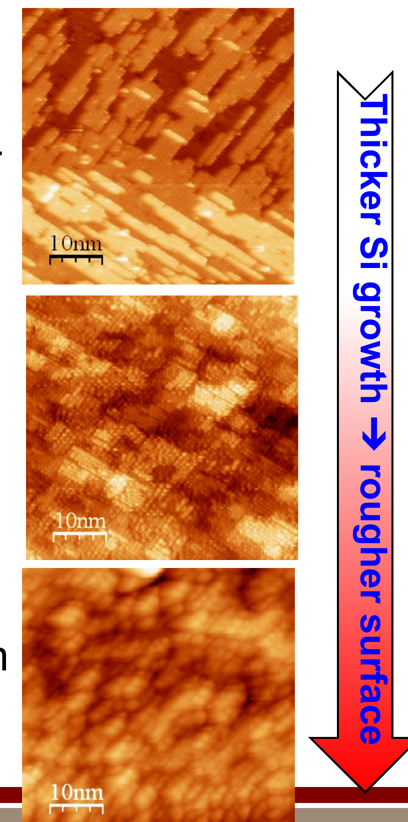
6. Bury device in epi-Si
(1/2011-2/2011)



0.7 ML

40 ML
~5 nm

80 ML
~10 nm

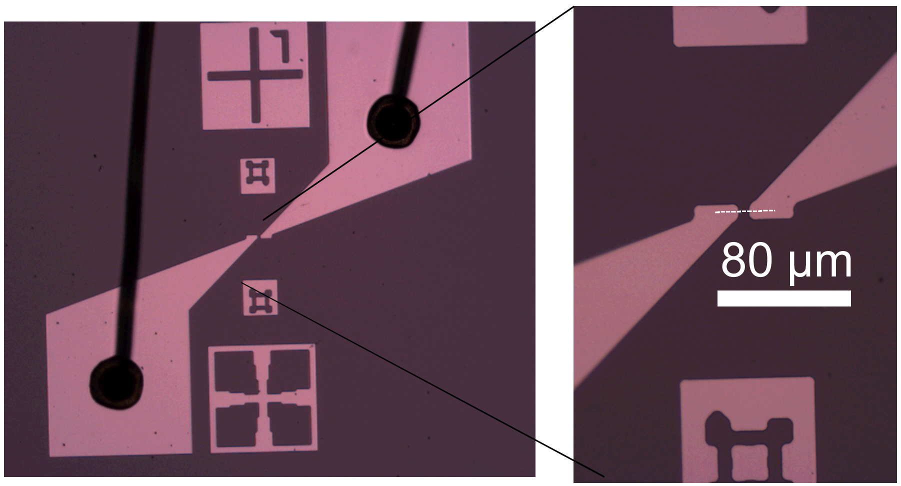


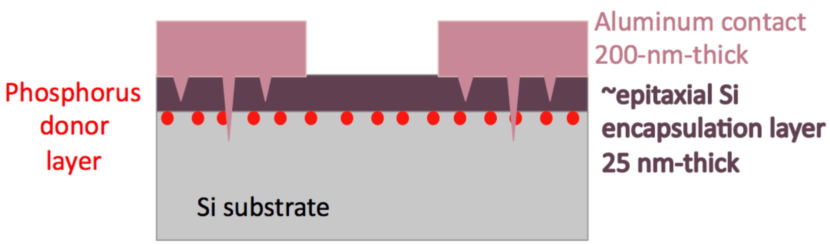
Fabricated initial test devices

(3/2012 - 5/2012)

- Fabricated and characterized two types of diagnostic devices verifying successful incorporation, encapsulation, and connection to highly doped P donor layer

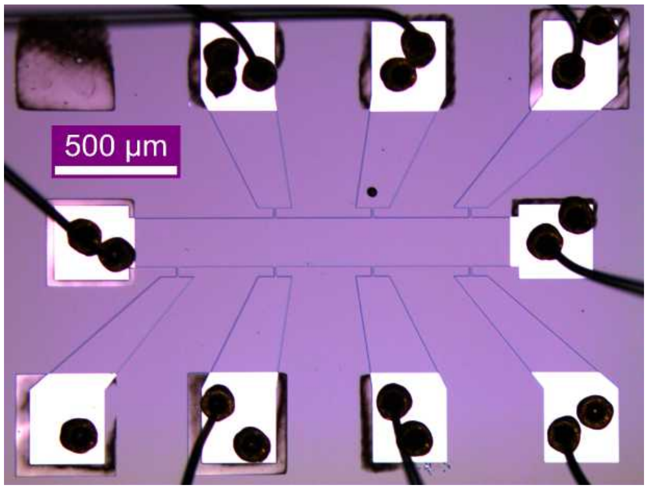
Two-contact device



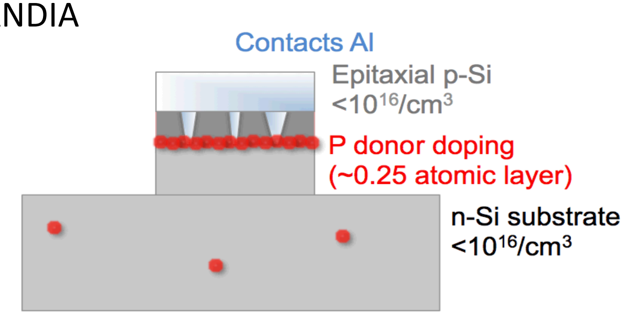


Device cross section schematic

Trench isolated Hall device



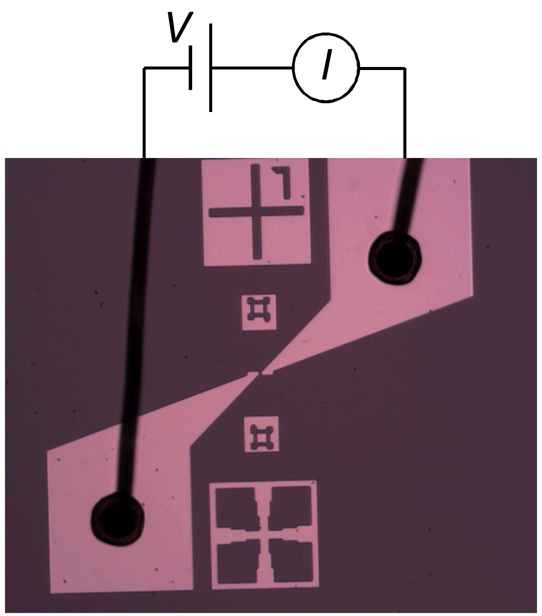
SANDIA

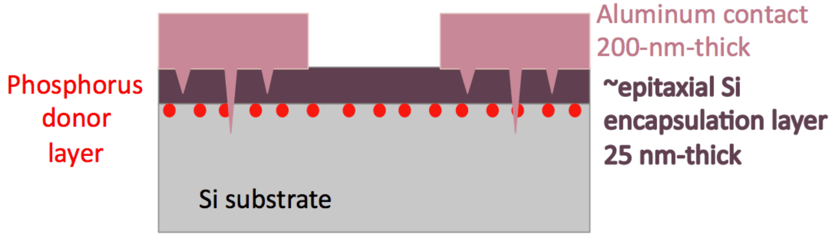


Device cross section schematic

Characterized initial test devices

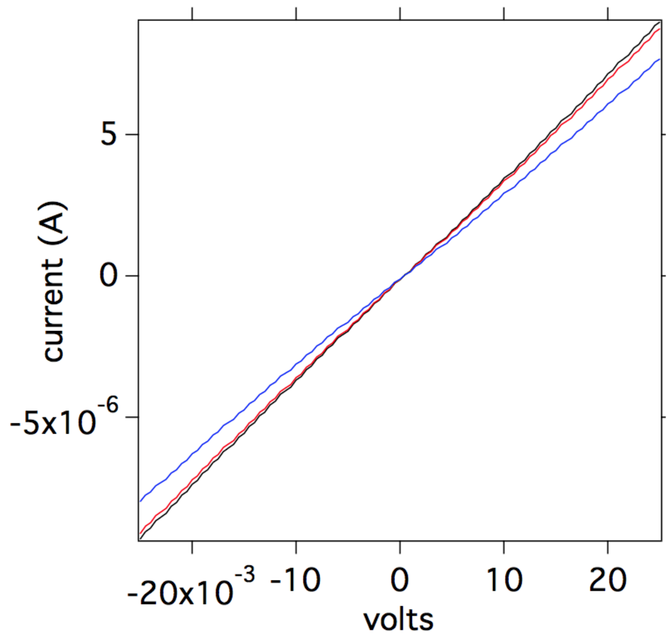
(3/2012 - 5/2012)





Device cross section schematic

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

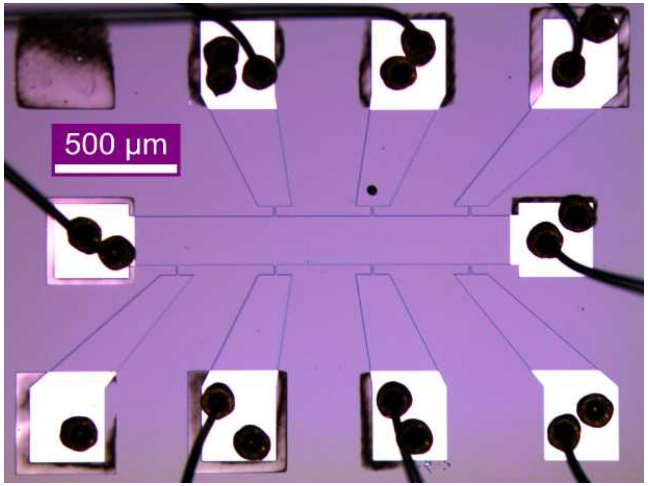


- **Ohmic conduction at 4K shows successful fab & connection to highly doped donor layer**
- **Typical resistances of 2-6 kΩ are similar to Simmons results (Nano Lett. 2004)**

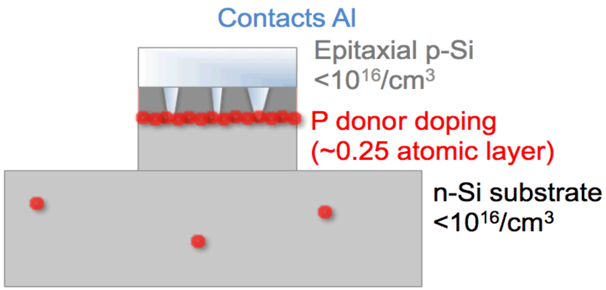
Characterized initial transport devices

(4/2012 - 5/2012)

Trench isolated Hall device



SANDIA



- 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

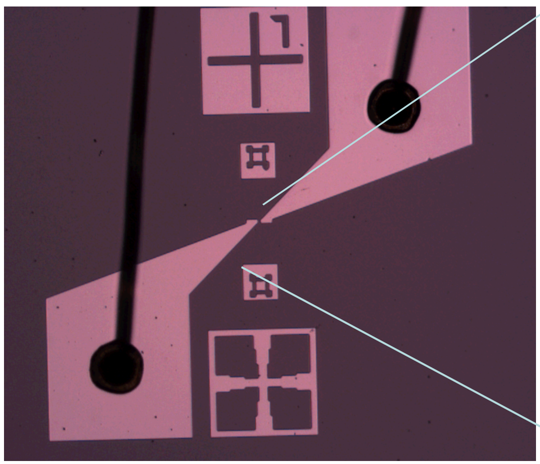
- **Similar Hall effect devices from Simmons yielded n = 1.2-1.7x10^{14}/cm^2 mobility<100 cm^2/Vs**

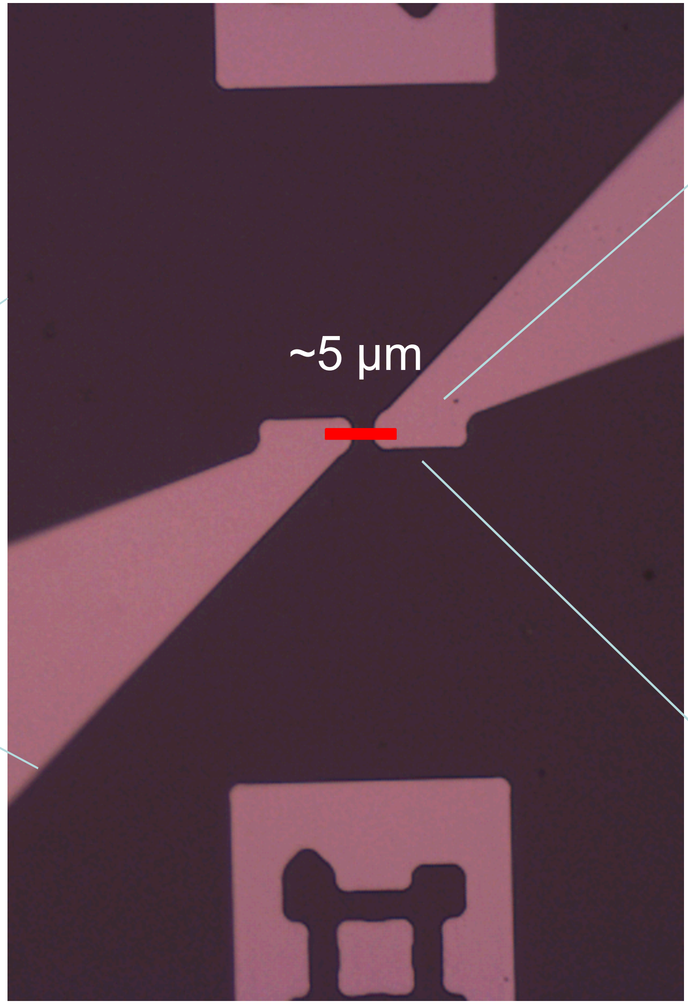
- **Donor and electron density sufficient for atomic precision devices**
- **Next step: implement complete atomic-precision fab technique**

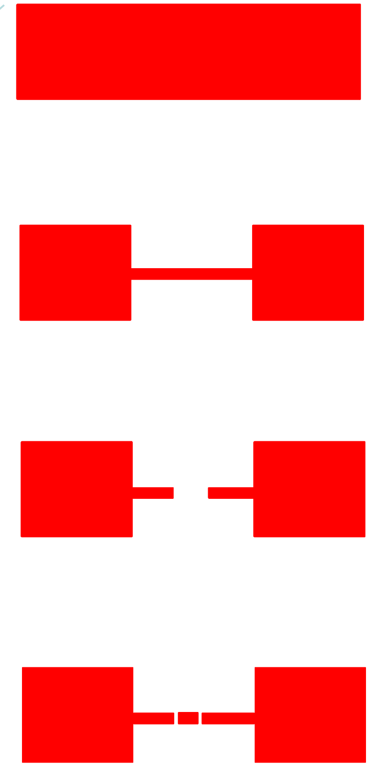
Present work: complete nano-device

- Do all fab steps sequentially to produce patterned nanoscale device (a milestone for this year)

Two-contact devices







- **After demonstrating two-contact test devices, we will try qubit structures (3+ contacts)**

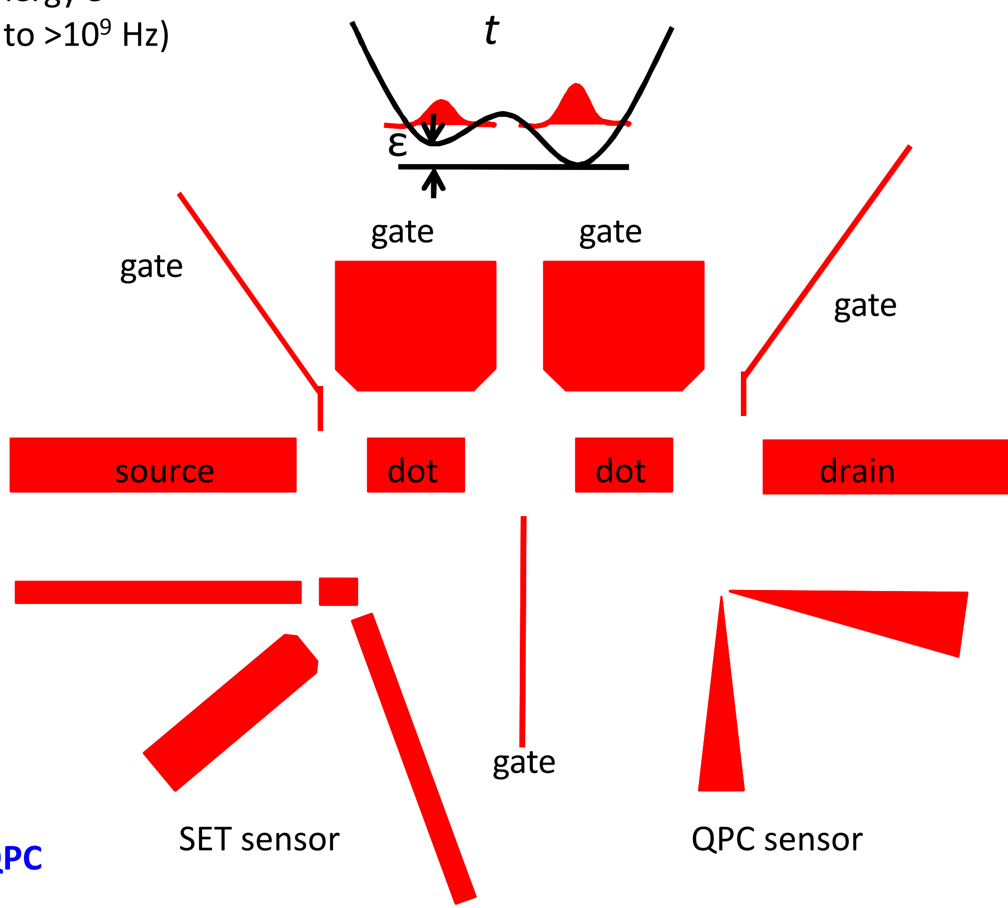
Preparing initial qubit designs

(4/2012-6/2012)

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

Tunable potential wells
Separated by tunable tunnel barrier



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**

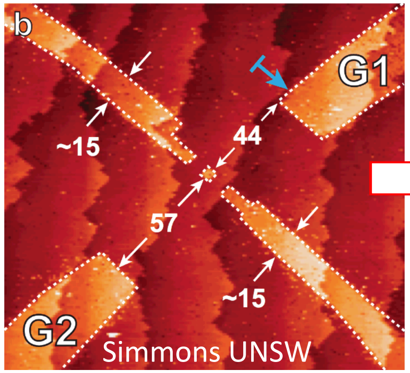
All elements are coplanar → crowding limits number of device elements

Electrostatic & transport modeling for qubit design

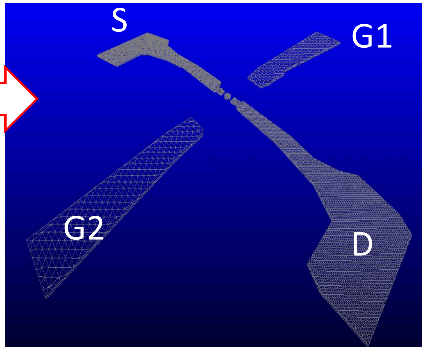
- Quantitative models have been demonstrated for donor devices
- NEMO (G. Klimeck): Atomistic detail, quantum properties…
- For charge qubit: use finite element models (FastCap) + transport model (CapNet)

Electrostatics modeling

6-7 donor dot (Fuechsle, Nature Nano 2010)



3D finite element (FastCap)



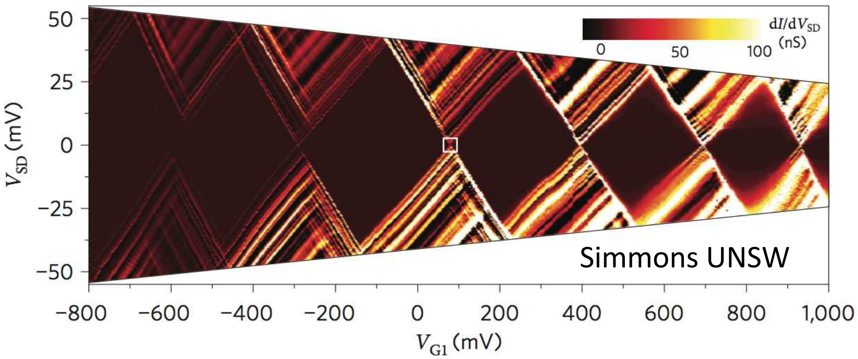
Dot capacitances (aF) & gate lever arms

	C_S	C_D	C_{G1}	C_{G2}	α_{G1}	α_{G2}
Experiment UNSW*	2.32	1.93	0.53	0.38	0.10	0.07
FastCap UNSW*	2.08	1.90	0.51	0.43	0.10	0.09
FastCap SNL	2.2	2.1	0.50	0.44	0.10	0.08

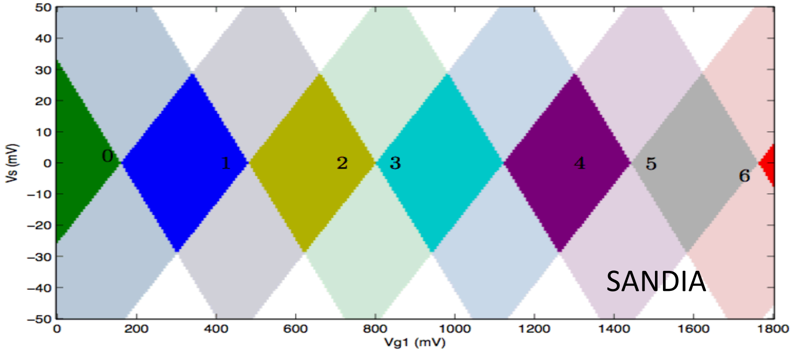
~ Quantitative agreement between model/experiment

Transport experiment and model

**In experiment, dot size depends on occupation

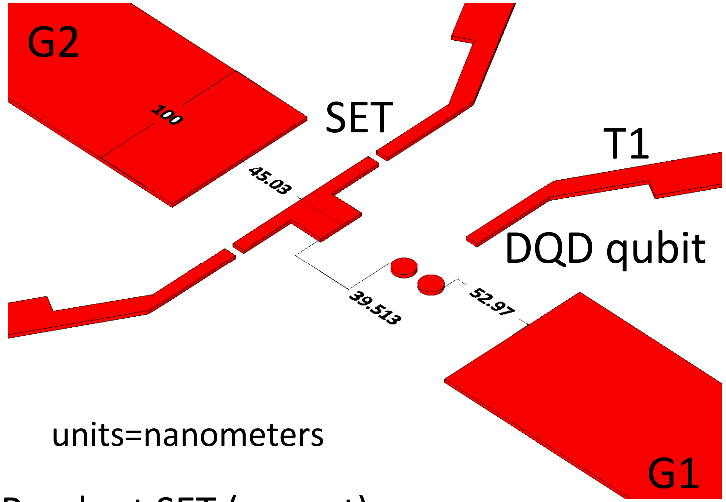


Transport (CapNet) (E. Nielsen, R. Rahman, SNL)

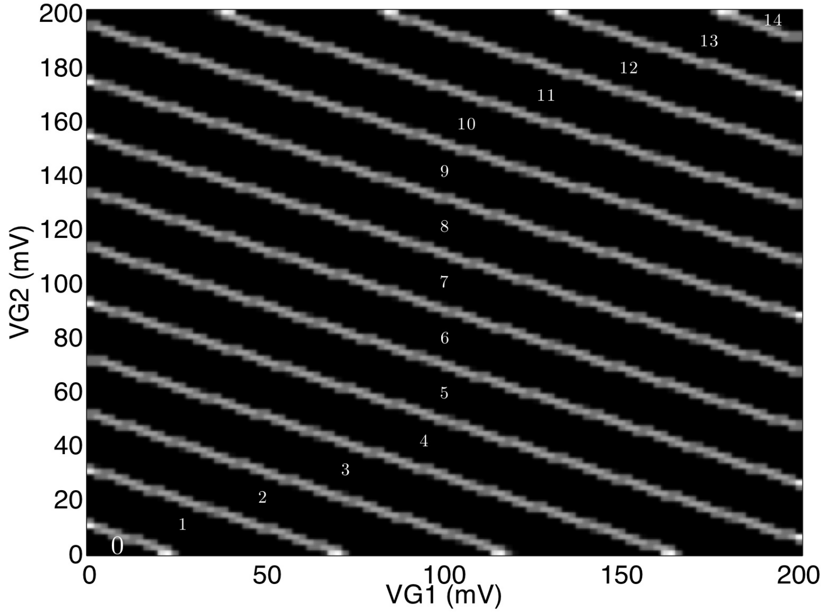


E_c ~ 25-50 meV vs E_c ~ 30 meV (Model)

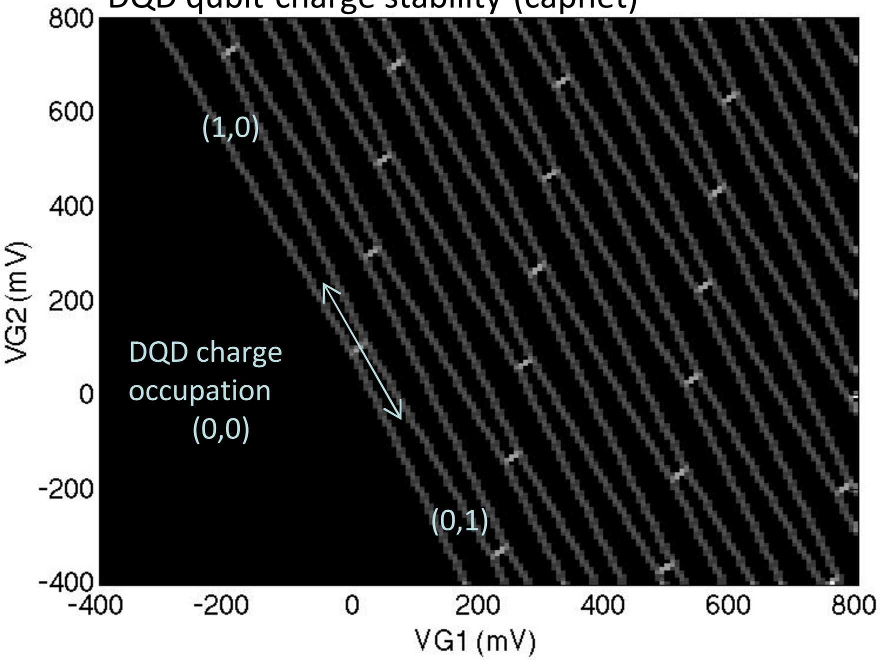
Initial charge qubit designs



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

Milestones for STM fab

- 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 (wires)
  - -Demonstrate single donor placement
- Year 3
  - -Demonstrate two donor placement
  - -Demonstrate transport through double donor
  - -Develop charge sensor for two donor system
  - -Demonstrate qubit

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  - ✔Incorporation of phosphorus on surface
  - ✔**Demonstrate initial transport test devices (wires) (Macroscopic Hall effect devices)**
  - -Demonstrate single donor placement
- Year 3
  - -Demonstrate two donor placement
  - -Demonstrate transport through double donor
  - -Develop charge sensor for two donor system
  - -Demonstrate qubit

Progress on fabrication steps

Sandia National Laboratories

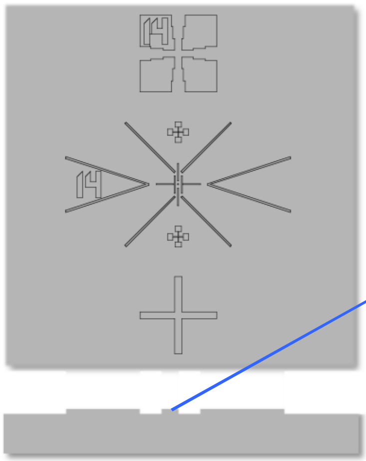
Testing PH_3 system

1. Start w clean Si(001)

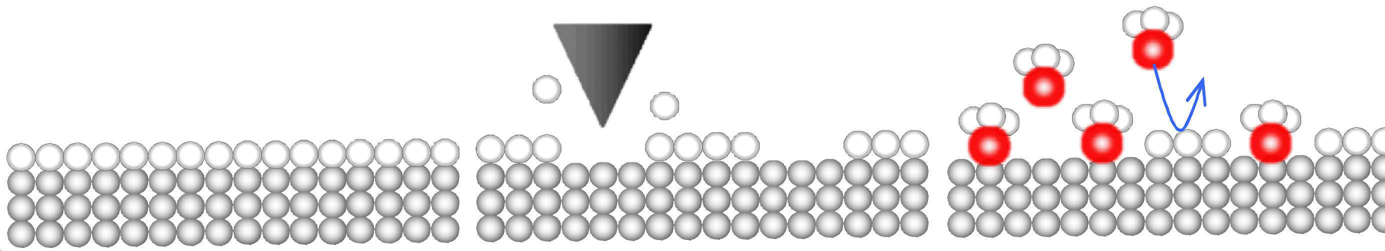
2. Adsorb H resist
Self-limiting 1 monolayer

3. Pattern w STM
Atomic-precision

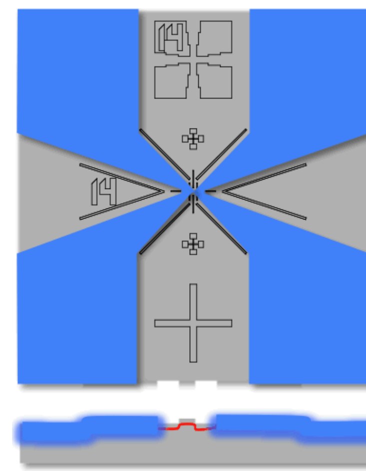
4. Adsorb PH_3

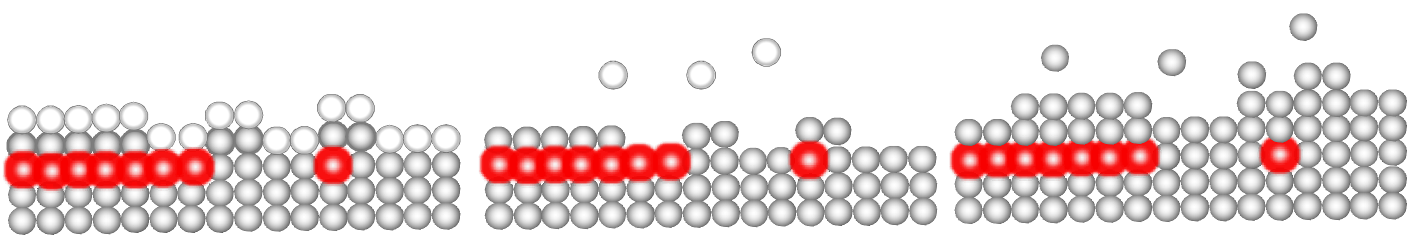


Etched alignment marks
J. Dominguez



Al depo+liftoff
J. Dominguez





5. Incorporate P
-Anneal→ Si-P swap
-H resist constrains P

6. Desorb H
anneal

7. Bury P in Si

8. Add contacts

Progress on fabrication steps

Sandia National Laboratories

1. Start w clean Si(001)

2. Adsorb H resist
Self-limiting 1 monolayer

3. Pattern w STM
Atomic-precision

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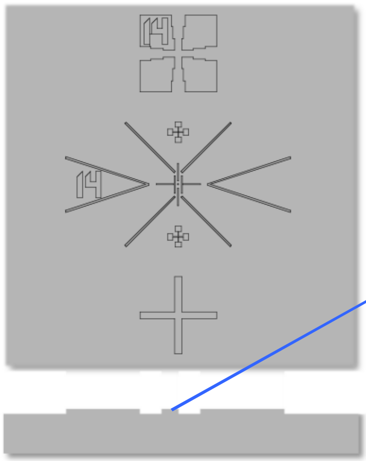

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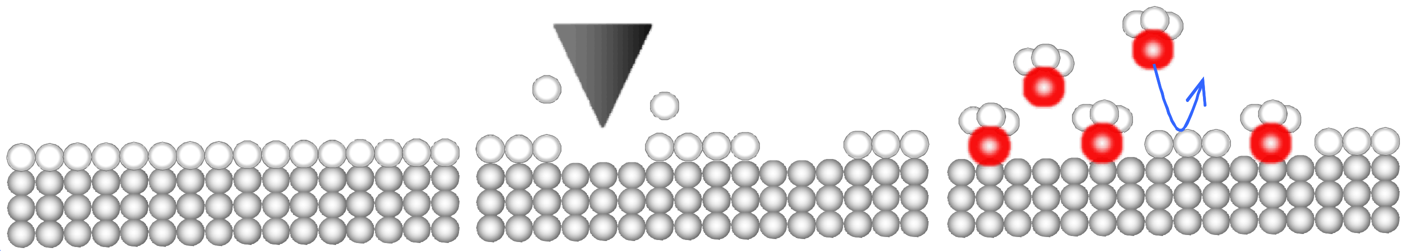

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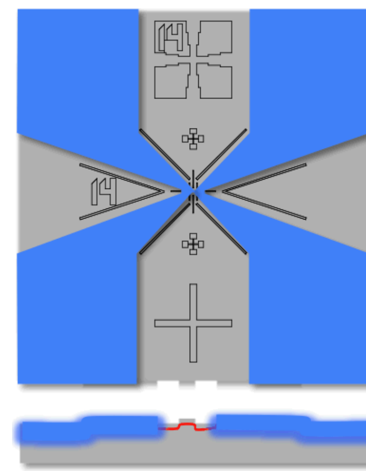

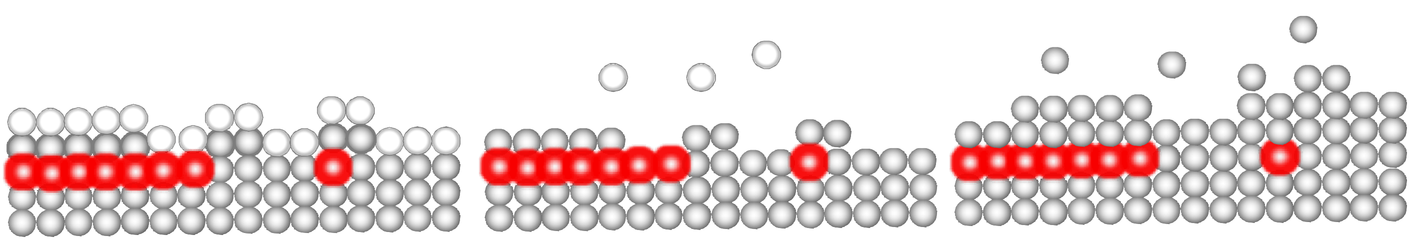

5. Incorporate P
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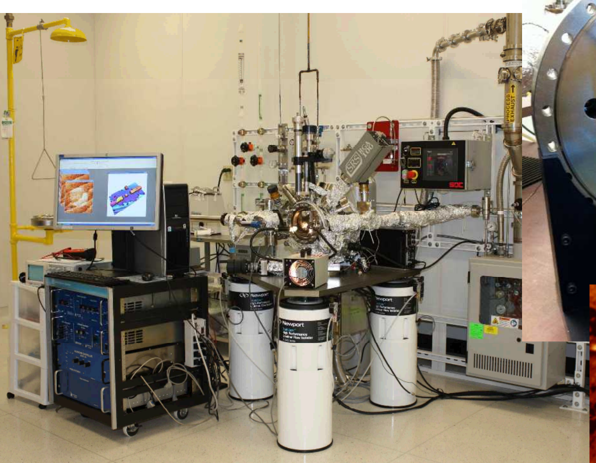
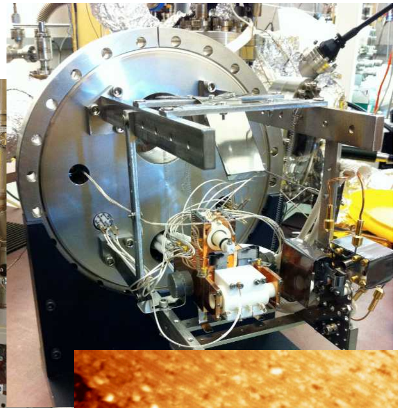
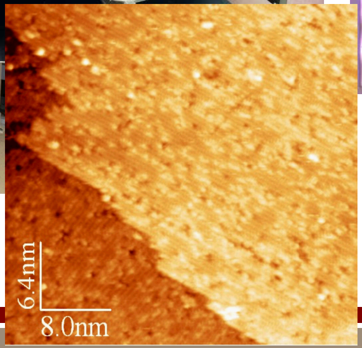
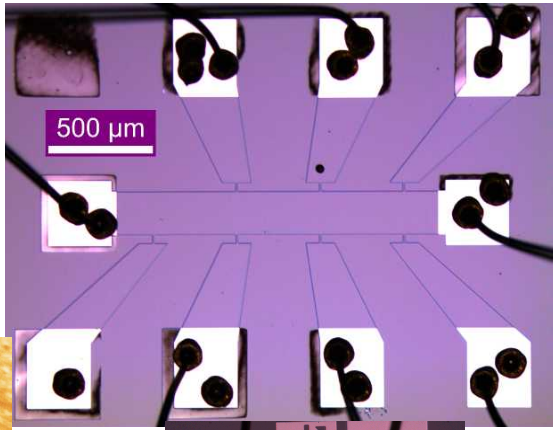
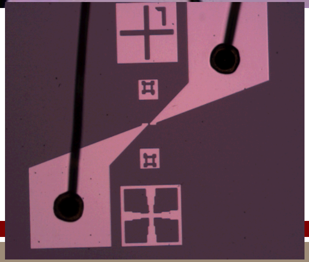
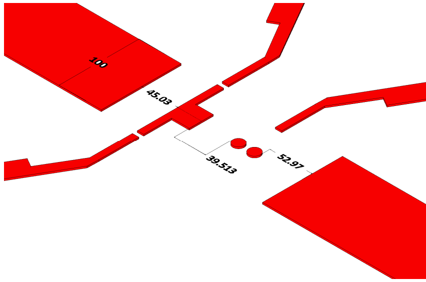
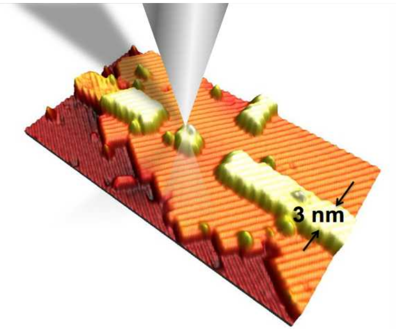
Summary of work

- Completed new lab and phosphine installation & testing
- Completed new STM, installed into cleanroom lab
- Fabricated our first macroscopic test devices in the new lab
    - -Performed 4K cryogenic characterization of devices
    - -Demonstrated P donor incorporation and encapsulation
- With Simmons fab steps reproduced in our lab, we are working to demonstrate atomic-precision STM fabricated devices via full Simmons process (in-progress)
- Design and modeling of initial qubit designs (in-progress)



Approach to qubit design

- **Identify necessary components for the qubit**

- **Study Simmons devices and tabulate design rules for device components**
  -feature sizes and layouts
  - mutual capacitances
  -gate lever arms
  - gate voltage ranges (leakage limits)
  -tunneling rate estimates (source-dot-drain, dot-dot)
  -charge sensor design and layout

- **Identify initial design rules and also potential design challenges/issues for a charge qubit device**
  -Optimal feature size and position for good coupling strengths (capacitive and tunnel couplings)
  -Charge sensing, readout QPC versus SET
  -Crowding of device elements in plane
  -Crowding of metal leads on top surface
  -Power dissipation (joule heating, electrons are moving in confined spaces)
  and dot leading to temperature variation

  -For a 27-nm-wide wire, 100 nA current threshold for heating (Ruess PRB 2007)
  -For 5 nm wide wire expect about 20 nA upper bound on current

- **Using Simmons designs as a starting point, propose some planar designs for a few D qubit,**
  -For Simmons devices, FASTCAP matches quantitatively with experimental data (predictive quantitative electrostatic modeling of proposed designs may be possible)
  -It would also be ideal to estimate tunneling rates for a given design.
  (Even just estimates of *relative* tunnel rates)

Qubit design starting points

Charge qubit components

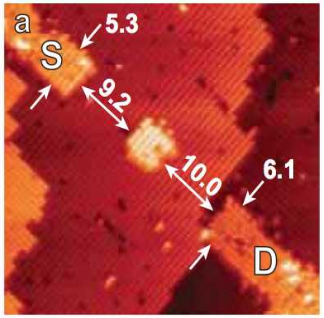
1. **Quantum dots**
2. **Source/drain leads and tunneling gaps**
3. **Gates**
- Plungers to tune chemical potentials (definitely)
- Barrier gates to tune tunnel barriers/rates
4. **Charge-state readout e.g. SET or QPC**

2D planar Lithographic delta-dope devices in Si:

Design= What shape? Size? How far apart?

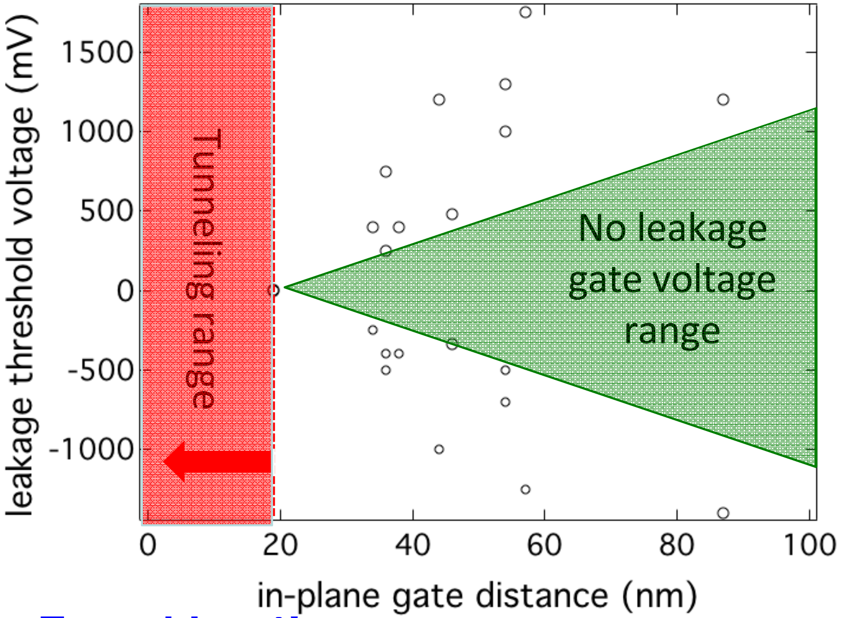
Gates: 50+ nm wide rectangles (Simmons)

Dots: few electron



UNSW
units=nm

Gate isolation gaps:



Source & Drain:
4-7 nm-wide lines

Tunnel Junctions:
8-10 nm

Charge sensor for qubit state

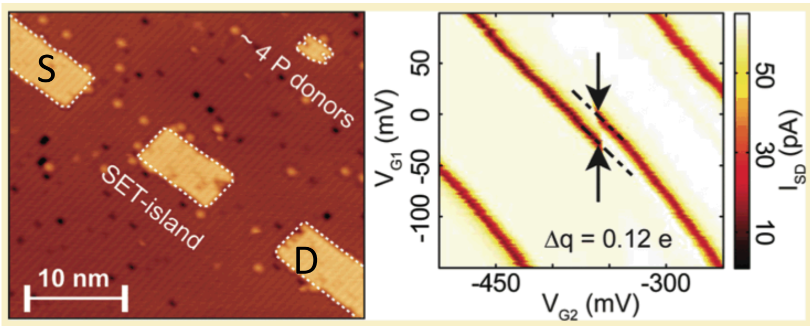
Sandia National Laboratories

- **SET has been demonstrated (12% charge transfer signal)**
- **Still no demonstration of charge sensing via QPC**

Charge sense via SET

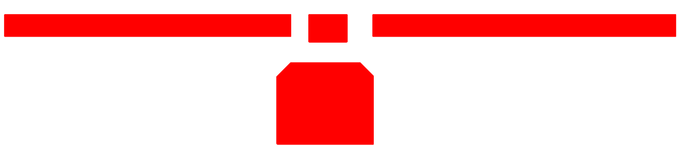
Mahapatra…Simmons Nano Lett 11, 4376 (2011)

UNSW



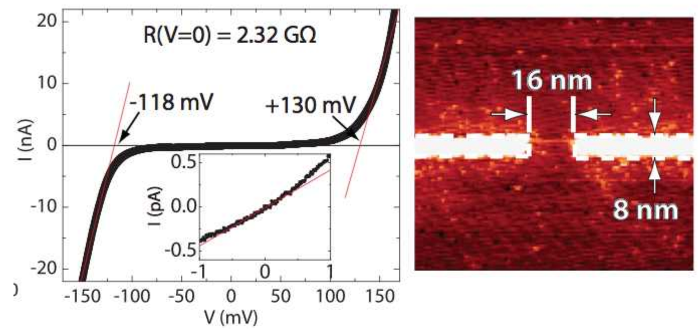
Single e^- on 4 donor dot induces V equivalent to 0.12 e^- on SET dot

→ abrupt change in SET S-D current



Charge sense via QPC (??)

Tunnel gaps have been characterized



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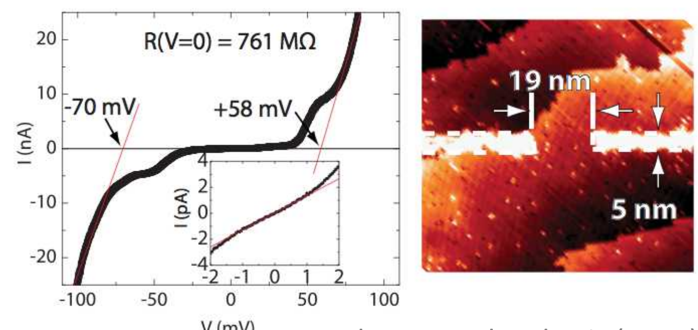

UNSW

W. Pok UNSW PhD thesis (2011)

Charge sensing via QPC not yet demonstrated, QPC may require less leads