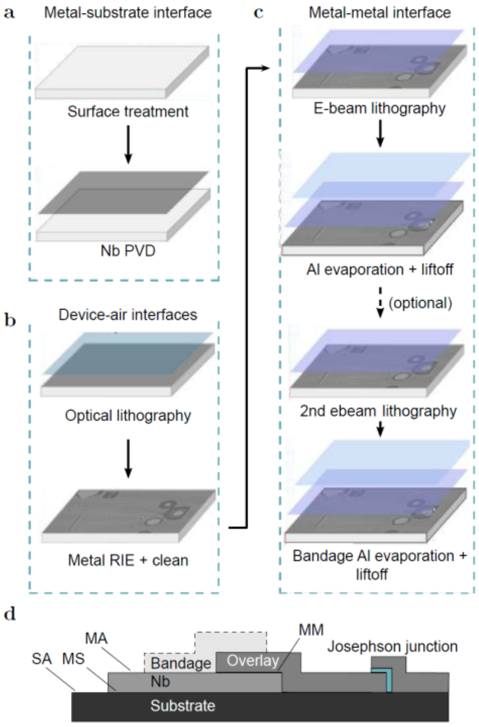
# Low temperature plasma processing of qubit materials

Malcolm Carroll and David Graves

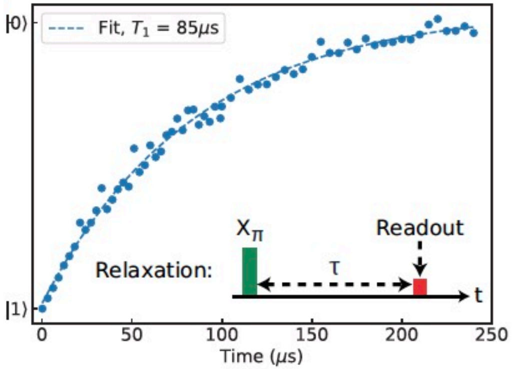
June 8th, 2021

## 1. Qubits & their fab



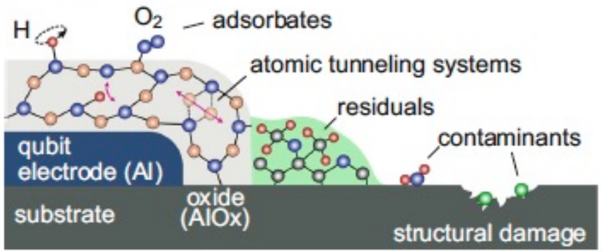

Nersisyan et al. arXiv:1901.08042

## 2. Qubit metrics (coherence)



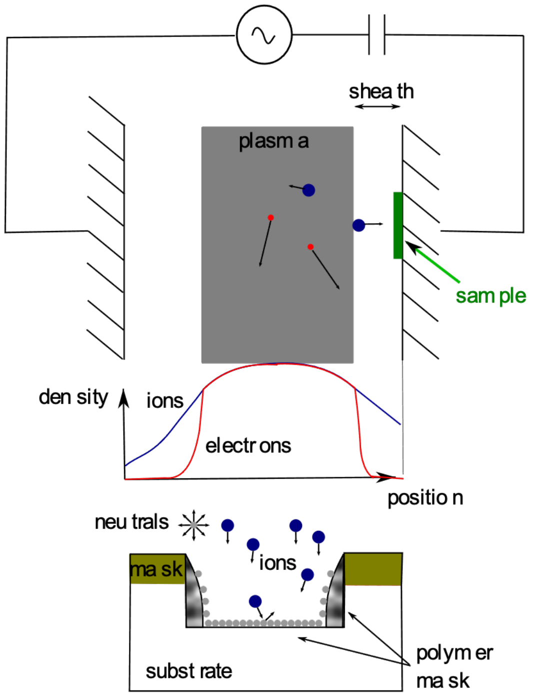

Krantz et al. Appl. Phys. Rev. 6 (2019)

## 3. Defects limit coherence




Lisenfeld et al. npj Quant. Inf. 5 (2019)

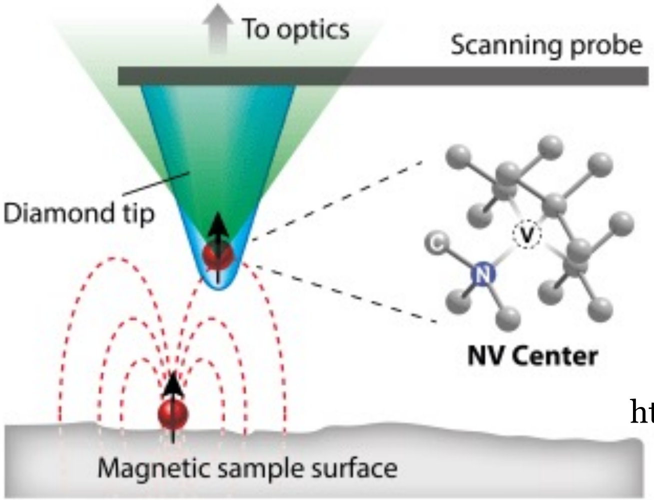
## 4. Plasma-surfaces: challenge & opportunity in QIS



# Motivations for quantum bit (qubit) applications




- Quantum computing promises speed up in critical areas




https://qzabre.com

- Quantum sensing offers the potential to outperform ‘classical’ limits
- Quantum communication introduces new forms of security and efficiency

# Motivations for quantum computing



- "While it may be years … to pay off, … quantum computing … is at best a missed opportunity, at worst an existential mistake"

From: "Where will quantum computers create value and when", BCG report 05/19

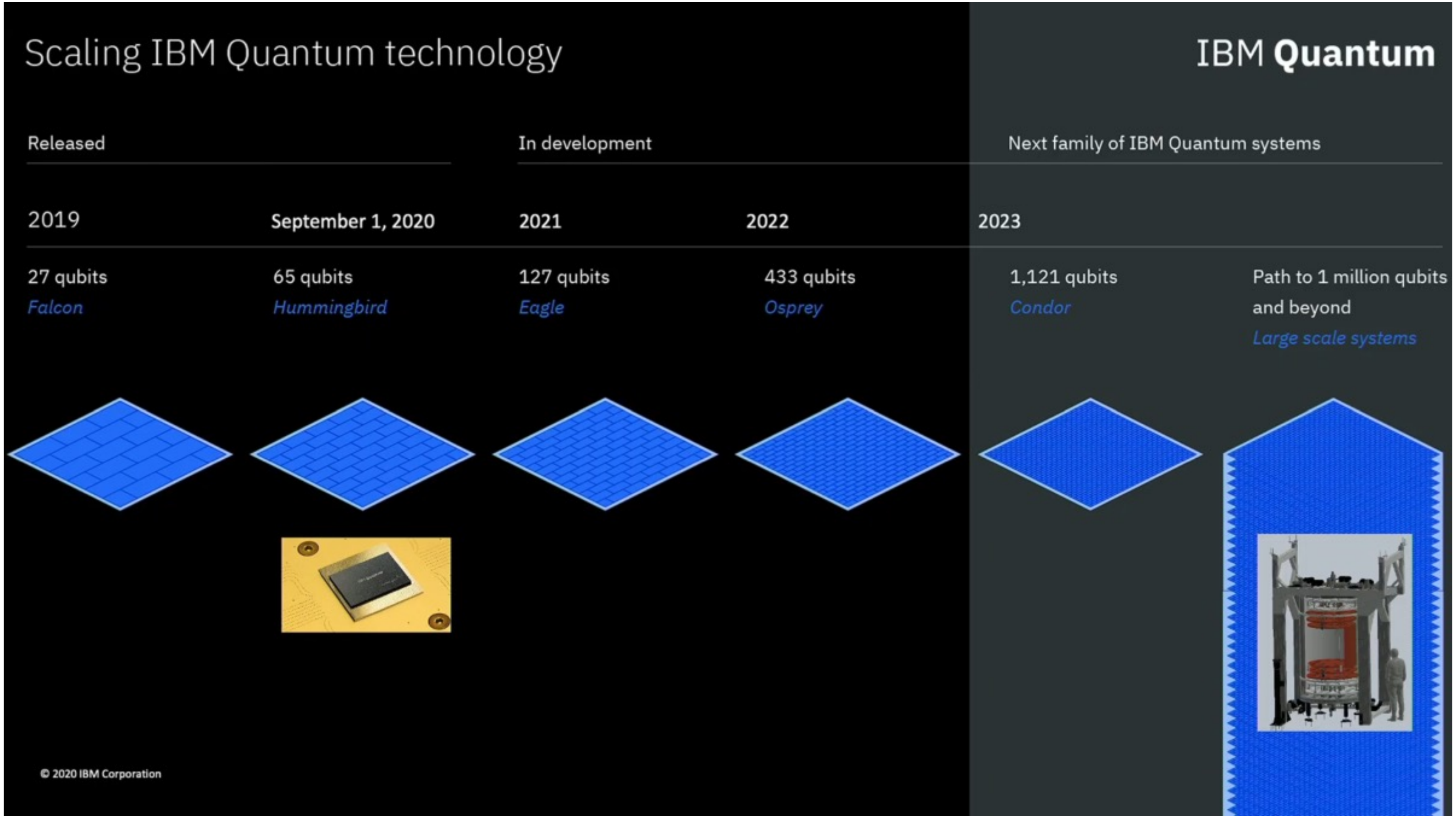
EXHIBIT 2 | The Expected Phases of Quantum Computing Maturity

| | NISQ era<br>3–5 years | Broad quantum advantage<br>10+ years | Full-scale fault tolerance<br>20+ years |
|---|---|---|---|
| Technical achievement | Error mitigation | Error correction | Modular architecture |
| Example of business impact | Material simulations that reduce expensive and time-consuming trial-and-error lab testing | Near-real-time risk assessment for financial services firms (e.g., quant hedge funds) | De novo drug design with large biologics that have minimal off-target effects |
| Estimated impact (operating income) | $2 billion–$5 billion | $25 billion–$50 billion | $450 billion–$850 billion |

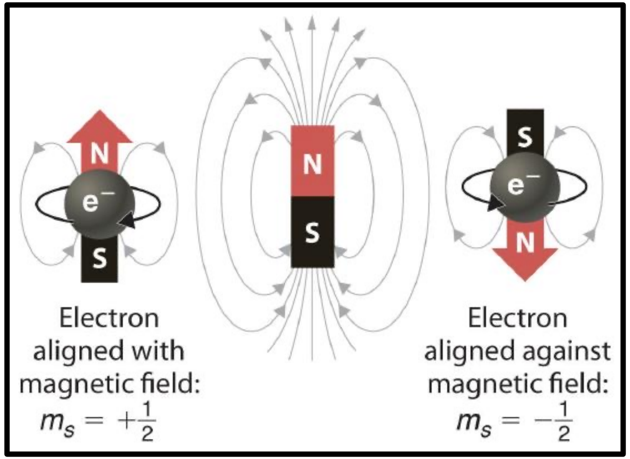
Source: BCG analysis.

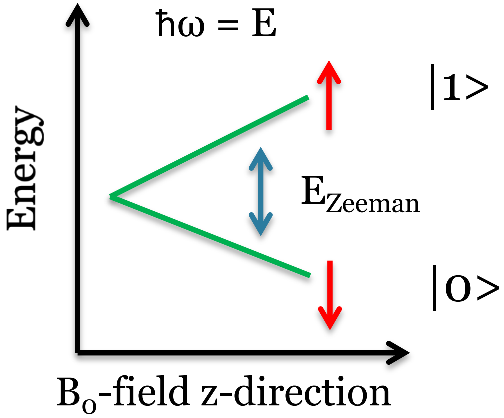
*Rough # of qubits:* *1000* *10,000-100,000* *>1,000,000*

# IBM hardware roadmap



# A quantum bit (qubit) are the transistor of quantum computers

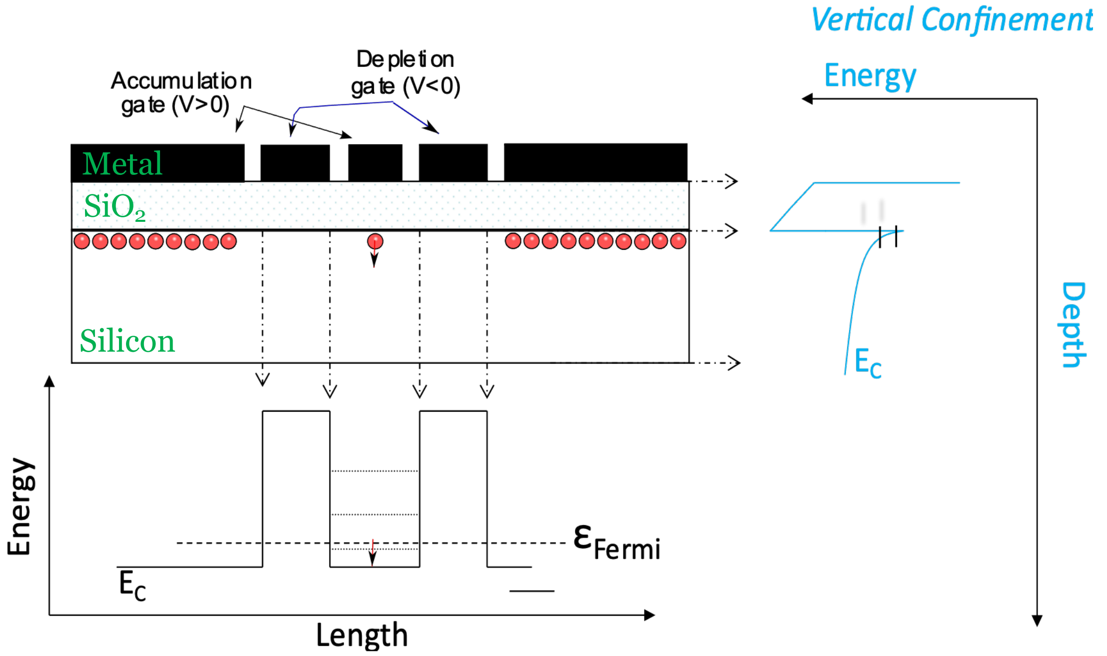



- Qubits are are defined by two stationary states labeled 0 and 1
- Any quantum mechanical two level system can be a qubit
- Canonical example is spin up/down

# Solid-state spin qubit example

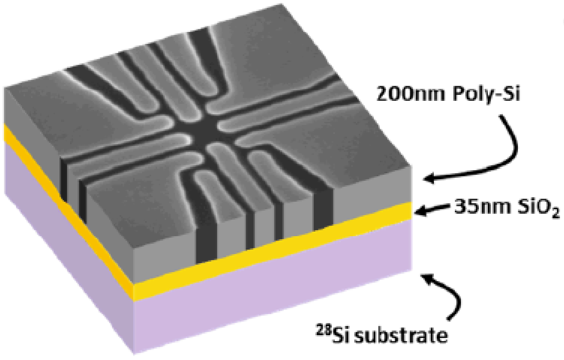





- Field effect transistor scaled to single electron spin
- Artificial atom with orbital energy of 5 meV for 40-50 nm well (in Si)
- Control: cryogenic temperatures & electron spin resonance

# All leading qubit candidates use thin film processing

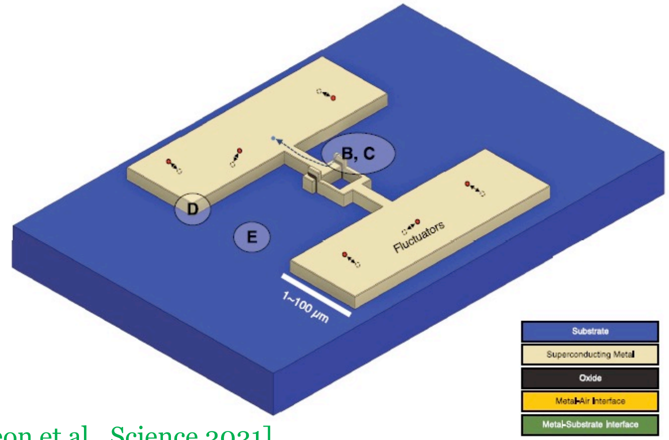
## *Spins*




[Rudolph et al. IEDM 2018]

Intel, SQC, ST-Micro, HRL, NTT, …

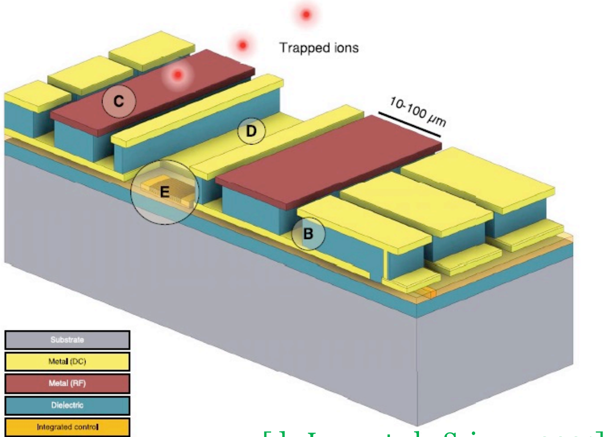
## *Superconducting*




[de Leon et al., Science 2021]

IBM, Google, Rigetti, Alibaba, Amazon, …

## *Ion Traps*




[de Leon et al., Science 2021]

Honeywell, IonQ, Alpine Quantum Technologies, …

- Several qubit platforms being pursued by a range of companies and research labs
- Today platforms are at the 10-100s of qubits
- Yield and integration challenge for the future – some analogies to IC fab

# Why thin film processing for Si spin qubits?



Jim Clarke, Intel (IEEE Spectrum, 24 August 2020)

"It's simple for us… **Silicon spin qubits look exactly like a tranistor**… The infrastructure is there from a tool-fabrication perspective. We know how to make these transistors. **So if you can take a technology like quantum computing and map it to such a ubiquitous technology, then the prospect for developing a quantum computer is much clearer**."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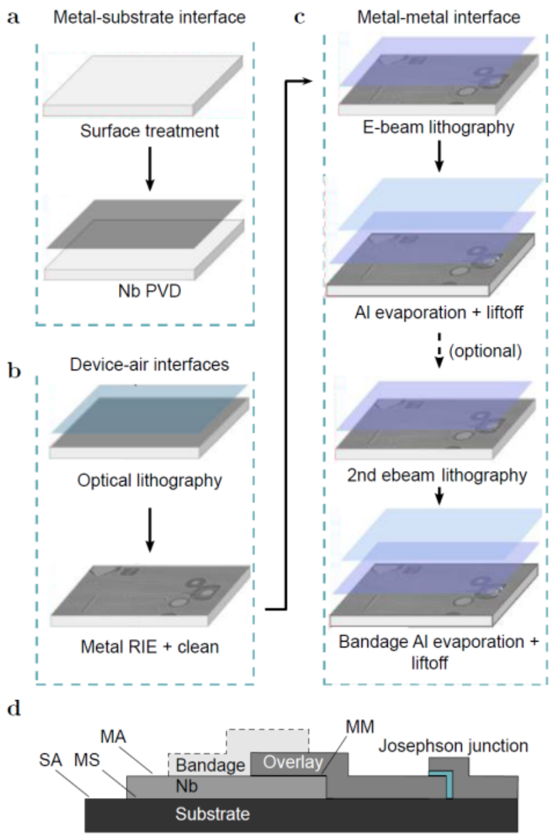
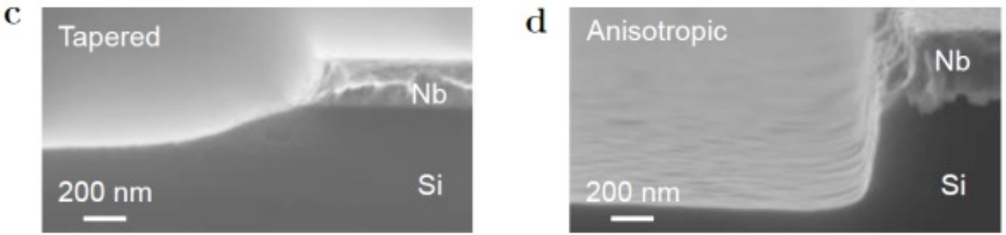
# Process flow example – superconducting qubits






- Fabrication uses relatively standard processing
- Common materials
  - Substrates: Si or sapphire
  - Electrodes: Al, Nb, Ta
  - Junction material: Al2O3

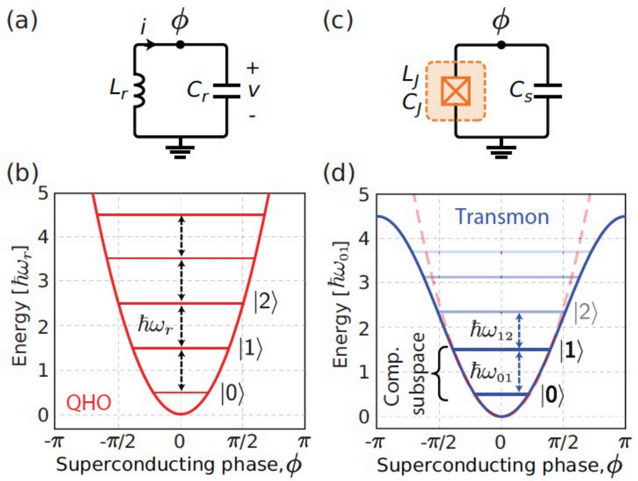
- Qubit performance depends on interfaces & etch profiles



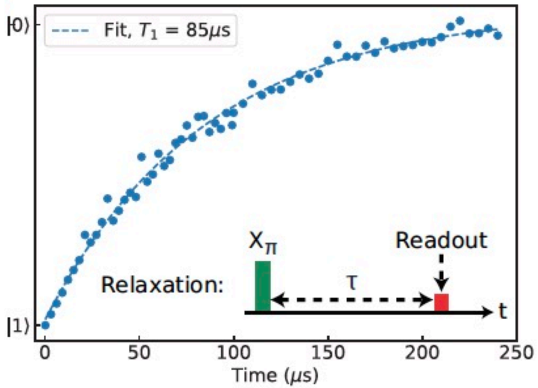

Nersisyan et al. (Rigetti)

# Qubit and qubit metrics

*Krantz et al. arXiv 1904.06560 (2019)*




*Energy relaxation*




- Superconducting qubit 'lifetime' has an analogy to circuit Q of resonator
- Qubit metric is 'coherence time'
- Example: energy relaxation to defects



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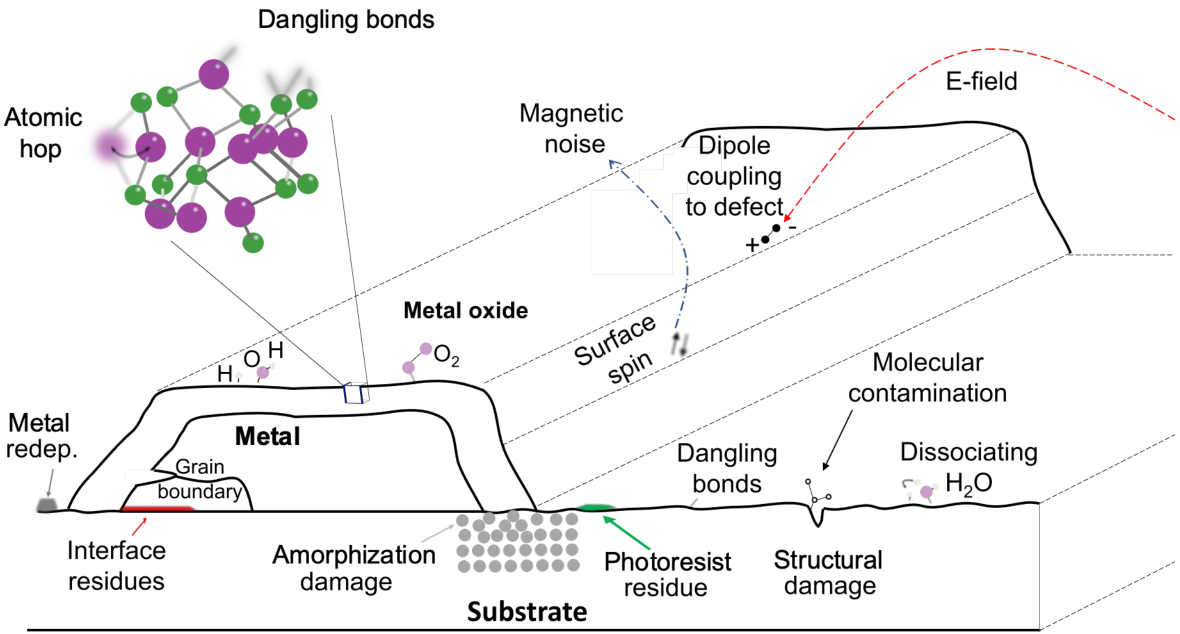
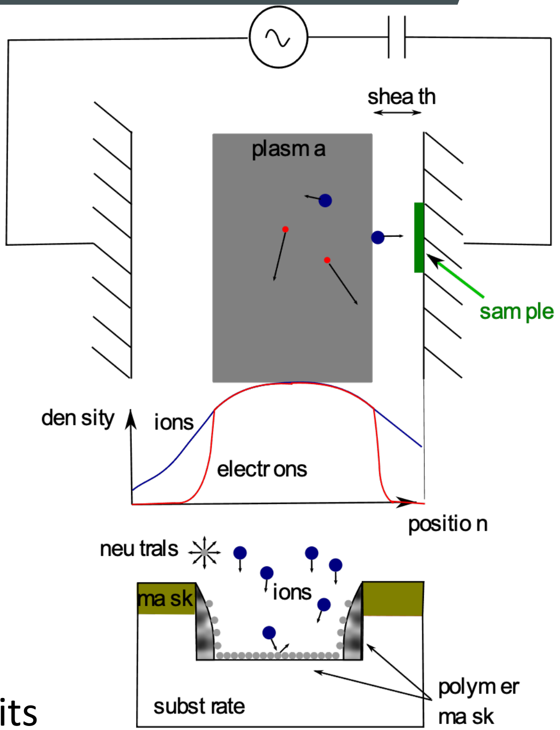
# Atomic scale perfection required



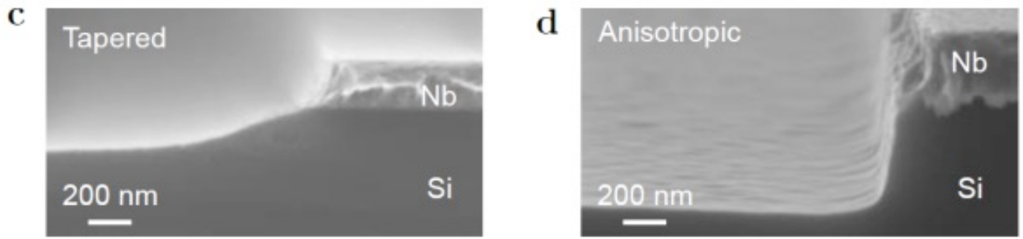



- Surface defects believed dominant source of decoherence in SC qubits
- There are challenges and opportunities for plasma-surface science in quantum computing
  - Defect reduction will be an enduring goal for quantum devices

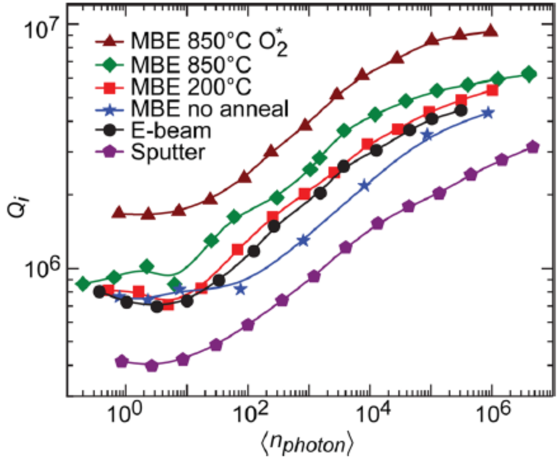
# Likely areas of opportunity for plasma processing

## Smooth surfaces



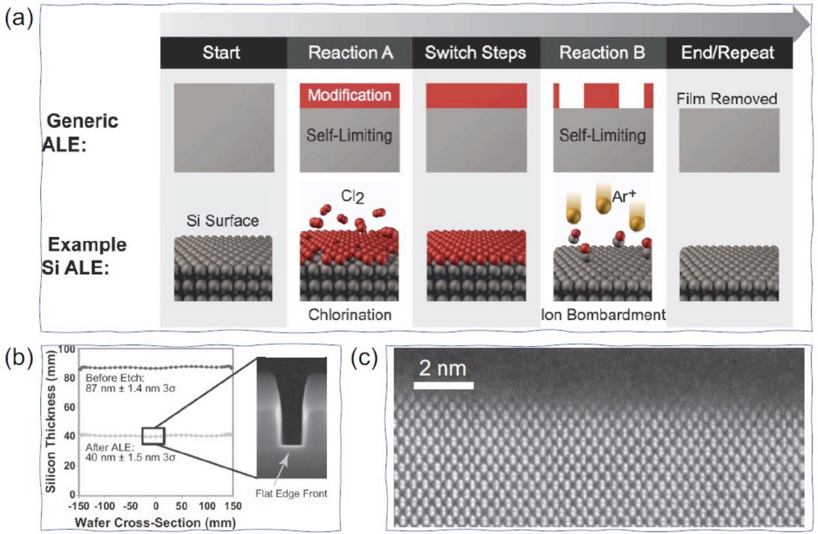

*Nersisyan et al., arXiv 1901.08042*

## Clean surfaces




*Megrant et al. APL (2012)*

## Development of atomic layer control



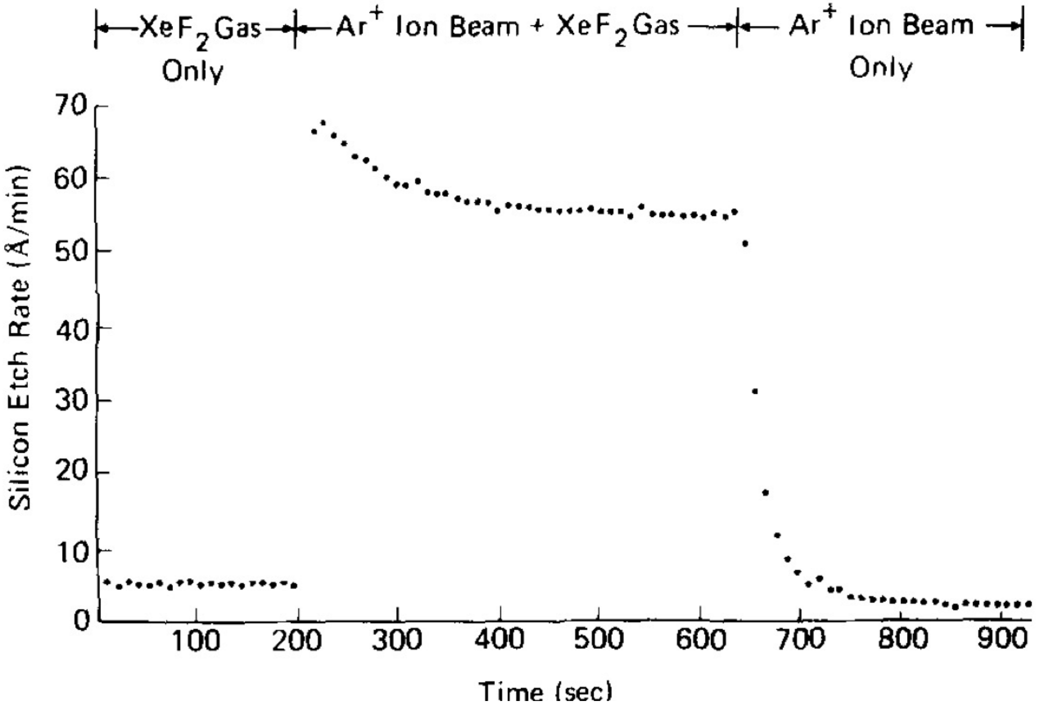

*Kanarik et al., J. Vac. Sci. & Tech. A (2015)*

# Challenges of *atomic level* control via plasma processes



- Basic principles of plasma etch reveal ***challenges of true atomic layer etch***
    - Seek selectivity, anisotropy, high rates (as well as uniformity and low contamination)
- Purely chemical etch can be highly selective but is usually isotropic
- Plasma-induced positive ion bombardment is inherently directional but has little selectivity
- ‘Reactive ion’ etching is a compromise between the need for selectivity and anisotropy
- Ion-neutral synergy increases etch rates, while providing some selectivity and anisotropy: without these ‘tricks’ there would have been no ‘Moore’s Law!’

# Ion-neutral synergy in plasma etch

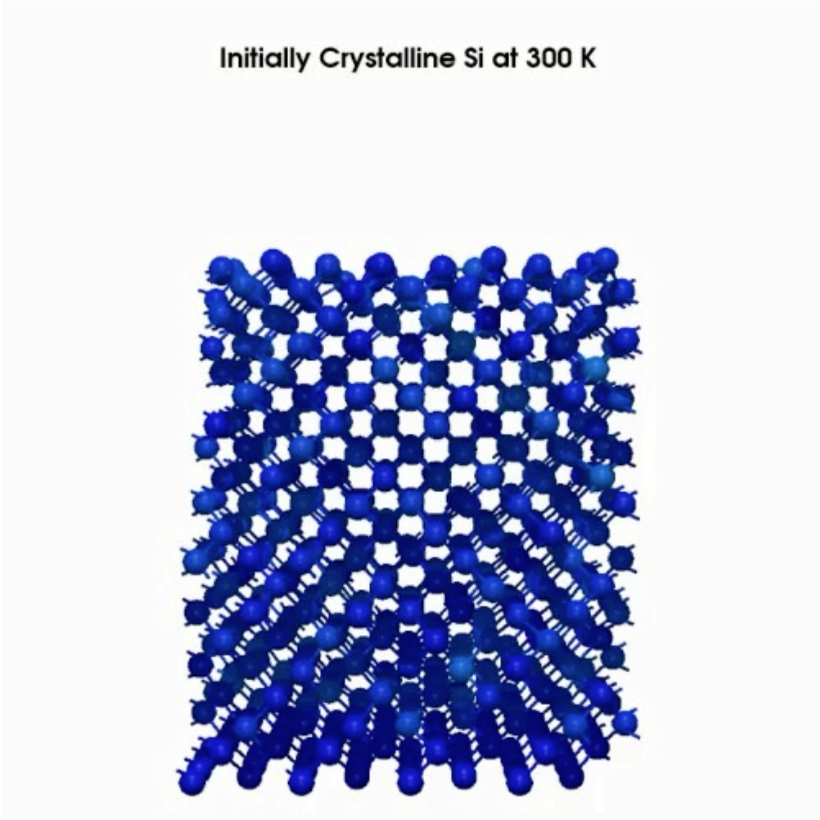



Ion-neutral synergy: etch rates much higher when *both* energetic ions and reactive F hit surface

Winter and Coburn, (1979)

# What happens when 200 eV $Ar^+$ hits Si surface?

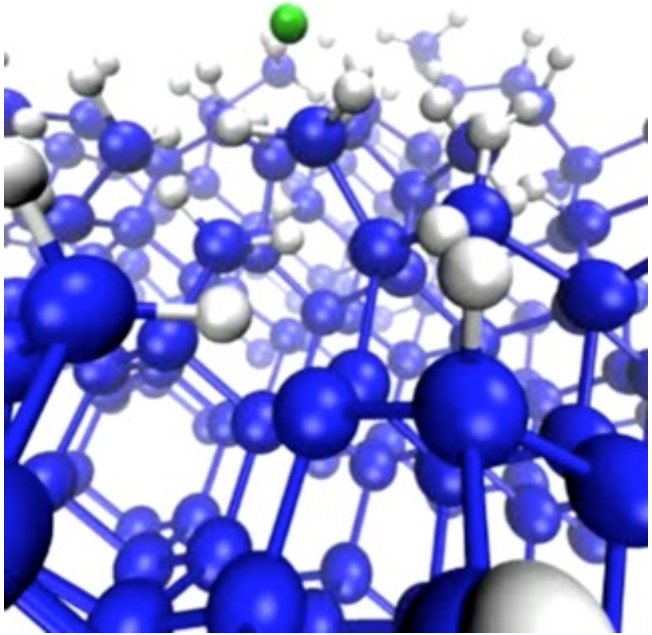





Impact of inert ion ($Ar^+$) adds energy to surface; promotes chemistry and mixing sub-surface atoms

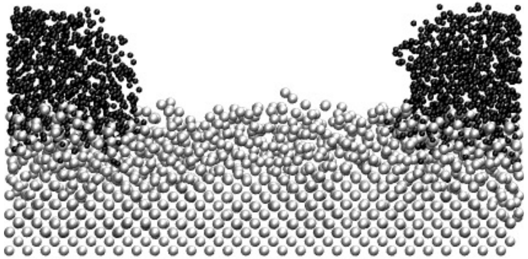
# What happens when 300 K F atom hits Si surface?



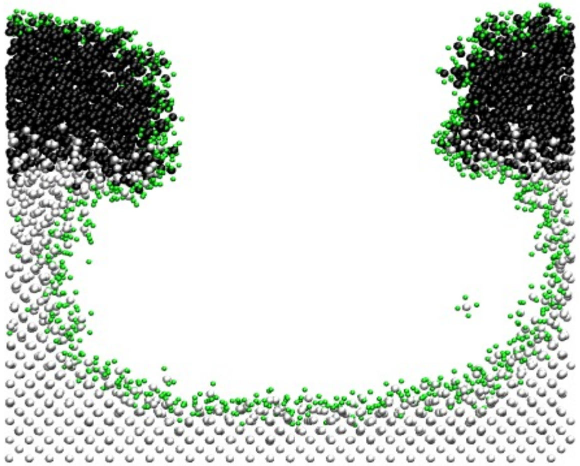


F atoms (300K) etches Si spontaneously.

# What happens when 300 K F atoms hit masked Si surface?



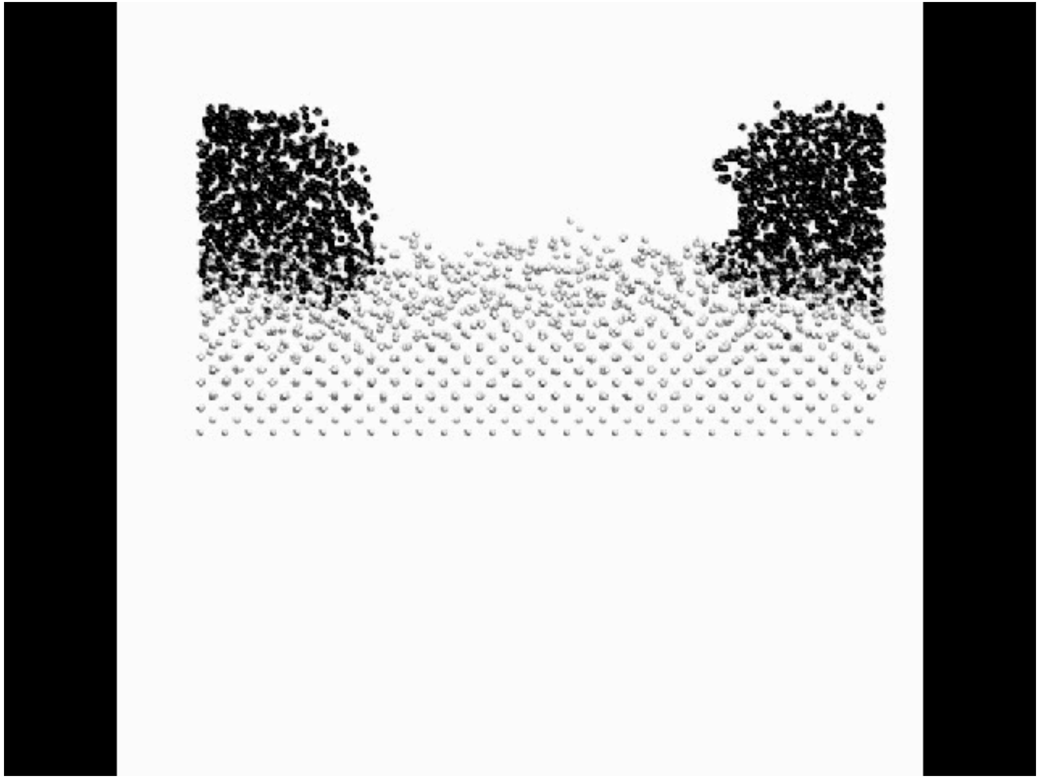
~1.58x10$^{18}$cm$^{-2}$ F



Chemical-only etching is isotropic – undercut of mask is key problem.

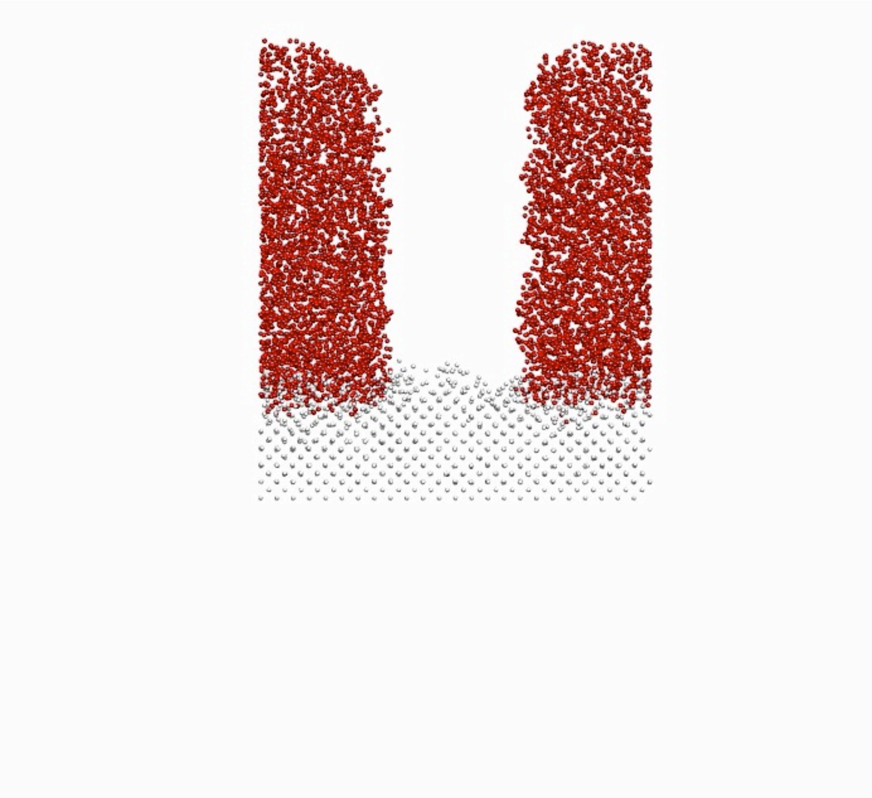
# Visualizing purely isotropic chemical etch





‘Snapshot’ movie links a series of individual F atom impacts

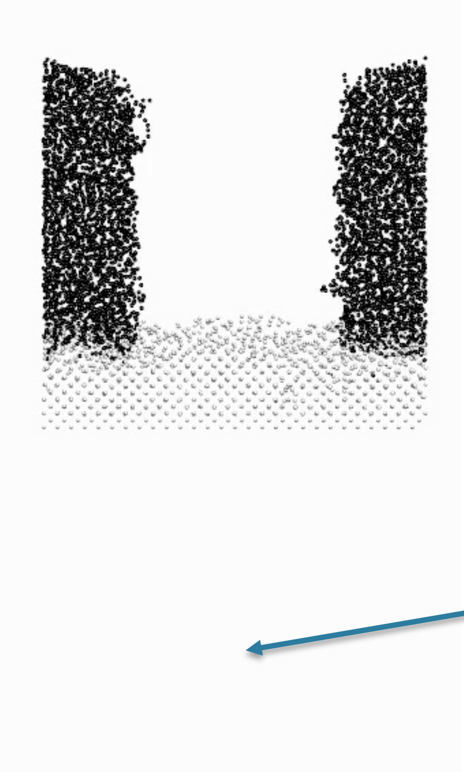
# $Ar^+$ impacting masked Si surface



$Ar^+$ - only provides no selectivity

# Combining F atoms with $Ar^+$: ion-neutral synergy results



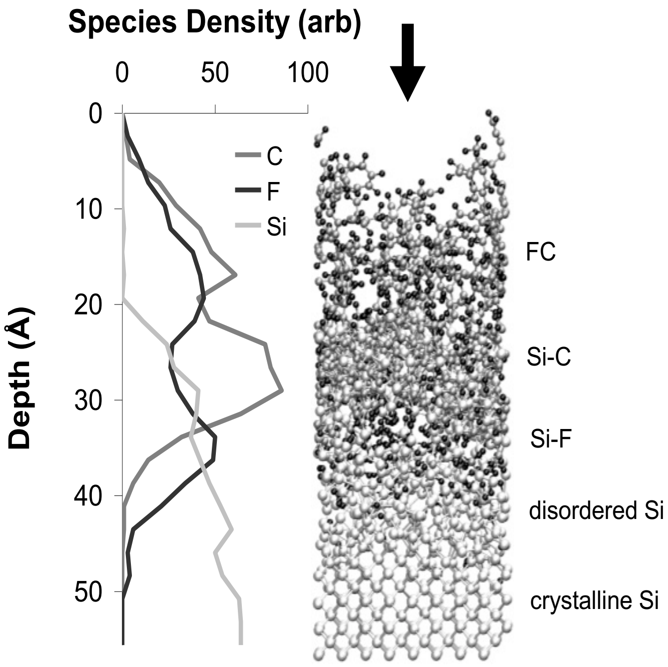


Combining $Ar^+$ and F atom allows for some degree of selectivity and anisotropy (100:1 $F/Ar^+$)

But note final degree of surface amorphization from ion bombardment.

# Complex mixed layers tend to form near-surface



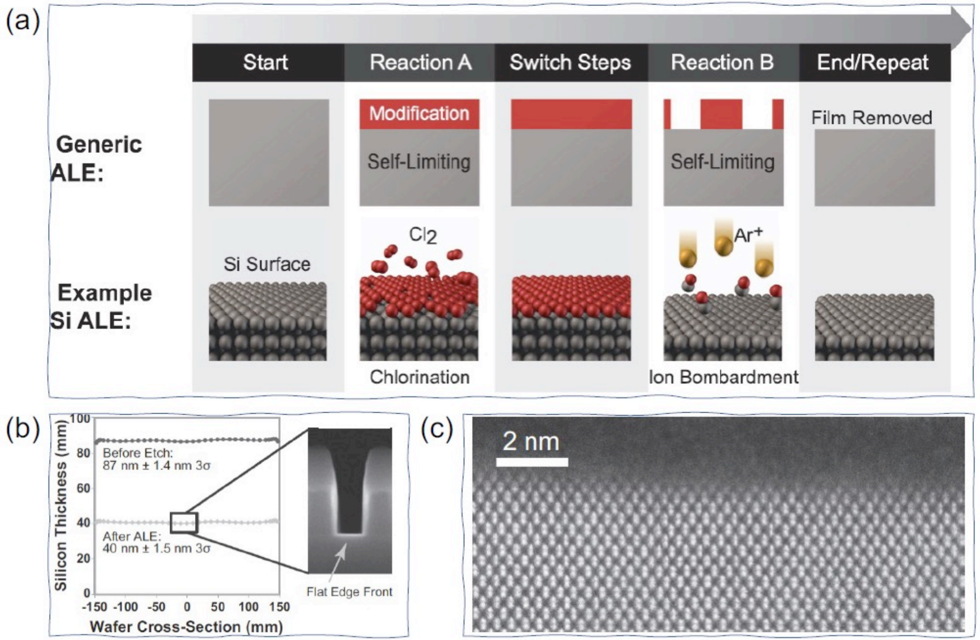


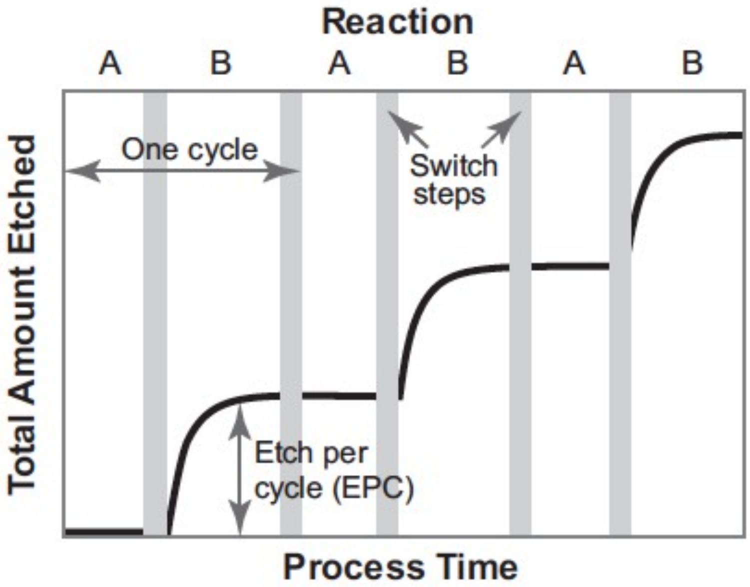

Combining etch (F) species with deposition (C2F4) species, energized by $Ar^+$ ions.

**Side view and depth profile of a cell from 5:5:1 $C_4F_4$/ F/ 200 eV $Ar^+$ (Si=white, C=grey, F= black).**

# How to approach desired atomic-layer control?






*Kanarik et al., J. Vac. Sci. & Tech. A (2015)*

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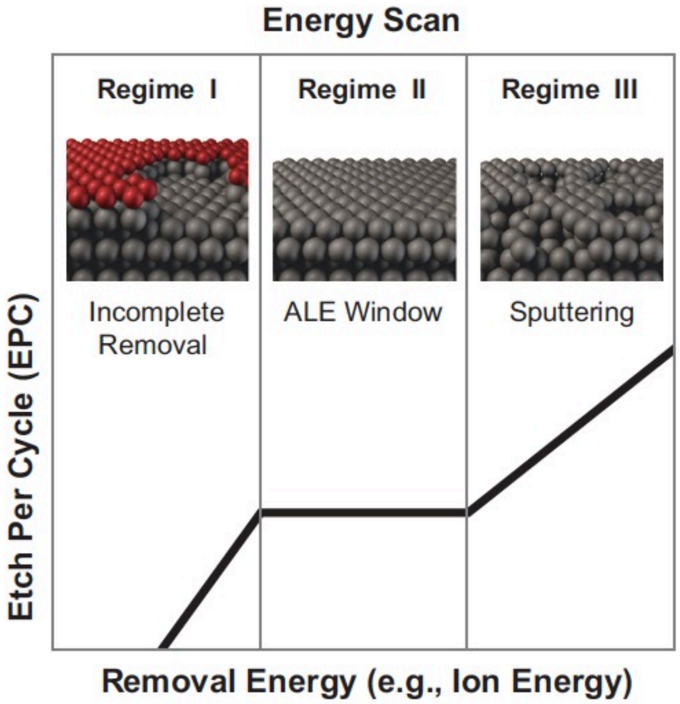
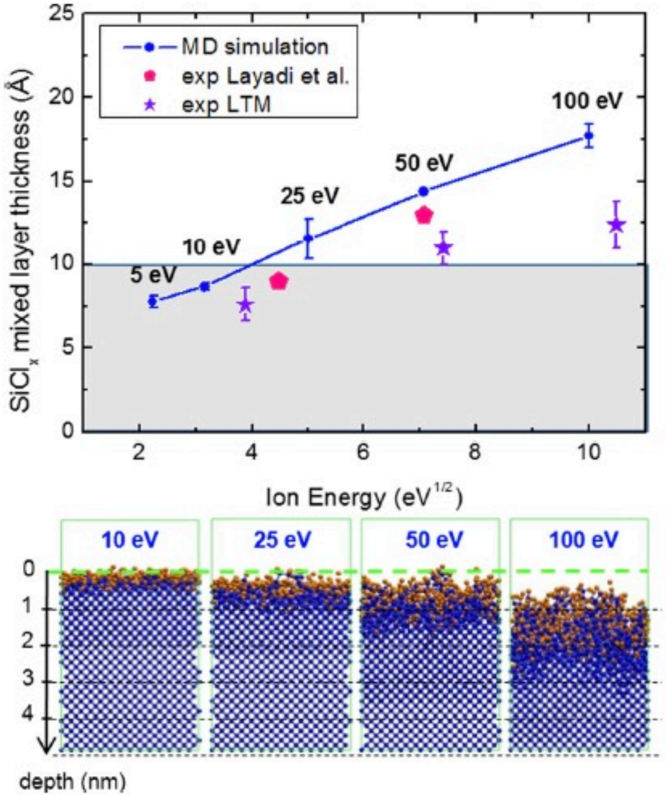



*Kanarik et al., J. Vac. Sci. & Tech. A (2015)*

*Brichon et al., J. Appl. Phys., 053303 (2015)*



# How to approach desired atomic-layer control?



- Separate chemical component and ion-induced removal: need as minimum a window of ion energies that allows product removal with minimal subsequent sputtering of underlying film
- Ion energy needs to be low – especially when chemical component present; relatively thick mixed layers are common in plasma etch
- Likely that we will need specially designed/operated plasma tools – e.g. e-beam sustained; B-fields; pulsing, etc.
- Can see that truly atomic layer etch with plasma will need careful control and better understanding of plasma-surface interactions!

# Plasma nanofabrication science: coupled challenges



*EM coupling; pulsed*

***plasma science*** → ***plasma diagnostics and 3D, transient modeling***

***electrons; ions; radicals; photons (UV/VUV); electronic/vib/transl/excited neutrals***

***External control parameters: > $10^{20}$ combinations (flow, composition, pressure, frequency, pulsing etc.)***

***Plasma fabrication science is at the interface of plasma and surfaces***

***plasma-surface coupling***

- ***near-surface atomic scale defects***
- ***surface texture: atomic scale roughness***
- ***electron-hole dynamics (e.g. plasmons/UV)***
- ***complex surface composition/structures***
- ***3D nanofeature transport/chemistry***

***surface & materials characterization; device physics; semiconductor/quantum materials; atomistic simulations of plasma-surface interactions***



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# Concluding remarks



- QIS materials and devices poised to make significant impacts
- Most QIS devices made via thin film processing and LTP is key technology, although there are major challenges ahead to minimize defects
- There is a strong need for highly interdisciplinary teams in this field: plasma science, surface science, material science and device science are all important
- A paper detailing these ideas is under preparation!


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