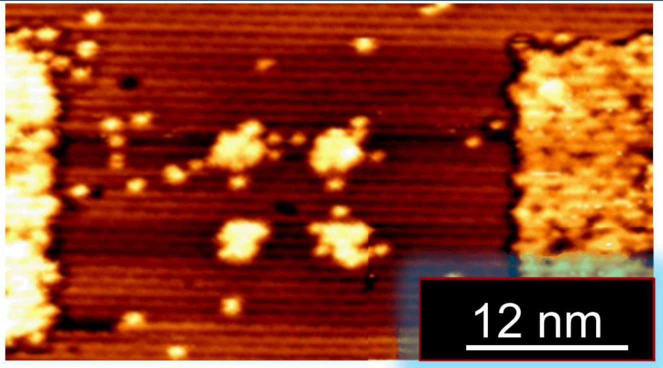
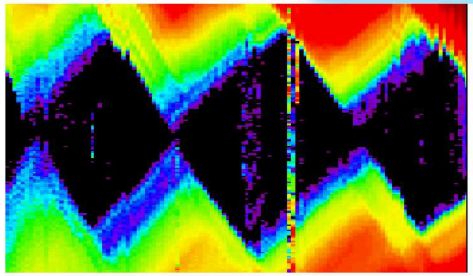
SAND2018-12253C





Device fabrication at the atomic scale

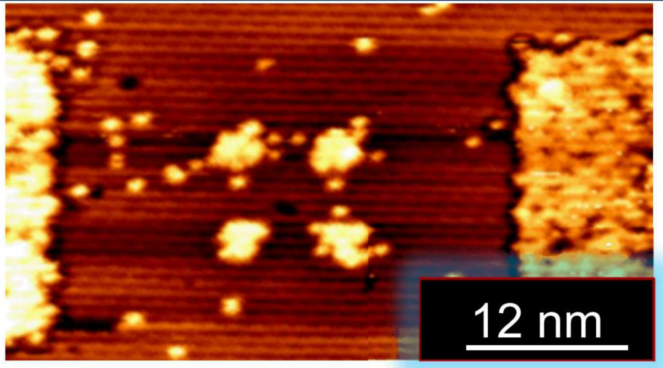
Shashank Misra

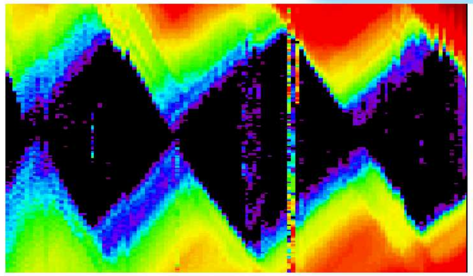
OSA Incubator

Defects by Design: Quantum Nanophotonics in Emerging Materials

October 28-30, 2018

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.





Device fabrication at the atomic scale

Ezra Bussmann

Workshop on atom by atom fabrication via electron beams and scanning probes at Oak Ridge National Laboratory

November 1 &2 , 2018

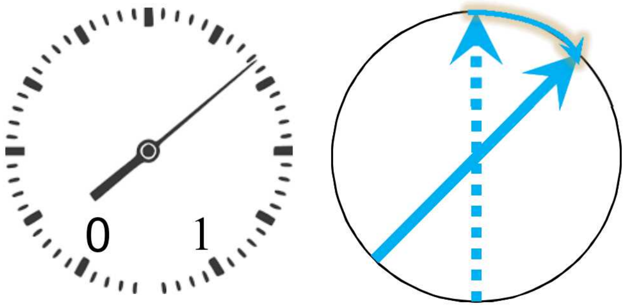
U.S. DEPARTMENT OF ENERGY
National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

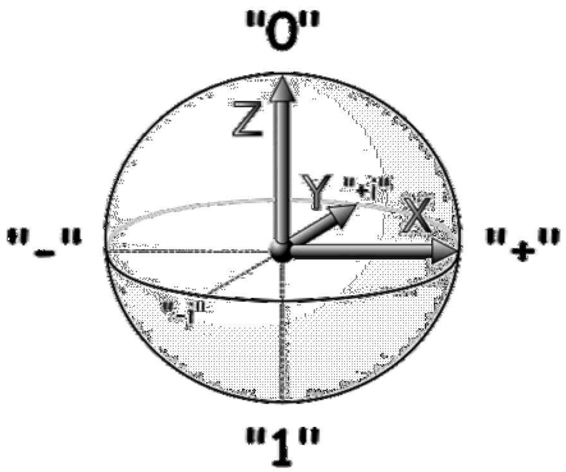
Outline

- Comparison of atomic scale techniques
- STM-based atomic-scale devices
- Future directions

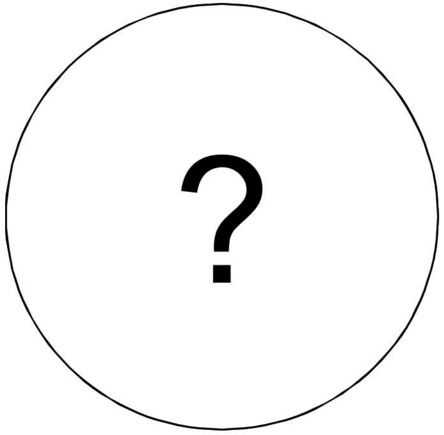
Making quantum systems is challenging



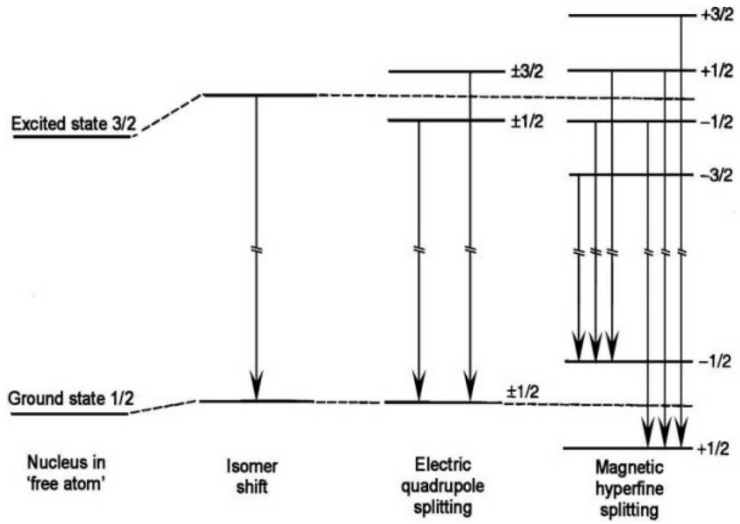
Measurement and manipulation



Quantum system



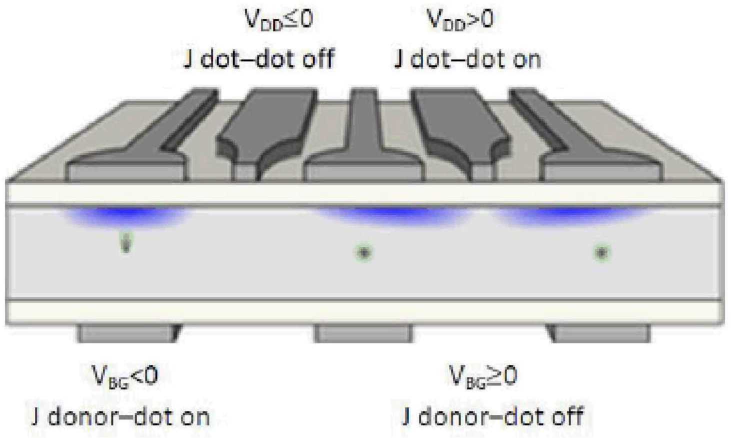
System under test



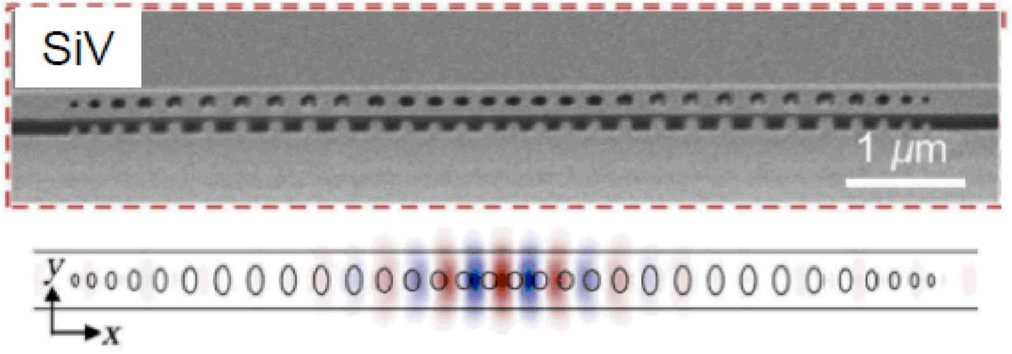
Requirements-

1. Single, isolated quantum thing
2. "Big" relative energy scales
3. Sensitive detection & manipulation

Making quantum systems is challenging



T. Schenkel et al., US 8,816,325 B2 (2014)



M. J. Burek et al., Phys. Rev. Applied 8, 024026 (2017)

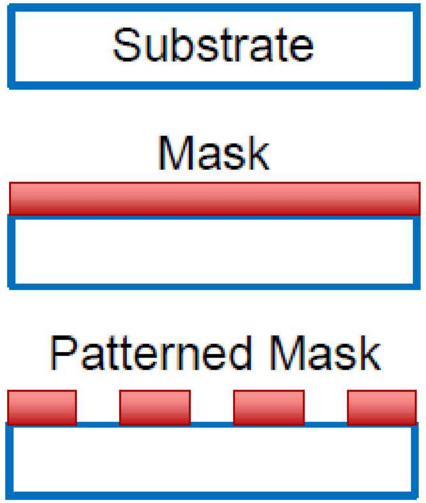
Requirements-

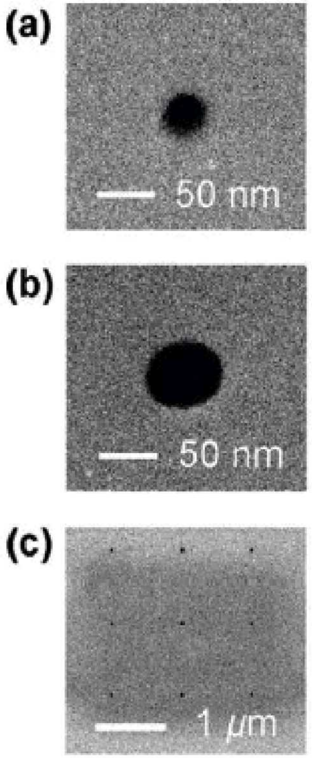
1. Single, isolated quantum thing
2. "Big" relative energy scales
3. Sensitive detection & manipulation

Translated-

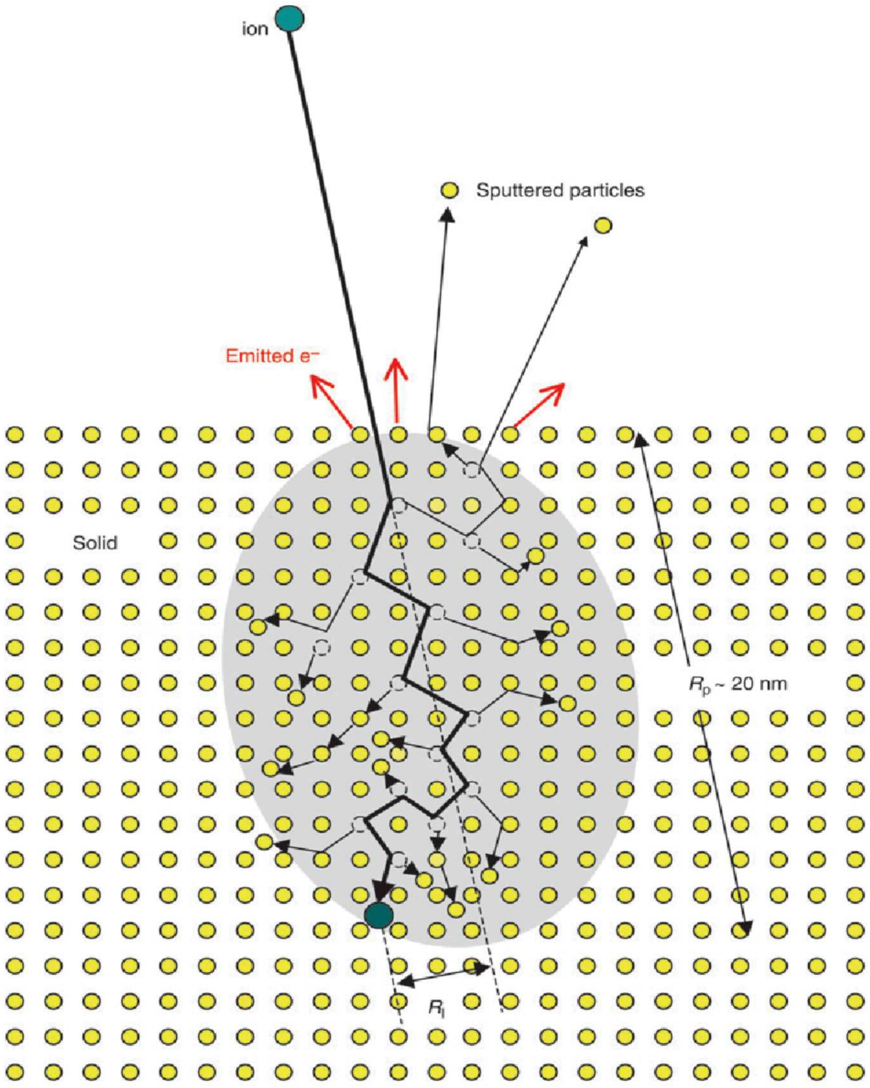
1. Create a single impurity …
2. At a fixed location …
3. In a clean, low noise analog device!

Options – masked implantation



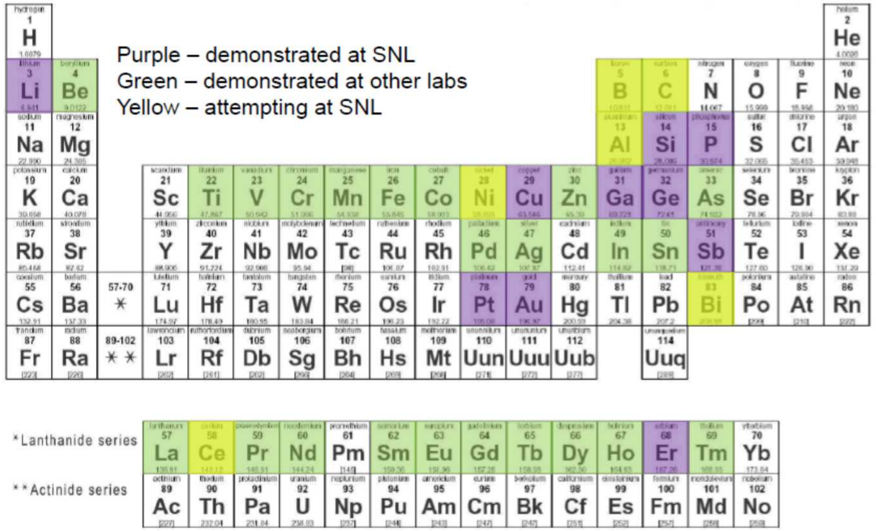


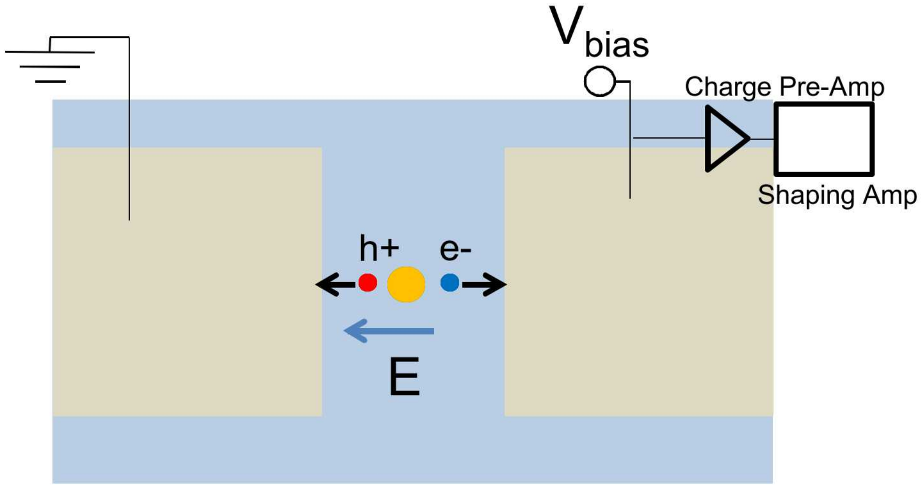
Toyli, Nano Letters (2010)



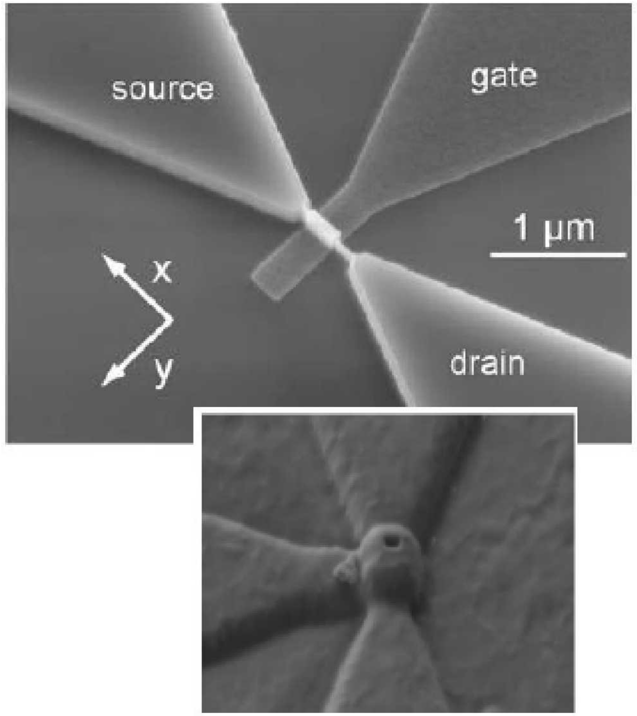
	Masked implant
Number	Variable
Atomic species	Large variety
Resolution	10's of nm
Substrate device flexibility	Large variety

Options – focused ion beam





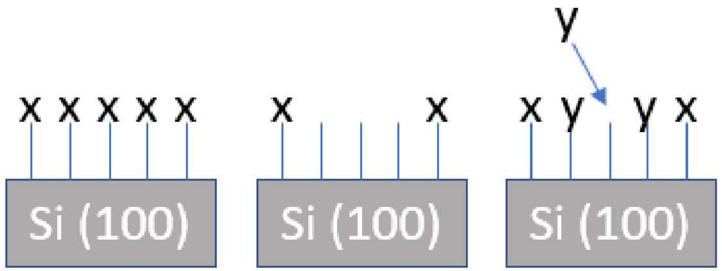
Top View

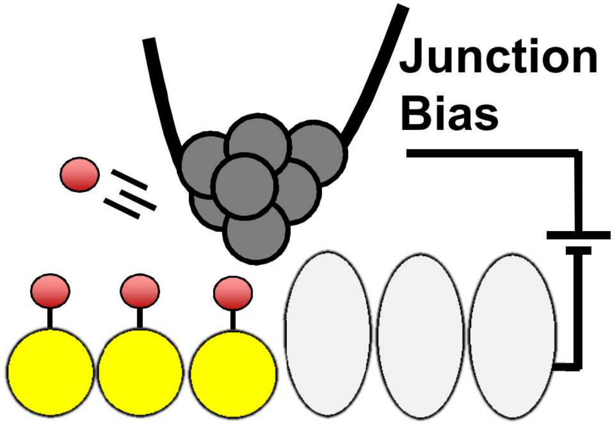


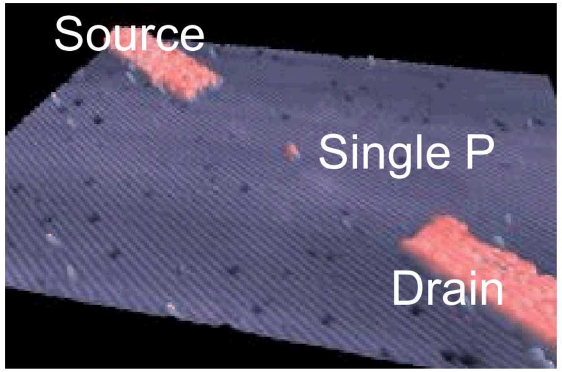
Weis, NIM B (2009)

	Masked implant	Focused ion beam
Number	Variable	1
Atomic species	Large variety	Some variety (liquid metal alloy)
Resolution	10's of nm	10's of nm
Substrate device flexibility	Large variety	Large variety

Options – STM-based fabrication







Fueschle, Nat. Nano (2012)

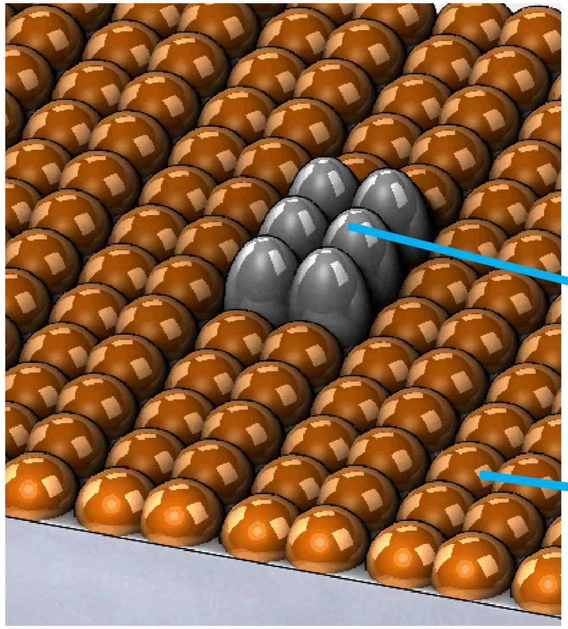
	Masked implant	Focused ion beam	STM-based fabrication
Number	Variable	1	1
Atomic species	Large variety	Some variety (liquid metal alloy)	P
Resolution	10’s of nm	10’s of nm	+/- 0.3 nm
Substrate device flexibility	Large variety	Large variety	Si

Outline

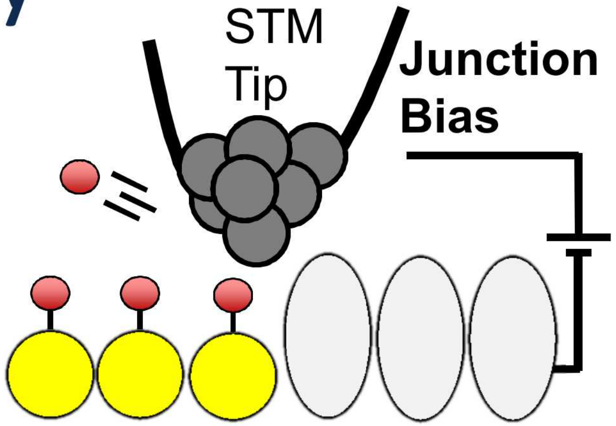
- Comparison of atomic scale techniques
- STM-based atomic-scale devices
- Future directions

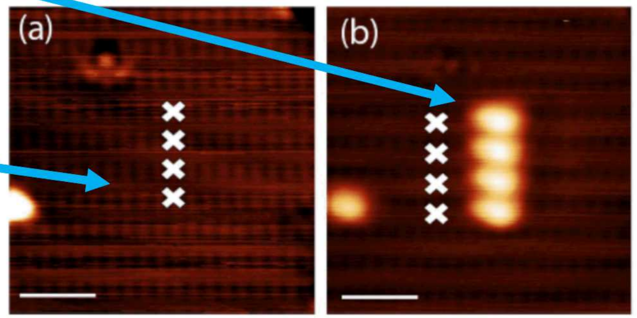
Hydrogen lithography

Clean Si (100): 1 unsatisfied bond/ atom



Passivate reactive bond with hydrogen

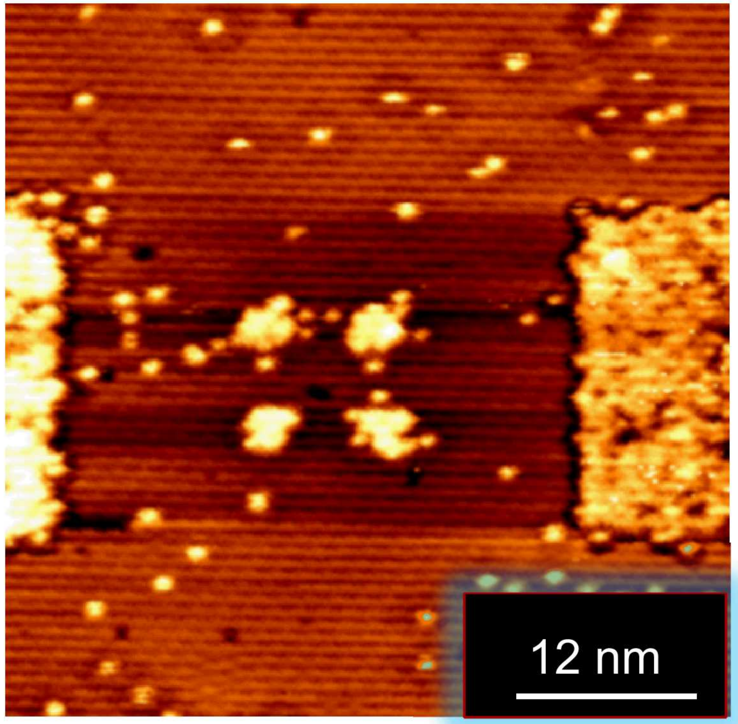




Moller, Nanotechnology (2017)

Scanning tunneling microscope

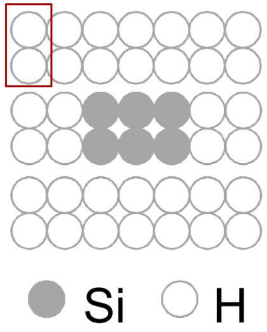
- Remove H one dimer at a time or areas up to 15 μm
- Image reactive dangling bonds
- Characterize chemistry

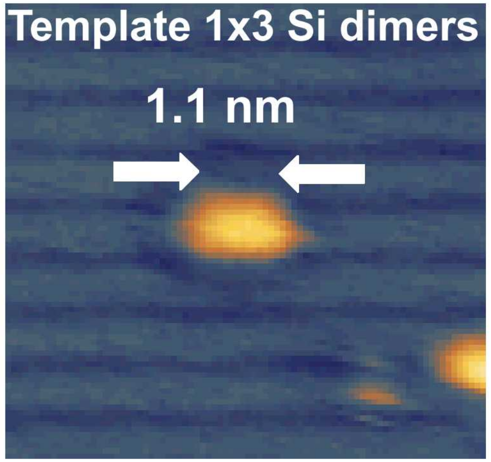


Phosphorus donors in Silicon

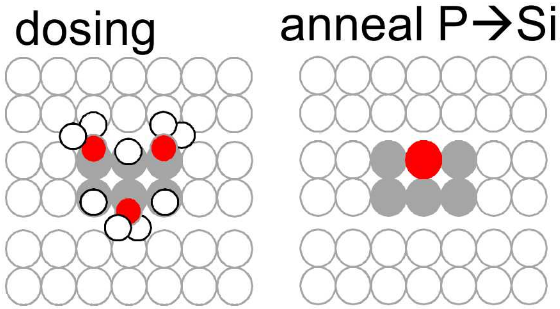
Step 1: STM H lithography

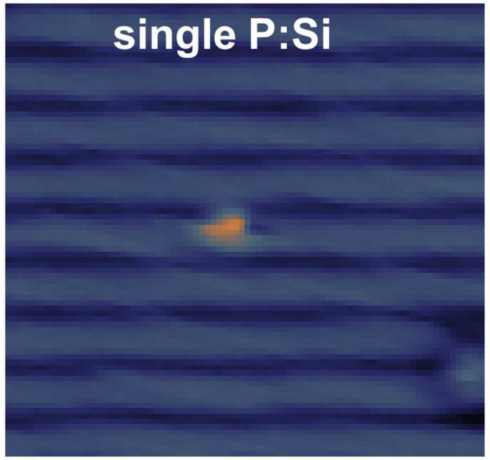
plane view

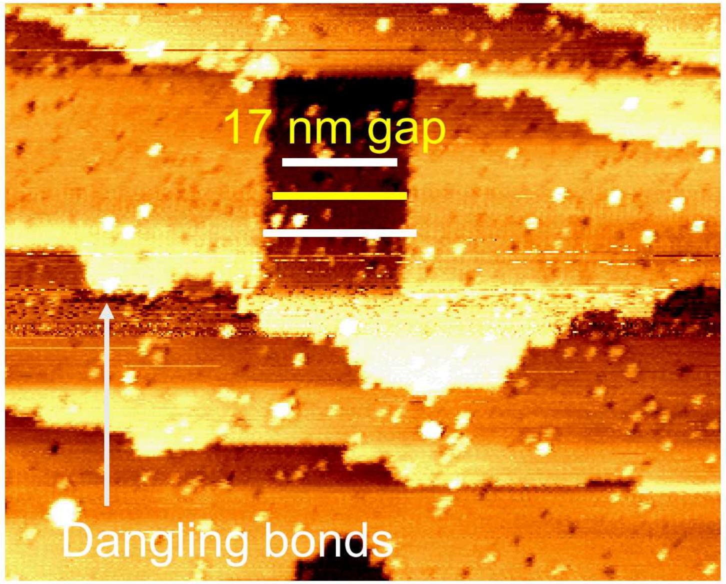


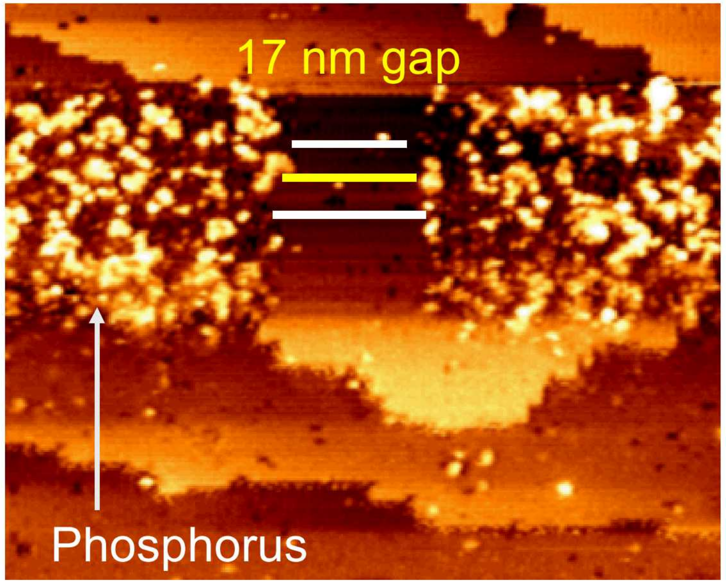


Step 2: P incorporation



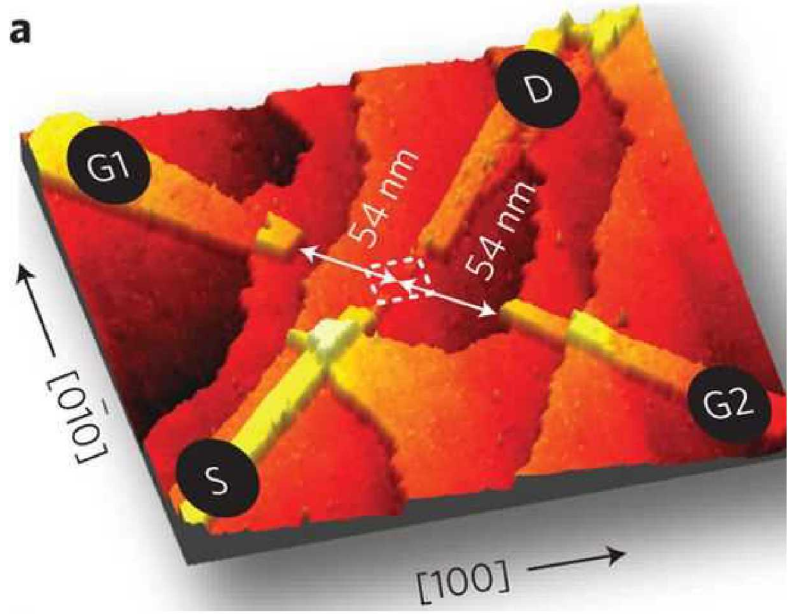


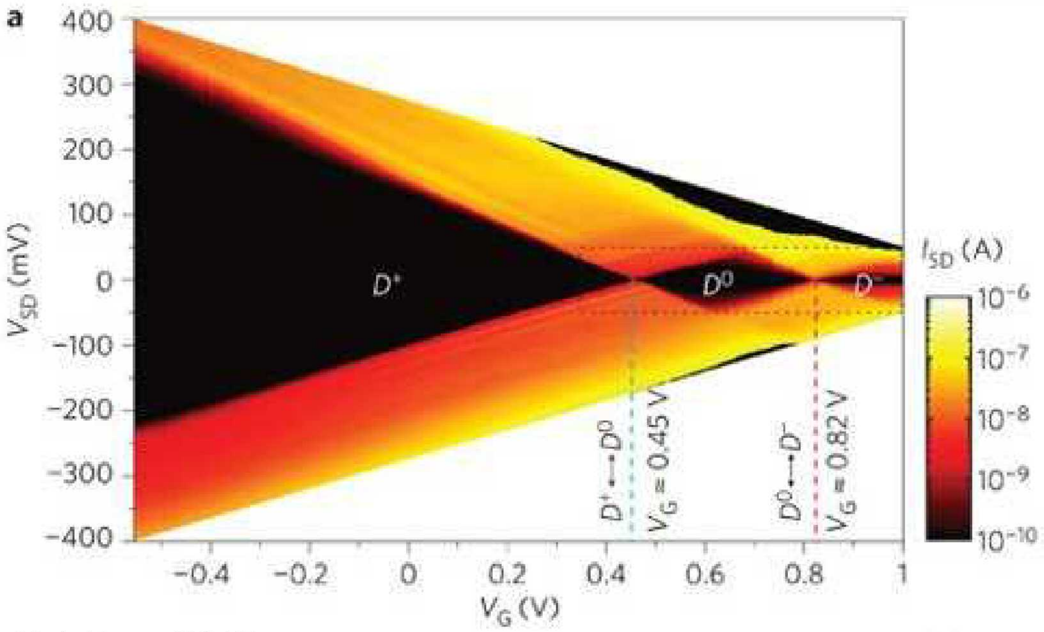




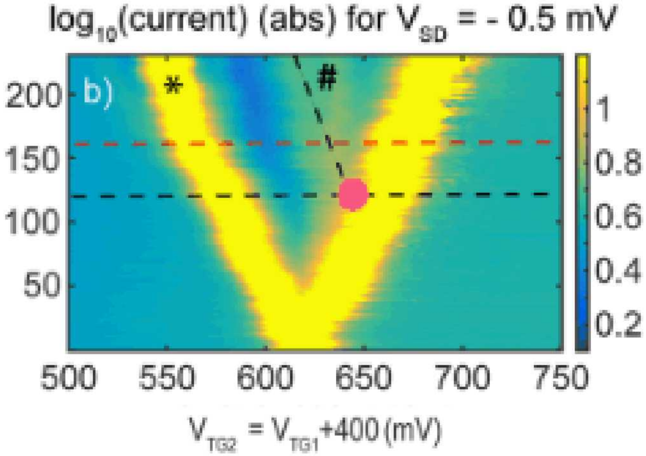
React phosphine into open patches as small as 3 by 2 atoms

Single atom transistor





Fueschle, Nat. Nano (2012)



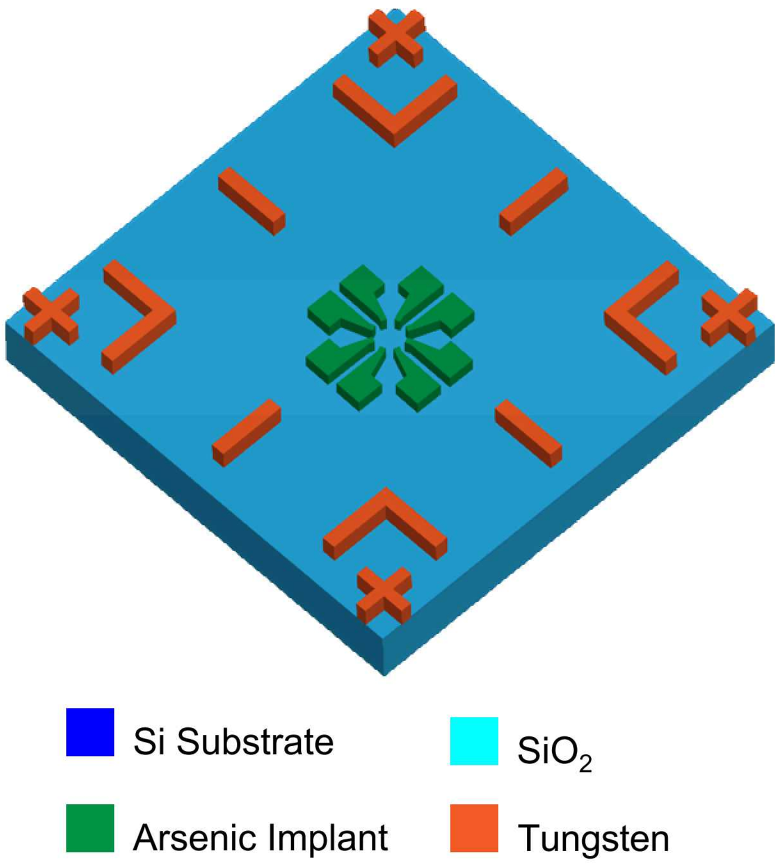
Tettamanzi, ACS Nano (2016)

Pattern sense and manipulation electronics using phosphorus (metallic)

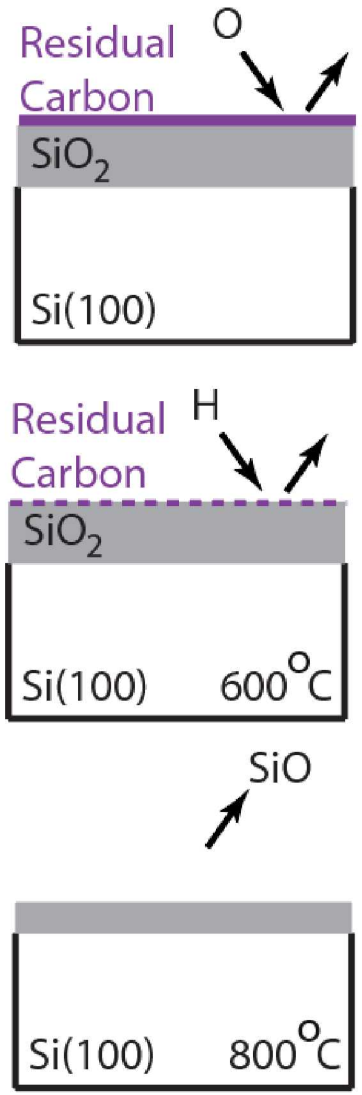
Ground state and excited state spectroscopy of a single P donor in Si

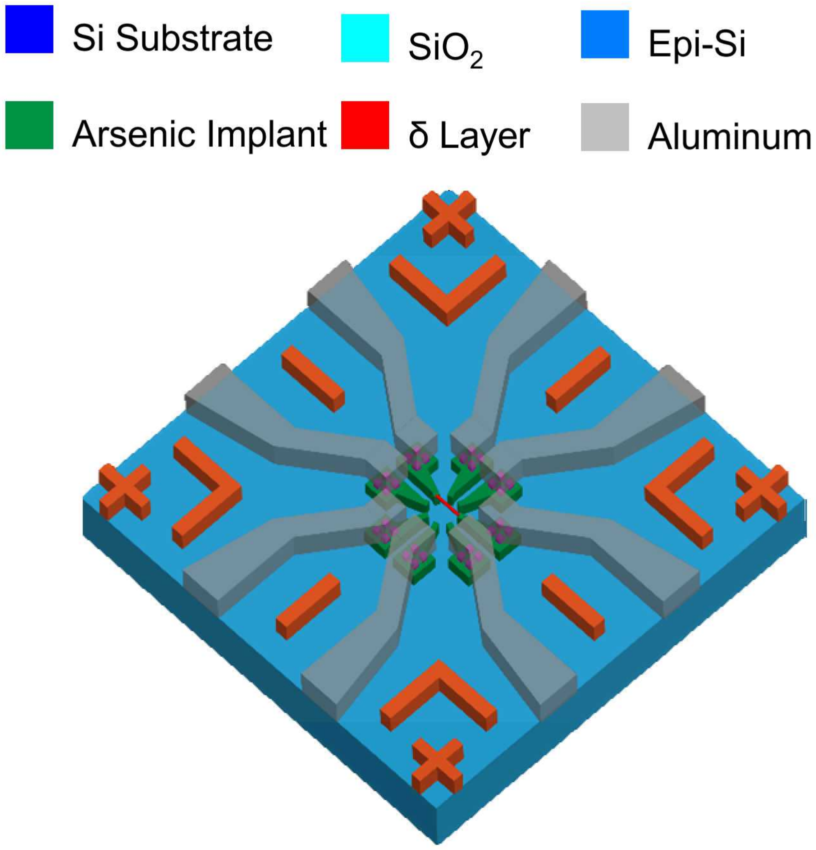
Limitations from thermal budget - integration

Pre-processing integration limited by sample clean.



Ward, APL (2017)





New SNL clean allows for all photolithographic process.
1 day to make contacts.

Limitations from thermal budget - quality

Post-processing integration limited by donor layer diffusion – 400 C.

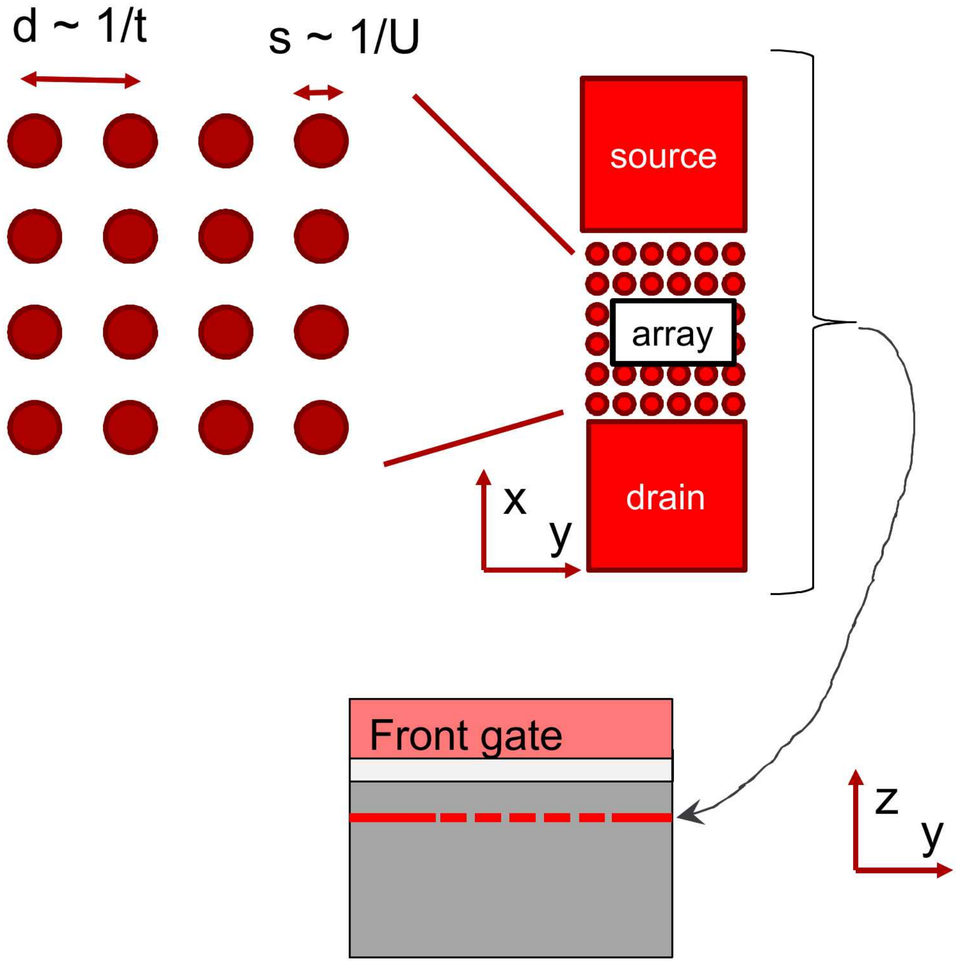
Silicon cap is low-temperature growth – lots of defects, which are themselves quantum systems

No path yet to integration with high quality MOS electronics.

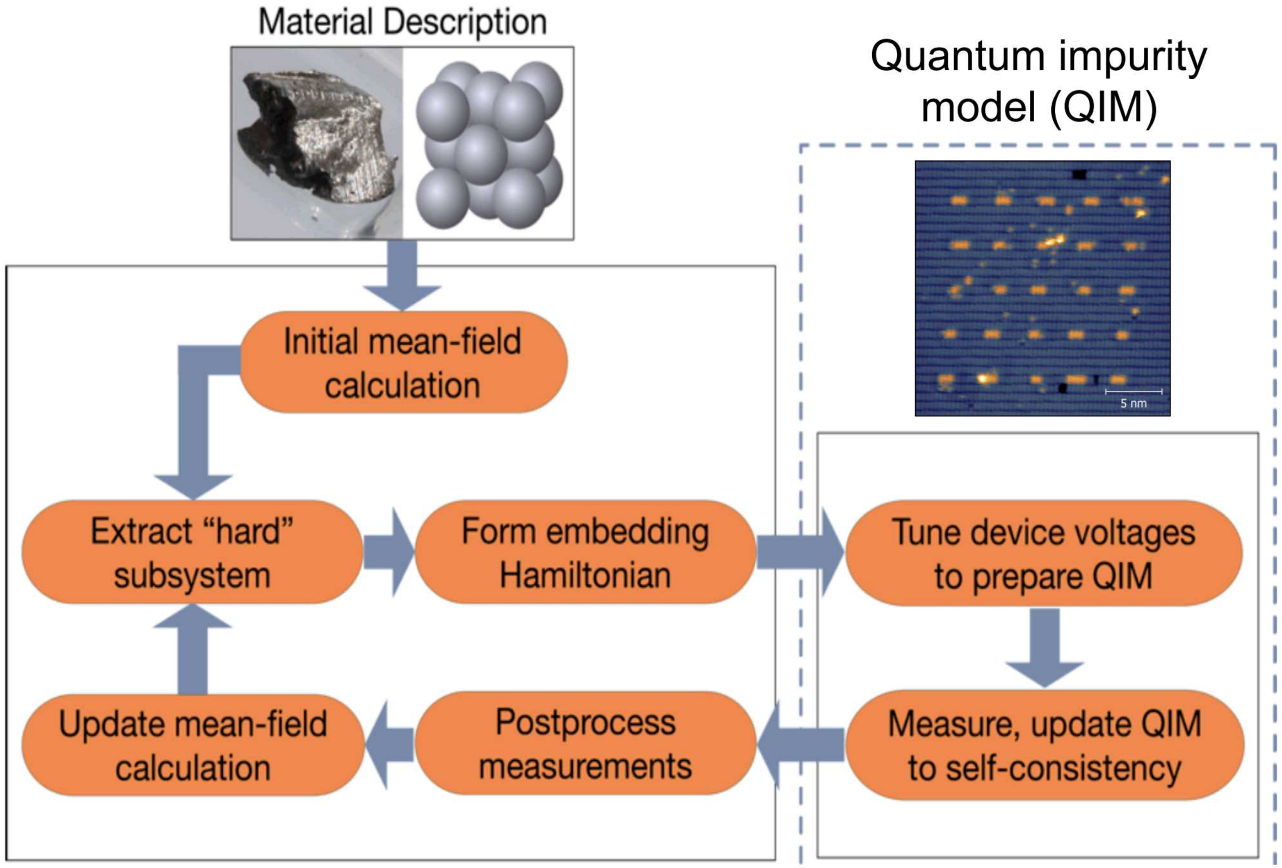
SNL, NIST, IBM, UNSW …

How are we using STM-patterned donor devices?

Analog quantum simulation



SNL & NIST



Extrapolation to real quantum materials problem

Analog simulation with finite size array

Baczewski (SNL)

Outline

- Comparison of atomic scale techniques
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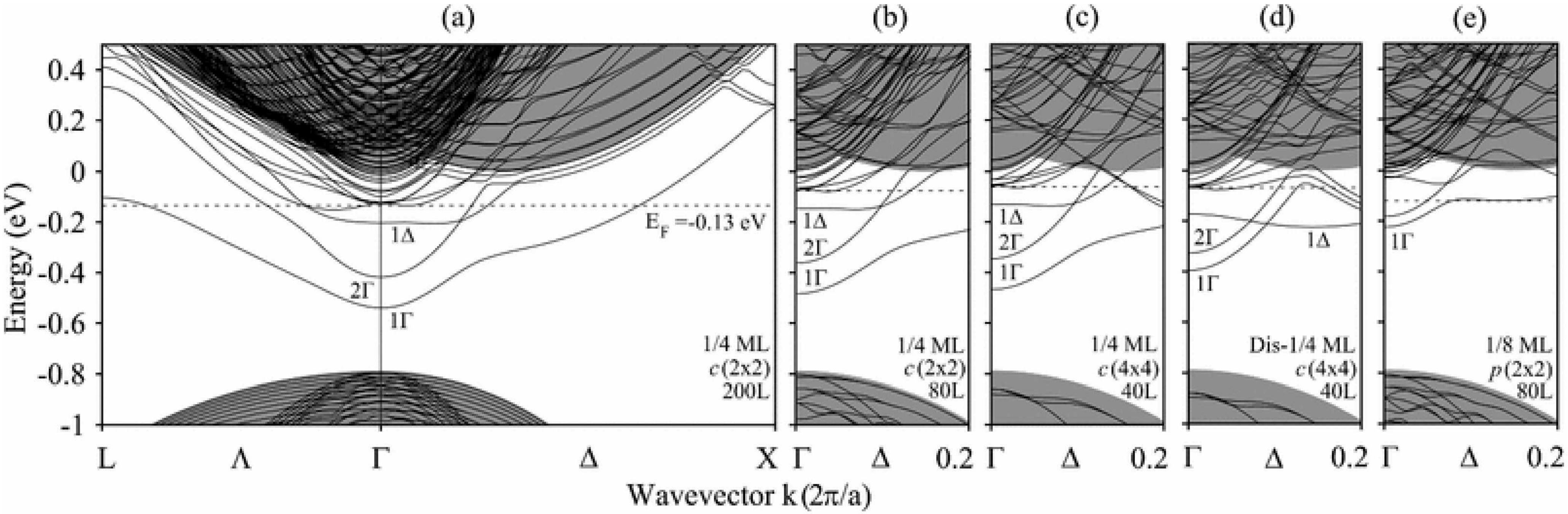
- Future directions

Future directions – optical response?

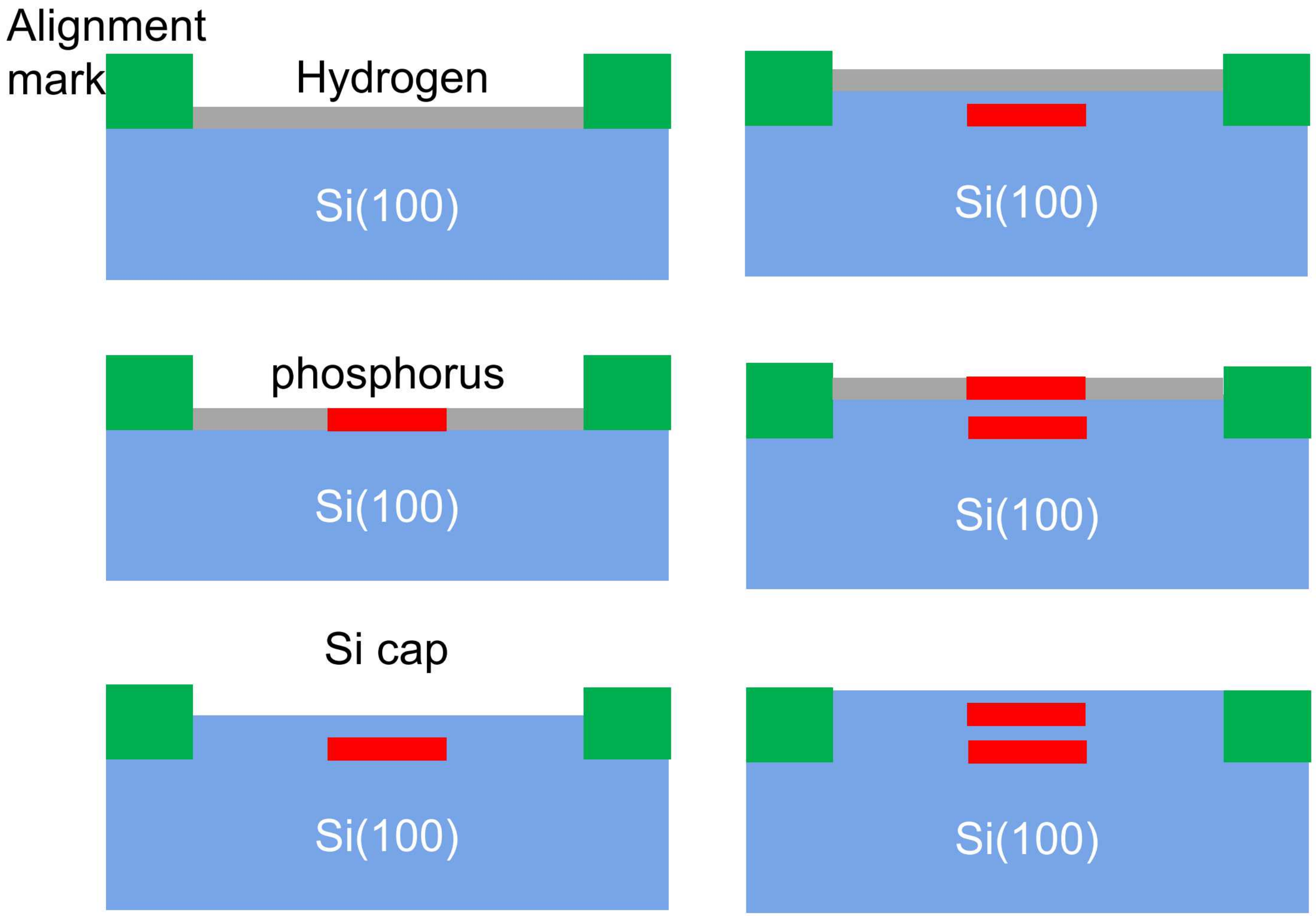


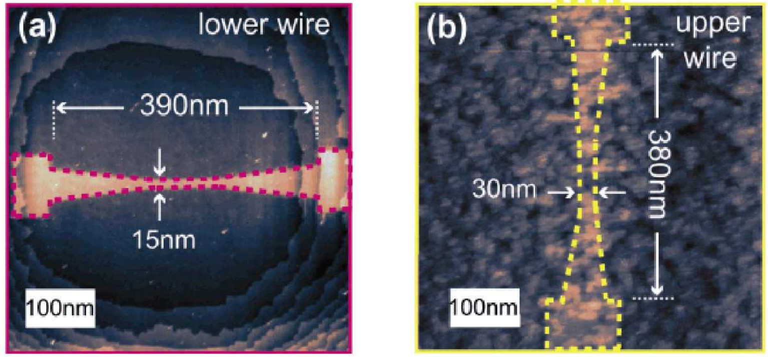
This much P in Si changes the electronic structure from parent Si.

$Si_{0.75}P_{0.25}$ is a direct band gap semiconductor

Future directions – 3D patterning?

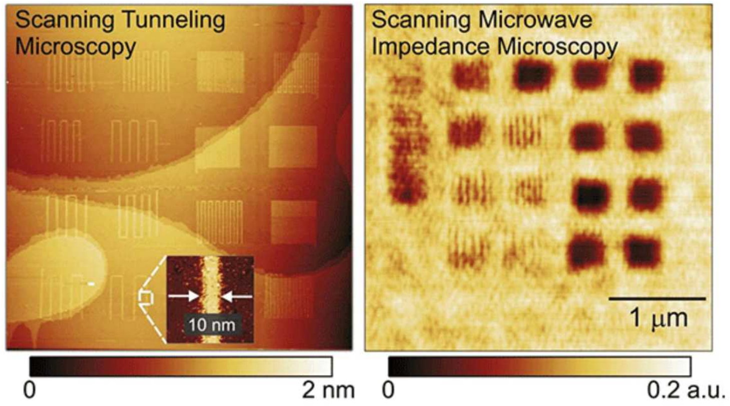
Sandia National Laboratories





McKibbon, Nanotechnology (2013)

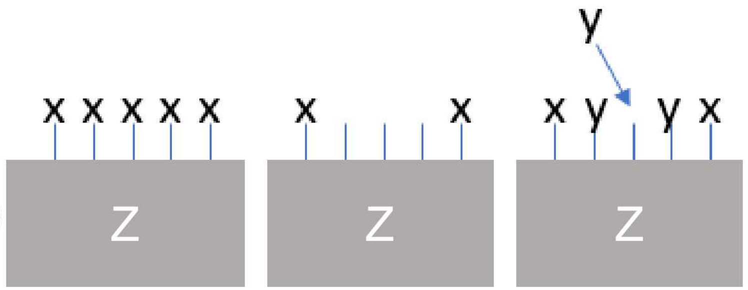
Alignment of sub-surface feature using alignment marks or sensing electrostatics



Scrymgeour, Applied Surf. Sci. (2017)

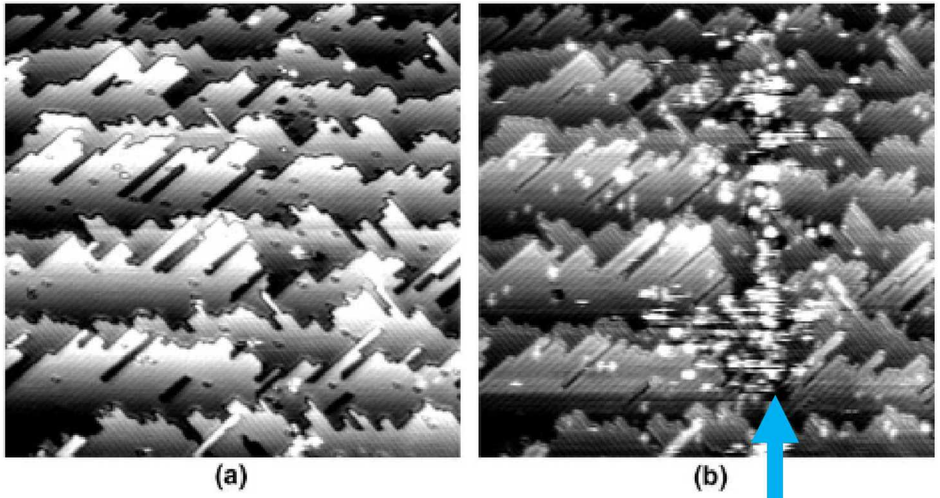
Future directions – color center in diamond?

Requirements
- Resist can be patterned
- Molecule is selective to reactive sites
- Combinatorial possibilities



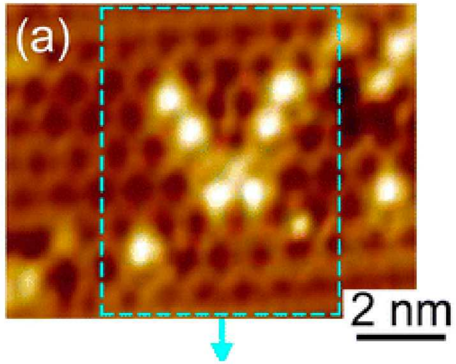
Right now…
- Z = Si
- X = H, Cl, I, Br
- Y = PH_{3}, AsH_{3}

Hydrogen lithography (X) on diamond (Z)

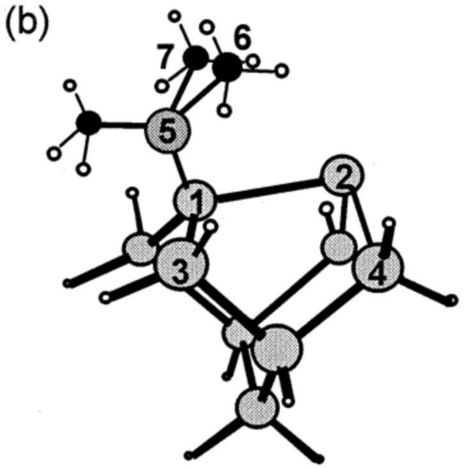


Bobrov, Surface Science (2003)

Trimethylamine (Y) on Silicon (Z)



Bobrov, Surface Science (2003)



Cao, JACS (2001)

Possibilities outside of column 4 as well – e.g. GaN

Thanks to the folks who do all the real work…

STM	Fabrication	Measurement	Modeling
Mike Marshall	DeAnna Campbell	Tzu-Ming Lu (DEAL)	Leon Maurer (DEAL)
Justin Koepke	Dan Ward	Lisa Tracy (DQM)	Andrew Baczewski (DQM)
Shashank Misra		David Scrymgeour	Mitchell Brickson (DQM)

DEAL = transistor work
DQM = Hubbard lattice work

If you'd like more information, please contact:

- *Masked implant:* Dan Ward
- *Focused ion beam:* Ed Bielejec
- *Modeling:* Andrew Baczewski
- *Hydrogen lithography:* Shashank Misra

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