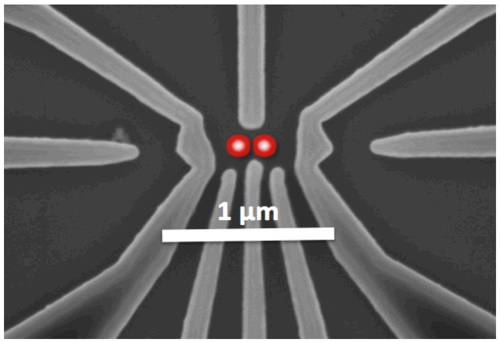

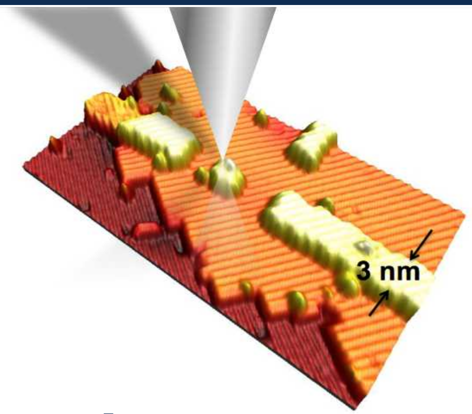

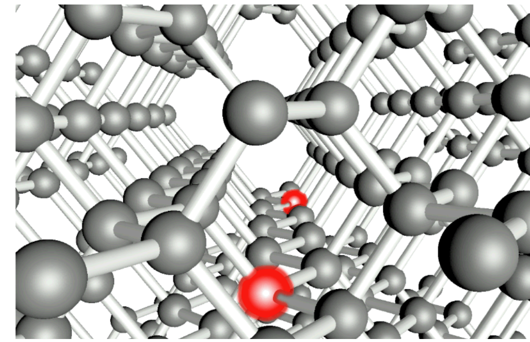

Donor charge qubits via STM assisted fabrication

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

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

LDRD

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Talk overview

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

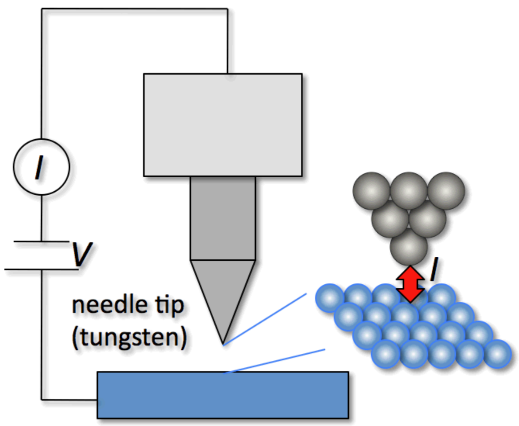
-Reproduced Simmons qubit fabrication steps in lab

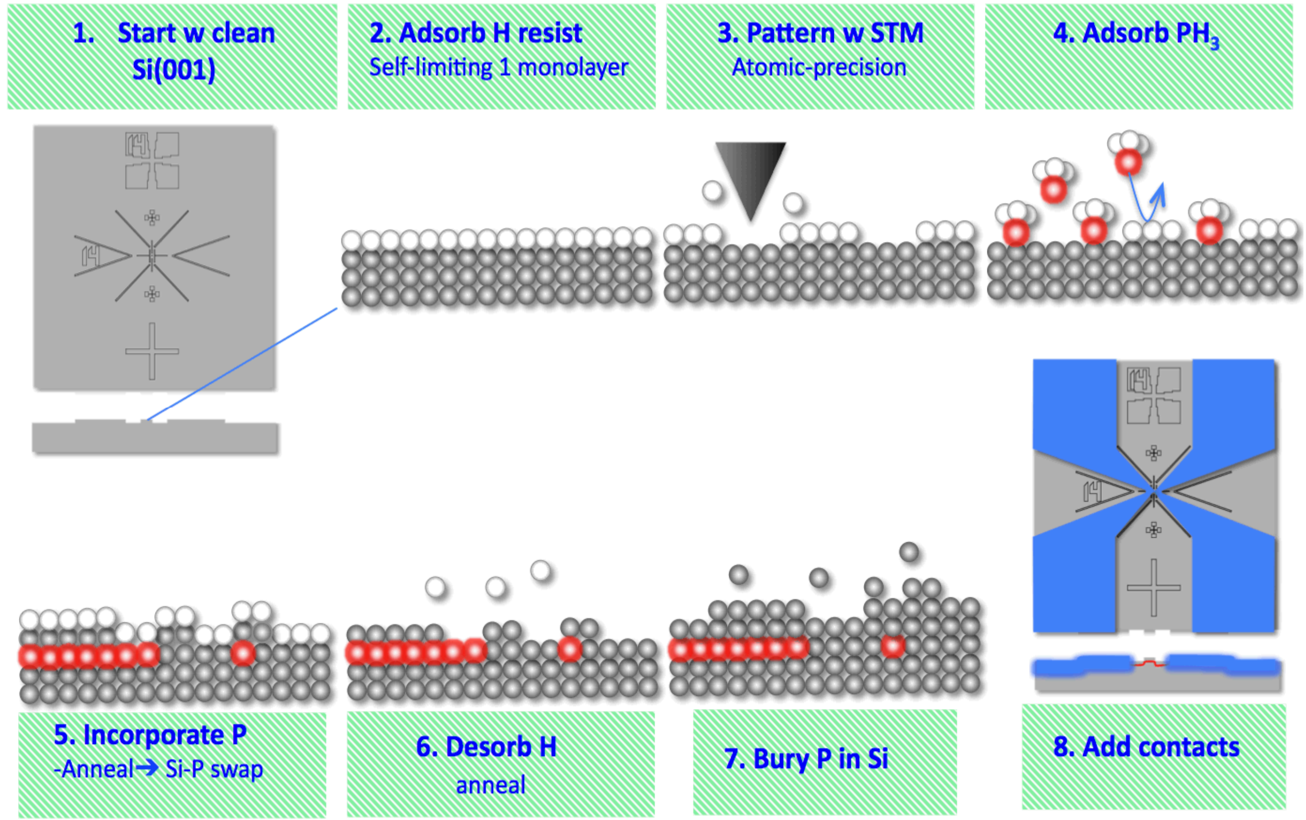
-Performed design & modeling of qubit

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

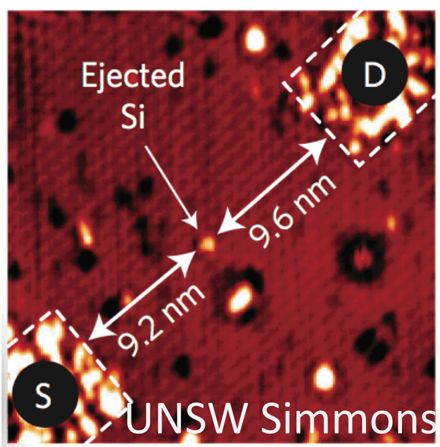
STM assisted fab overview

- STM : an atomic resolution surface imaging and manipulation tool



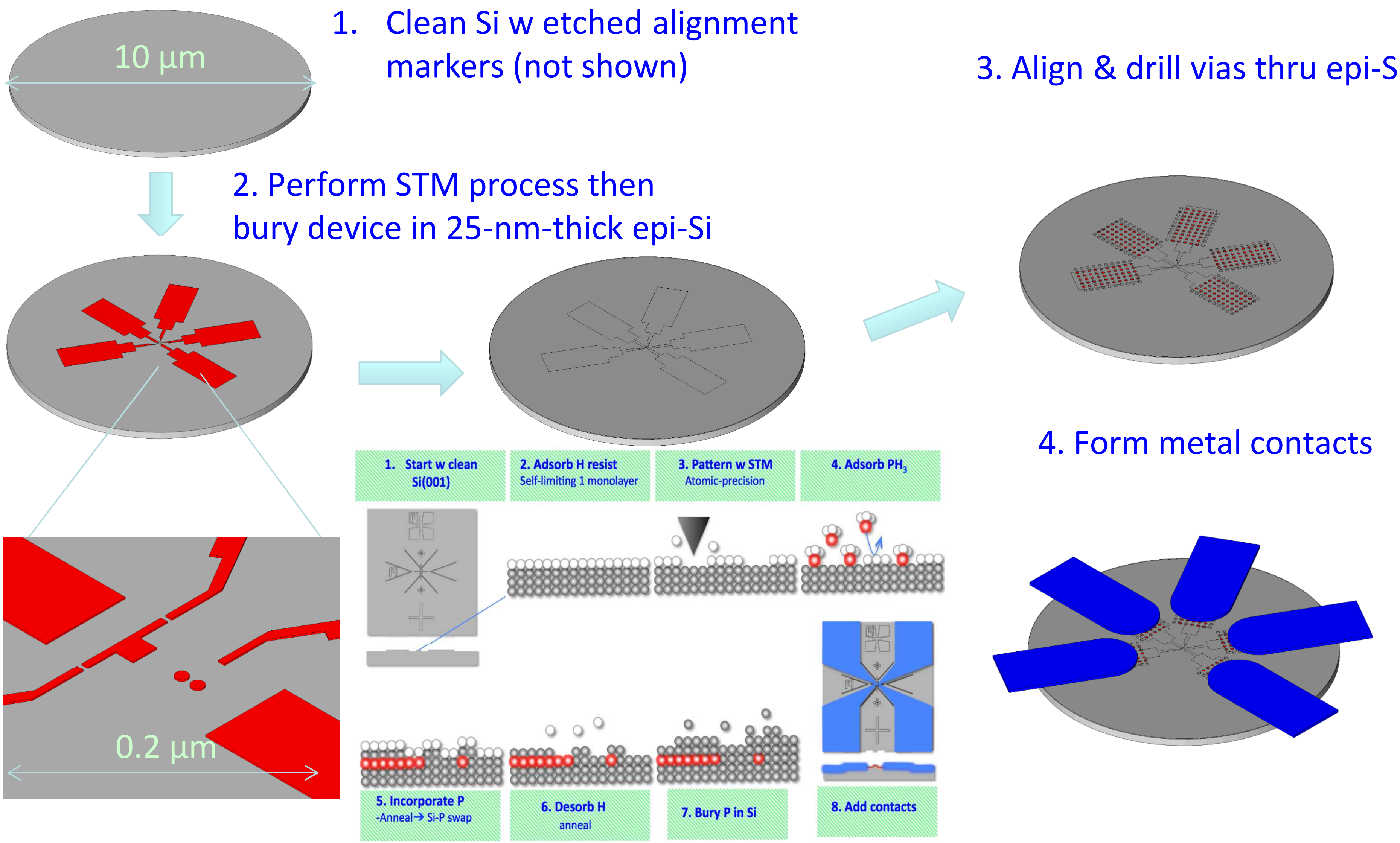


Single P atom transistor in Si



1. M.Y. Simmons et al.
2. F.J. Ruess et al. Nano Letters (2004)
3. M.Fuechsle et al. Nature Nanotech (2012)

Target device: donor charge qubit



- Objective: demonstrate fabrication of single charge qubit

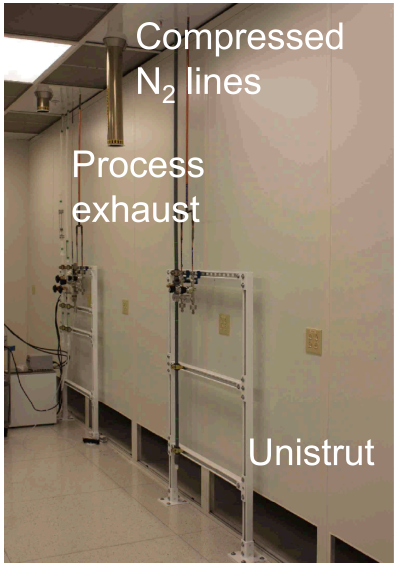
Milestones for STM fab

- 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

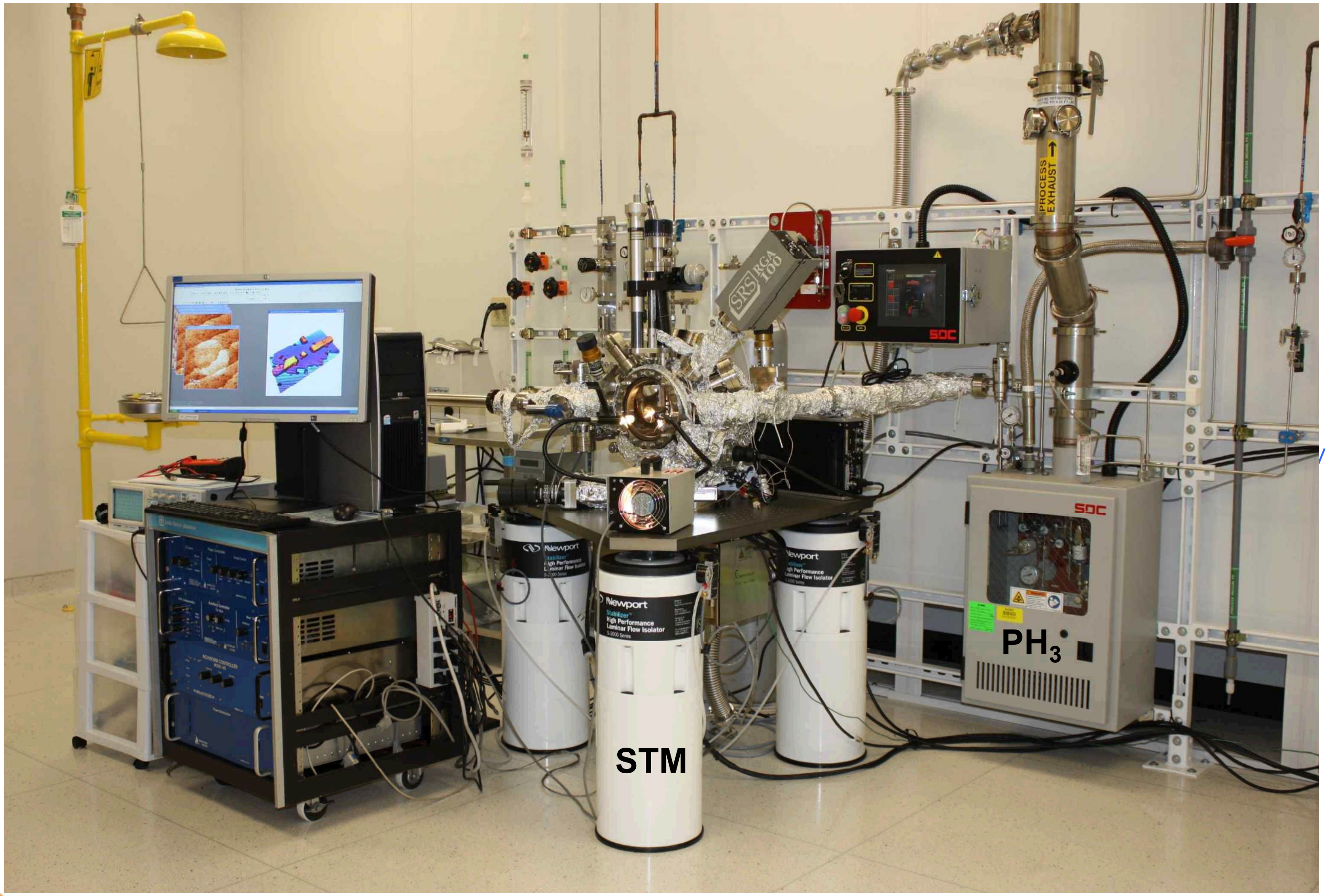
Milestones for STM fab

- 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
  - -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) (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

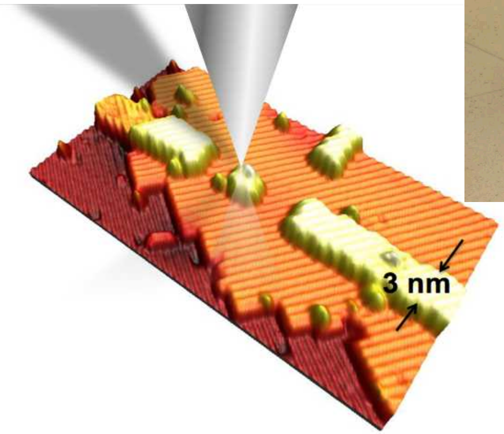
Completed new lab in cleanroom



8/2011



5/2012



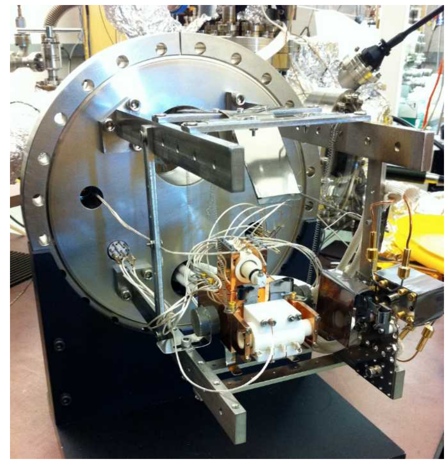
(7/2011-5/2012)

Completion of new STM for Si fab process

Sandia National Laboratories

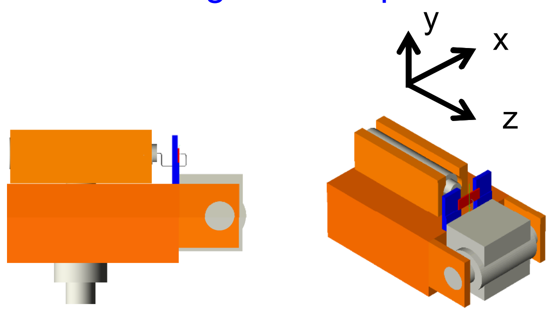
(mid-2011-3/2012)

11/2011



1/2012

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



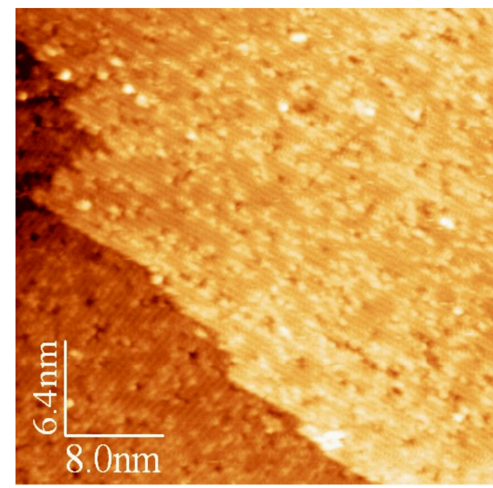


Image obtained w new STM (3/2012) near-atomic resolution

Progress on fabrication steps

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Testing PH_3 system

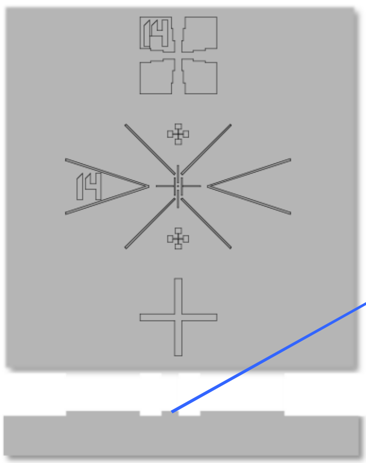
1[st] EAB

1. Start w clean Si(001)

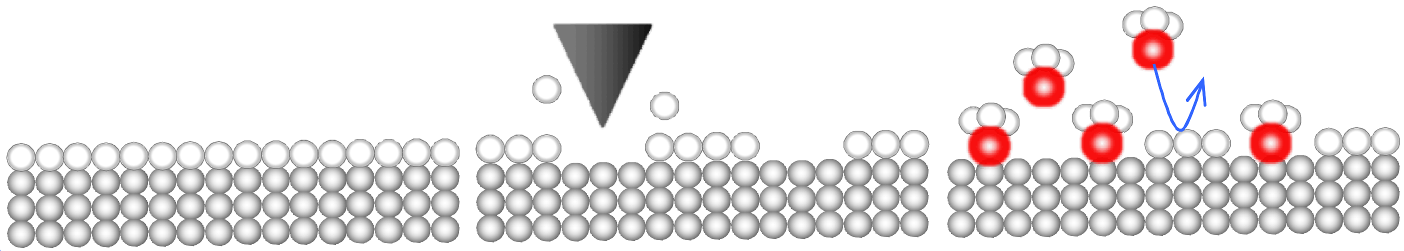
2. Adsorb H resist
Self-limiting 1 monolayer

3. Pattern w STM
Atomic-precision

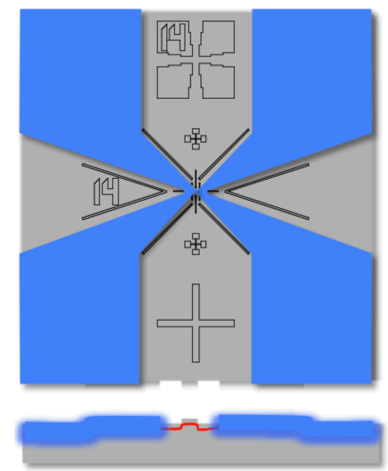
4. Adsorb PH_3

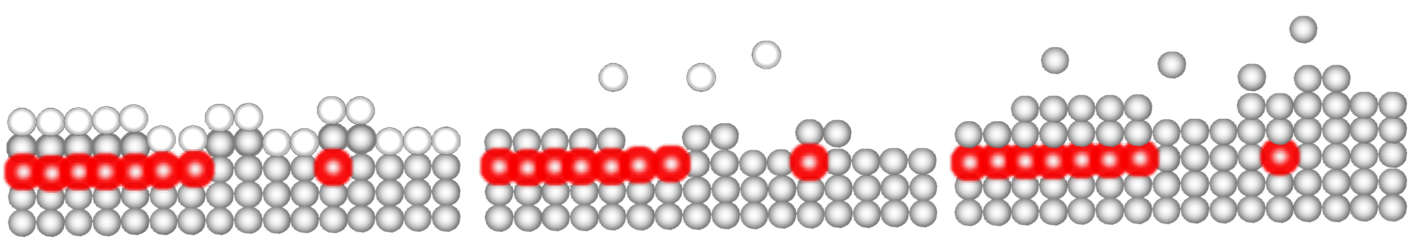


Etched alignment marks
J. Dominguez



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

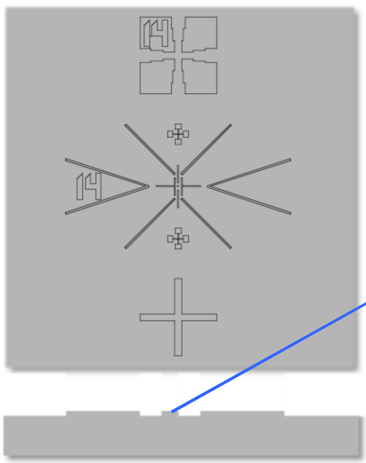
1st EAB

1. Start w clean Si(001)

2. Adsorb H resist
Self-limiting 1 monolayer

3. Pattern w STM
Atomic-precision

4. Adsorb PH_3



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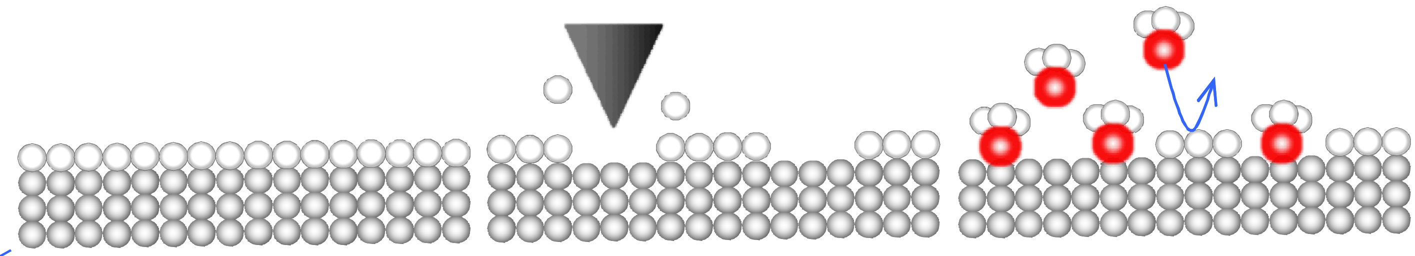
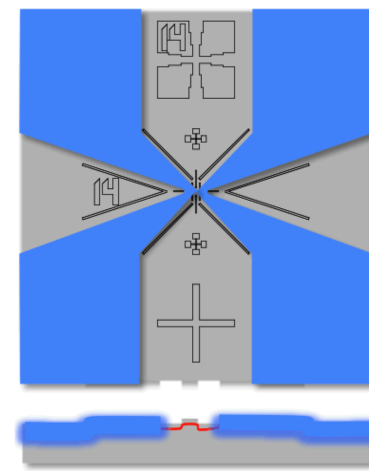
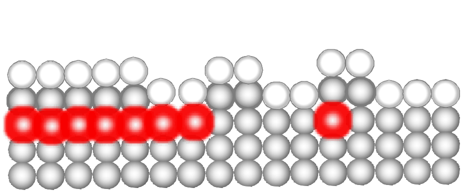
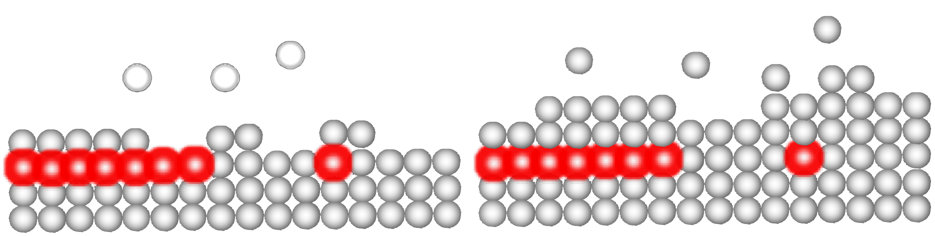




Al depo+liftoff
J. Dominguez





5. Incorporate P
-Anneal→ Si-P swap

6. Desorb H
anneal

7. Bury P in Si

8. Add contacts

Progress on fabrication steps

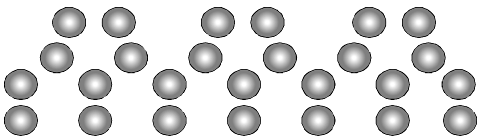
Sandia National Laboratories

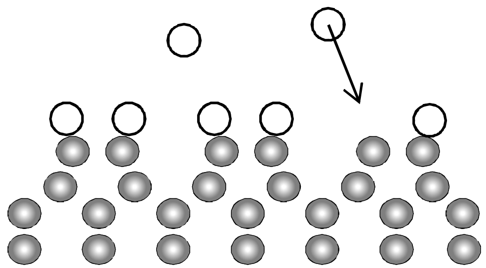
1. Prepare clean Si(001) (10-11/2010)

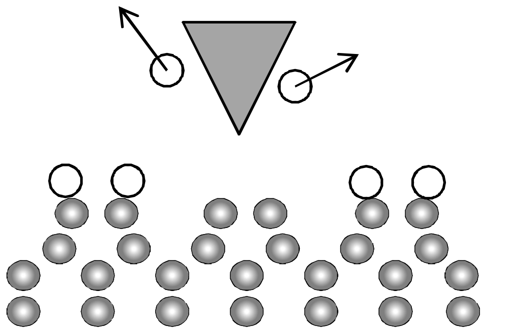
2. Low-defect H resist layers (11/2010)

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

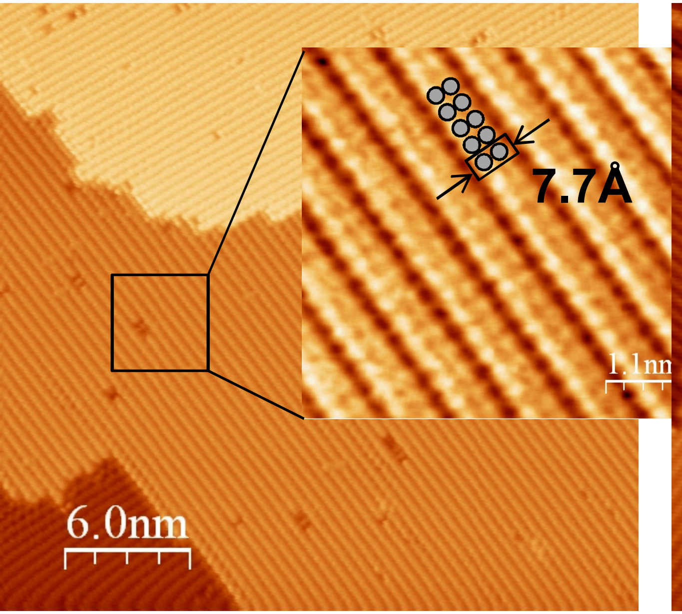
side views



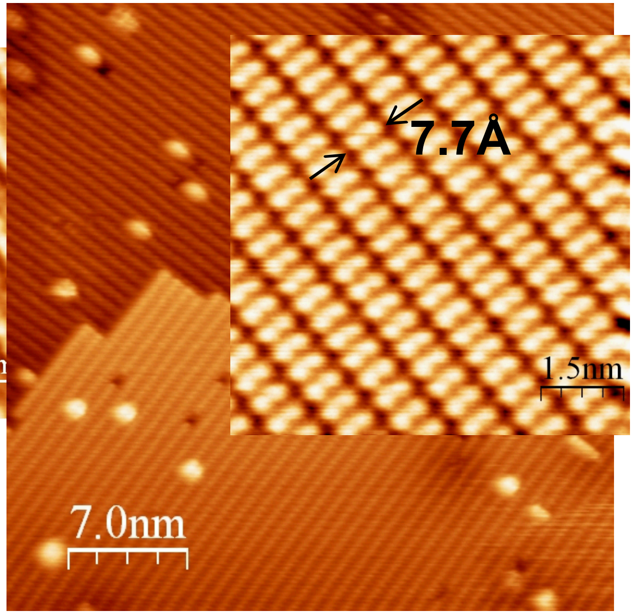




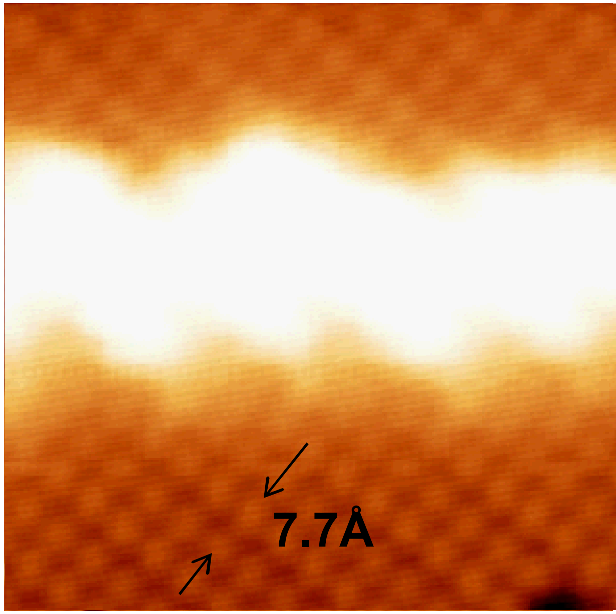
top views



Si(100)-2x1



Si(100)-2x1-monohydride

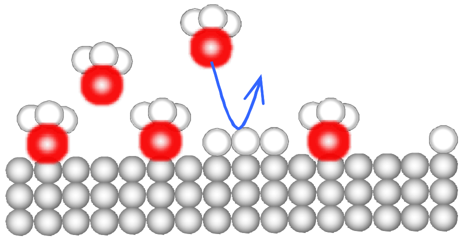


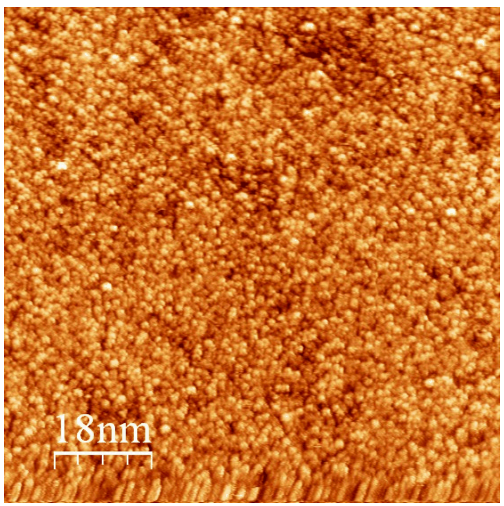
Progress on fabrication steps

Sandia National Laboratories

4. Adsorb PH_3 (3/2011-1/2012)

- **Expose to PH_3 gas**

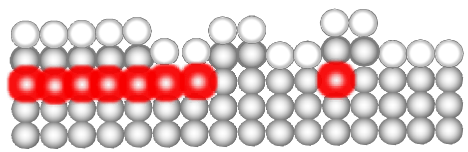


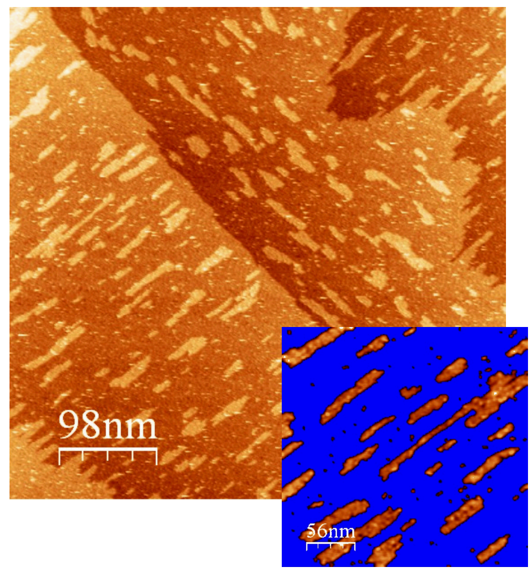


Mixed phase of H/PH_X
On Si surface

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

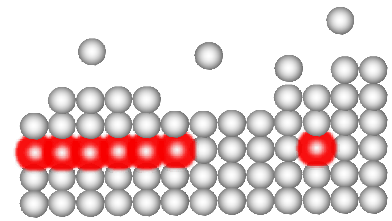
- **Anneal 350C-500C**





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

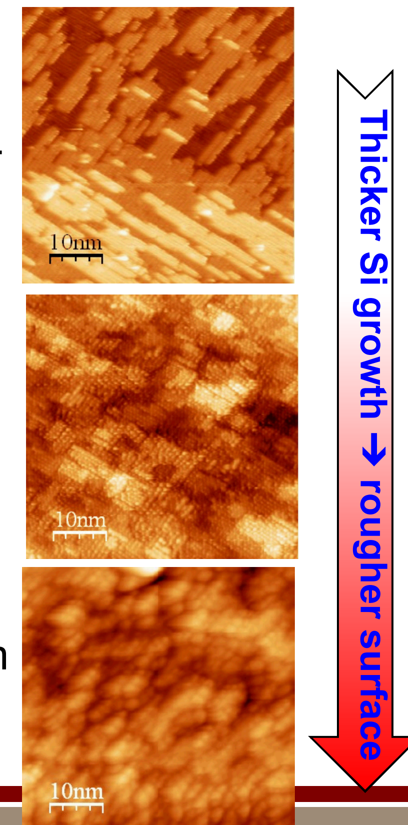
6. Bury device in epi-Si
(1/2011-2/2011)



0.7 ML

40 ML
~5 nm

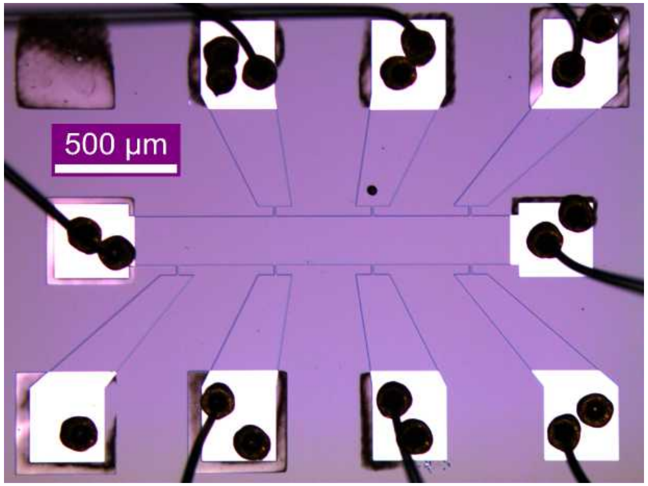
80 ML
~10 nm



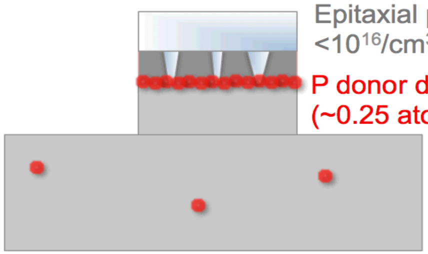
Initial transport test devices

(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 $n = 1.2\text{-}1.7 \times 10^{14}/\text{cm}^2$ mobility<100 cm^2/Vs

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

Preparing initial qubit designs

(4/2012-6/2012)

Brainstorm on what we need for device

1. Tunable tunnel barriers
   (ideally tunnel rates from 0 to >10^9 Hz)

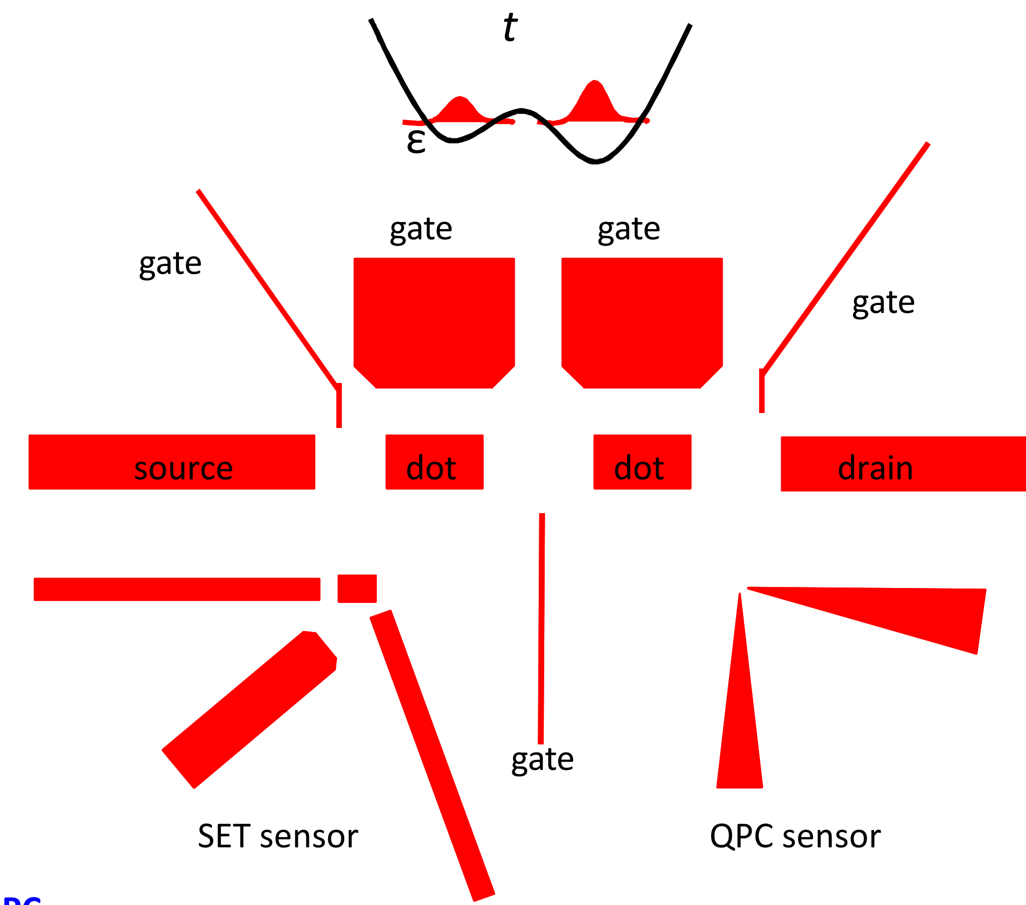
1. Tunable ε and dot occupation—few electron

3. A charge sensor

Charge qubit components

1. **Quantum dots (possibly single donor)**
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**

Tunable potential wells
Separated by tunable tunnel barrier



All elements are coplanar → crowding limits number of device elements

Approach to qubit design

Sandia National Laboratories

- **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 estimates of *relative* tunnel rates)

Qubit design starting points

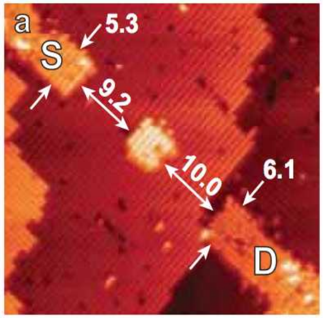
Charge qubit components
1. **Quantum dots**
2. **Source/drain leads and tunneling gaps**
3. **Gates**
- Plungers to tune chemical potentials (definitely)
- Barrier gates to tune tunnel barriers/rates
4. **Charge-state readout e.g. SET or QPC**

2D planar Lithographic delta-dope devices in Si:

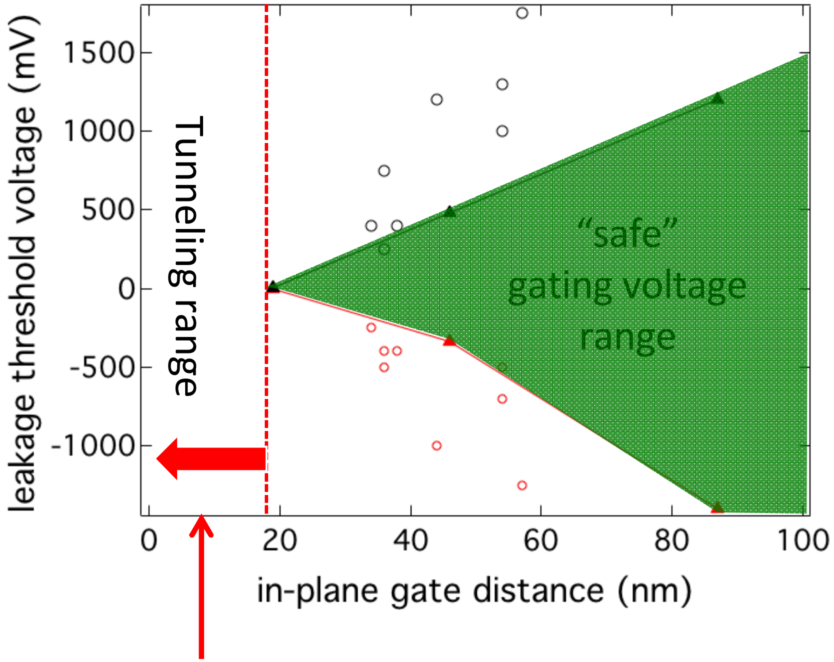
Design= What shape? Size? How far apart?

Gate isolation gaps:

Dots: few electron



UNSW
units=nm



Source & Drain:
4-7 nm-wide lines

Tunnel Junctions:
8-10 nm

Charge sensor for qubit state

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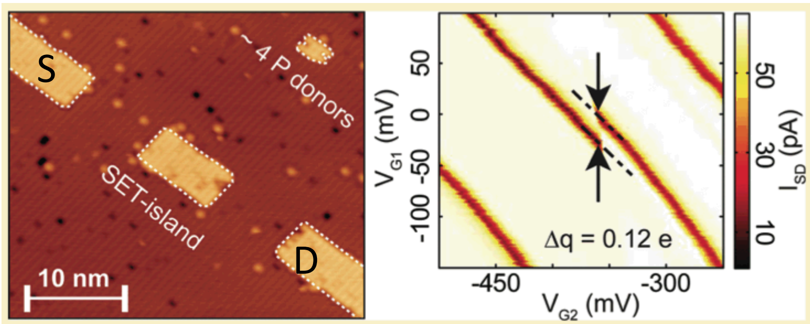
- **SET has been demonstrated (12% charge transfer signal)**
- **Still no demonstration of charge sensing via QPC**

Charge sense via SET

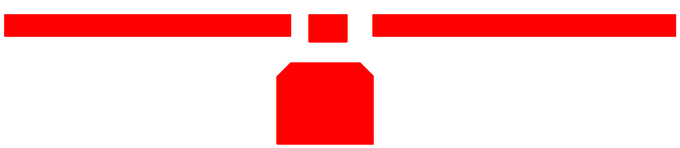
Mahapatra…Simmons Nano Lett 11, 4376 (2011)

U N S W



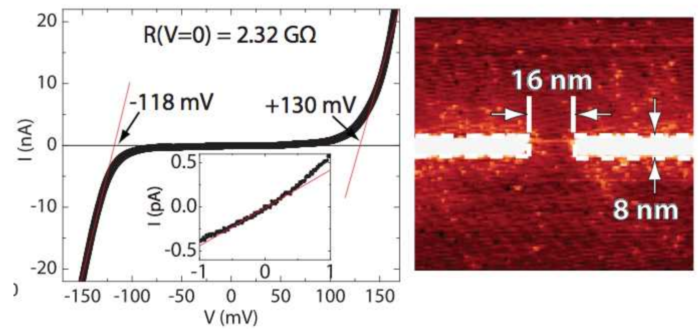
Single e^- on 4 donor dot induces
V equivalent to 0.12 e^- on SET dot

→ **abrupt change in SET S-D current**

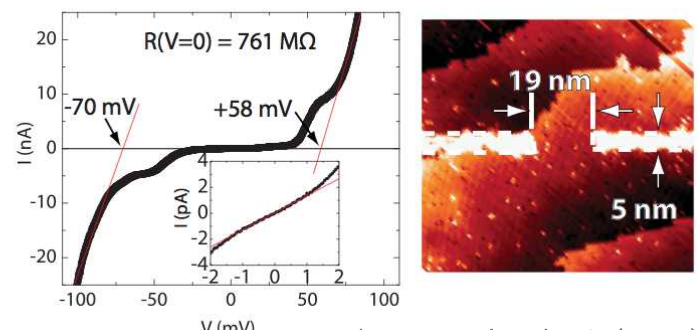


Charge sense via QPC (??)

Tunnel gaps have been characterized



U N S W



U N S W

W. Pok UNSW PhD thesis (2011)

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

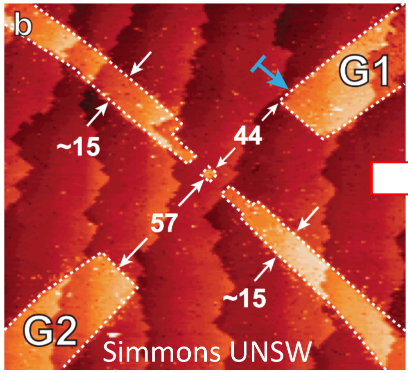
Electrostatic & transport modeling for qubit design

Sandia National Laboratories

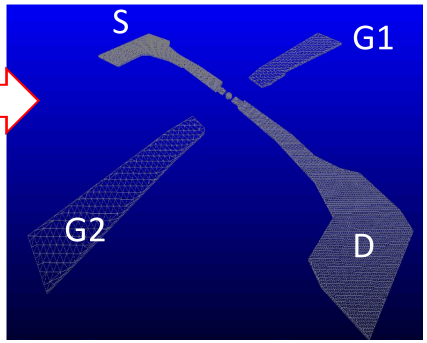
- Quantitative models have been demonstrated for donor devices
- NEMO (G. Klimeck): Atomistic detail, quantum properties…
- For charge qubit: use finite element models (FastCap) + transport model (CapNet)

Electrostatics modeling

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



3D finite element (FastCap)



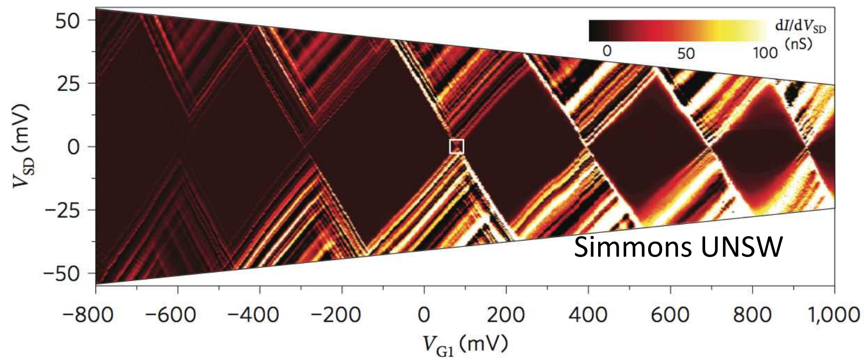
Dot capacitances (aF) & gate lever arms

	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

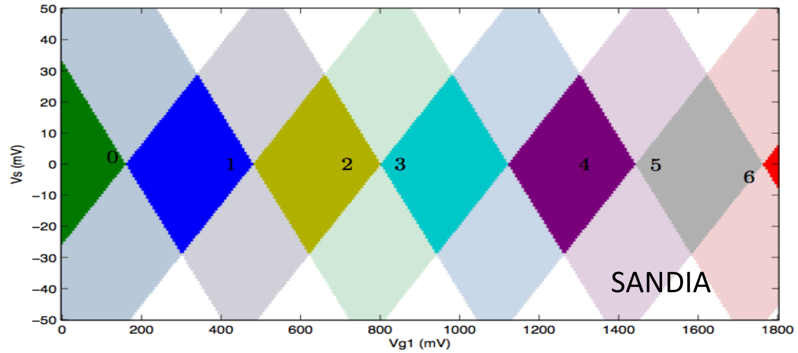
~ Quantitative agreement between model/experiment

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)

*Fuechsle, UNSW PhD thesis 2011

Initial charge qubit designs

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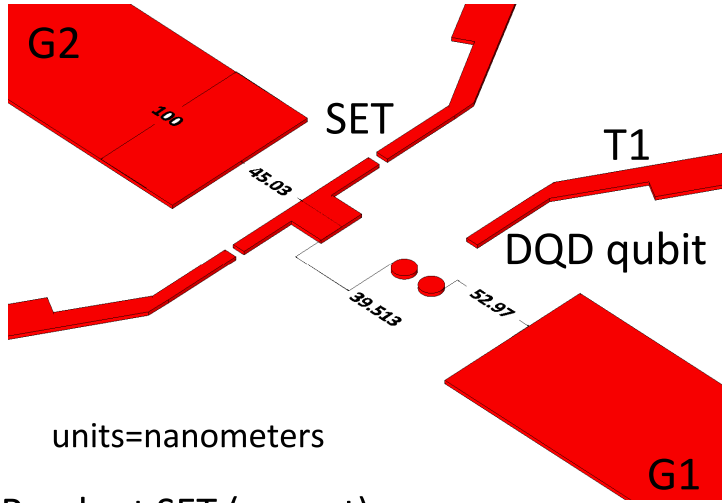
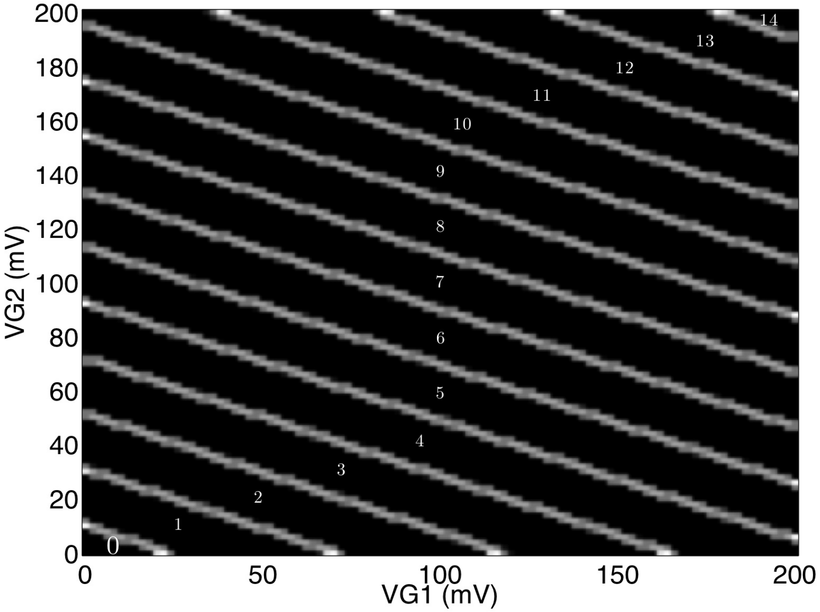
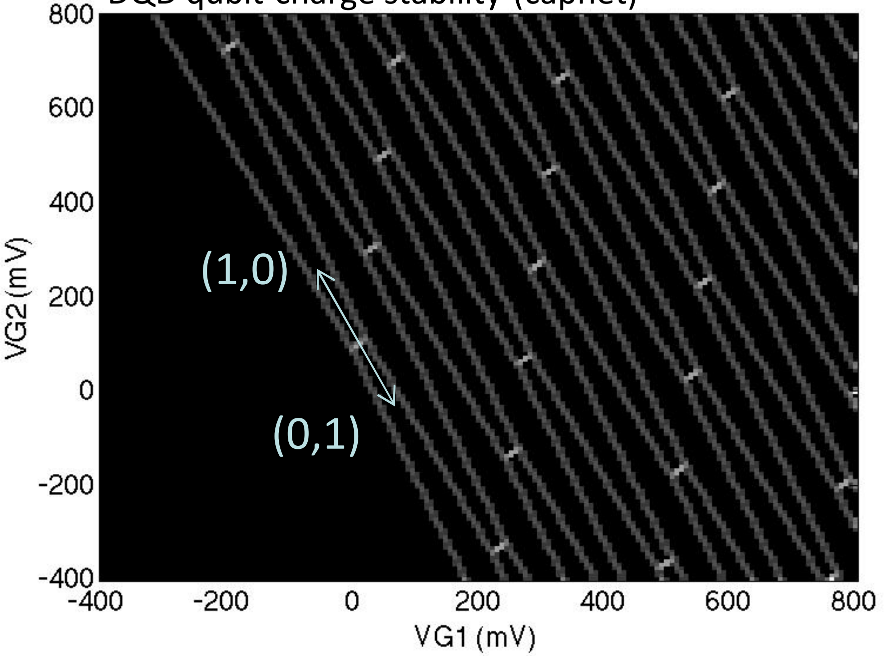


Readout SET (capnet)



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

DQD qubit charge stability (capnet)



- Many DQD charge states accessible in a realistic range of VG1 & VG2
- The SET has many 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

Sandia National Laboratories

- 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

Milestones for STM fab

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- Year 1
  - -Recover old STM chamber outside of clean room for non-toxic gas experiments
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  - ✔Build clean room STM
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- 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) (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

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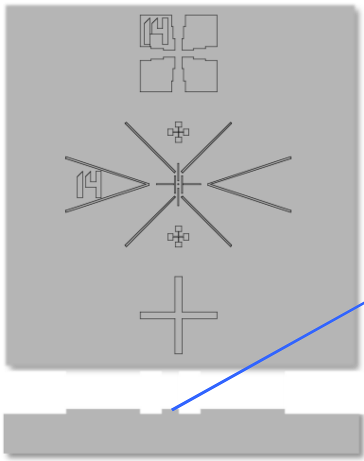
Testing PH_3 system

1. Start w clean Si(001)

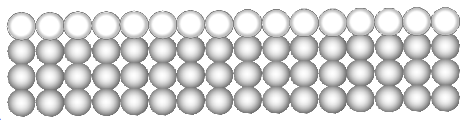
2. Adsorb H resist
Self-limiting 1 monolayer

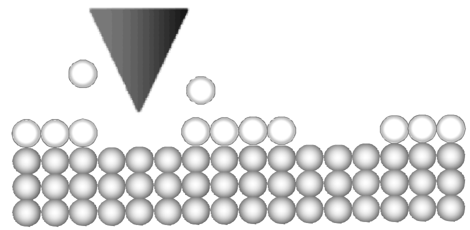
3. Pattern w STM
Atomic-precision

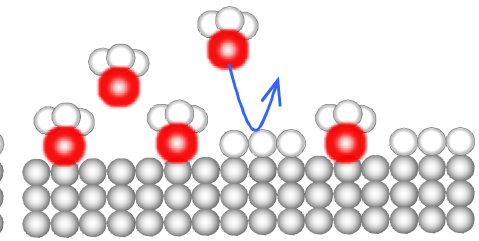
4. Adsorb PH_3



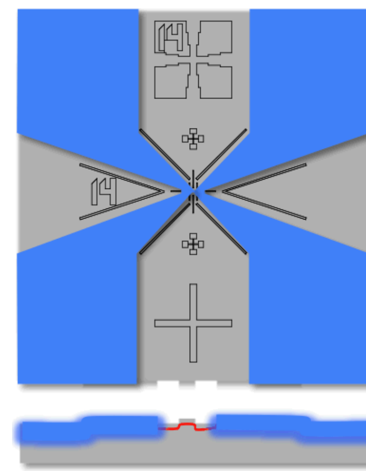
Etched alignment marks
J. Dominguez

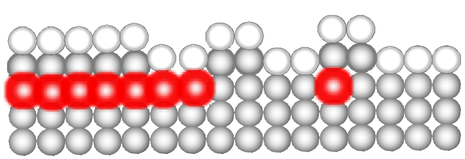


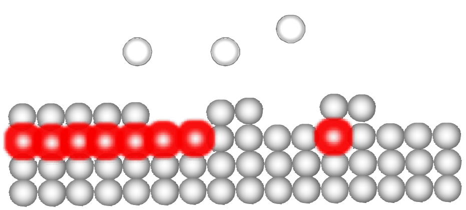


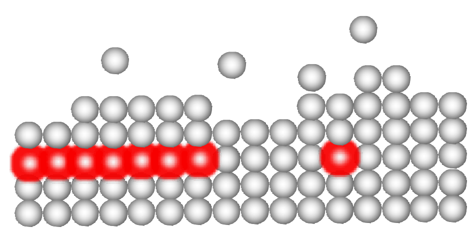


Al depo+liftoff
J. Dominguez









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

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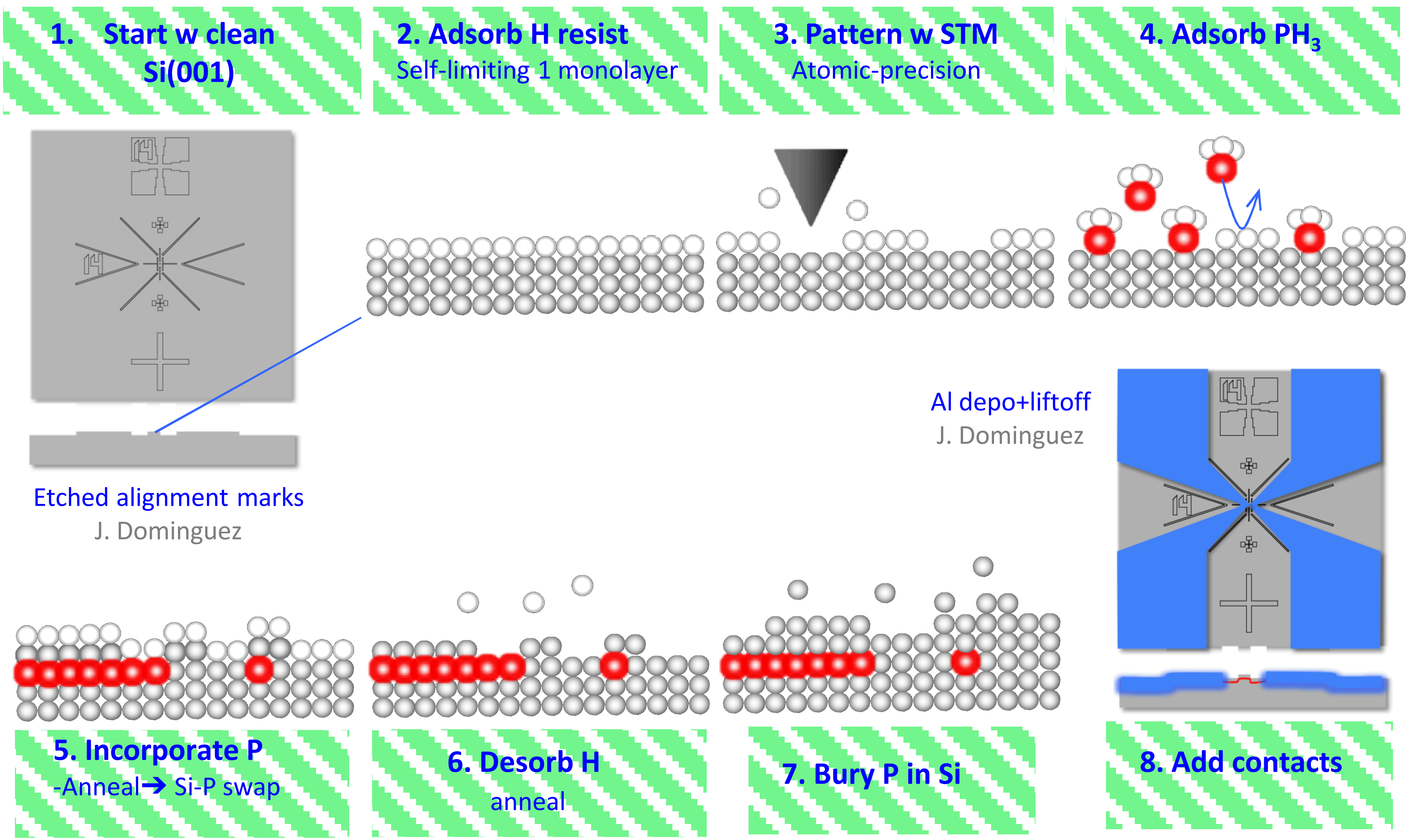

Summary of work

- 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
- Design and modeling of initial qubit structures in-progress