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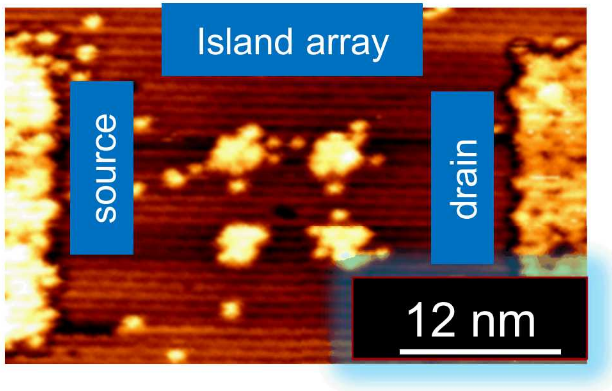


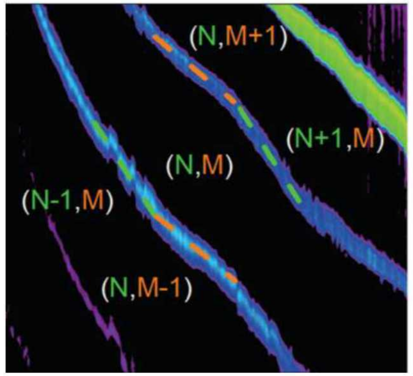


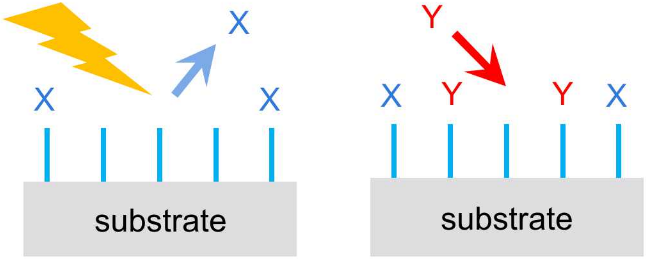


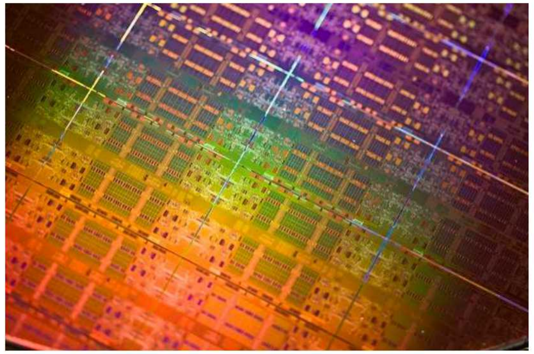

# Photothermal alternative to device fabrication using atomic precision advanced manufacturing techniques

A. M. Katzenmeyer, S. Dmitrovic, A. D. Baczewski, E. Bussmann, T.-M. Lu, E. M. Anderson, S. W. Schmucker, J. A. Ivie, D. M. Campbell, G. T. Wang, D. R. Ward, **Shashank Misra**

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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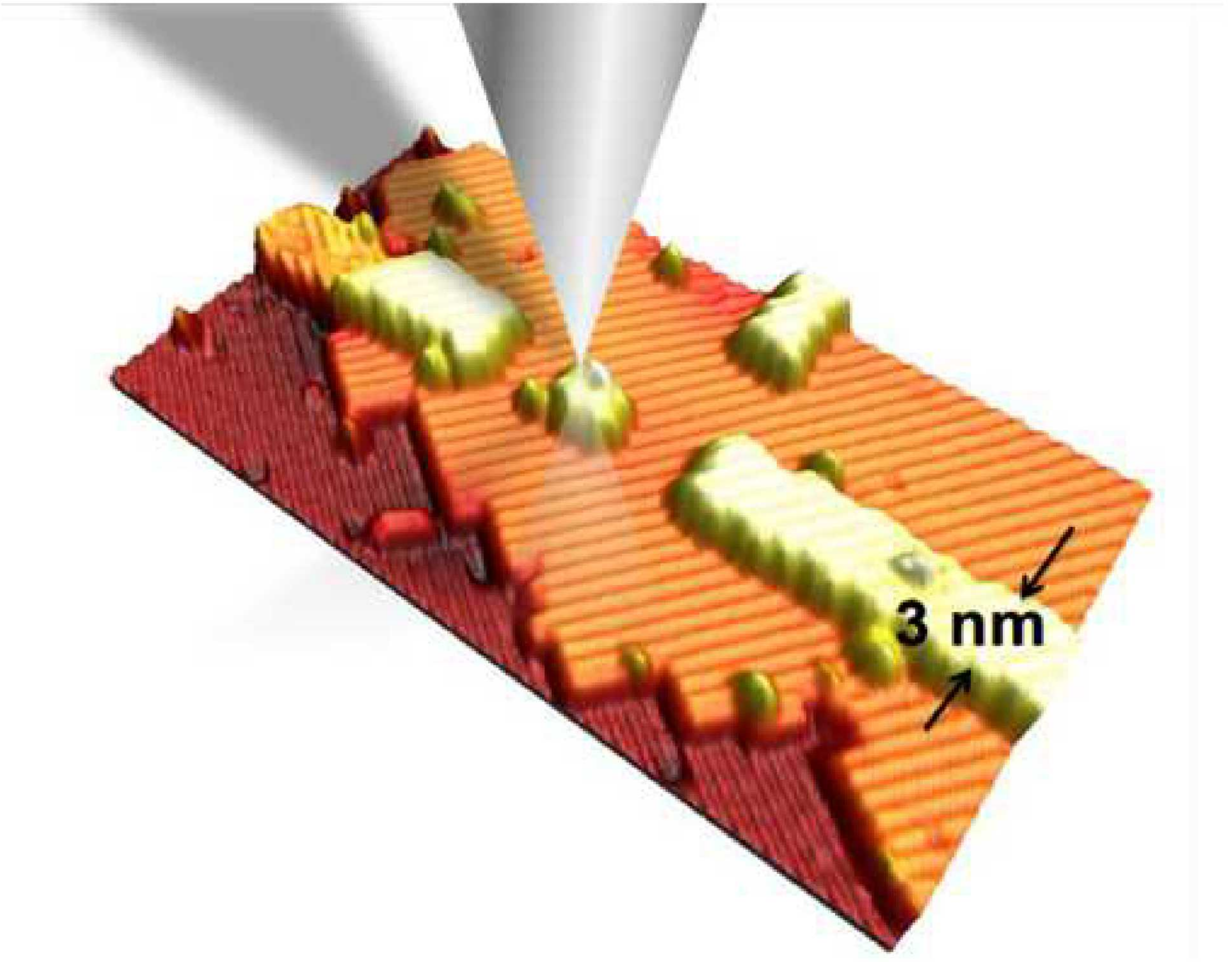
# Atomic Precision Advanced Manufacturing




Assess the opportunities presented by atomic-scale devices and processing for the digital microelectronics of the future

# What is the opportunity?

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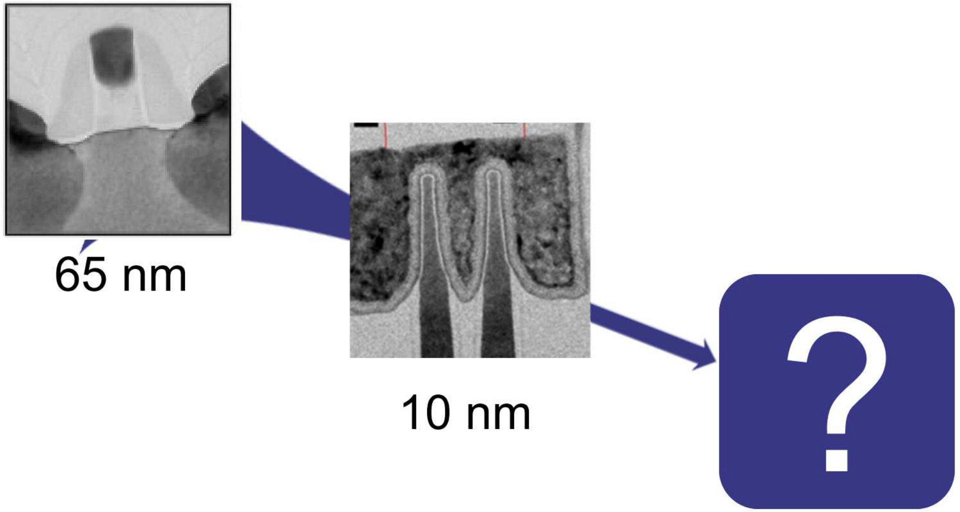
Rising cost to R&D and unclear technology path

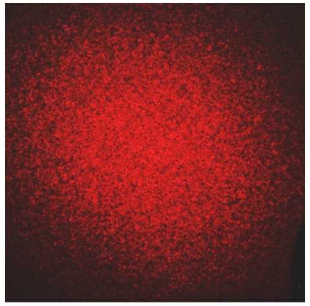



5-7 nm

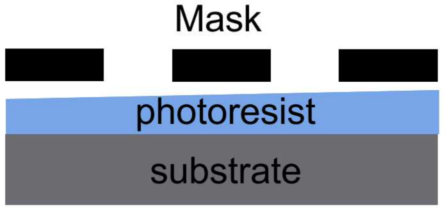
**Assess device ideas from the atomic limit**

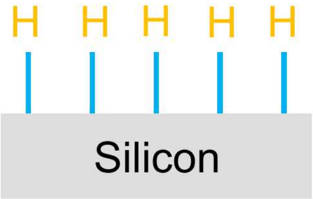
Increasing difficulty from process limitations

Inhomogeneity of light



Inhomogeneity of resist



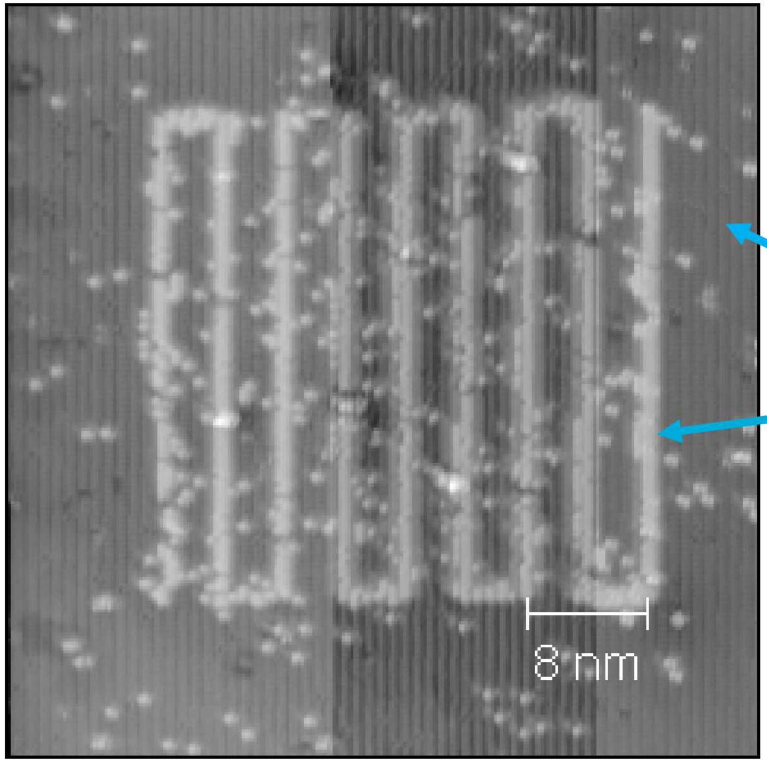



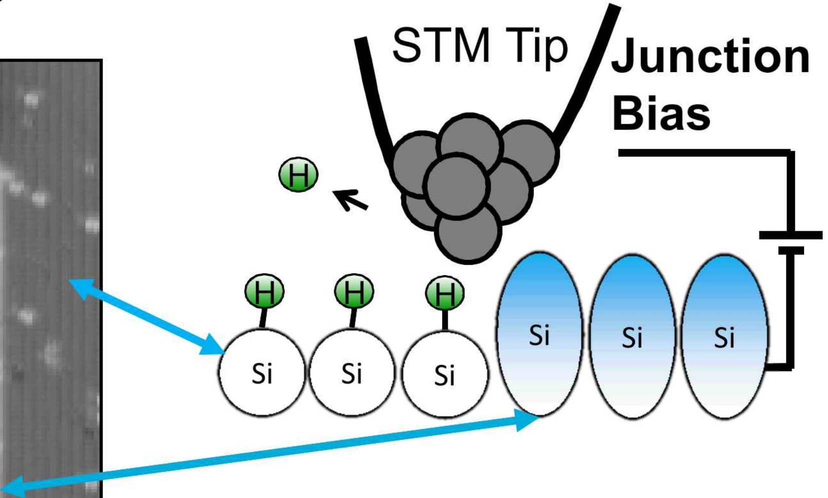

New processing paradigm with **atomic-scale chemistry**

# How does Atomic Precision Advanced Manufacturing (APAM) work?

## "Chemical contrast" at Si surface

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




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

# Phosphine surface chemistry

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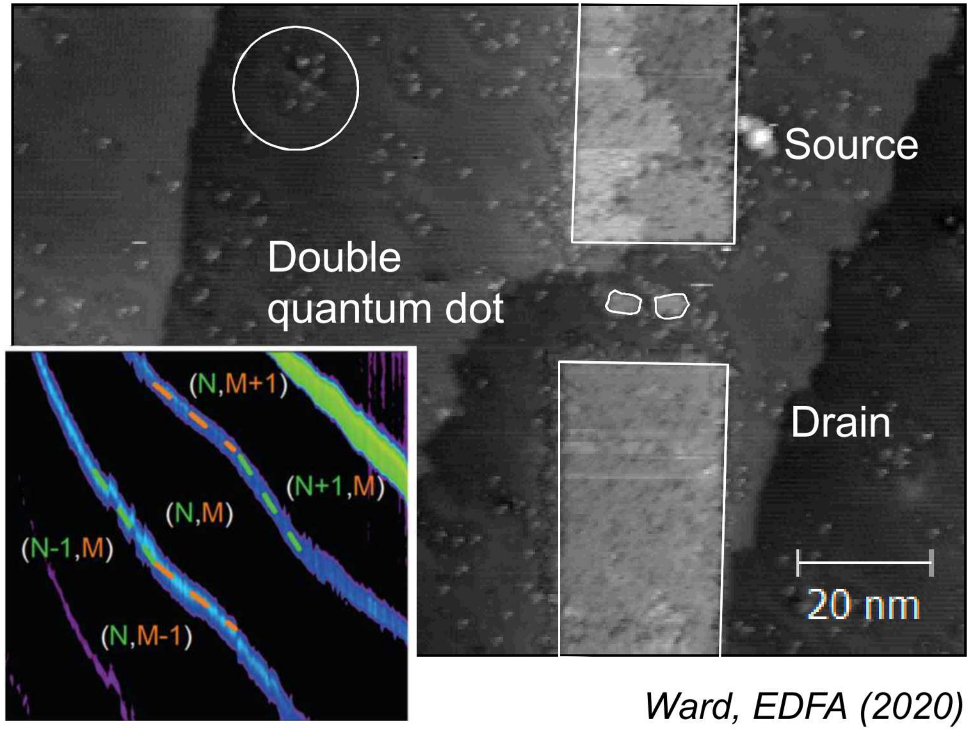
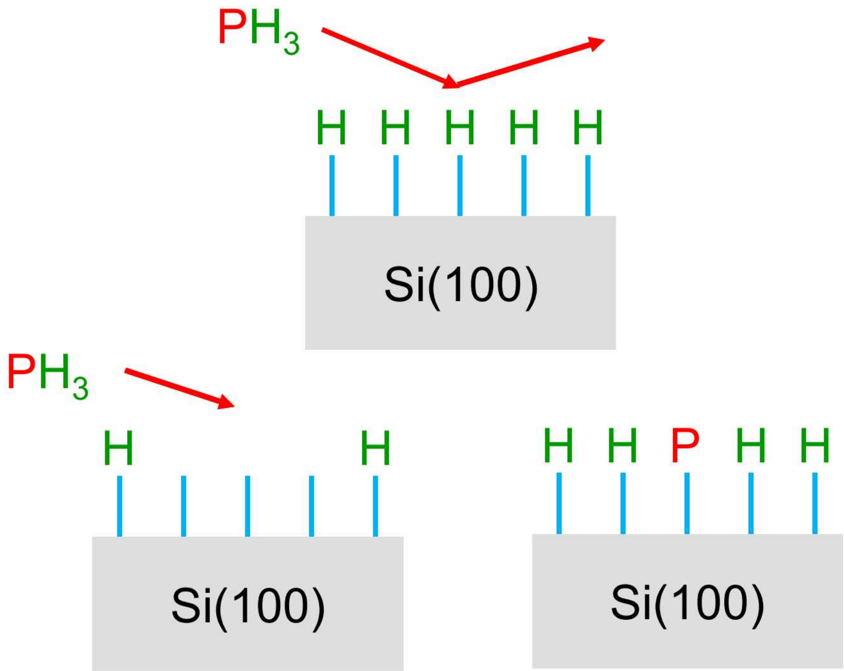
Top view




*Ward, EDFA (2020)*

Phosphorus ‘donates’ an electron to silicon.



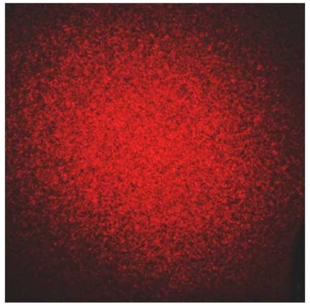

Chemical error correction : need 3 open sites for phosphine

Opportunities outside of just atomic-scale devices for quantum demonstrations

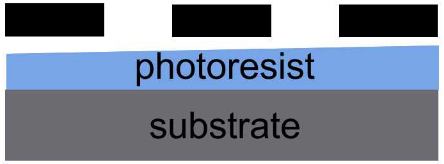
# Why photolithography with APAM (1)?

## Traditional (analog) resist

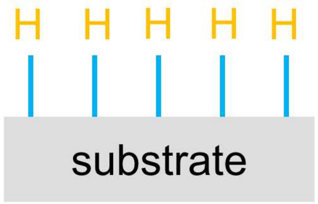
Inhomogeneity of light



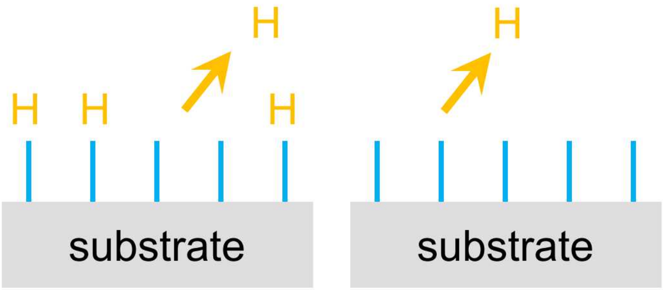
Inhomogeneity of resist




## Atomic-scale (digital) resist




Underexpose = like no exposure




*Exposure 1* *Exposure 2*

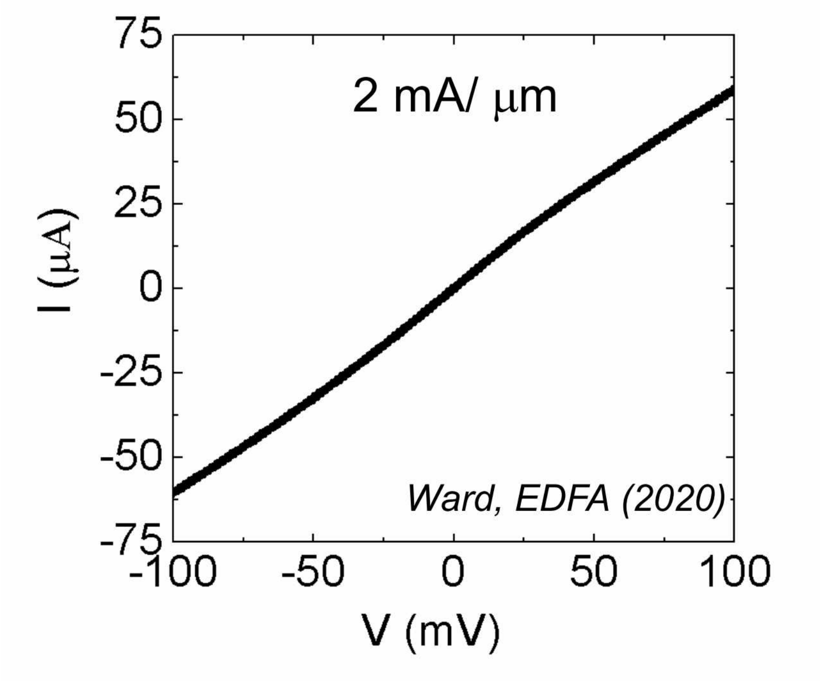
No overexposure on multiple exposure

**APAM processing has unique advantages**

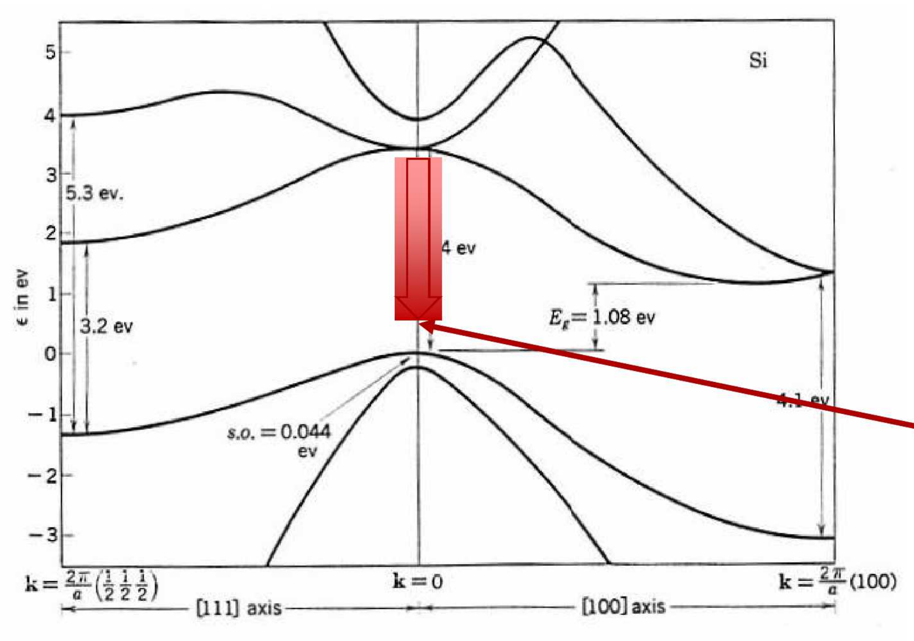
# Why photolithography with APAM (2)?

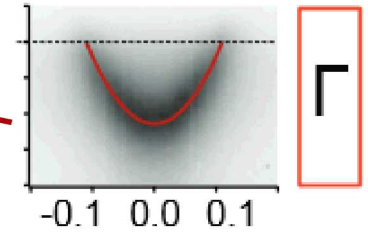
Exceeds solid solubility limit by 10x

Confinement




Electronic structure

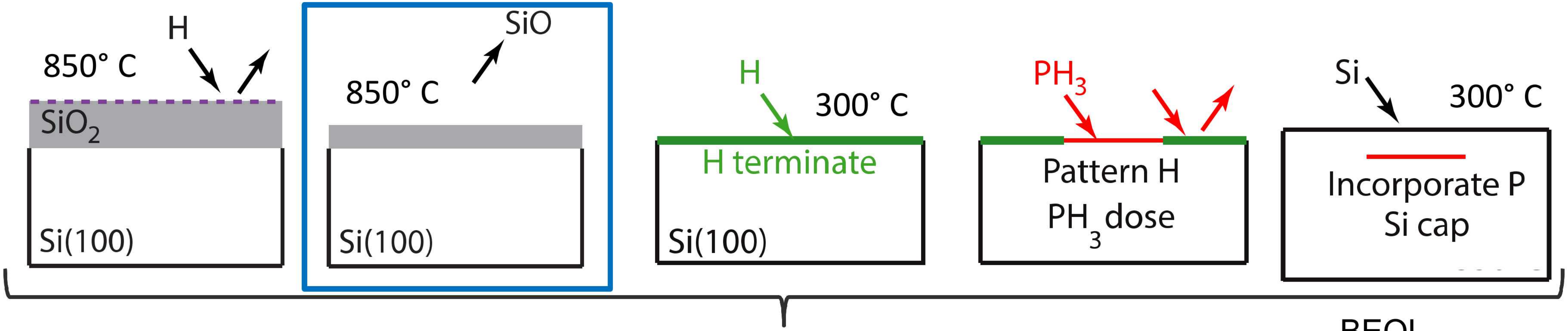


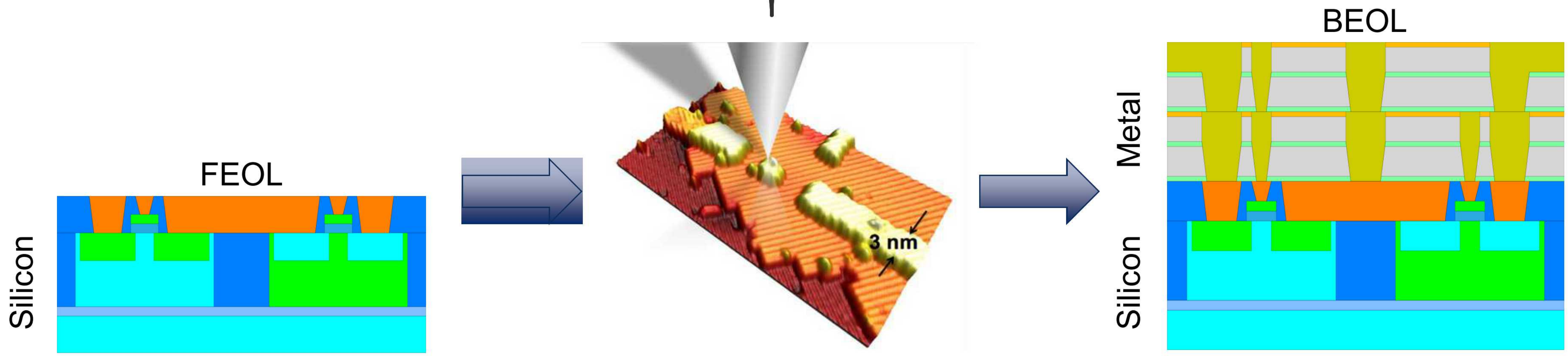




*Holt, arXiv:1911.08274*

Ultra-doping transforms properties of silicon.

# Why photolithography with APAM (3)?



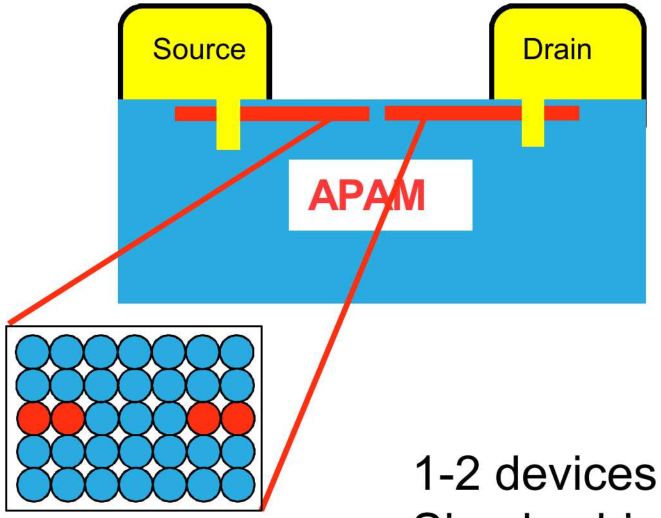




Integrate non-atomically precise features at wafer scale

# Needed for atomic-scale devices too…

Now (3 US labs, 6 labs worldwide)

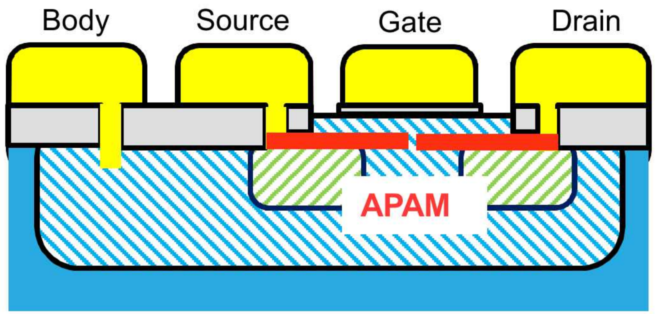
Simple devices




1-2 devices per chip.
Simple chips

Desired future state

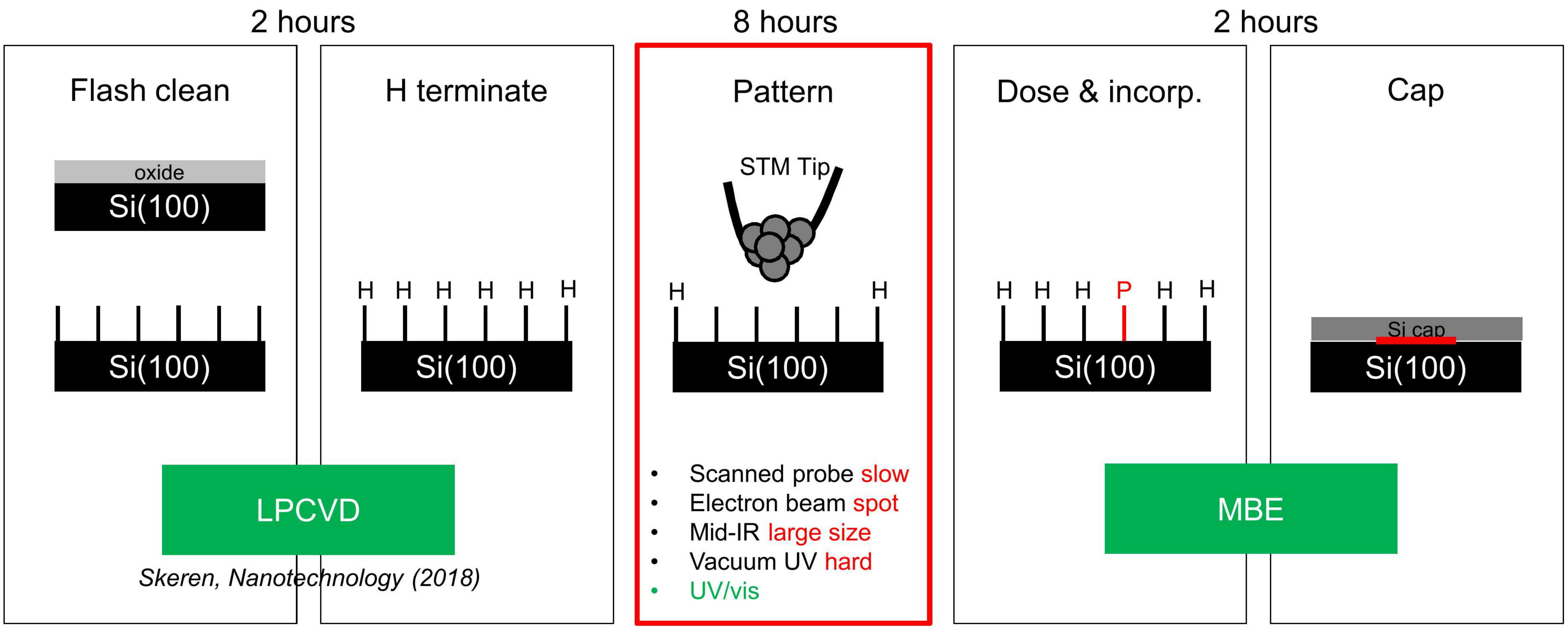
"Real" transistor




Many devices per chip.
Integrated with CMOS.

STM lithography not close to the throughput needed for process development

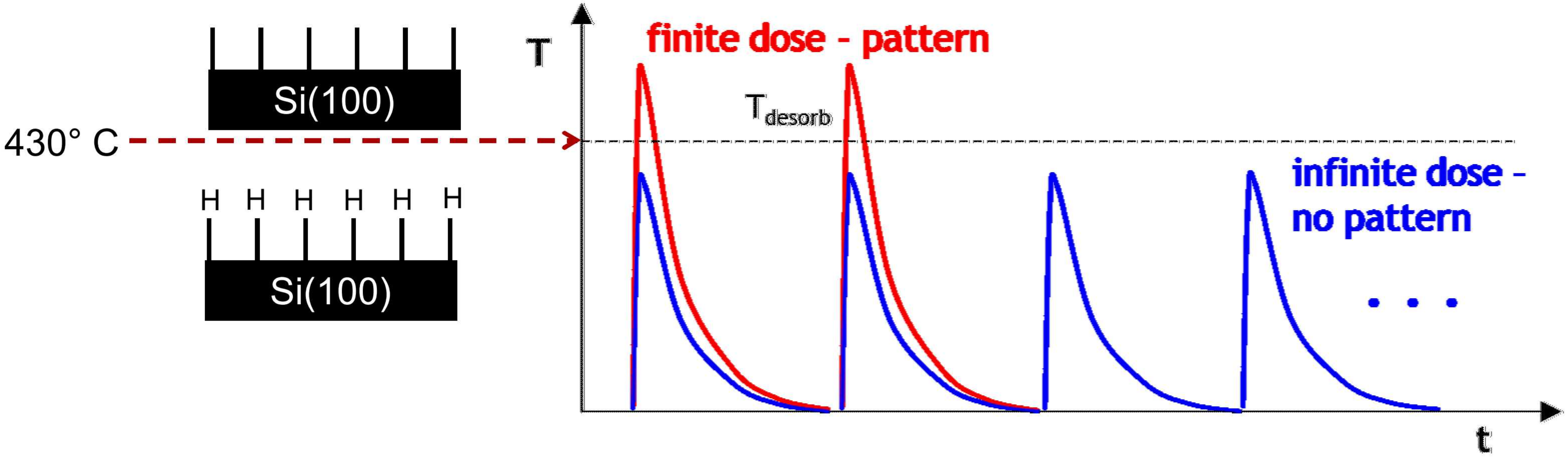
# What’s a scalable path to APAM?




UV-Vis wavelengths (180-1000 nm) : easy optics vs. size of features

# Mechanism

UV-Vis wavelengths (180-1000 nm)
$\lambda$ > band gap
$\lambda$ < Si-H bond energy

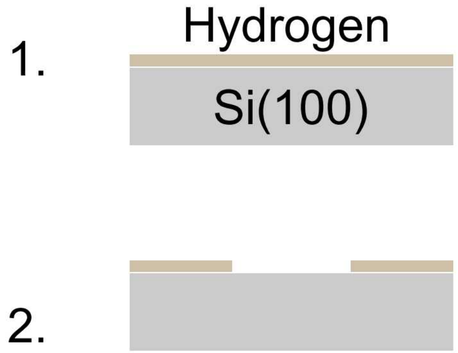



Concept of dose is not relevant for photothermal desorption.

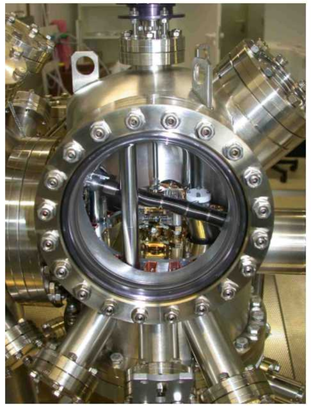
- Below threshold = no H desorbed.
- Above = no penalty for over-exposure

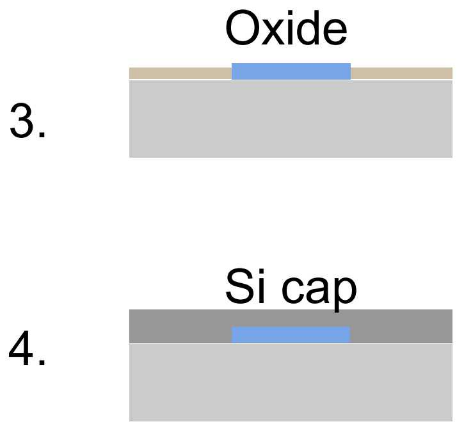
# Photothermal desorption of hydrogen

Native oxide process flow

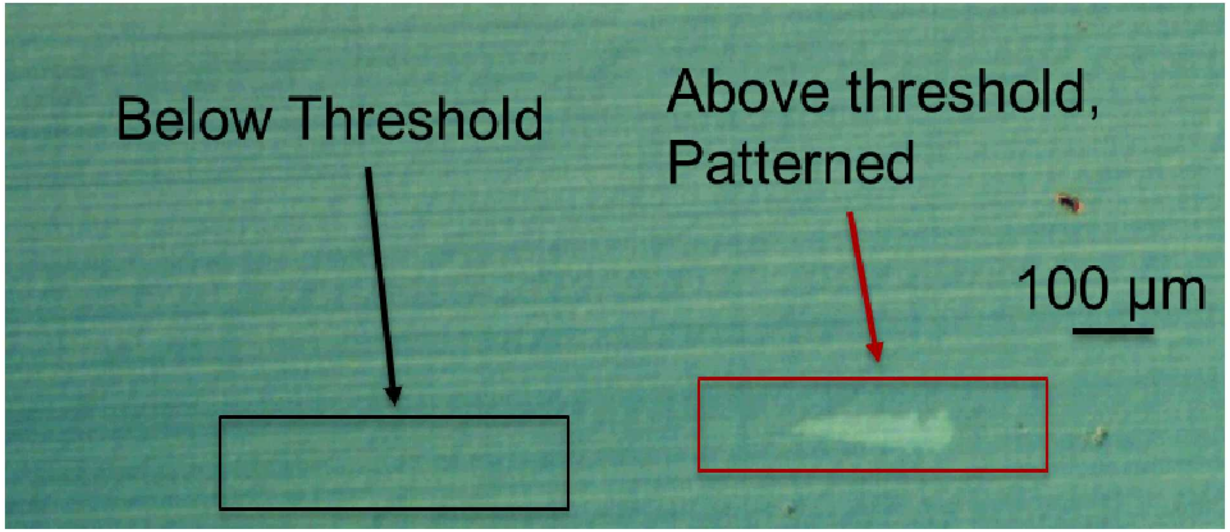








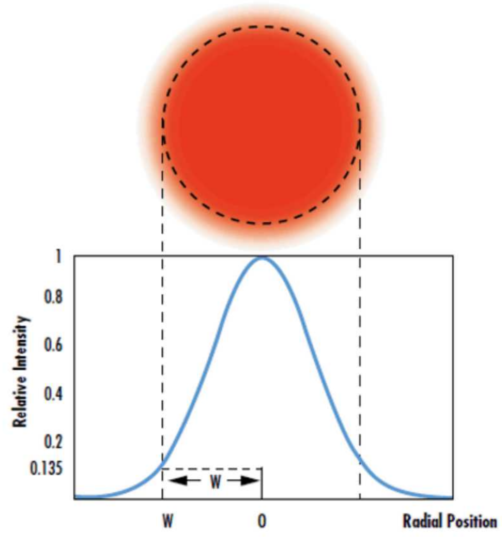

Fast path to reduce a huge phase space (pulses, energy density, etc.)



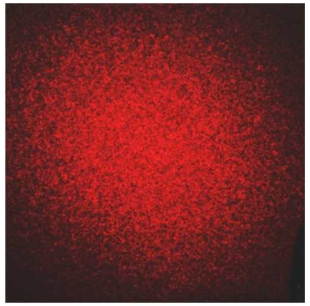

10% change in energy density
337 nm, single 3.5 ns pulse

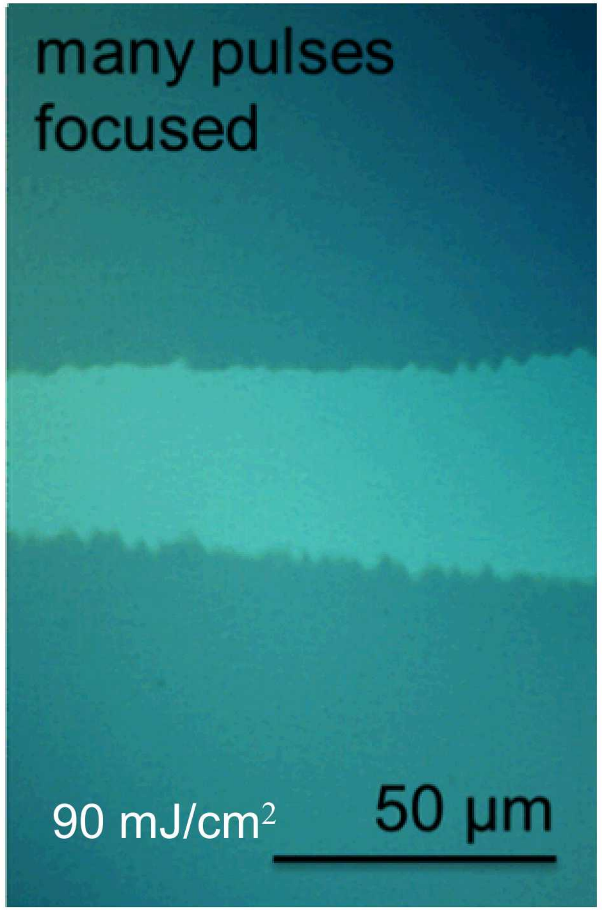
# Advantages of atomic resists


Origin of edge roughness



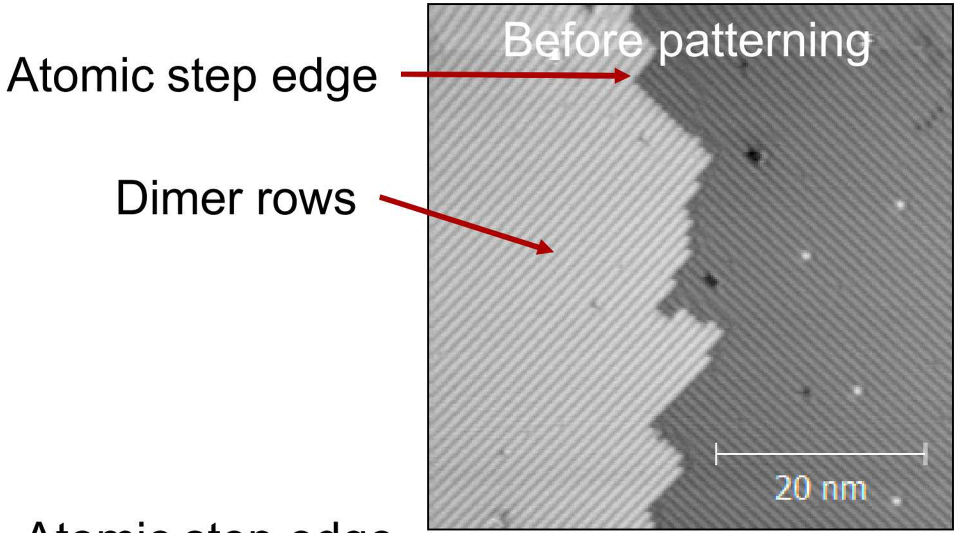

Inhomogeneity of light

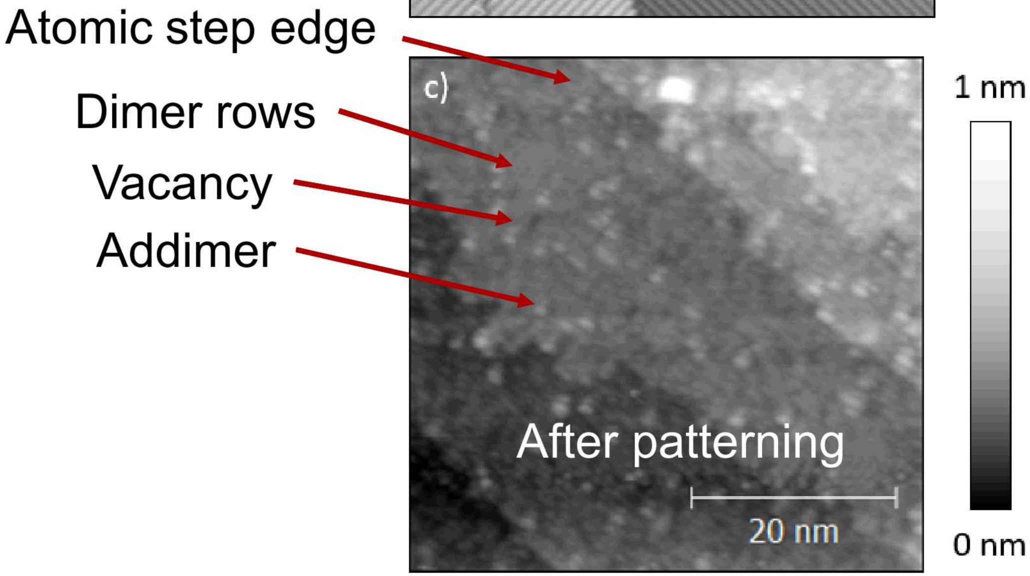





Edge rougness reduced.
Interior can't be over-exposed.

# How wide is the window of operation?



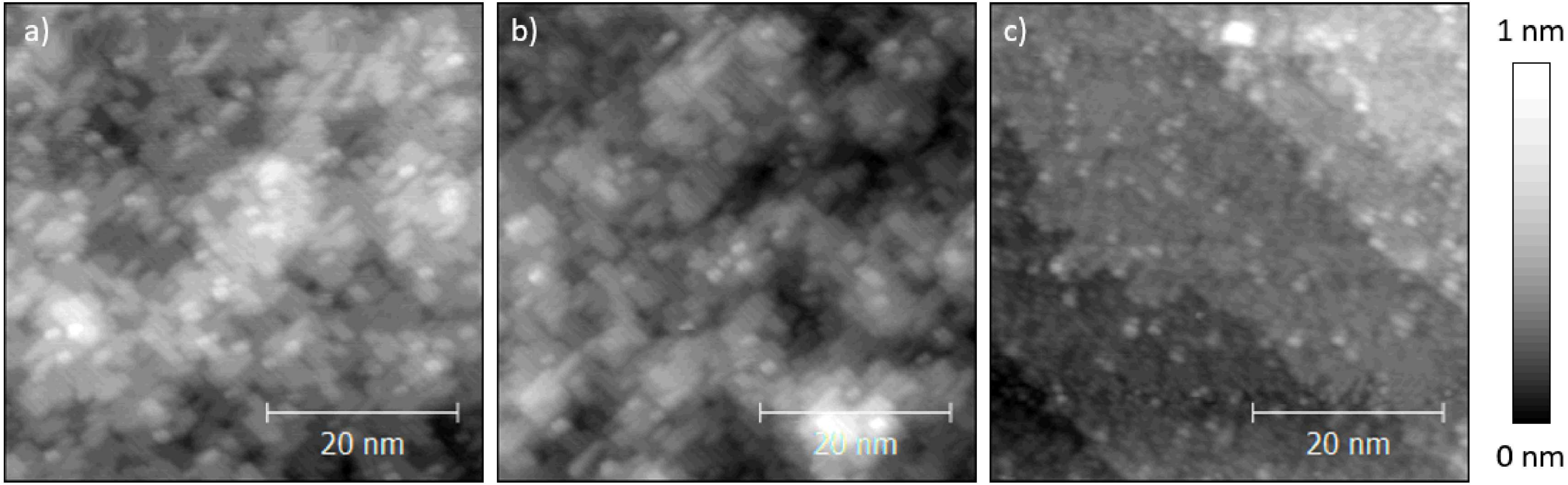

Hydrogen desorption: 430° C
Silicon melting: 1400° C

Roughening of surface at atomic scale.
Does not resemble “frozen” hot surface

Working to capture data right at threshold, as a function of number of pulses

# Surface roughness

101 mJ/cm$^2$ 90 mJ/cm$^2$ 81 mJ/cm$^2$



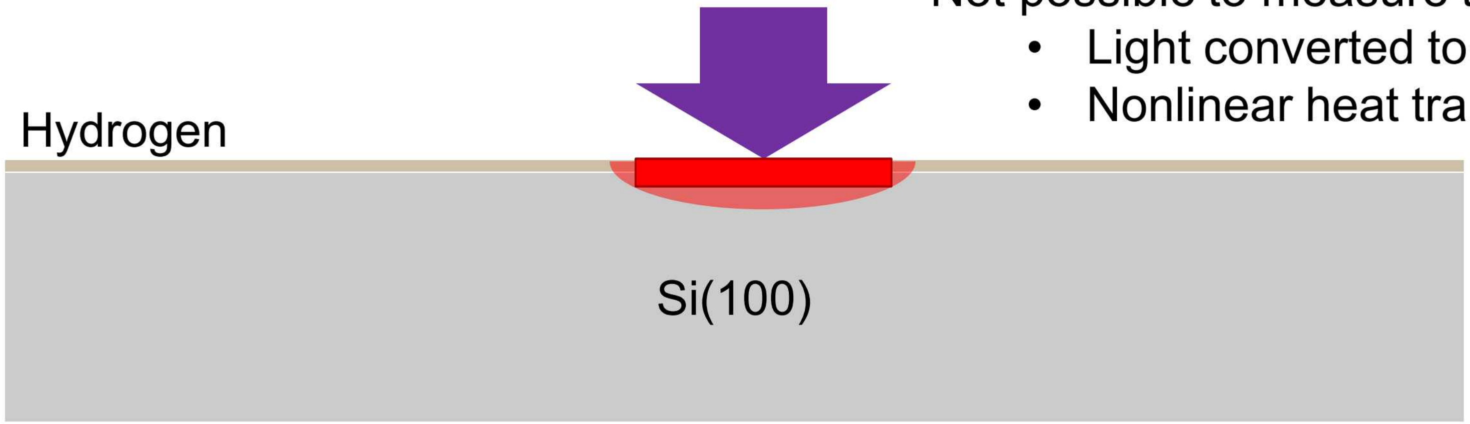

Pits and islands Single layer

Window for photothermal desorption without roughening is narrow.

# Photothermal model

Not possible to measure temperature… need model

- Light converted to heat (10 nm)
- Nonlinear heat transport away from spot



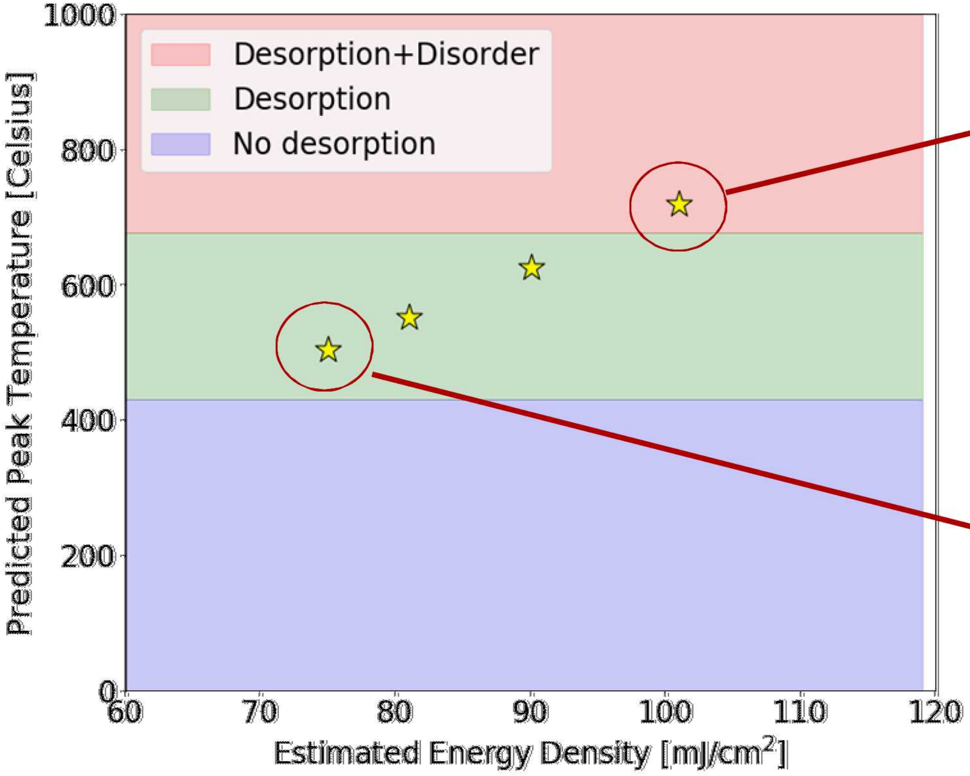

intensity, reflectivity, diffusivity, duration

$$T_{peak} \approx T_{init} + \frac{2I(1-R)}{GM\left[\kappa(T_{init}), \kappa\left(T_{peak}\right)\right]}\sqrt{\frac{GM\left[D(T_{init}), D\left(T_{peak}\right)\right]\Delta}{\pi}} + \mathcal{O}\left(\left[\alpha\sqrt{D\Delta}\right]^{-1}\right),$$

Thermal conductivity

*Ong, JOSA B (1986)*

# Some remaining questions



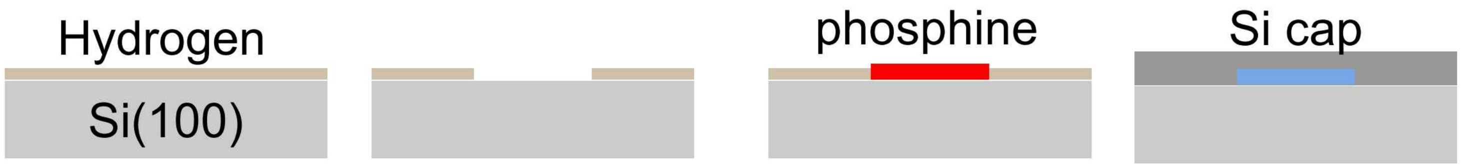

Roughening mechanism unclear –

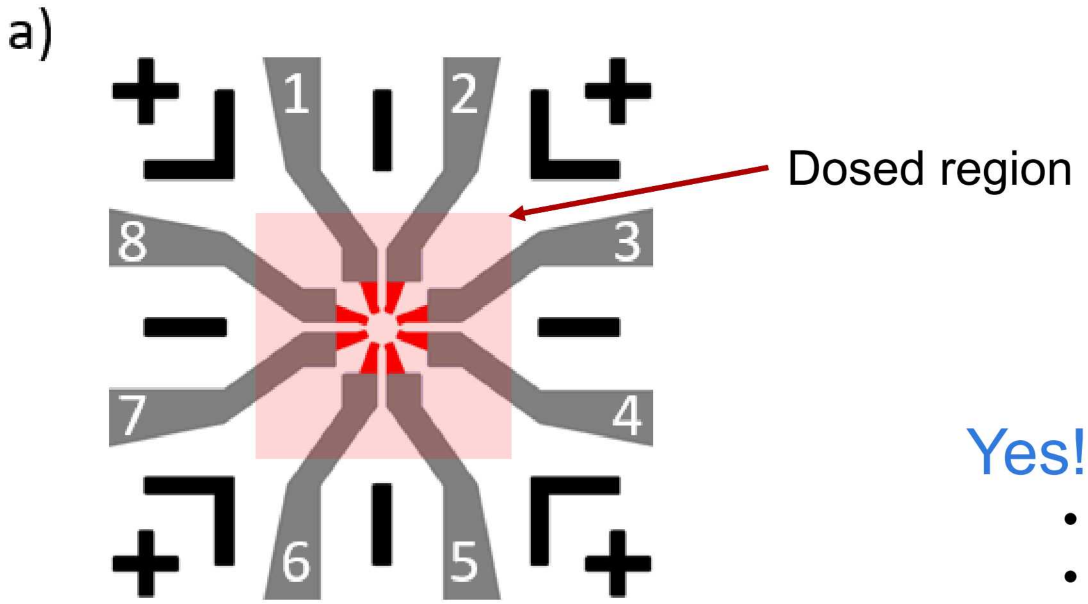
- No mechanism at this temperature.

Hydrogen desorption mechanism unclear –

- Full depassivation in 3.5 ns suggests T is near melting point

# Did it work? Similar electrical properties?




$\mu = 51.7\ \mathrm{cm}^2(\mathrm{Vs})^{-1}$

$n_{2D} = 4.83 \times 10^{14}\ \mathrm{cm}^{-2}$!

Yes! Mobility is as expected. Density is high.

- Geometry of VdP measurement?
- Not related to roughness

# Demonstrated viability of photothermal patterning for fast, large-scale APAM

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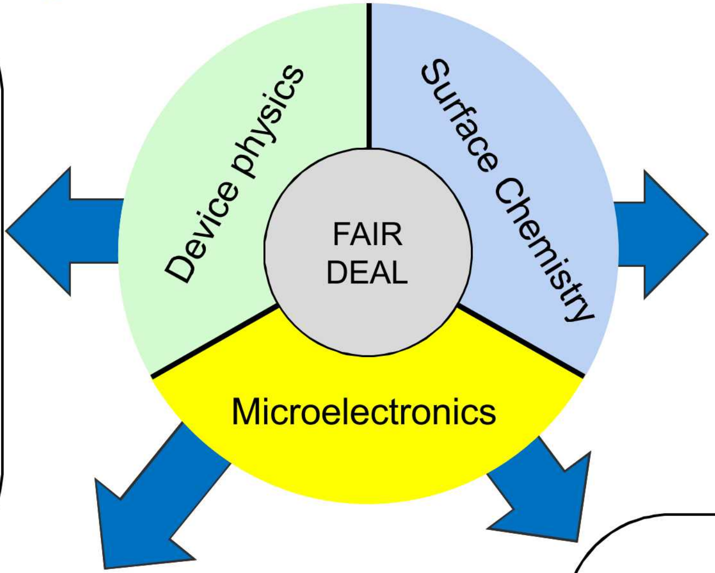
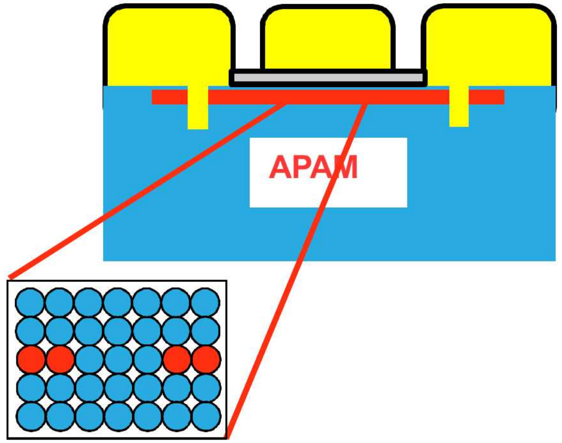
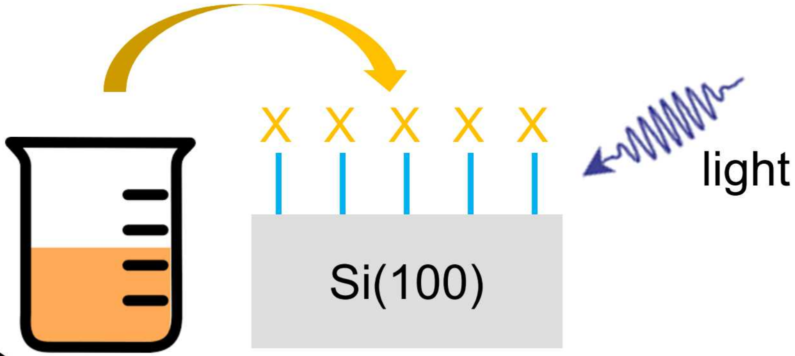


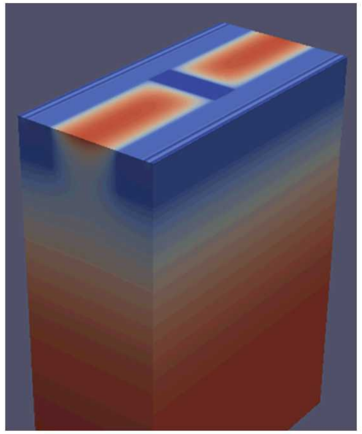

## APAM Device development




## Manufacturability




## Modeling & Simulation



Check out SPIE proceedings article

## CMOS integration