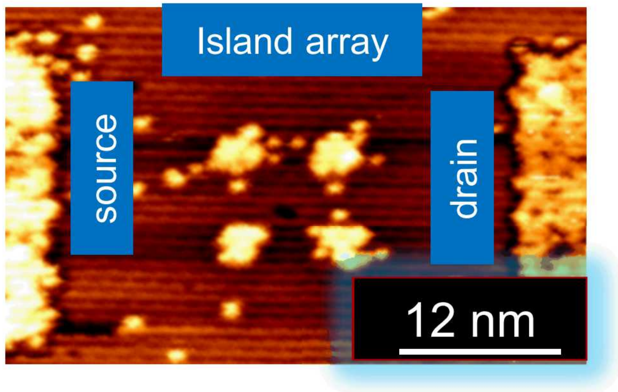
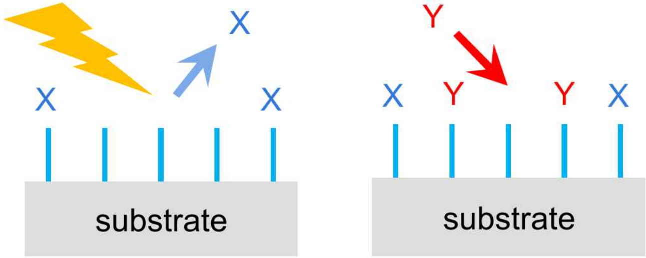
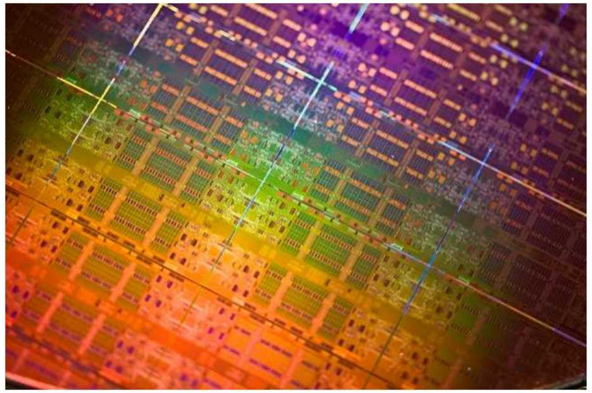
SAND2019-2220C







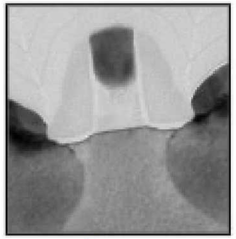
Precision Manufacturing

Shashank Misra

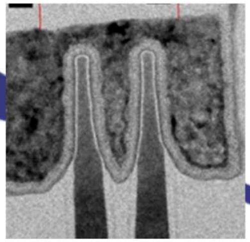
Sandia National Laboratories

Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. This presentation describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

What if you could make devices atom-by-atom?



65 nm



10 nm

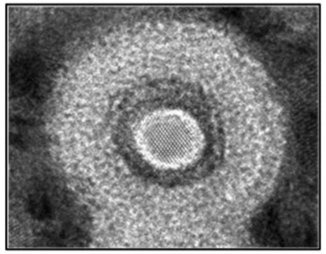
Top-down fabrication

?

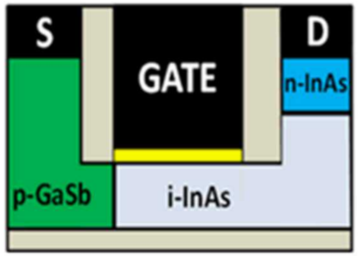
5-7 nm

Atomic Limit

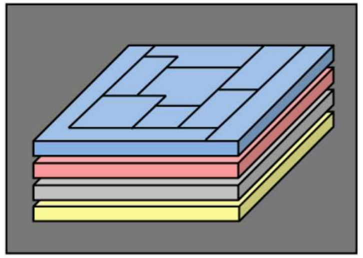
What would it take to evaluate new device opportunities with control at the atomic limit?



Nanowire Transistors

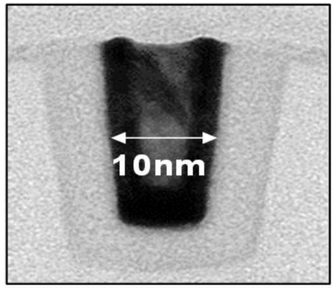


III-V Transistors

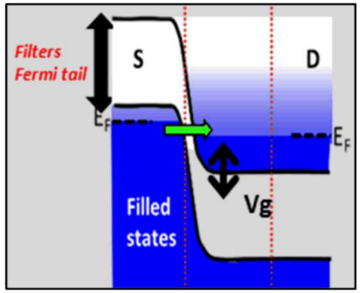


3D Stacking

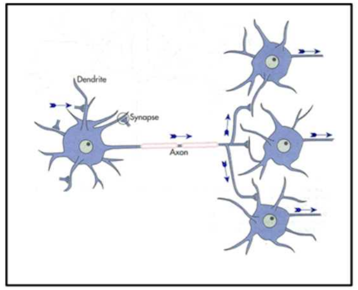
Mark Bohr, Intel 2018



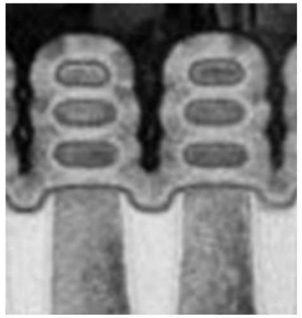
Dense Interconnects



Tunnel FETs

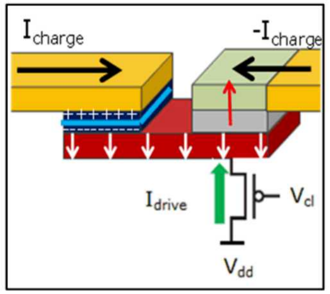


Neuromorphic Computing

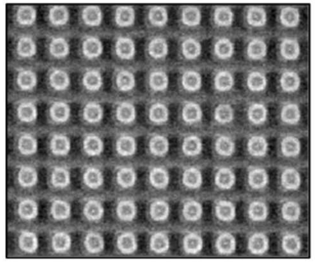


Nanosheets

Huiming Bu, IBM 2017



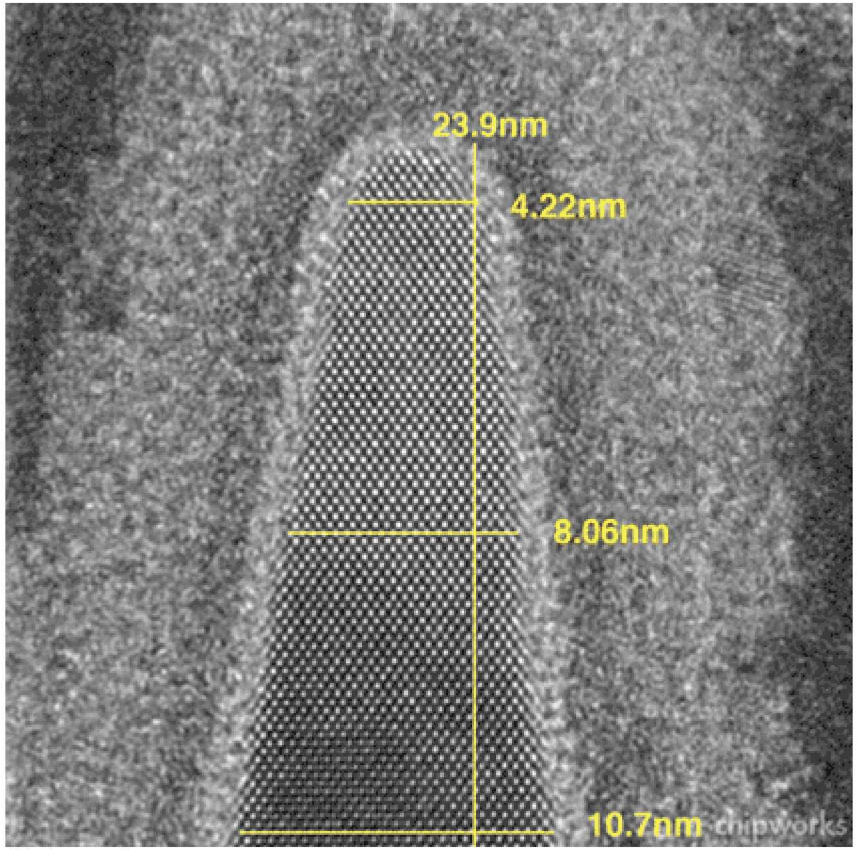
Spintronics



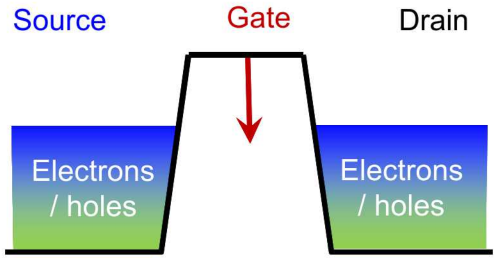
Dense Memory

Opportunities at the atomic scale

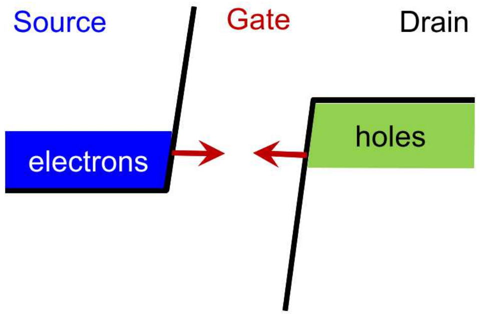
- Processing
- Device physics
- Characterization



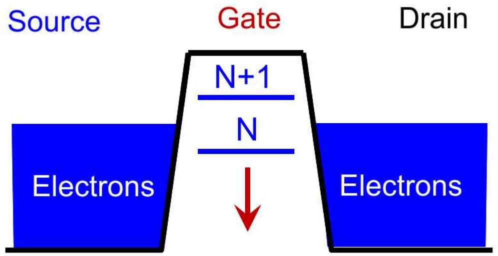
Chipworks



Drift/diffusion

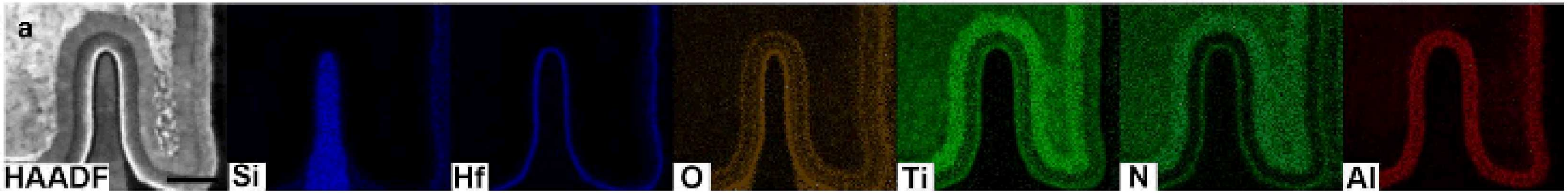


Band-to-band tunneling

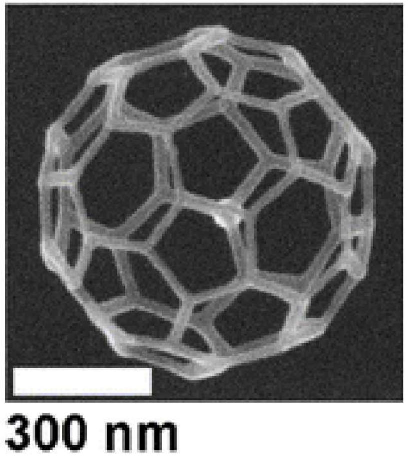


Quantization

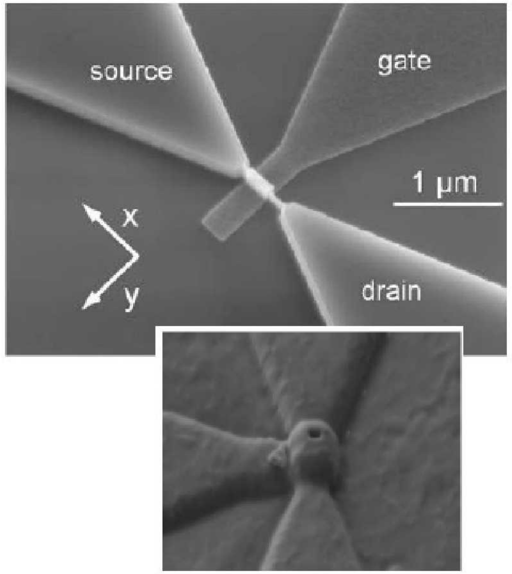
UCSD, Qualcomm, Verioscale, Cameca, PNNL



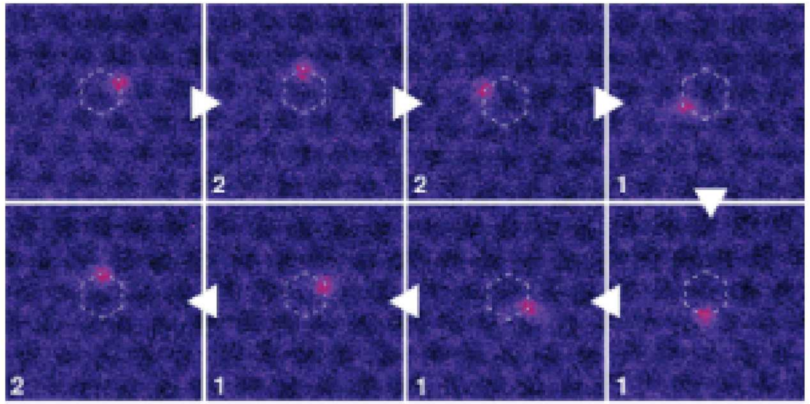
Different approaches



Fowlkes, ACS Nano (2016)



Weis, NIM B (2009)



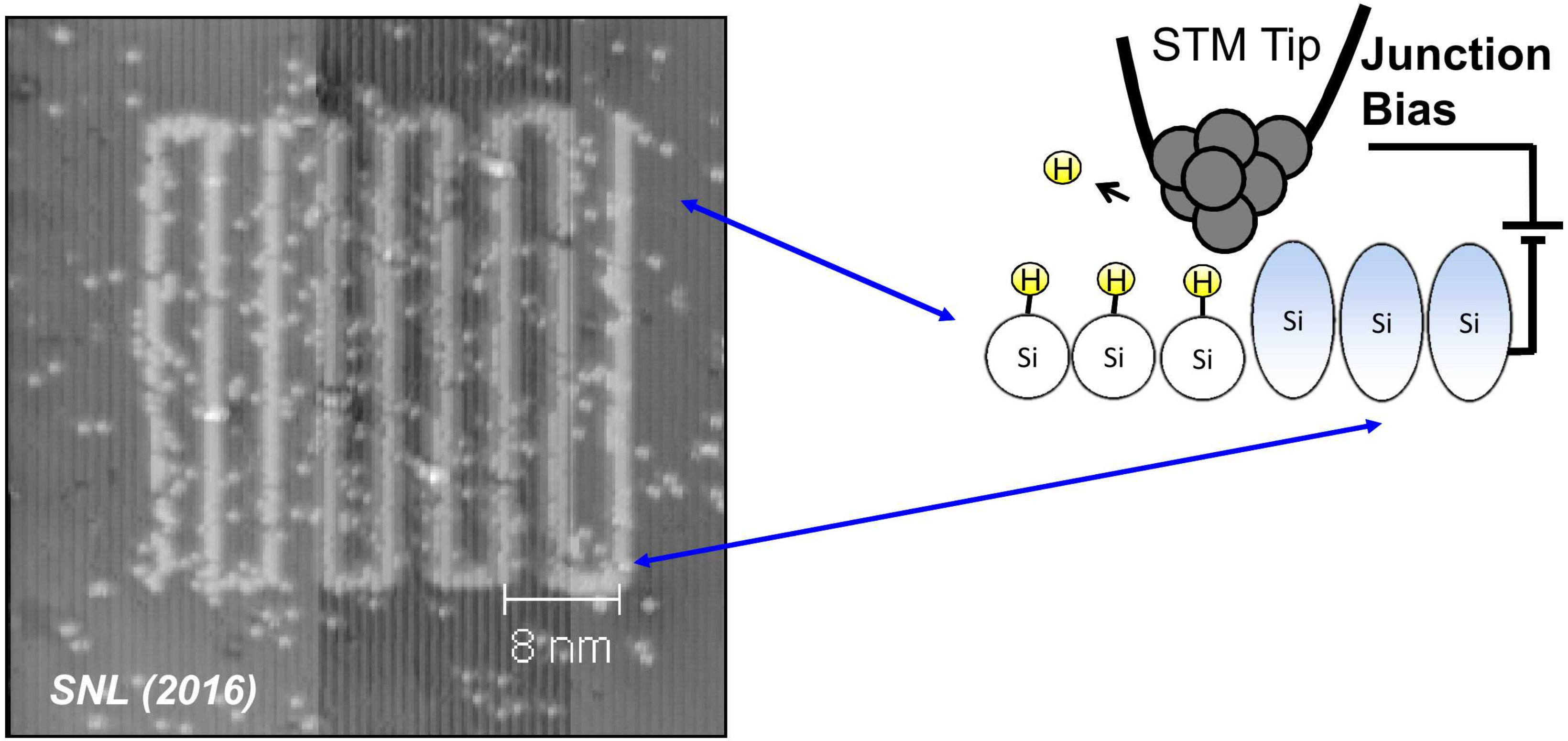
Tripathi, Nano Letters (2018)

Beam induced deposition	**Counted ion implant**	**Beam induced dopant manip.**	**STM-based Hydrogen Litho.**
10’s of nm	10’s of nm	Atomic site	Atomic site
Many atoms	Single atom	Single atom	Single atom
Widely integrable	Widely integrable	Not integrated	Limited integrability

Atomically precise advanced manufacturing (APAM)

“Chemical contrast” at Si surface

- Unterminated Si: 1 reactive bond/ atom
- H-terminated Si: unreactive

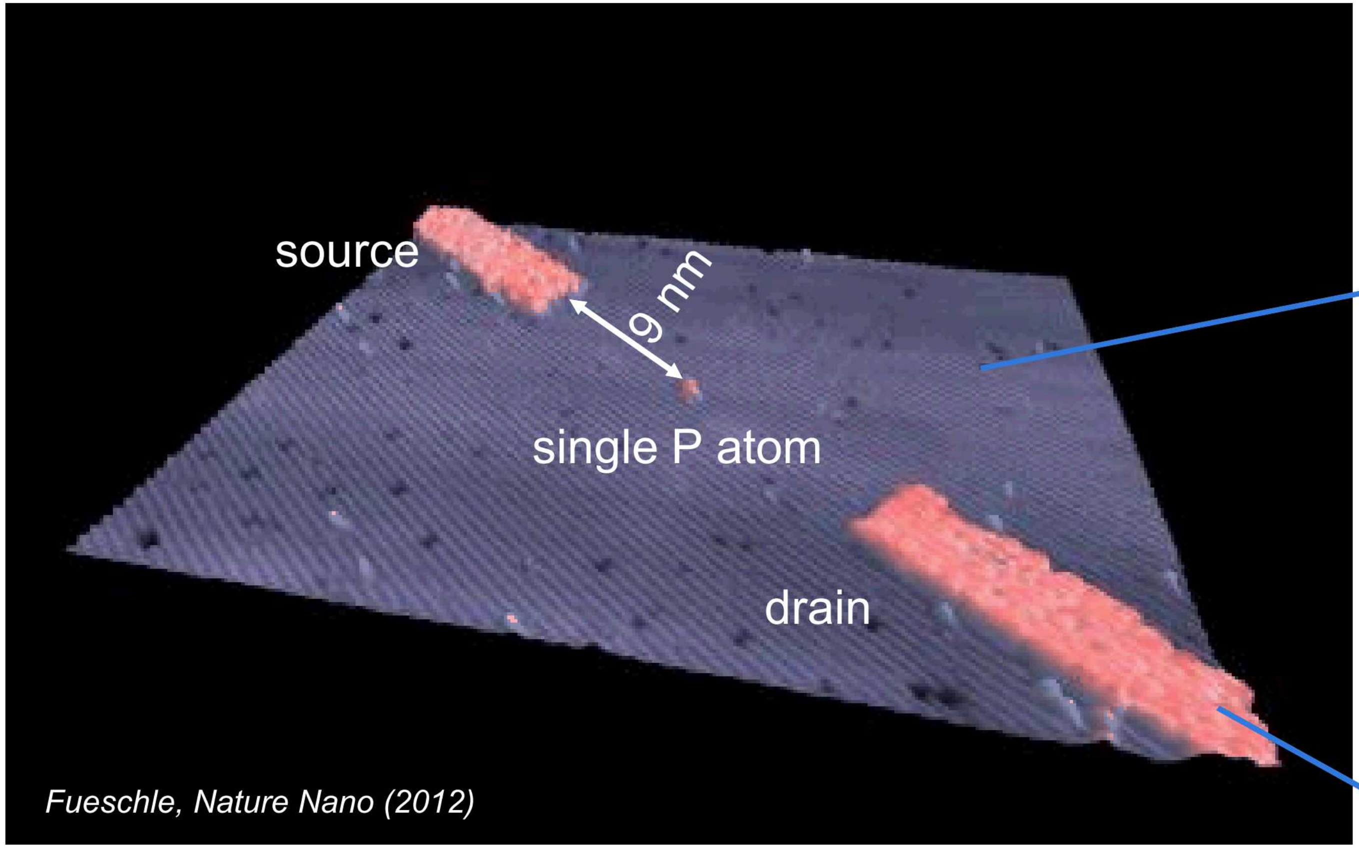


SNL (2016)

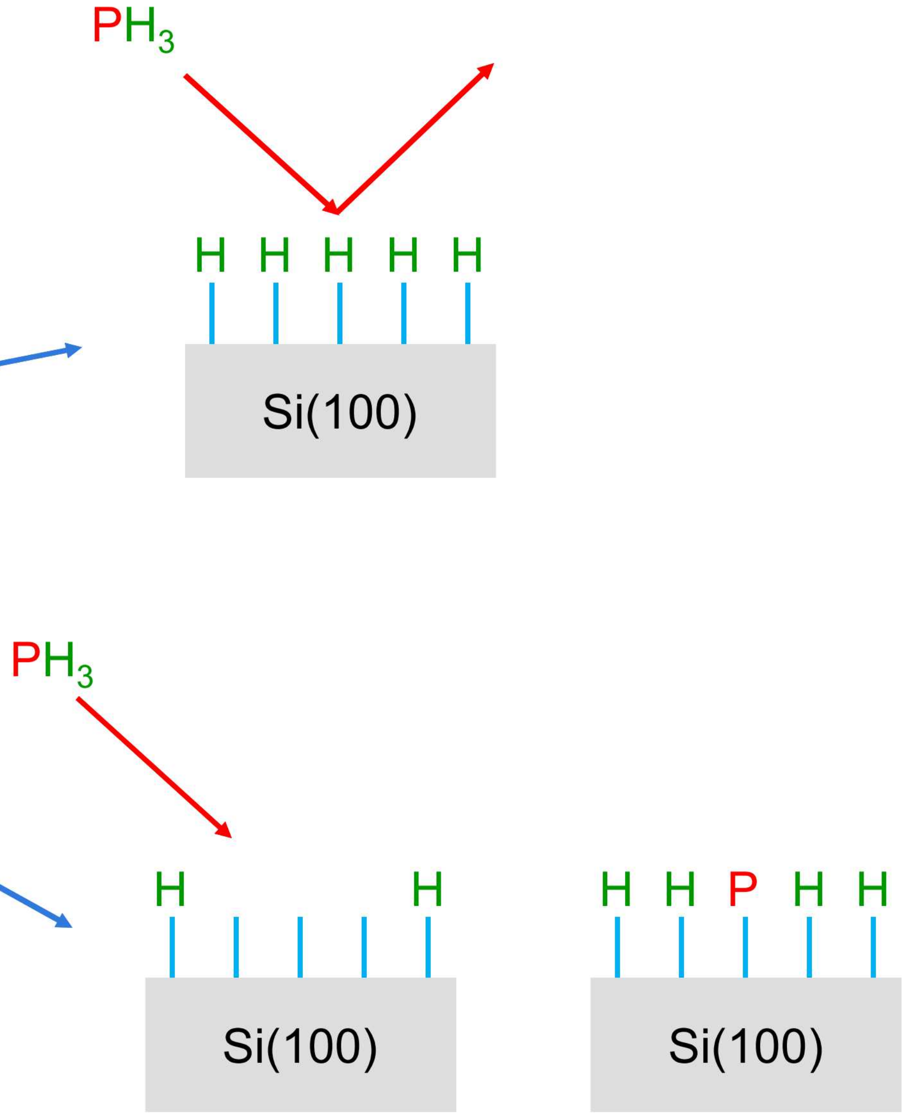
Scanning tunneling microscope (STM) can image and pattern the H-terminated surface

Originally: Swartzentruber, Hamers, Lyding, Shen, Avouris

Electronic devices at the limit of single atoms



Fueschle, Nature Nano (2012)

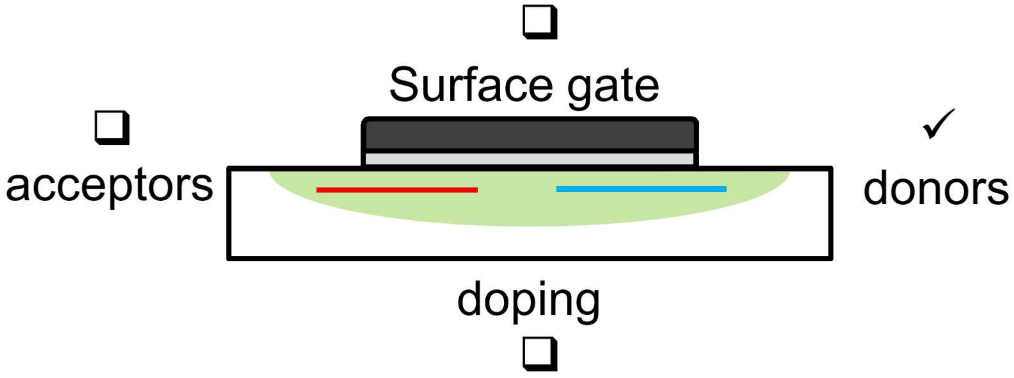


2D areas of highly P doped Si to +/- 1 lattice site precision

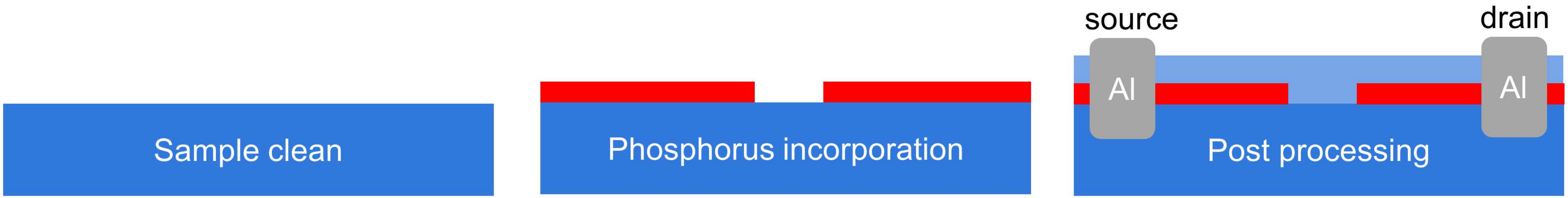
Originally: Simmons

Challenge #1: Complete the device toolbox

Device cross-section



Technology	Result
Acceptor chemistry	Complementary transistors
Doping	Room temperature operation
Surface gate	Control, program device

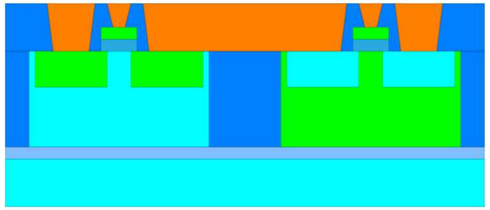


Expanding device toolbox – new limitations vs. CMOS

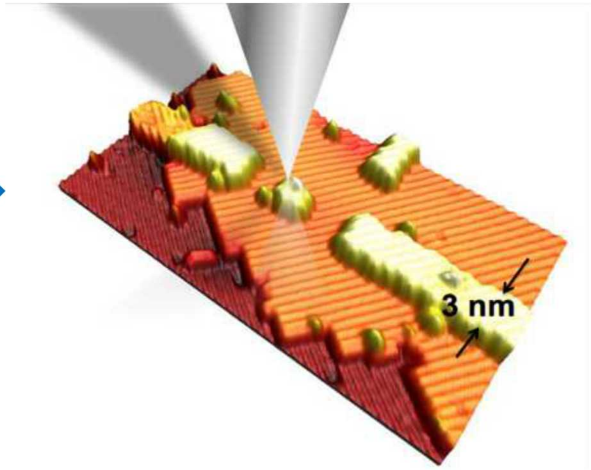
- Project performance
- Interdisciplinary problems – surface chemistry, microelectronics, device physics

Challenge #2: CMOS Integration

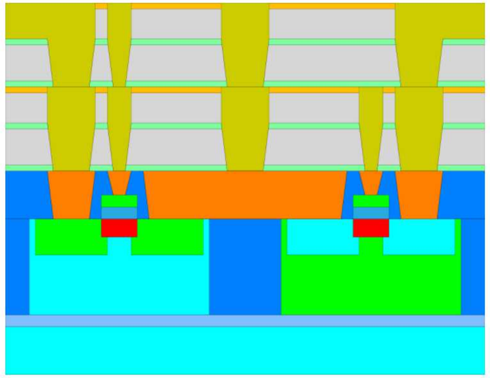
CMOS FEOL



APAM



CMOS BEOL

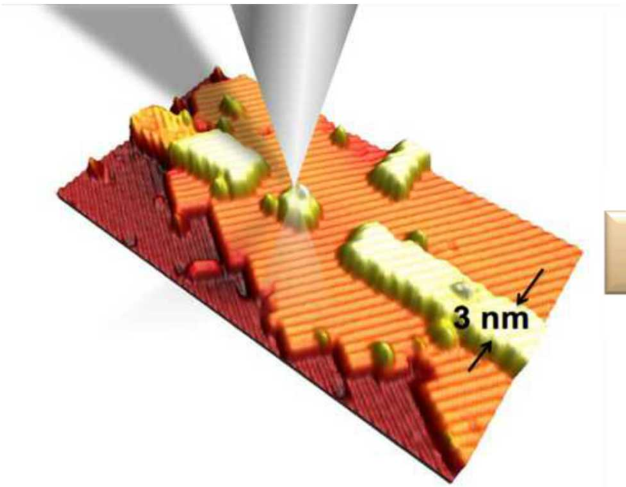


- Enhance CMOS circuit with small number of APAM devices
- Add APAM processing into regular CMOS manufacturing

- Challenging compatibility issues
  How do CMOS and APAM process affect one another?
  How do CMOS and APAM devices interact?

Challenge #3: M&S Co-Design

APAM



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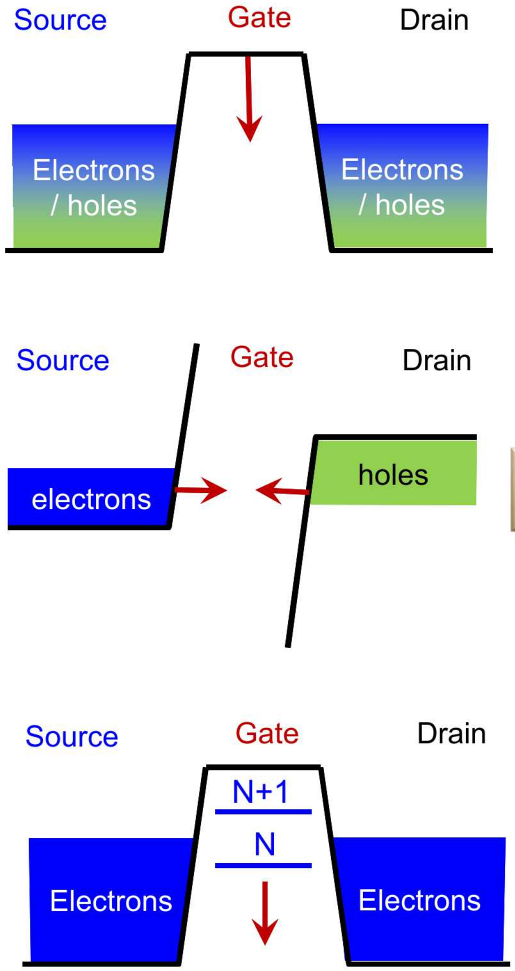

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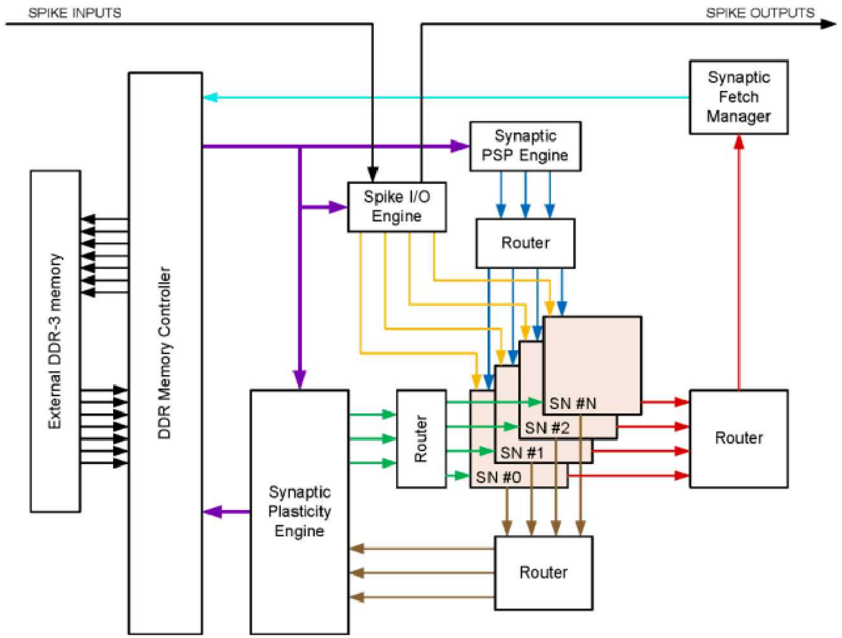

Atomic-scale control gives access to new device physics – new modeling required.

What transistor technologies does a given architecture need?

This is a design problem, not an optimization problem.