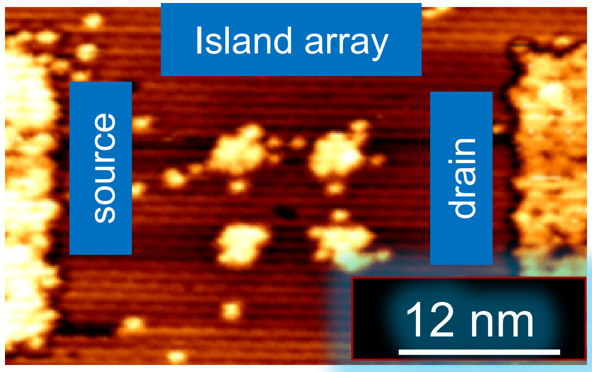
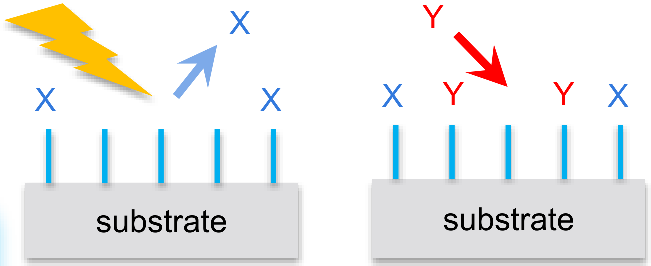
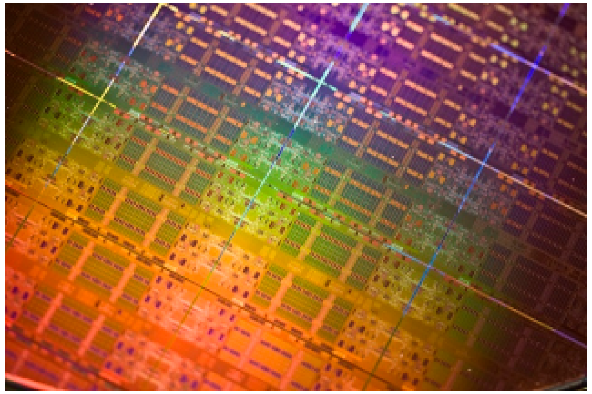
SAND2021-8429PE

Exceptional service in the national interest

Sandia National Laboratories







FAIR DEAL GC Technical Overview

Shashank Misra

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Overview of EAB #4

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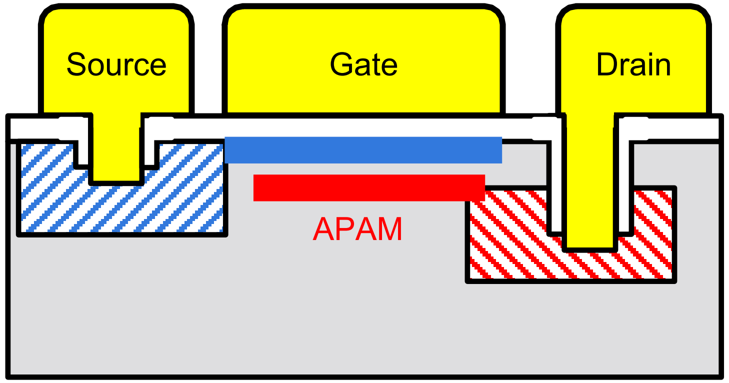
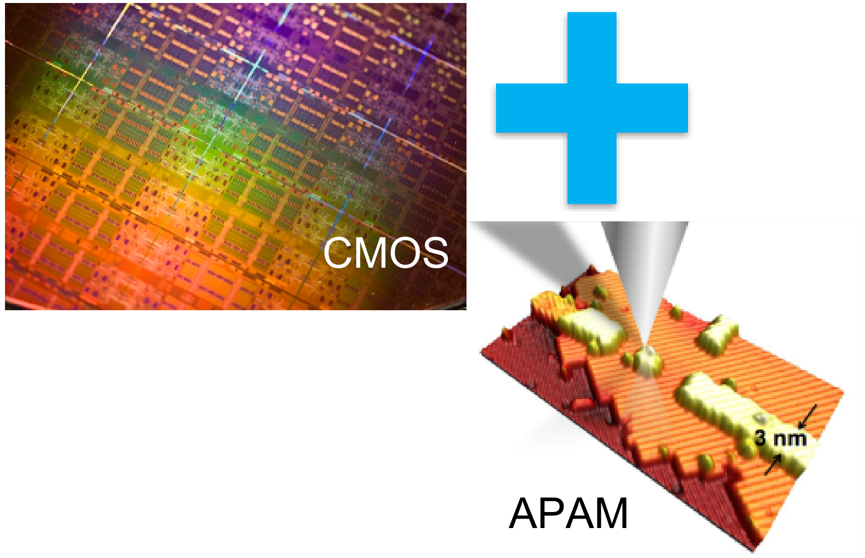
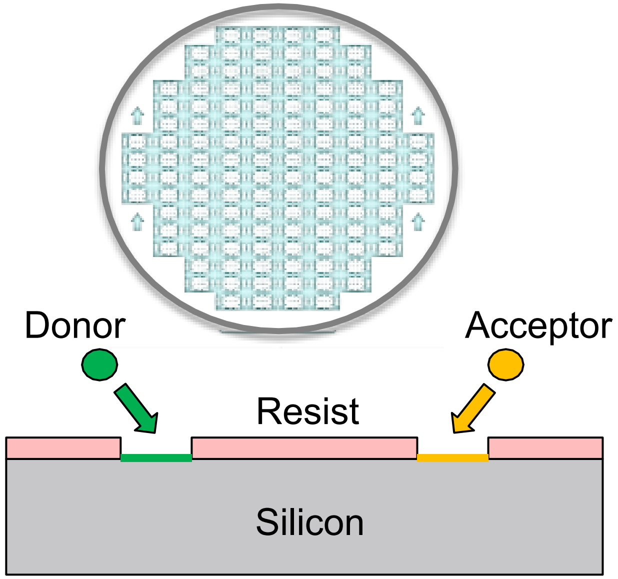
APAM transistor



CMOS – APAM integration



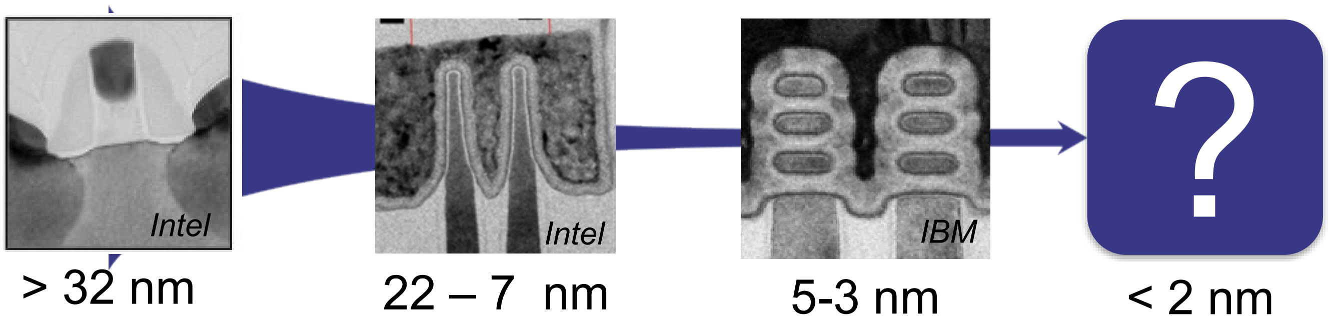
Manufacturability



- **Audacious technical goals accomplished (Day 1)**
- **Established a foundation that is being taken in many directions (Day 2)**
- **We aren't near critical mass. What do we do next? (Board)**

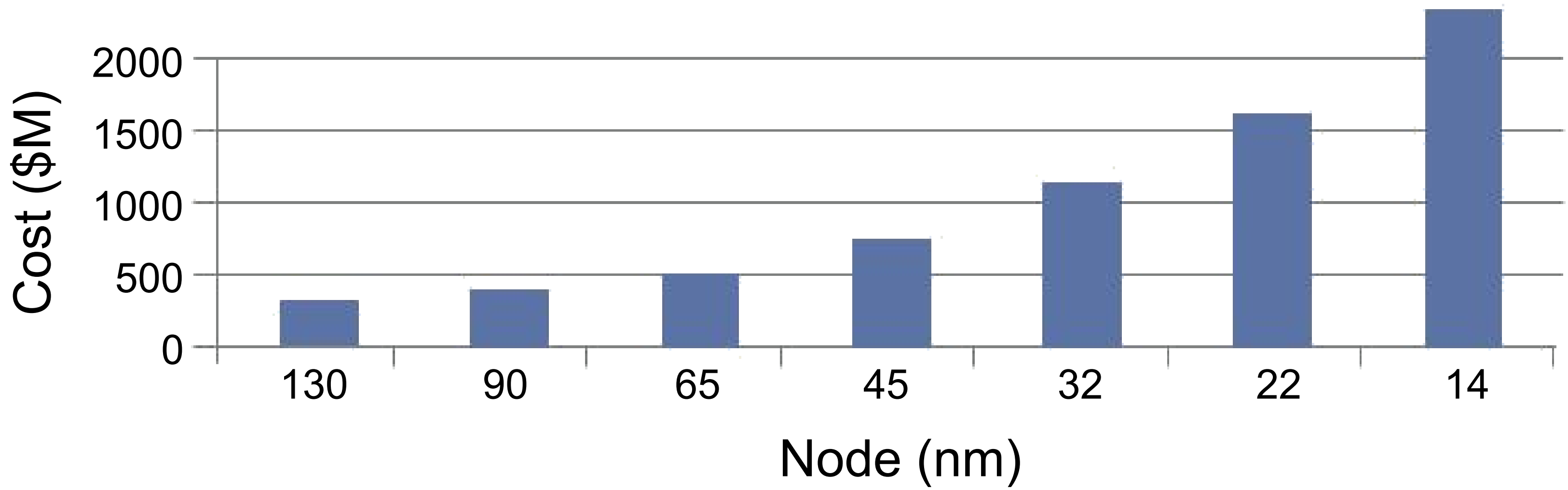
Where is microelectronics headed?

Historically, shrink transistor
→ more functionality and declining cost



R&D costs rising exponentially
→ Unclear path forward

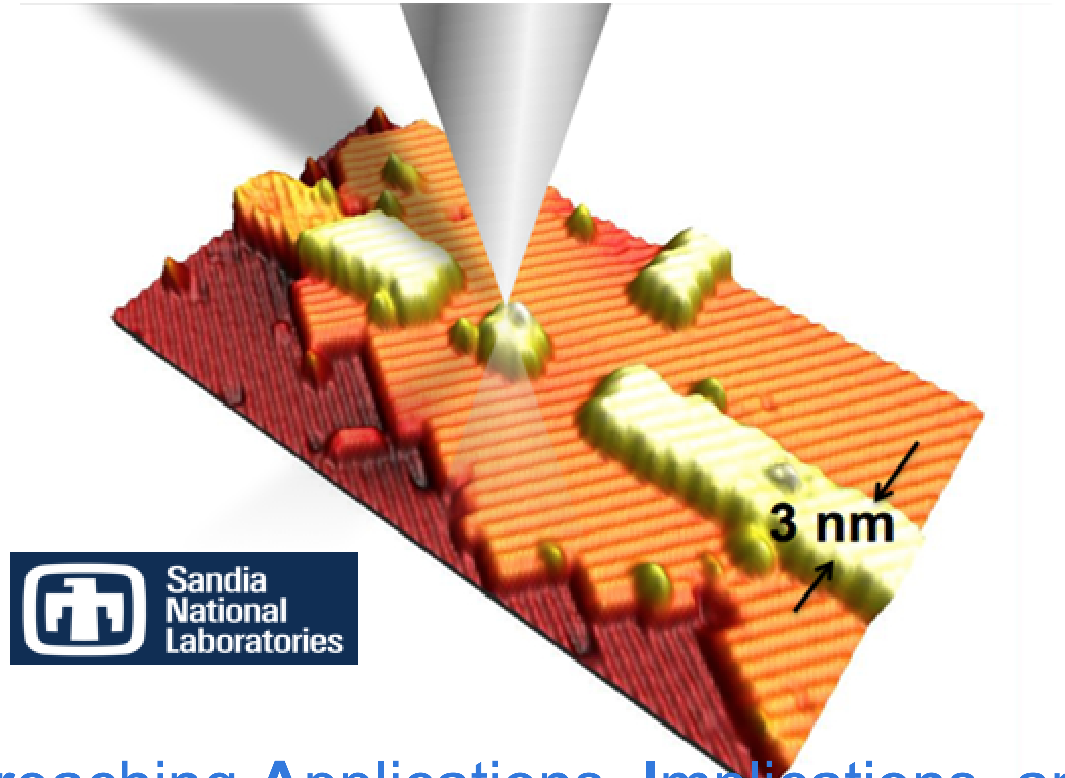
Process technology development cost by node *Common Platform & Alix Partners Analysis*



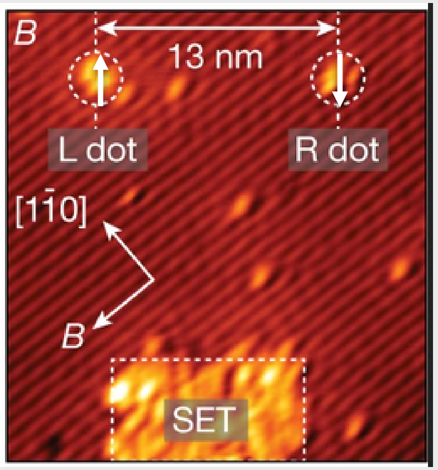
Opportunity for non-scalable R&D pathfinding

Atomic Precision Advanced Manufacturing (APAM)

Our mission: To assess the opportunities presented by APAM-enabled devices and processing for the digital microelectronics of the future



APAM for quantum



Far-reaching **A**pplications, **I**mplications, and **R**ealization of **D**igital **E**lectronics at the **A**tomic **L**imit

How does Atomic Precision Advanced Manufacturing (APAM) work?

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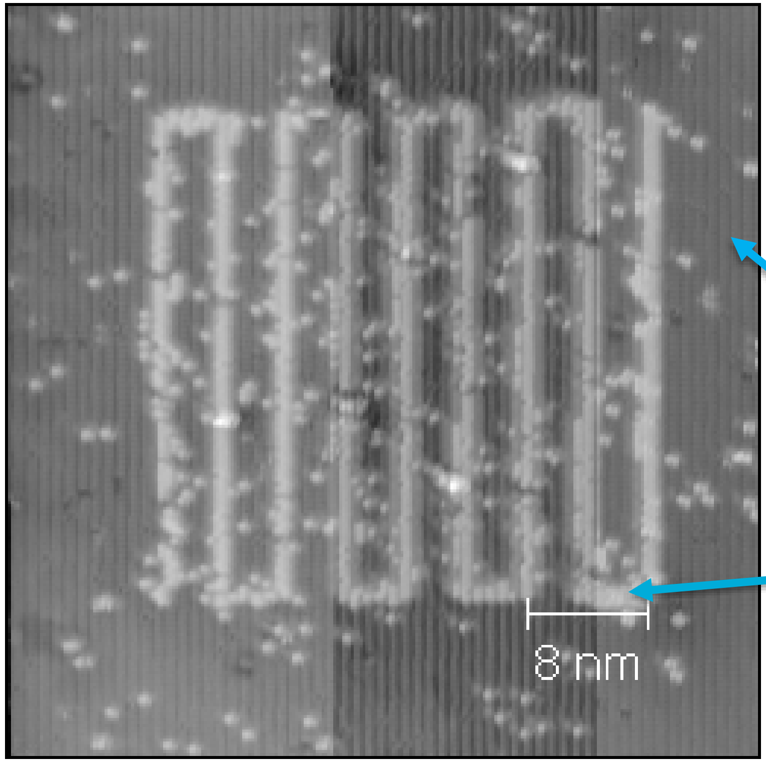
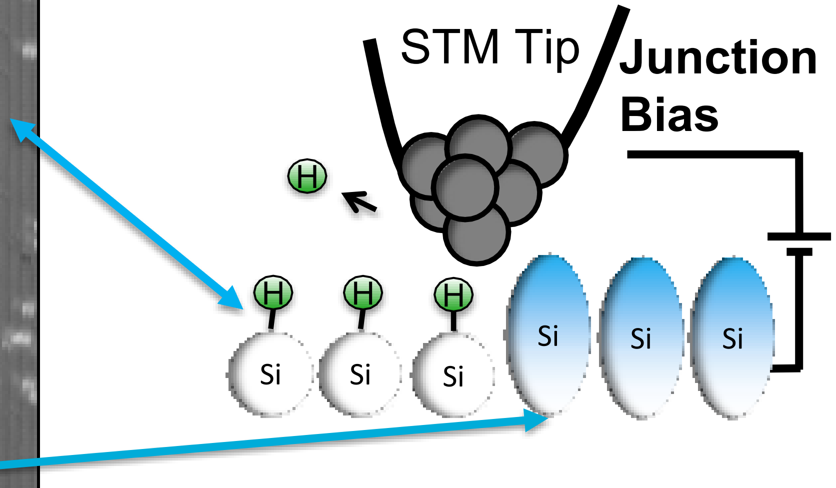


Scanning tunneling microscope (STM) can image and pattern the surface

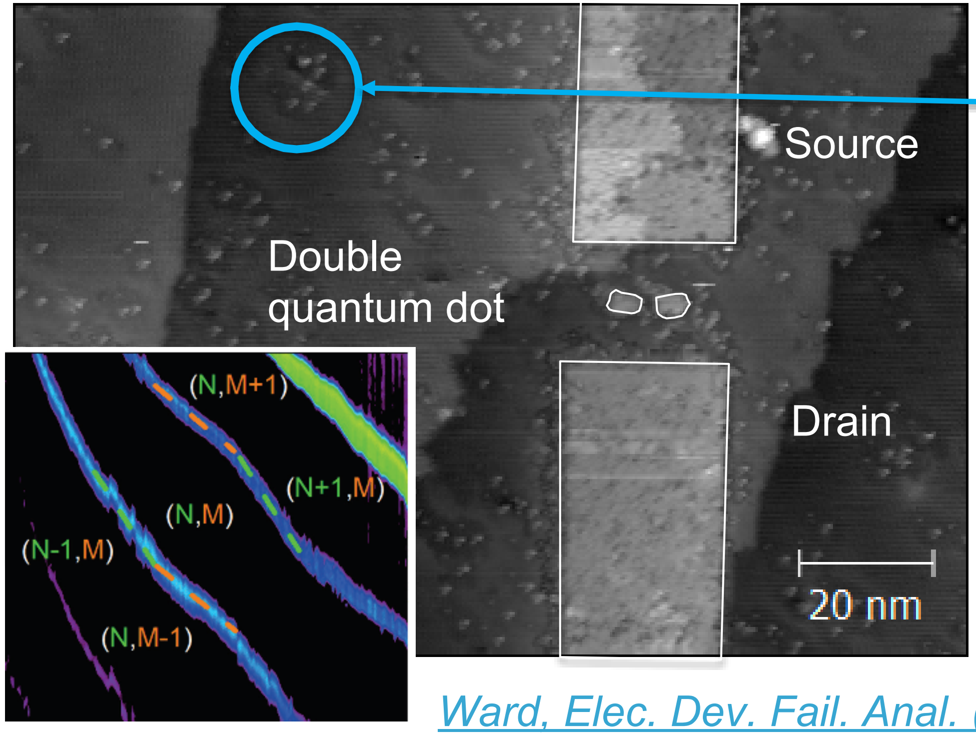


"Chemical contrast" at Si surface

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

Doping using phosphine surface chemistry

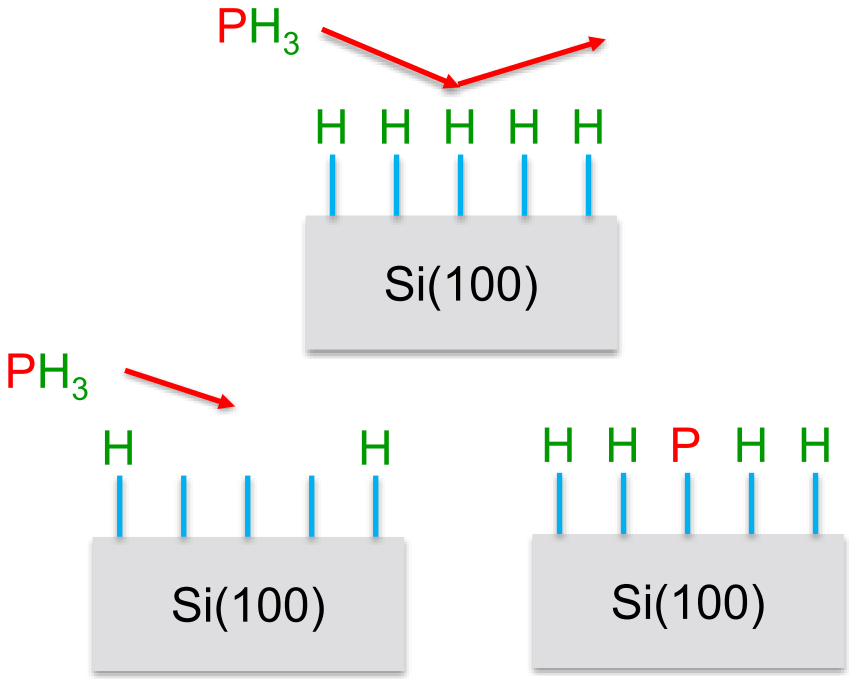
'Artificial molecule'



Chemical error correction : need 3 open sites for phosphine

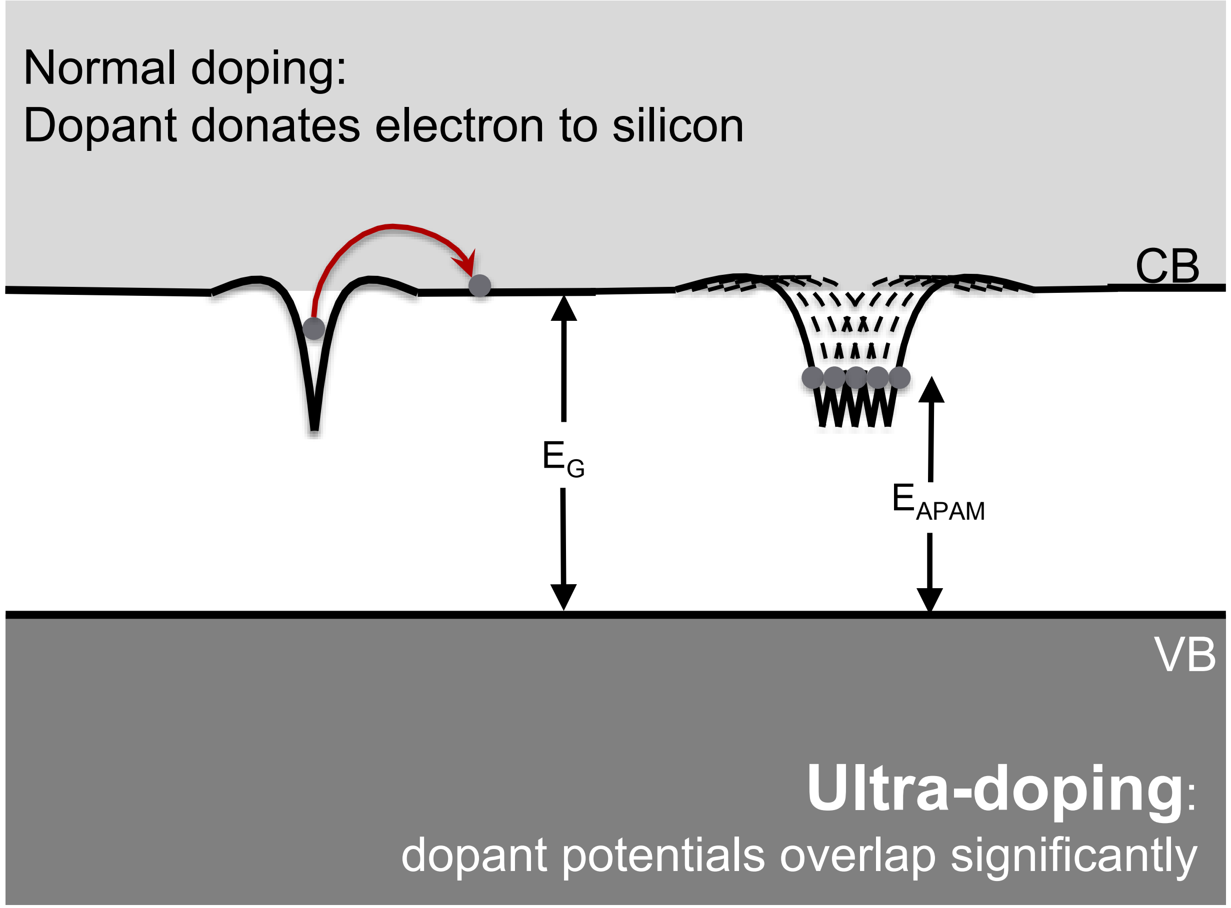
Ward, Elec. Dev. Fail. Anal. (2020)

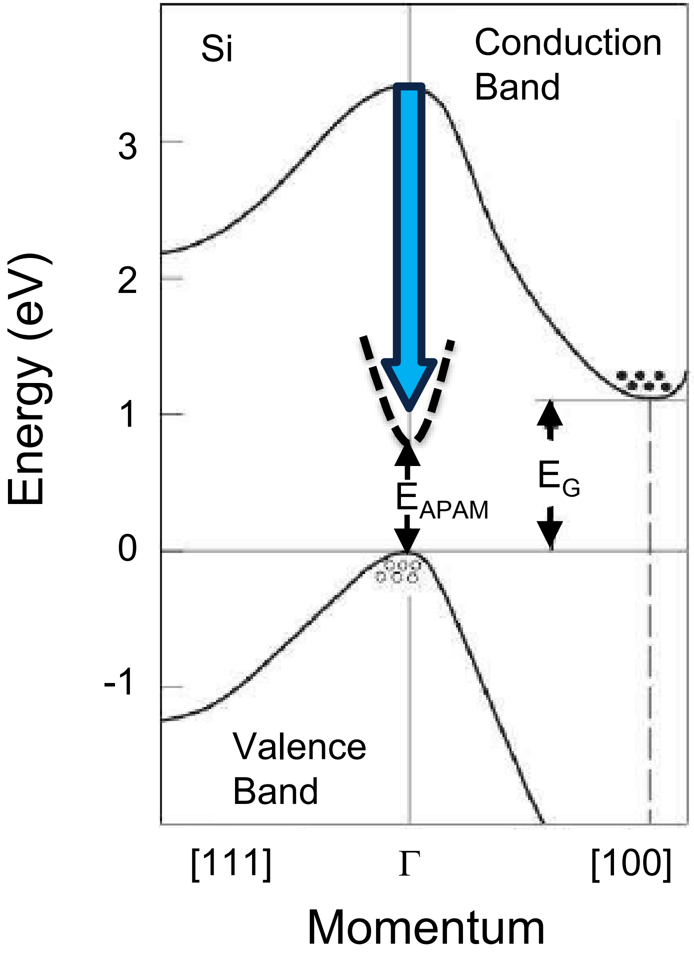
Phosphorus 'donates' an electron to silicon.



Fundamental opportunities 1 & 2: Chemistry-based atomic-scale processing

What does APAM produce that's special?

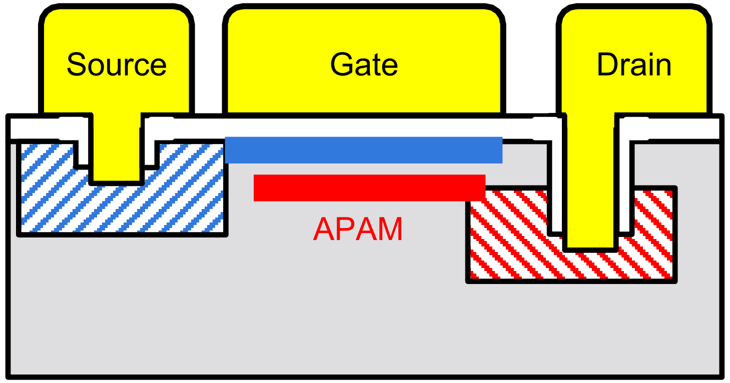




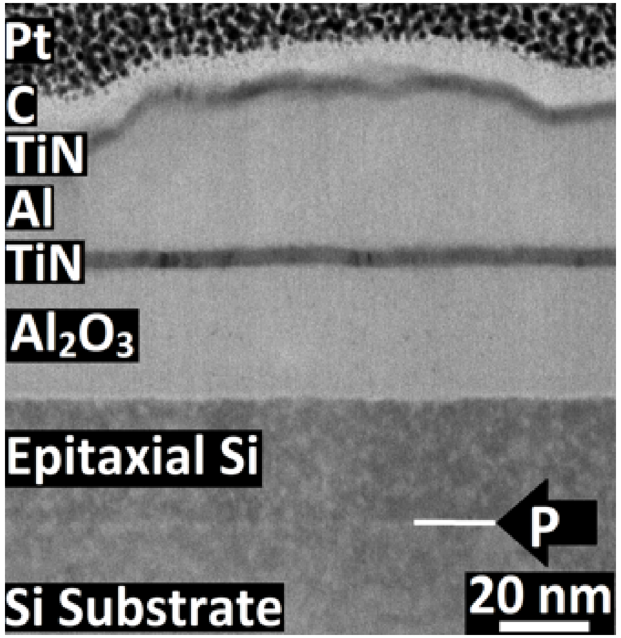
Fundamental opportunity 3: Fundamentally change electronic structure of silicon

Outline

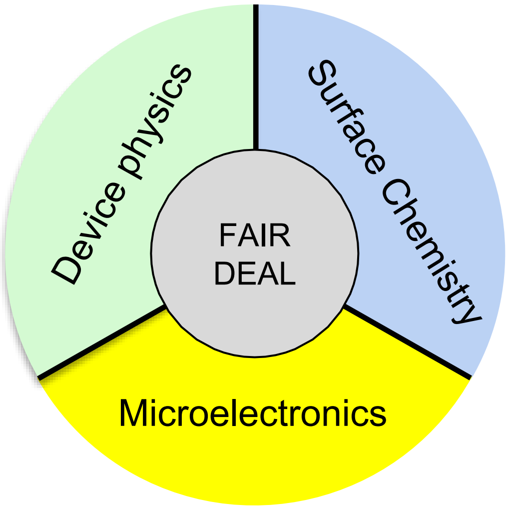
1. Goals



2. Accomplishments



3. Our future



Technological benefit of atomic-scale control

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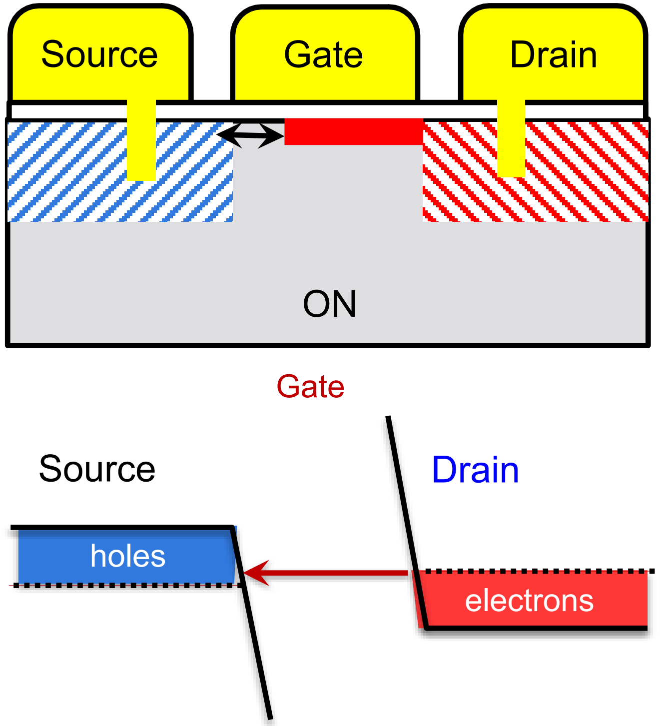
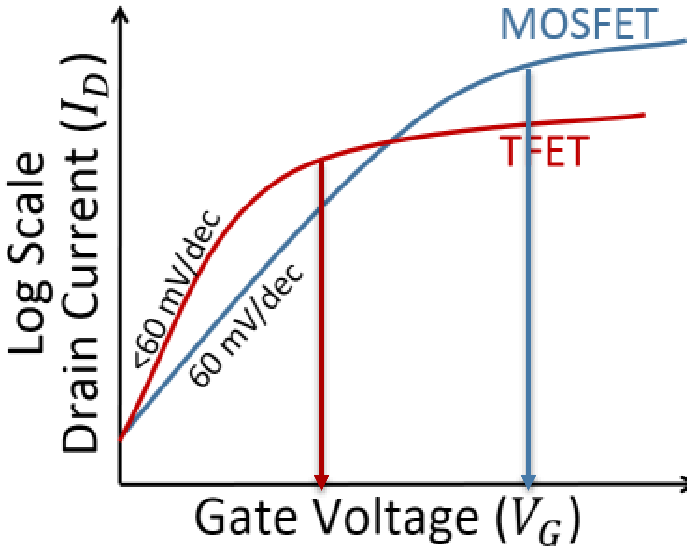
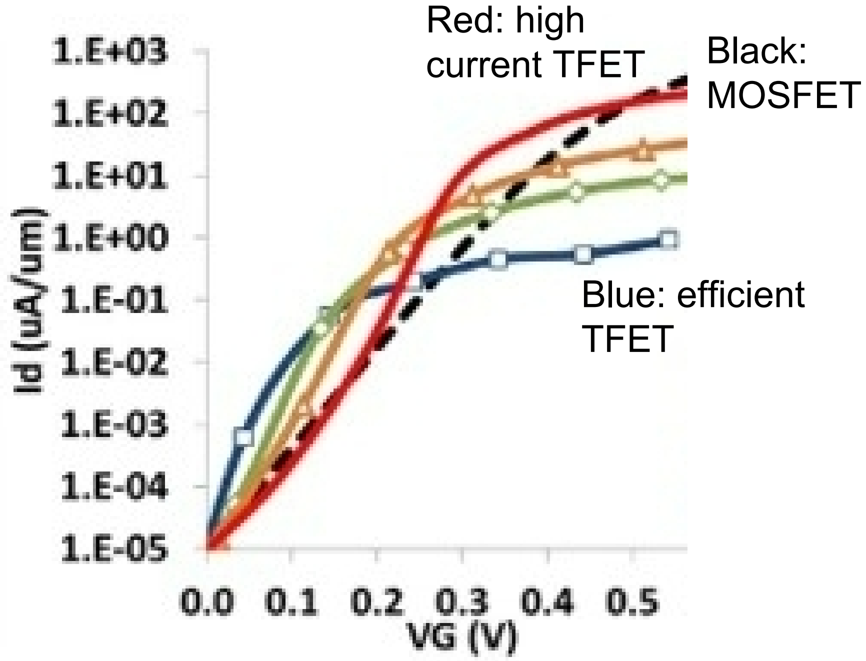
Tunnel field effect transistor (TFET)





TFETs 10x energy efficiency in theory

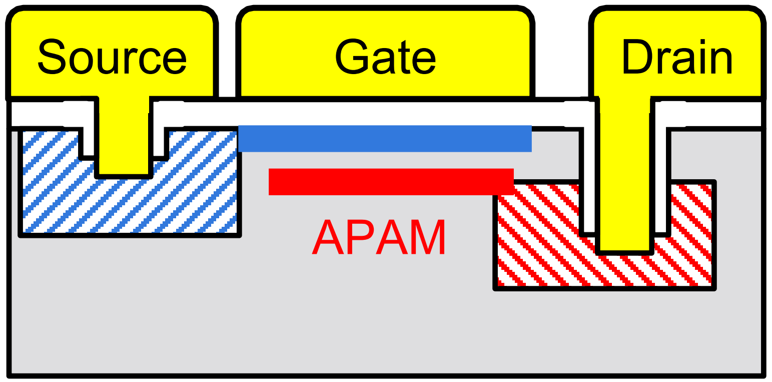


TFETs have not realized their promise in practice

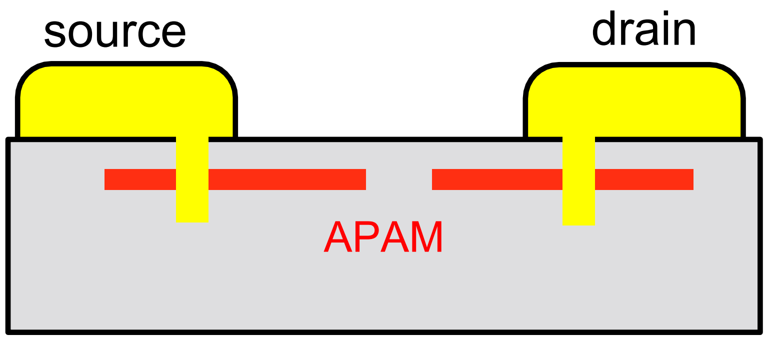
Explore new transistor technology armed with atomic precision

How to overcome limitations to TFETs

APAM TFET



APAM (2018)



APAM-enabled vertical TFET:

- Atomically abrupt doping profile & energy efficiency
- Vertical geometry & current density

What work needs to be done?

- Missing device components
- Lack of complementary doping type
- Absence of modeling tools to enable design

FD Goal: Before making an APAM transistor, need to establish underlying components

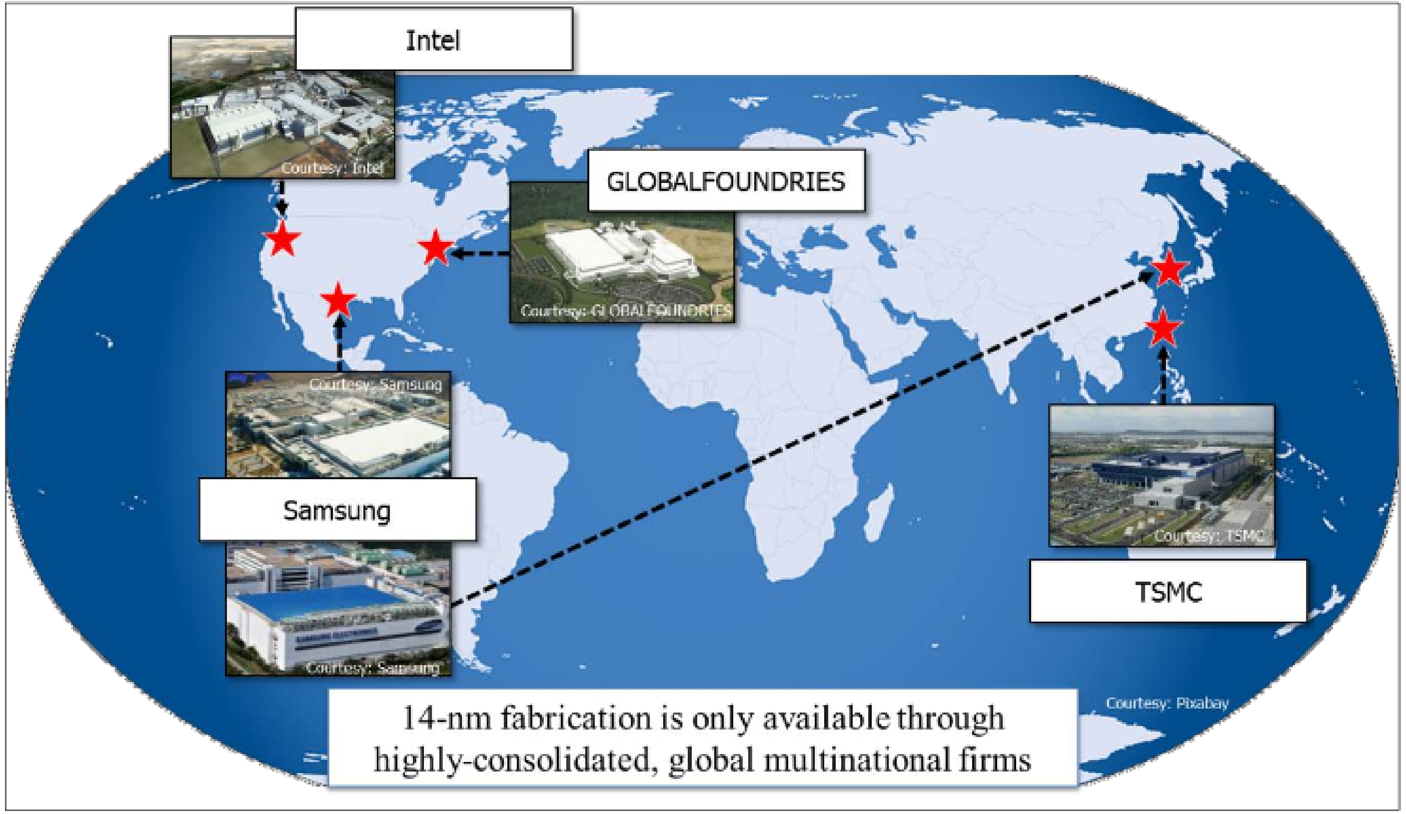
Technological benefit of using chemistry for processing

Sandia National Laboratories

Chemistry-based processing is very flexible – don't need a thermal activation (e.g. implant or epitaxy)

Modern supply chains are global.

Need to protect the USG's information.



Atomic scale – can be used to anticipate future opportunities

Unusual integration points during manufacturing – new possibilities

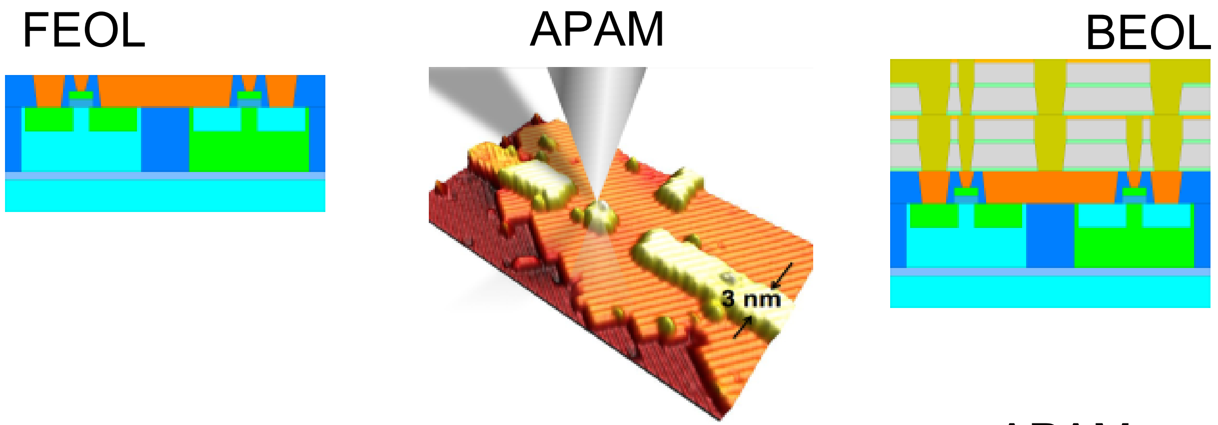
Seek to develop hardware trust and security features

APAM – CMOS integration

Sandia National Laboratories

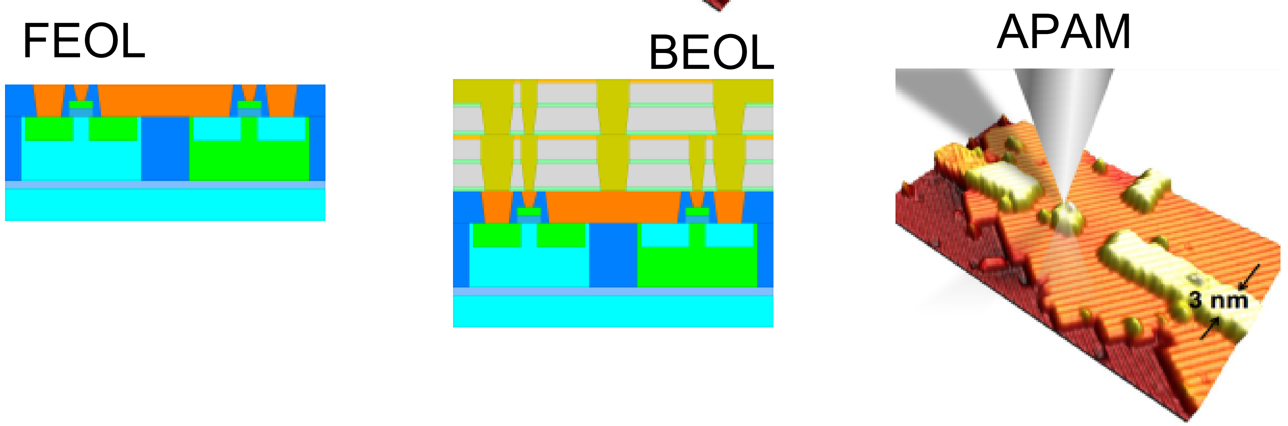
<u>Goal: Direct integration</u>

- Anticipate future opportunities
- Split fabrication – untrusted FEOL



<u>Goal: Post-CMOS integration</u>

- Zero trust – untrusted FEOL & BEOL
- Add features outside of typical flow



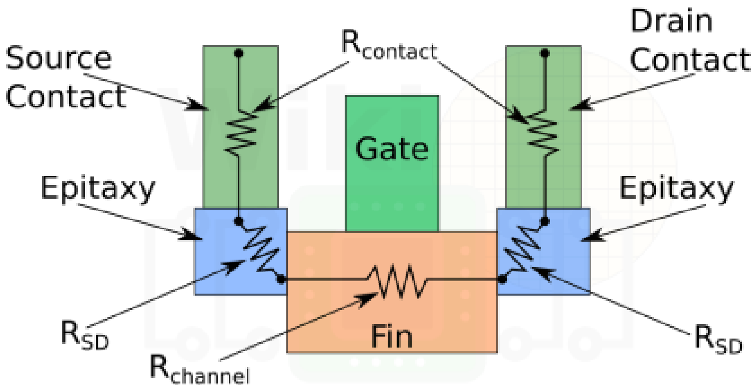
<u>What work needs to be done?</u>

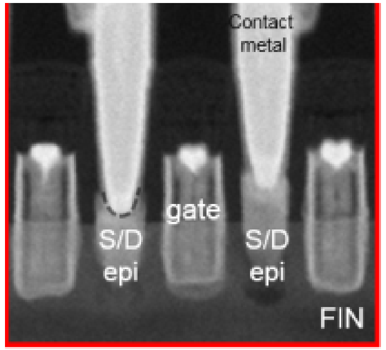
- Determine insertion point
- New APAM processes
- Robustness of APAM vs. CMOS

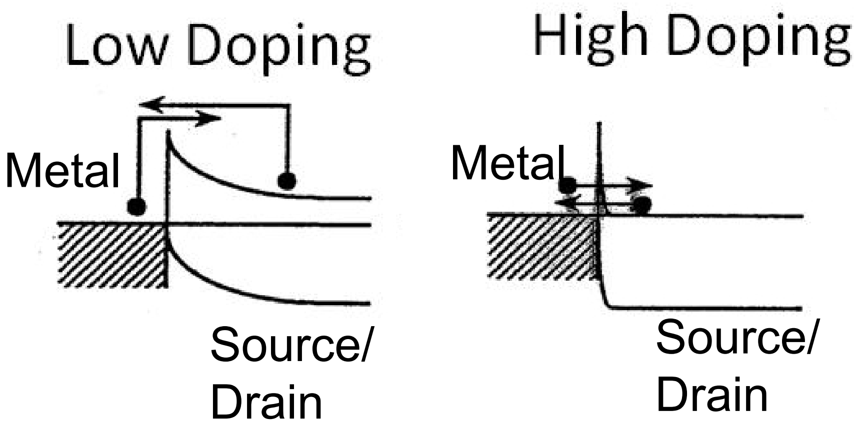
FD Goal: Before making APAM hardware trust & security elements, need to establish underlying integration flows

Technological benefit of atomic-scale manufacturing

Application pull: contact resistance





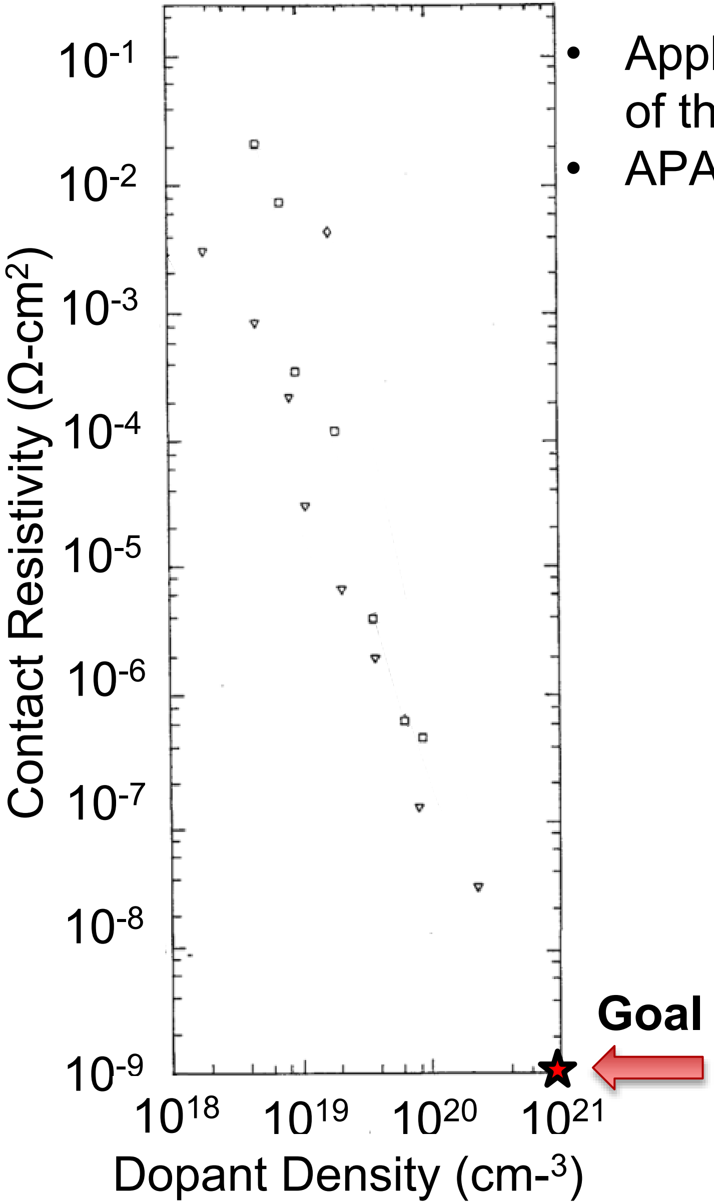


As transistors shrink, channel resistance goes down, but contact resistance goes up

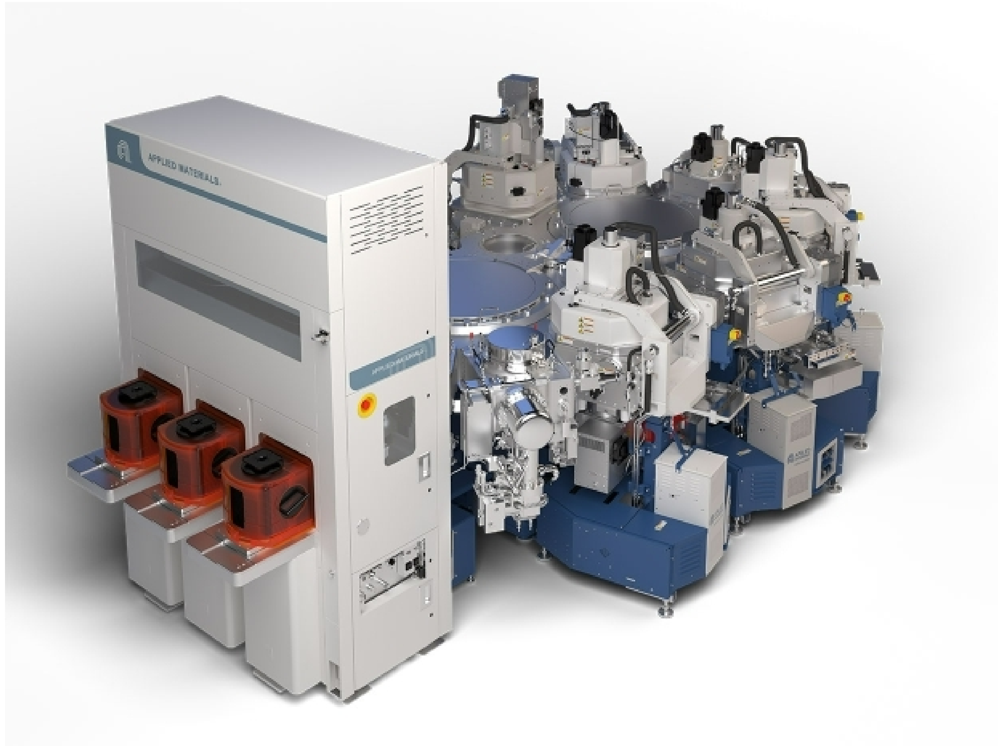
Contact resistance is determined by the size of the speed bump – depends on doping

APAM dopant density exceeds solid solubility limit
Big change to electronic structure makes for better CMOS contacts

APAM manufacturability



- Applied Materials state of the art : ~ 4e20 cm^{-3}
- APAM can beat that.



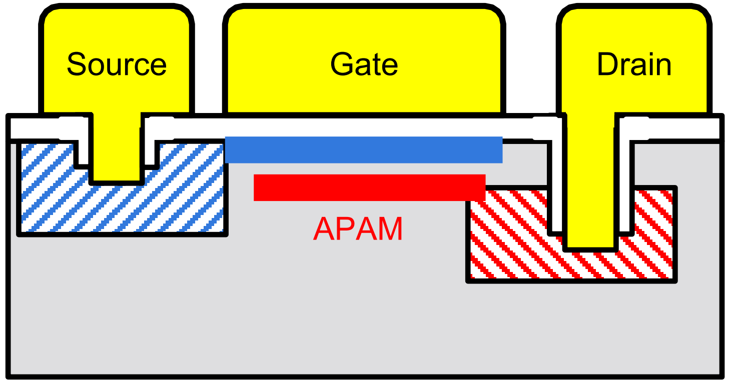
<u>What's missing?</u>

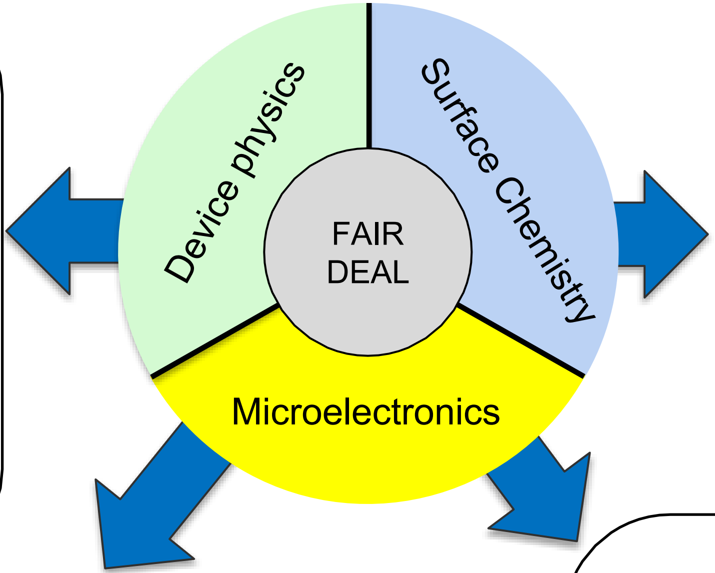
- 3D doping profiles
- donors & acceptors
- Parallel lithography
- 8" (or larger) wafers

FD Goal: To pursue many applications, need to expand principles underlying manufacturability

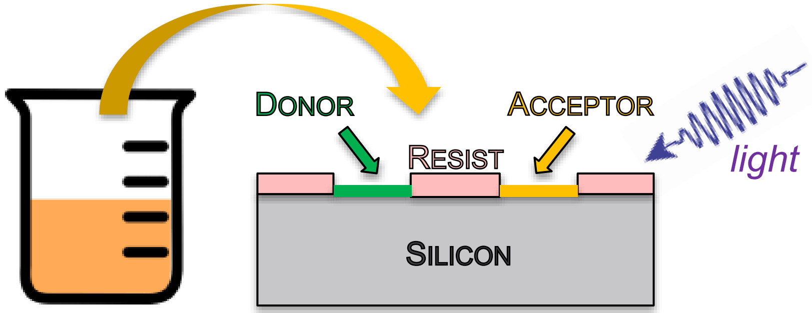
Digital electronics at the atomic limit (DEAL)

Thrust 1: APAM-enabled Devices

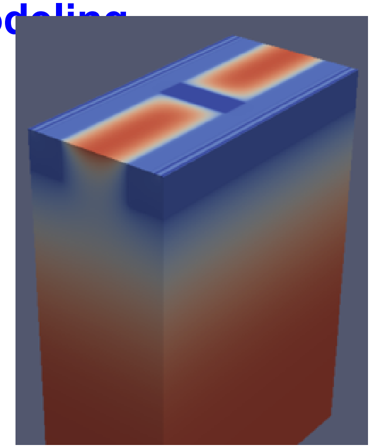




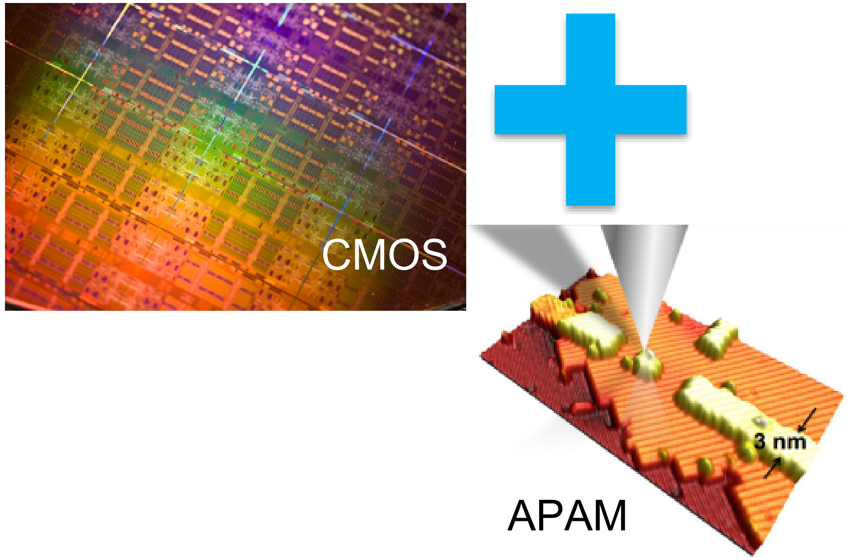
Thrust 4: APAM toolbox



Thrust 2: APAM Modeling

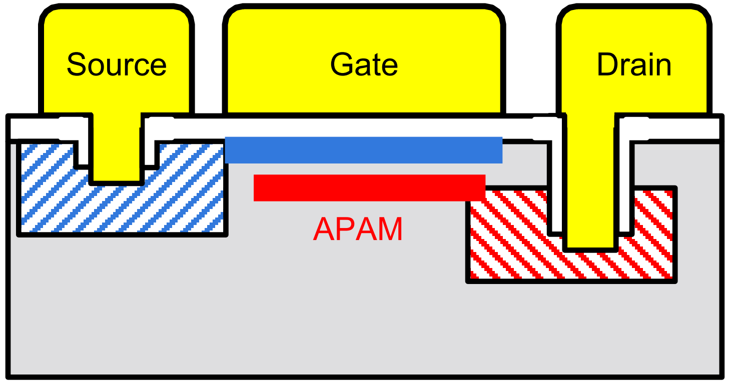


Thrust 3: CMOS Integration

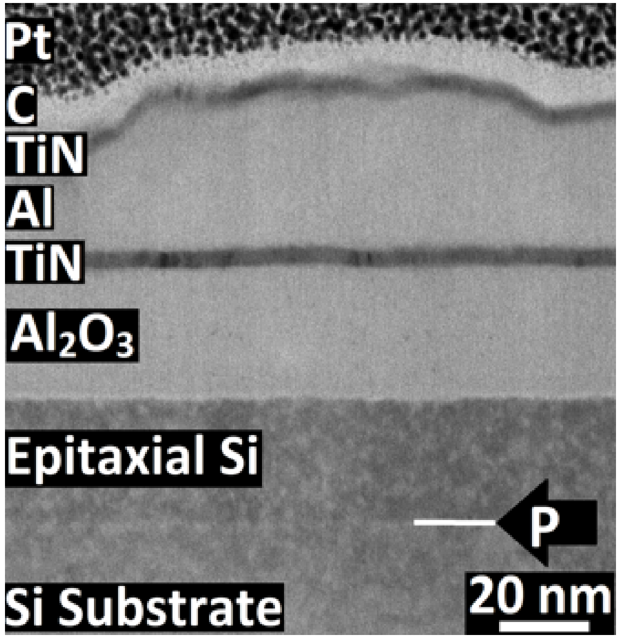


Outline

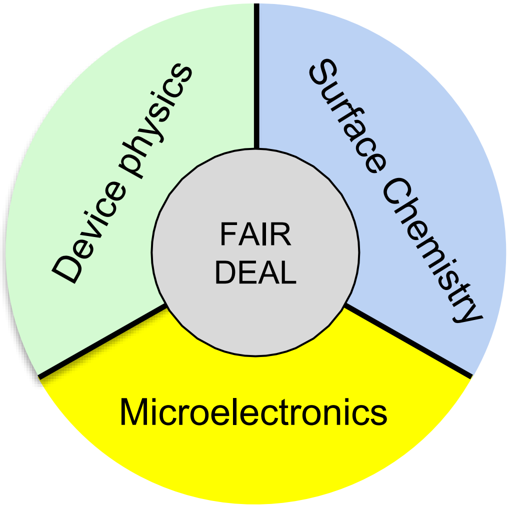
1. Goals



2. Accomplishments



3. Our future

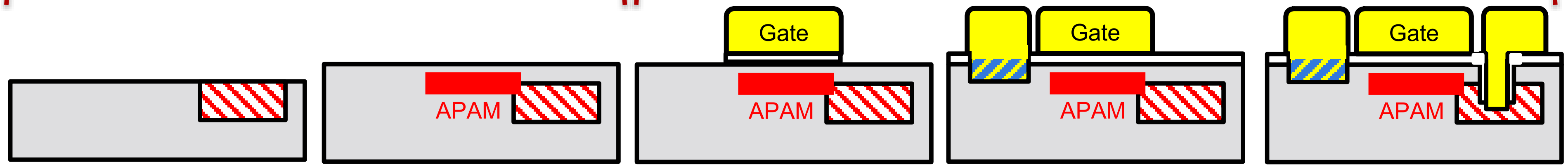


APAM transistor

Requirements:

Keep existing device structures on chip intact

Add device structures while preserving APAM



TFET

Task-level components:

APAM CMOS integration prep

Surface gate

Silicide contact

Room-temp operation

Semiclassical and quantum modeling used throughout for device designs, and to understand data

We have established relevant device components & workflows, and an APAM TFET is imminent

APAM-CMOS Integration

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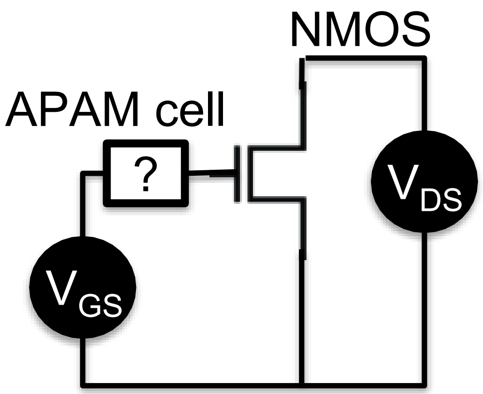
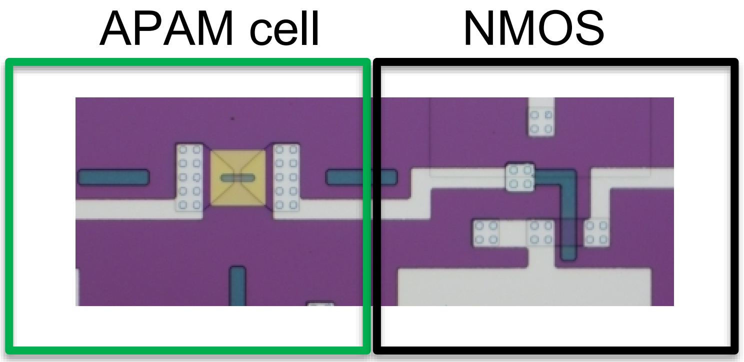


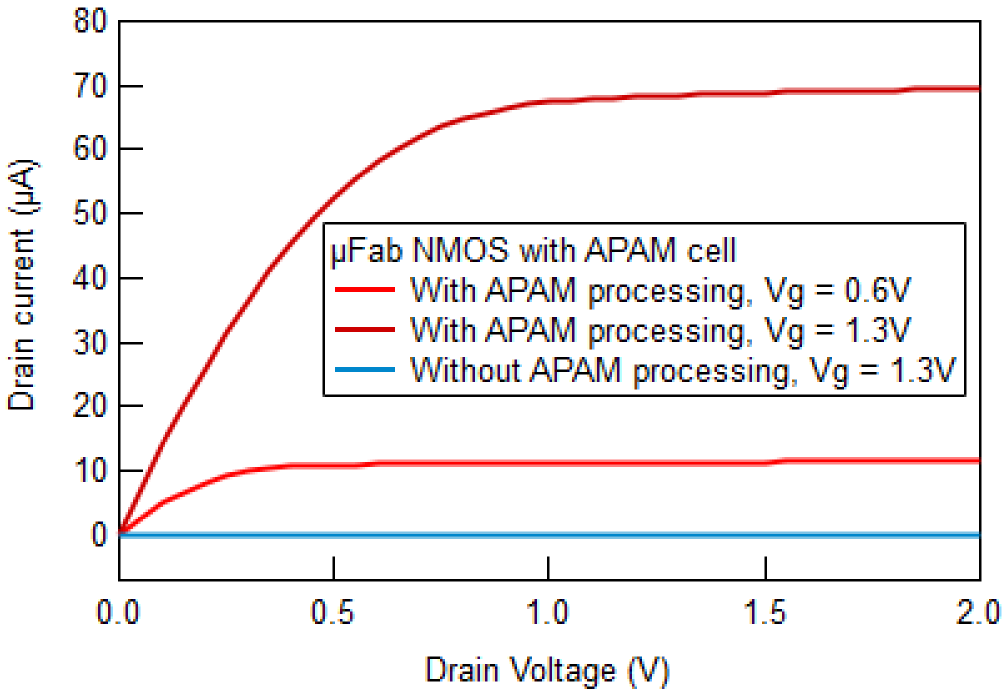


Drive gate of NMOS transistor with APAM cell

Blue: nothing

Brown: metal wire

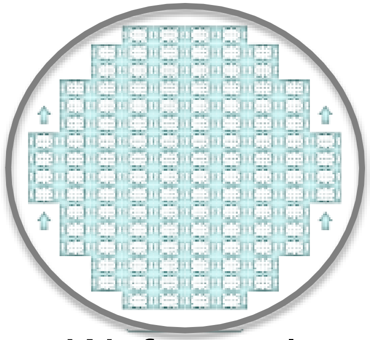
Red: APAM wire



Semiclassical and circuit modeling used to design CMOS circuits, understand impact of APAM processing and devices

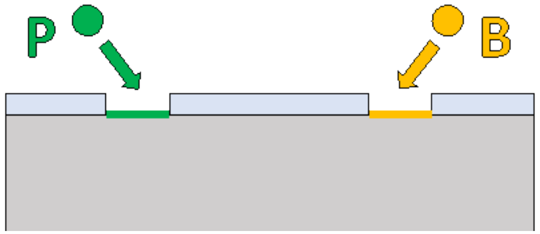
We have succeeded in integrating APAM with CMOS

APAM toolbox



Wafer-scale lithography

Application pull – CMOS contacts



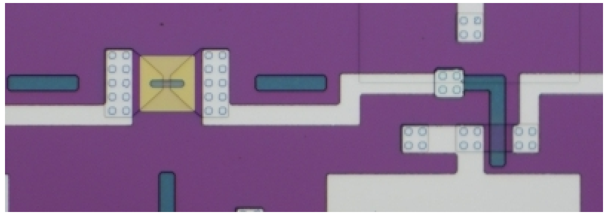
Acceptor precursor discovered

Path forward for manufacturability
Able to expand APAM chemistry

Other major technical accomplishments

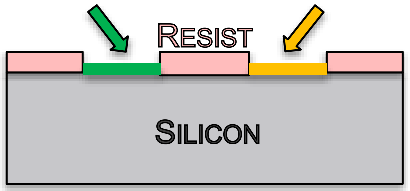
Sandia National Laboratories

A. Microfab integration platform

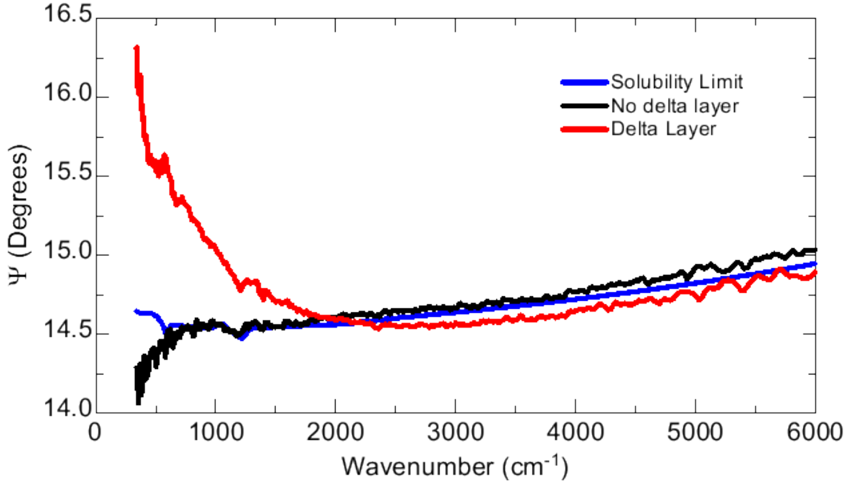


B. Expansion of APAM-compatible chemistry

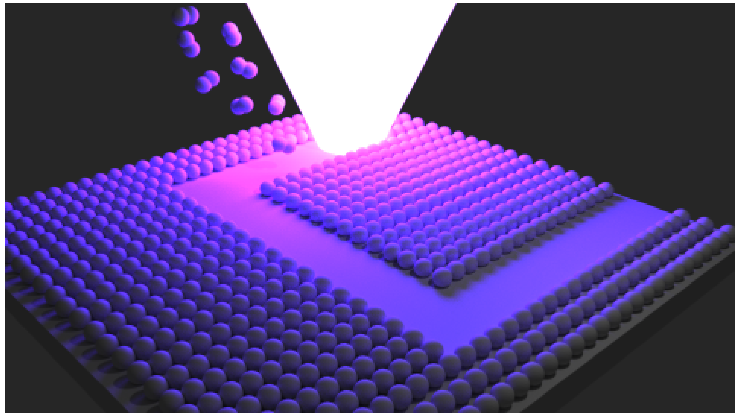
metal oxide



C. Optical response of APAM



D. Hydrogen photolithography



Sandia and partners are in a leading position

Output

Thrust 1: APAM-enabled Devices
- 1 technical advance
- 5 published papers
- 1 book chapter
- 4 papers in preparation

Thrust 2: APAM Modeling
- 3 papers published
- 2 papers in preparation

Thrust 3: CMOS Integration
- 1 patent
- 1 technical advance
- 1 published paper
- 4 papers in preparation

Thrust 4: APAM toolbox
- 1 patent (photolitho)
- 6 published paper
- 5 submitted papers
- 6 papers in preperation

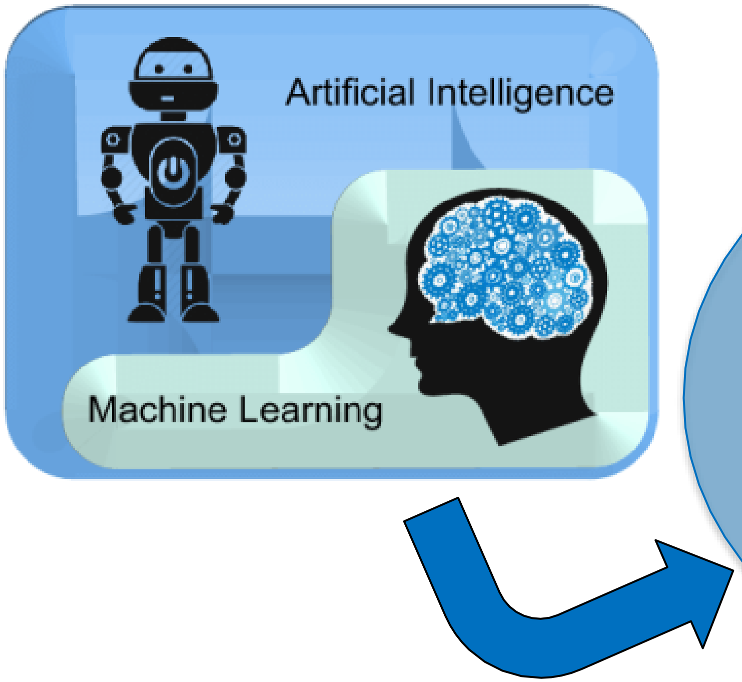
IEEE, Physical Review, Journal of Material Research, SPIE, J. Physical Chemistry, Langmuir

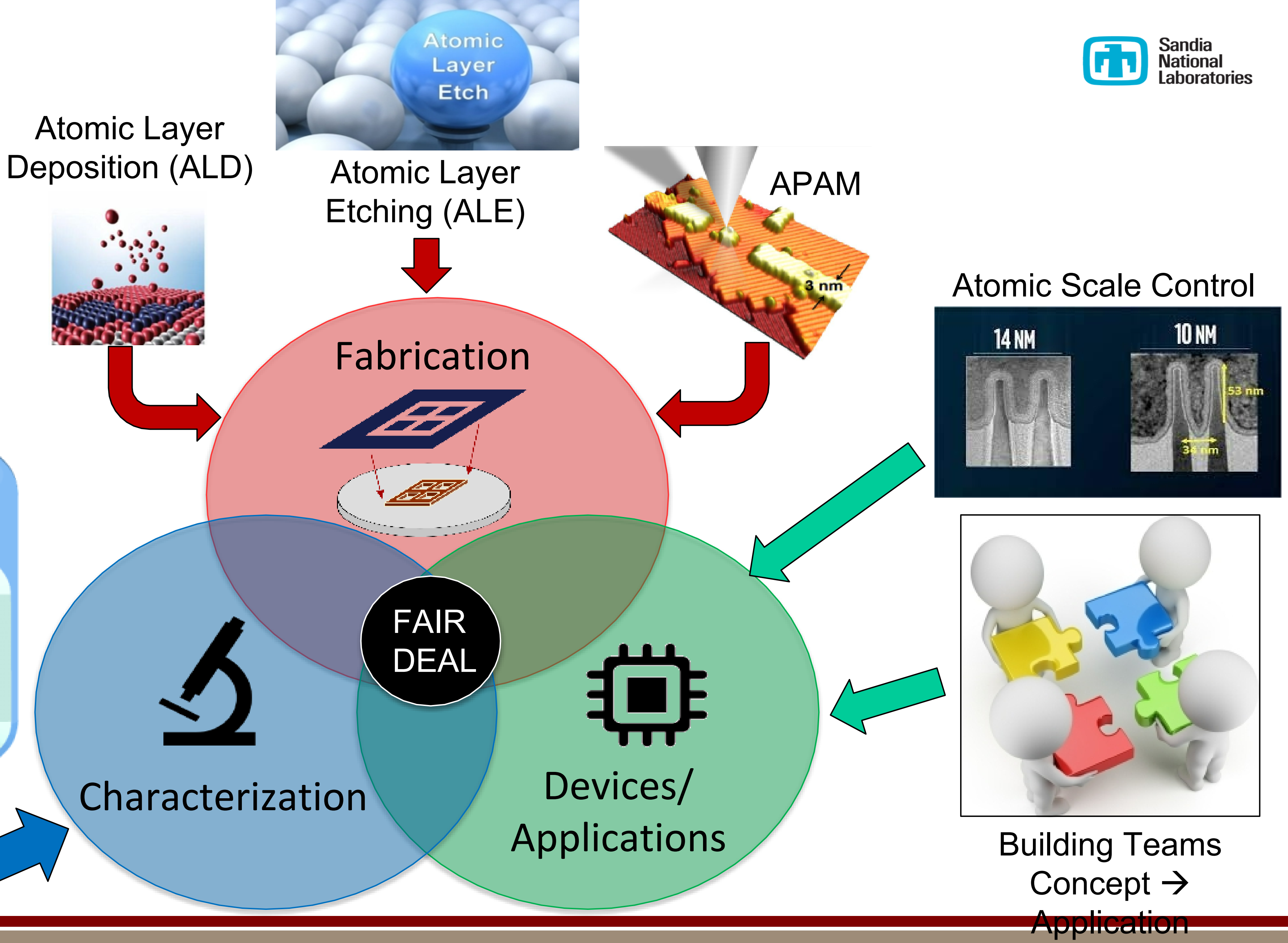
Partnerships

zyvex LABS, LPS, UD, R, APPLIED MATERIALS, UF

NYU, Columbia, BNL, APL

April 2021 Workshop





Staffing accomplishments

Sandia National Laboratories

Program Leadership
PI: Shashank Misra
PM: Robert Koudelka
Deputy PM: Paul Sharps
Dir. Champion: David White

APAM-enabled devices
Lead: Shashank Misra

Modeling
Lead: Suzey Gao

Integration
Lead: David Scrymgeour

APAM toolbox
Lead: George Wang

Support Team
Financial: Jennifer Woodrome
Logistics: Jennifer Woodrome
Web: Jennifer Woodrome
IP: Marty Finston

Measurement: Lisa Tracy, Tzu-Ming Lu, Albert Grine, Connor Halsey, Ping Lu, Aaron Katzenmeyer, Chris Allemang

Microfabrication: Andrew Leenheer, DeAnna Campbell, Mark Gunter, Phillip Gamache

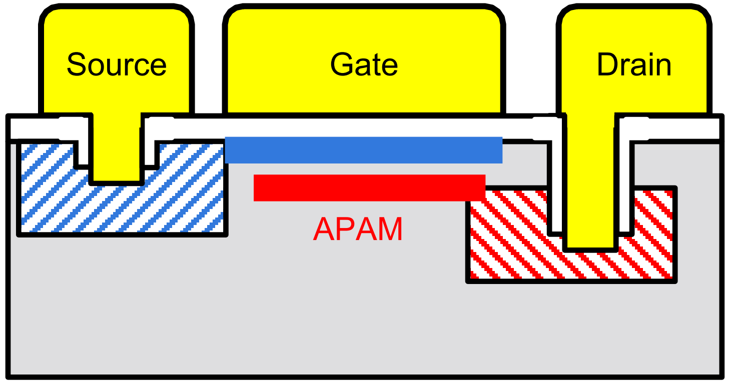
Modeling: Denis Mamaluy, Juan Granado, William Lepkowski, Andrew Baczewski, Quinn Campbell, Steve Young

Surface Science: Scott Schmucker, Evan Anderson, Jeff Ivie, Ezra Bussmann, Fabian Pena, Aaron Katzenmeyer, Esther Frederick, David Wheeler

Underlined = new hire, or promoted

Outline

1. Goals



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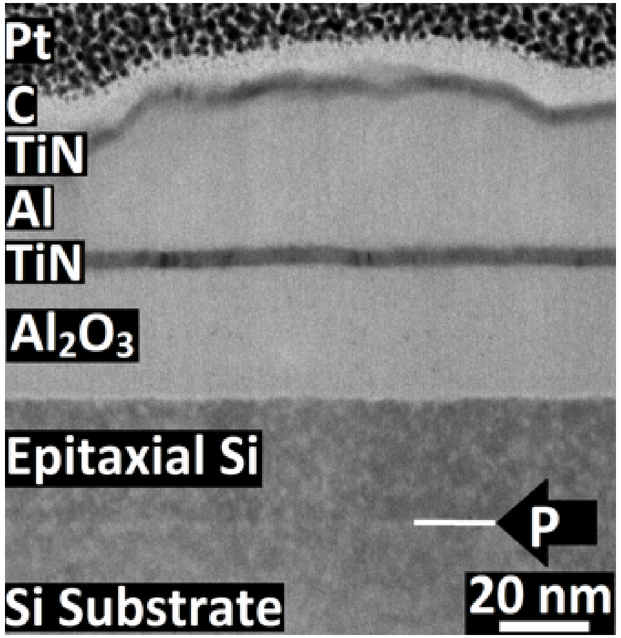

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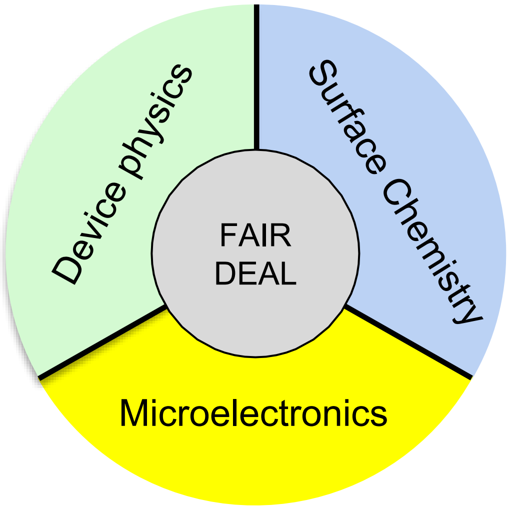
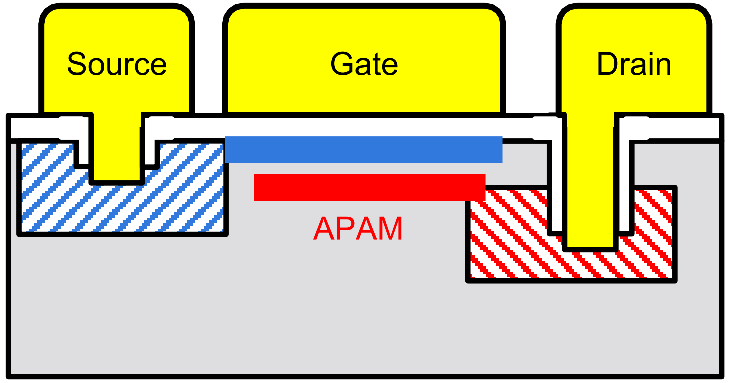
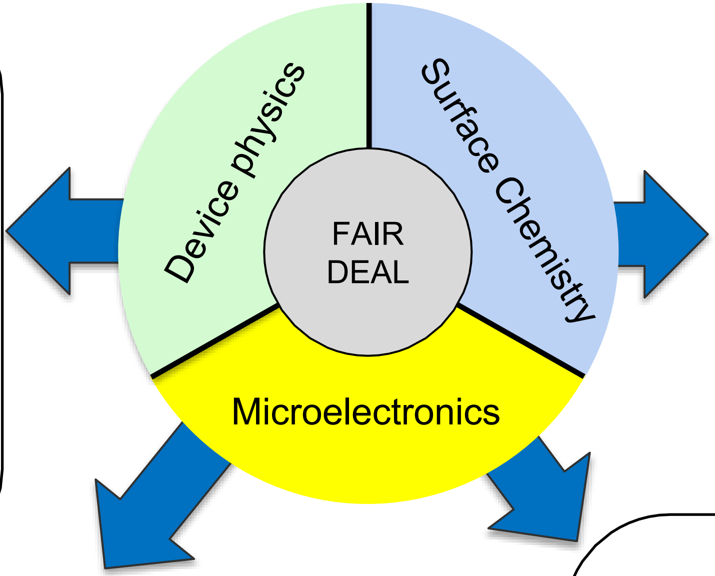


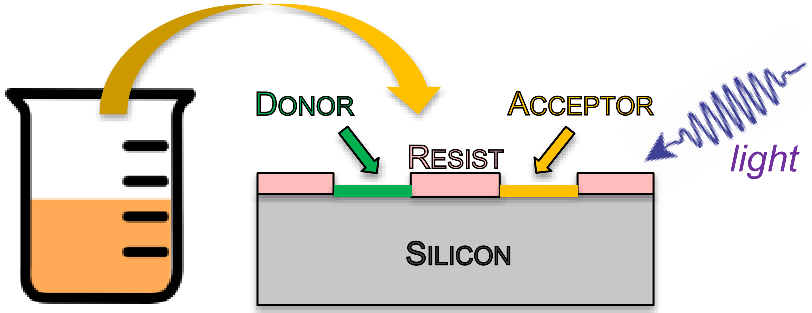
Where do we go from here?

Thrust 1: APAM-enabled Devices

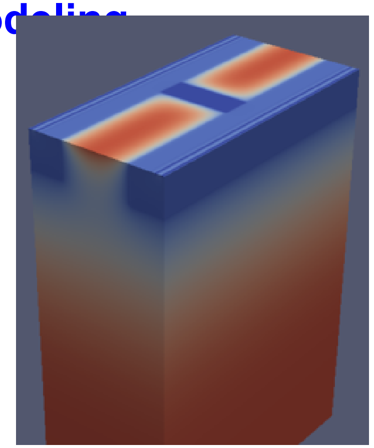




Thrust 4: manufacturability



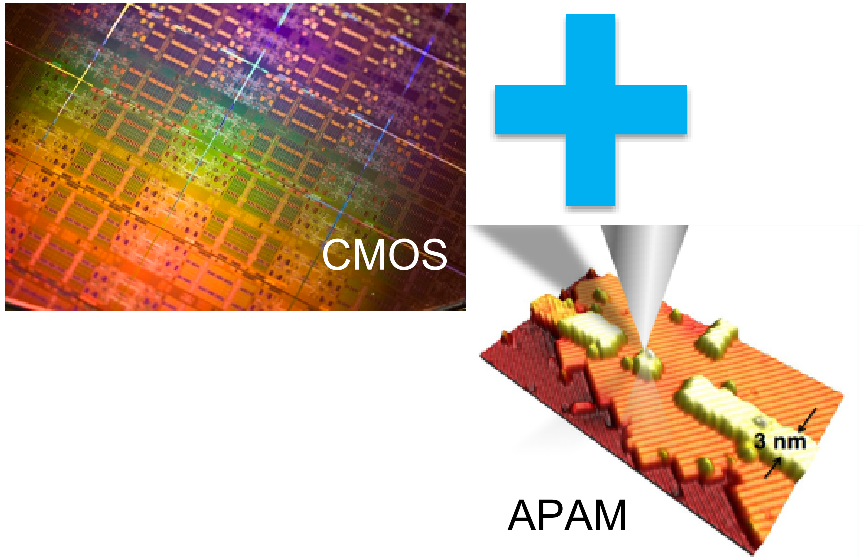
Thrust 2: APAM Modeling



FAIR DEAL established a science and technology foundation. TRL 1→3

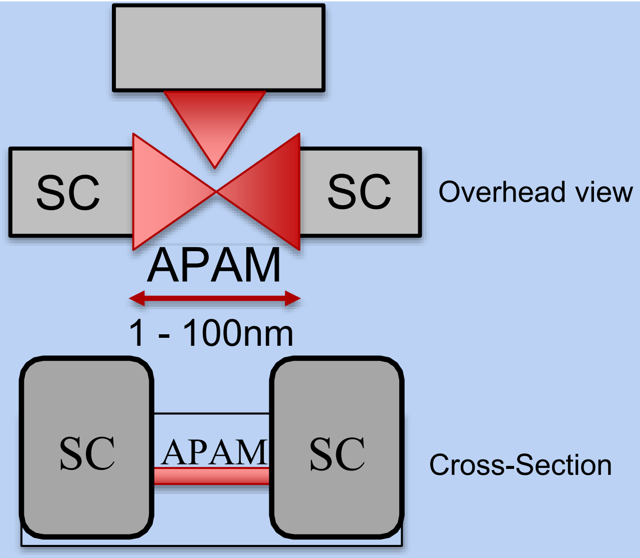
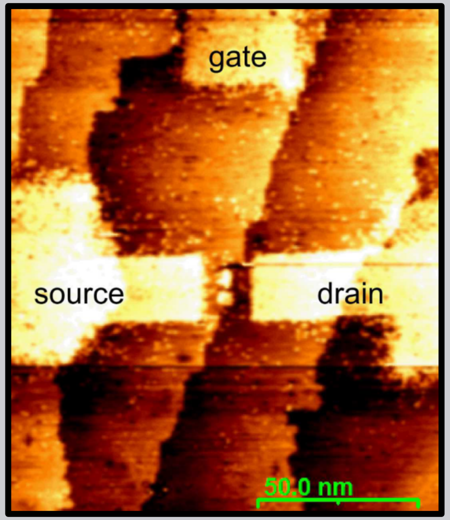
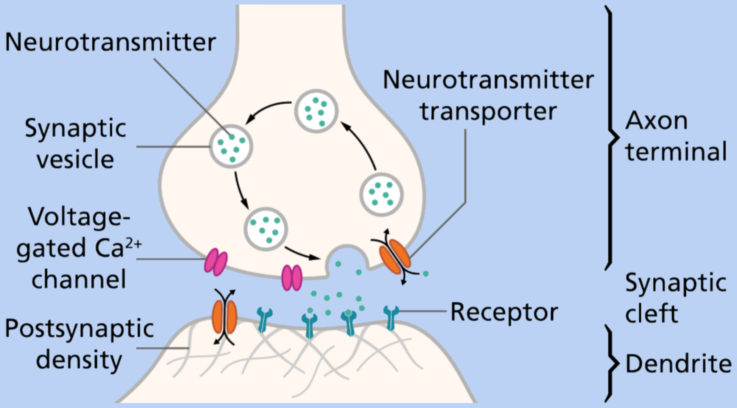
Next: Build applications on that foundation & expand the science of APAM based on what we learned.

Thrust 3: CMOS Integration

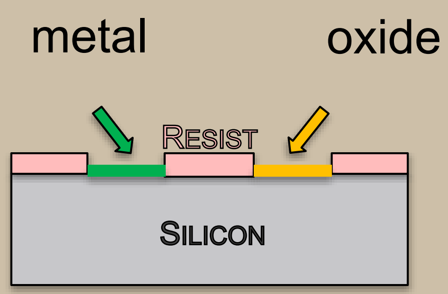
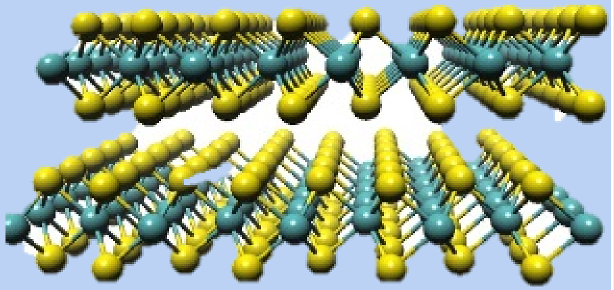
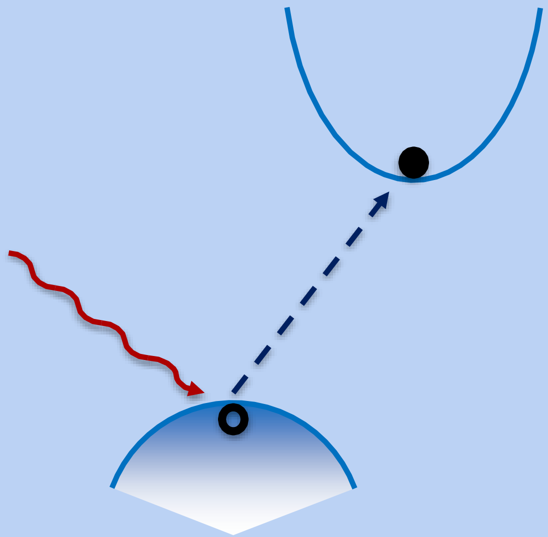


New Science

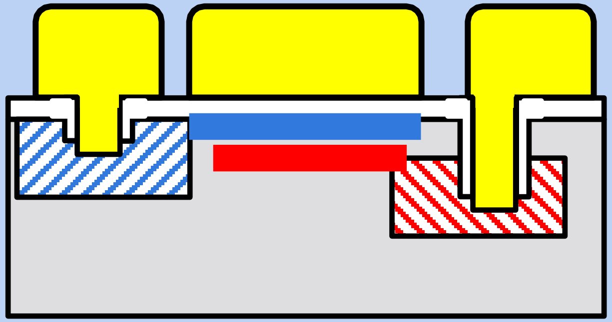
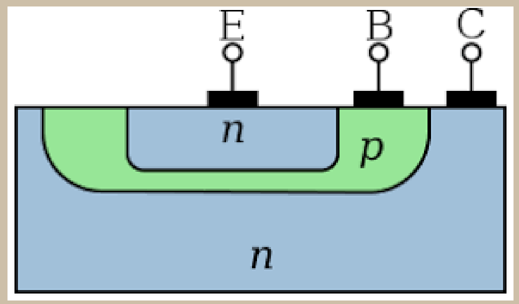
Sandia National Laboratories

Name	Super/semi qubits	Room temperature SET	COINFLIPS
Blue = day 2 Brown = day 1 Gray = skip			
Description	Gated superconducting devices	Electrometer for sensing	Probabilistic computing paradigm
Agency	DOE/BES & ARO	ARO	DOE/ SC & SNL LDRD
Dollars	$250 k / $800 k	$800 k	$500 k / $125 k
TRL	2→3	2→3	1→2 (codesign)
Science goal	Superconductivity in APAM & understanding defects	Tunneling & temperature	Understand defects in tunneling & random number generation
Builds on	Thrusts 1 & 2	Thrusts 1 & 2	Thrusts 1 & 2

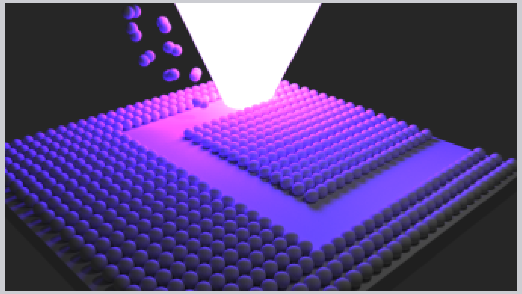
New Science

Name	APAM + ALD/ALE	2D Materials	Optoelectronics
Blue = day 2 Brown = day 1 Gray = skip			
Description	Atomic-scale ALD & ALE	APAM on 2D materials	Optically active silicon
Agency	USG	SNL LDRD	SNL LDRD
Dollars	Whitepaper in progress	$125 k	FY 22 idea
TRL	2→3	1	2→3
Science goal	Expand chemistry & understand non-ideal environments	Rules for what materials you can do APAM on	Expand chemistry & understand band structure
Builds on	Thrusts 2 – 4	Thrust 4	Thrusts 2 – 4

Applications

Name	BEETS	Hardware Trust	BJT Amplifiers
Blue = day 2 Brown = day 1 Gray = skip			
Description	Energy efficient transistor	Reconfigurable circuit	High gain*bandwidth amp
Agency	DOE/AMO	SNL LDRD	DOE/ AMO (Zyvex Labs)
Dollars	$500 k	$500 k	$125 k
TRL	3→4	2→3	2→3
Technology goal	Proof-of-concept demonstration	Assessment	Modeling-based projection
Builds on	Thrusts 1 & 2	Thrusts 1 – 3	Thrust 2

Applications

Name	Fingerprint	Contact Resistance	Photolithography
Blue = day 2 Brown = day 1 Gray = skip			
Description	Supply-chain assurance marker	APAM-infused CMOS contacts	Atomic resist for EUV
Agency	USG	Applied Materials	SNL LDRD / LBNL
Dollars	Whitepaper in progress (small)	Proposal in progress (very small)	FY 22 idea
TRL	2→4	Hard to tell. Perhaps 3→4	2→4
Technology goal	Proof-of-concept demonstration	Determine impact of world-record dopant density	Compare to leading resists in EUV tool
Builds on	Thrusts 1 – 3	Thrusts 1 – 4	Thrust 4

Conclusion

- The perspective from January 12, 2018.
  - Science & technology risk in an application-driven world
- We have a path forward.
  - FAIR DEAL was ~ $5 M/yr
  - $4 M in proposed/funded work for FY 22.
- The future remains uncertain.
  - What are we missing?