ALE for Low Loss Quantum Devices

Dr. Russ Renzas

Oxford Instruments Plasma Technology

OI Quantum Technology

Plasma Technology
Device Fab

- Atomic Layer Deposition
- Atomic Layer Etching
- Reactive Ion Etching
- Chemical Vapor Dep
- IBD/IBE

Improving Qubit performance

NanoSciences
Cryogenics & Measurement

- Teslatron
- ProteoxMX
- ProteoxLX

Measuring Qubit performance

Asylum
AFM

- Cypher
- MFP 3D Infinity
- Jupiter

Reducing losses at interfaces

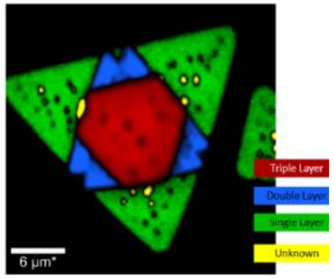
Andor
Quantum Optics

- Ultra-sensitive scientific cameras
- Modular Spectrographs
- Optical Cryostats (down to 3K)

Detect each photon with confidence

WITec
Raman

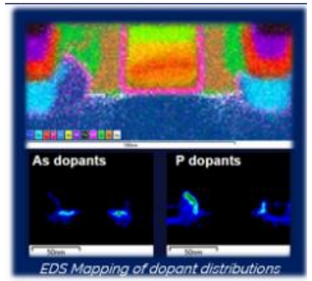
- Raman



Vibrational Spectroscopy

NanoAnalysis
Composition

- EDS
- WDS
- EBSD



Composition and Crystallinity

What is "Quantum"?

Many Modalities

- **Super-conducting**
- **Photonic**
- **Ion Trap**
- **Color Centers**
- **Spin**
- **Cold Atom**

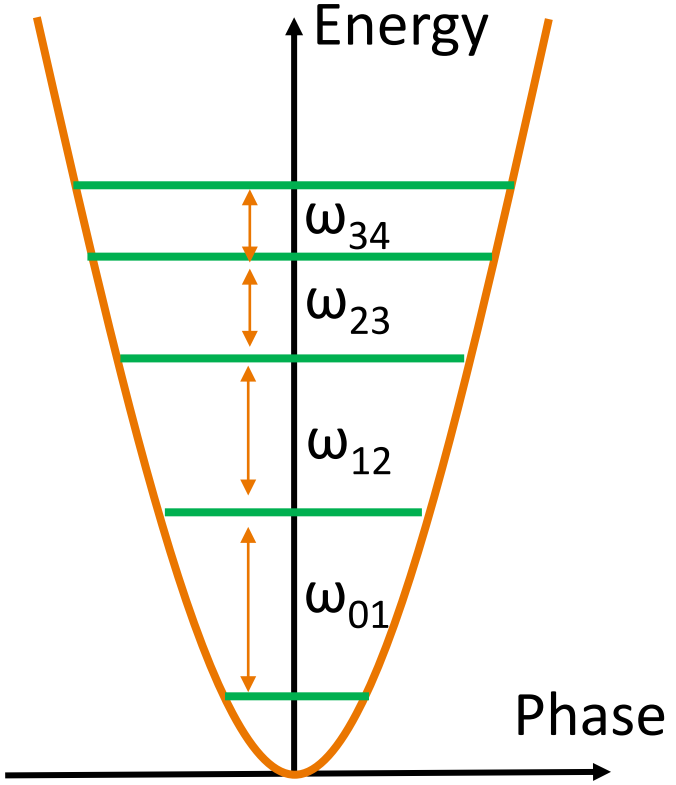
Computing	Supercomputer Co-Processor
Communications	Security
Sensing	Magnetometry, microscopy, radar
Adjacent Technologies	Single Photon Emission/Detection Transducers, Quantum Amplifiers Superconducting cabling

QC Requirements

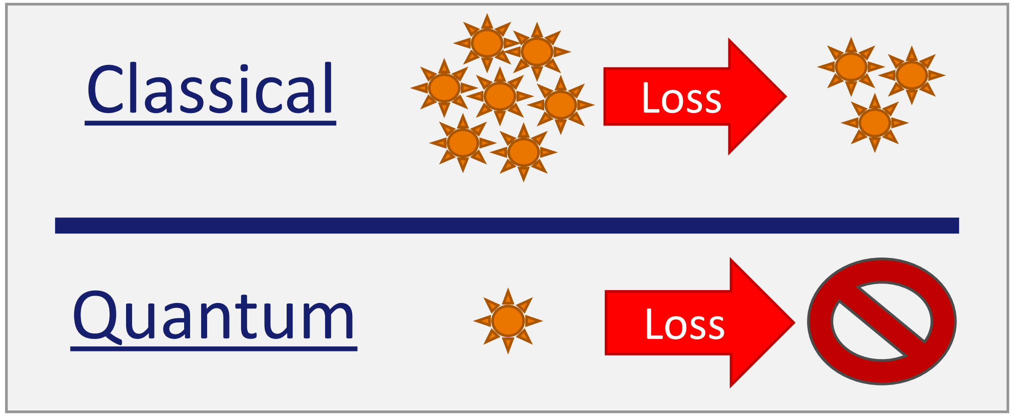
DiVincenzo Criteria	
Well-defined qubits • Encode in microwave photon, spin, energy level, photon mode…	$\|0\rangle$, $\|1\rangle$
Initialization to pure state	$\|000000\rangle$
Universal gate set	X, Y, Z, P, CNOT
Qubit-specific measurement	$\|001011\rangle$
Long coherence times • Low loss system	$T_1, T_2 \gg T_{gate}$
Interconvert stationary & flying qubits • Quantum Transducers	Chip ↔ Fiber
Transmit flying qubits	Repeaters

Two-Level System

$\omega_{01} \neq \omega_{12} \neq \omega_{23} \neq \omega_{34} \neq \ldots$



Common Challenges: Loss & Scale



- Algorithms need <u>many</u> 1Q & 2Q gates
  - High fidelity, high scale
  - Fidelity↑ = ECC Overhead↓
- Scale may incur loss
  - Photonics: More susceptibility to missed photon detection events
  - Superconducting: Increased electric field participation in lossy surfaces, JJ tuning
  - Ion Traps: Shuttling losses, ion loss, vibration
- Scale is hard
  - Higher coherence requirements
  - Increased fab & hardware needs

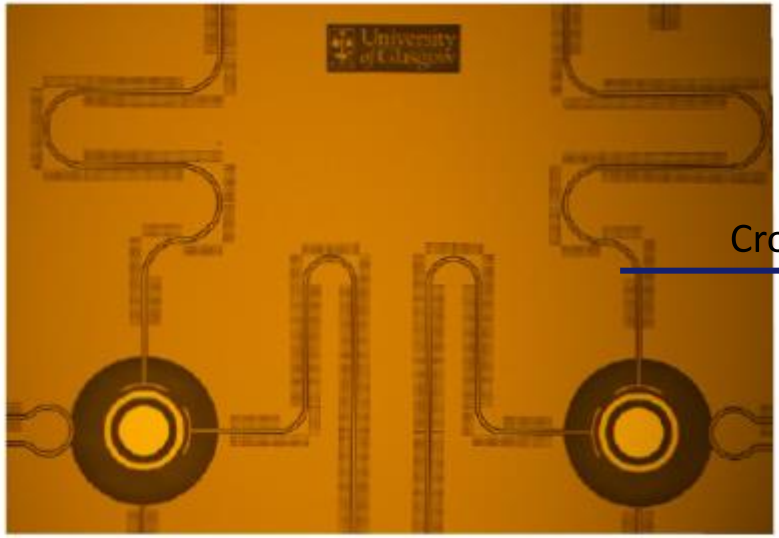

Proteox™LX
Next Generation Thinking

Cryofree® dilution refrigerator
for quantum computing
scale-up

nanoscience.oxinst.com/ProteoxLX

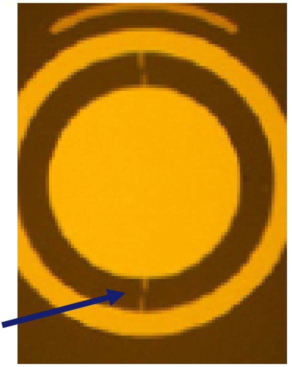
LC Resonator Interfaces

SC QC Chip



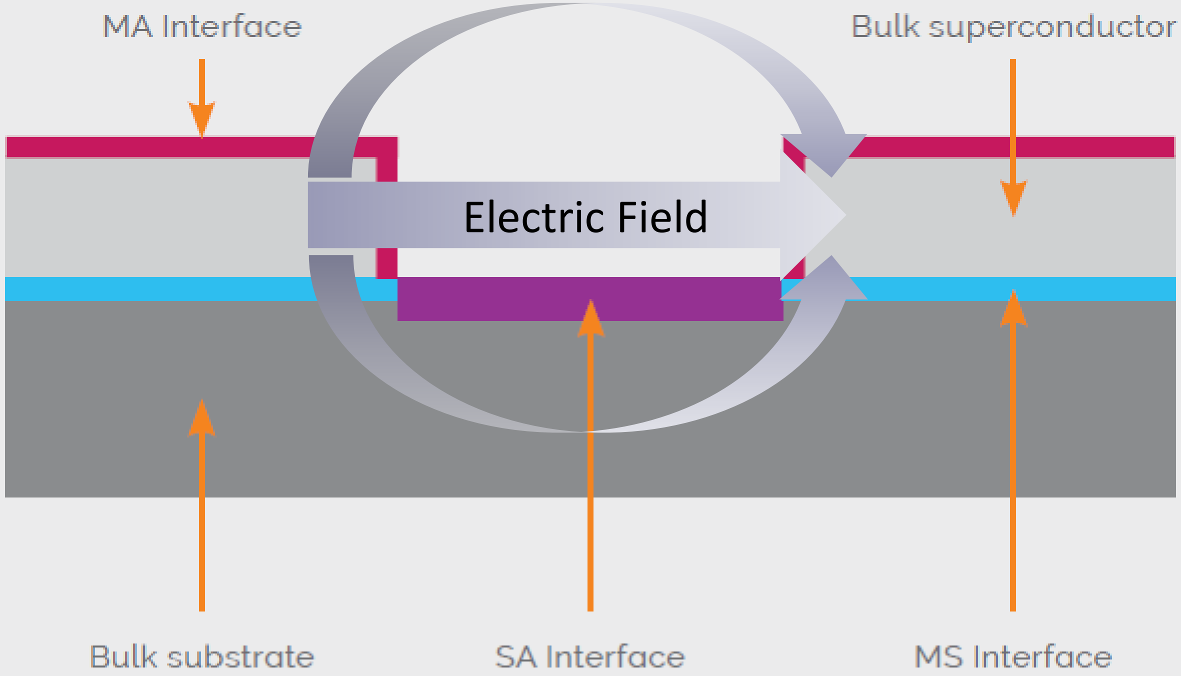
Cross-Section

Weak, dispersive coupling between resonator and qubit enables control & readout

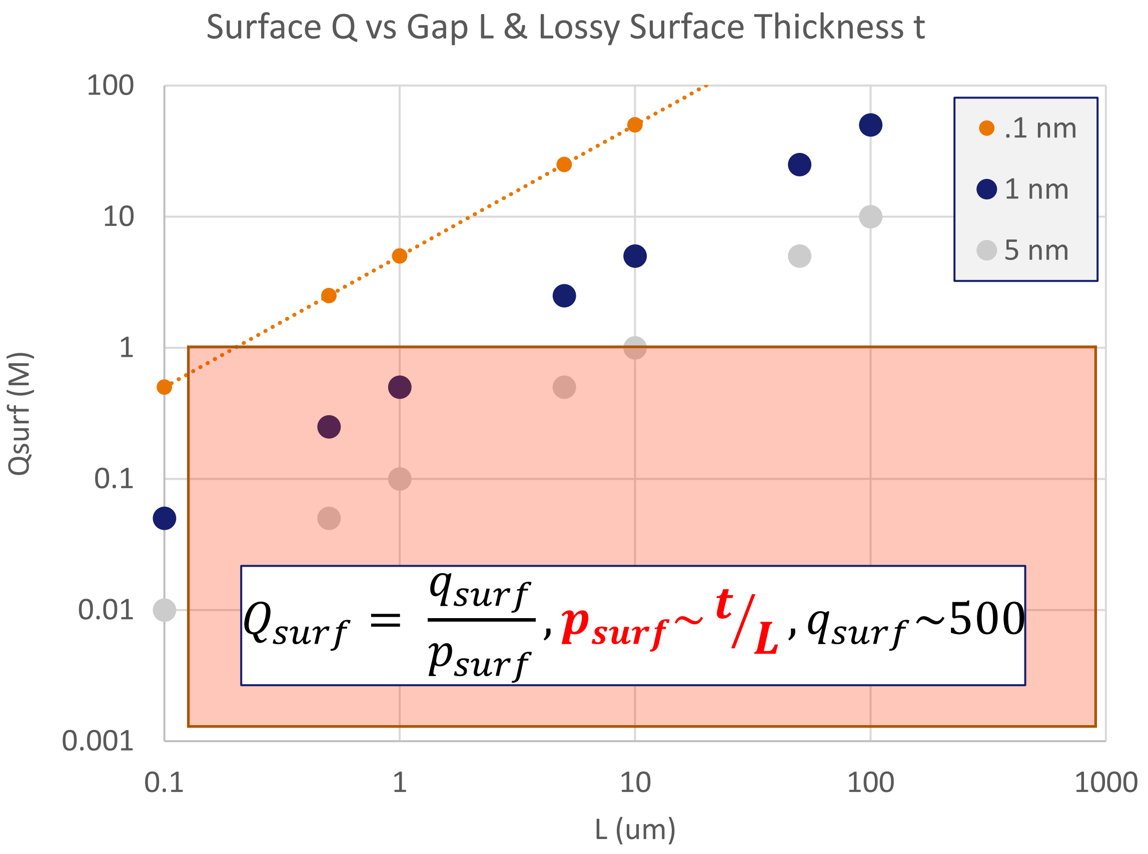


Josephson Junction

Resonator Cross-Section

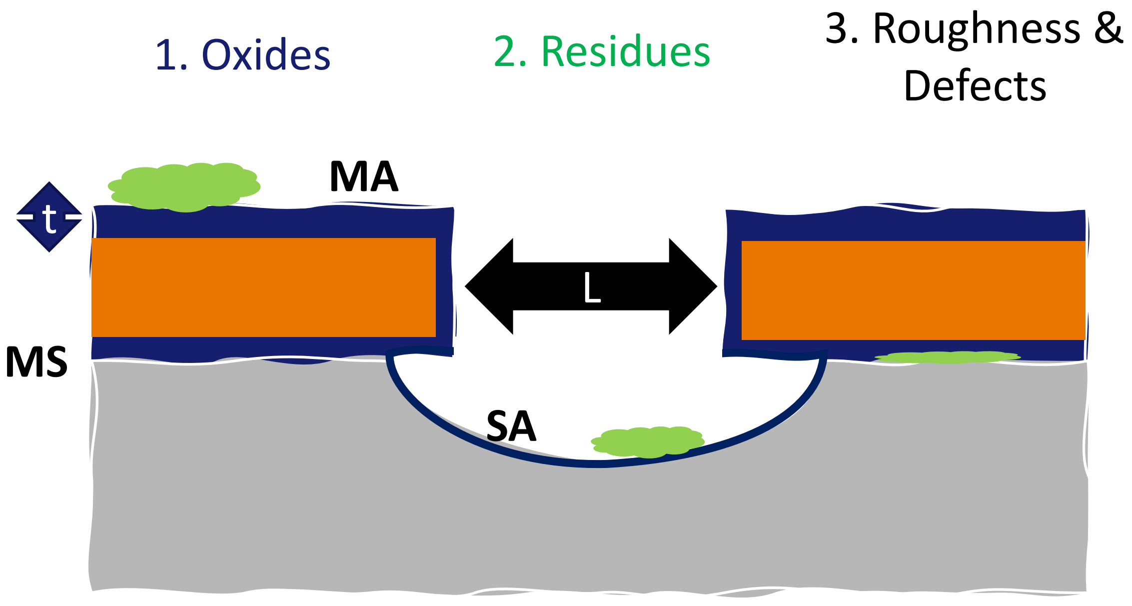


Surface Loss Impedes Scaling



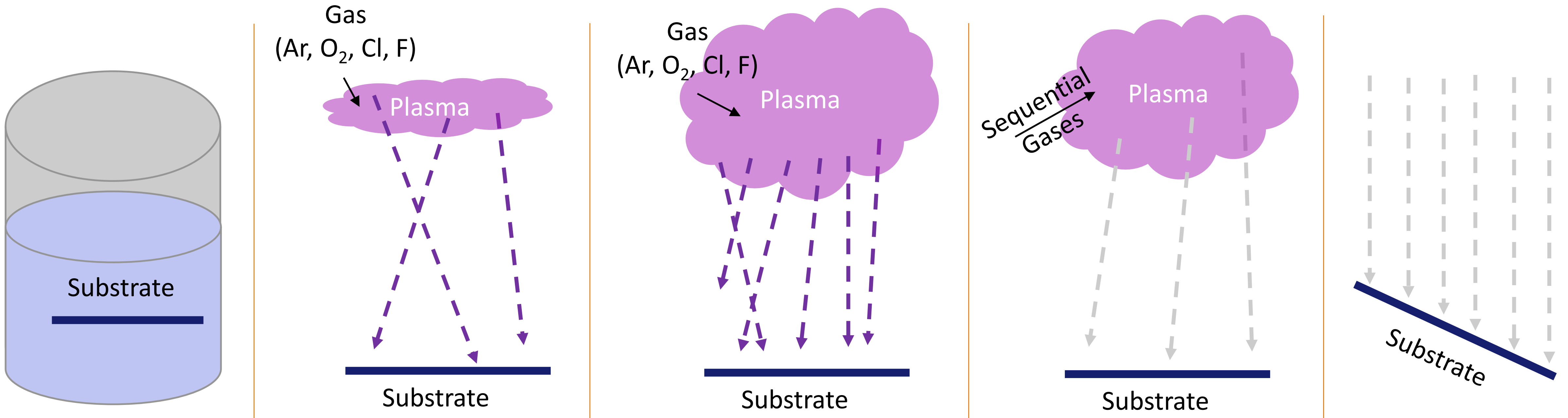
$$Q_{surf} = \frac{q_{surf}}{p_{surf}}, \boldsymbol{p_{surf} \sim {}^{t}/_{L}}, q_{surf} \sim 500$$

Q↓ as devices shrink → Loss Impedes Scaling



*Detailed mechanisms include TLS, quasiparticles, interface dissipation, surface spins…for details see McRae, Corey Rae Harrington, et al. "Materials loss measurements using superconducting microwave resonators." *Review of Scientific Instruments* 91.9 (2020): 091101. and references therein.

Etch Methods (PP80, Cobra 300, IonFab)



Wet Etch
- Time, Temp.
- Bulk

Basic RIE
- Pressure, Plasma Power, Time

ICP RIE
- Pressure, Power, Bias, Temp., Time
- High density plasma → higher % radicals

ALE
- Pressure, Power, Bias, Temp., Dose/Purge
- Slow, smooth, ultra-low damage

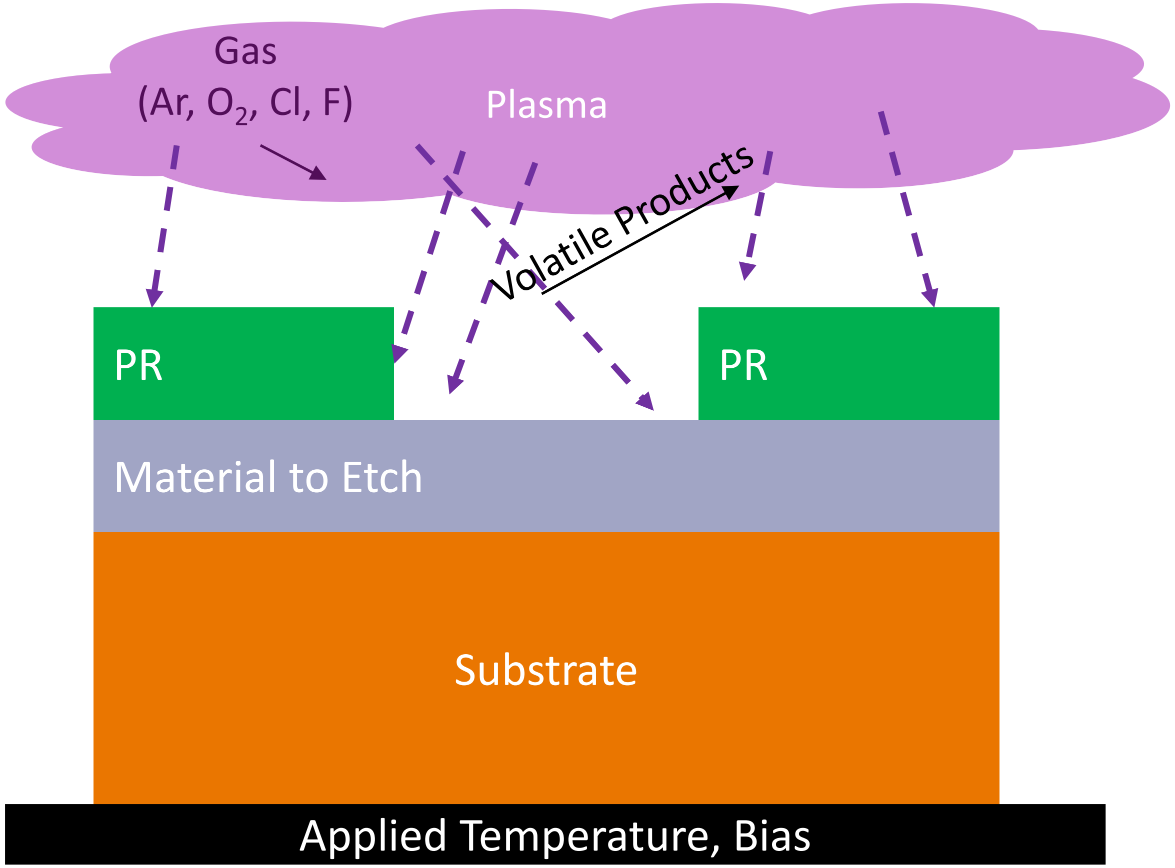
IBE
- Bias, Angle
- CAIBE, RIBE
- Angled gratings

Small Parameter Space, Limited Flexibility ⟷ Large Parameter Space, Very Flexible

RIE Chemical and Physical Components

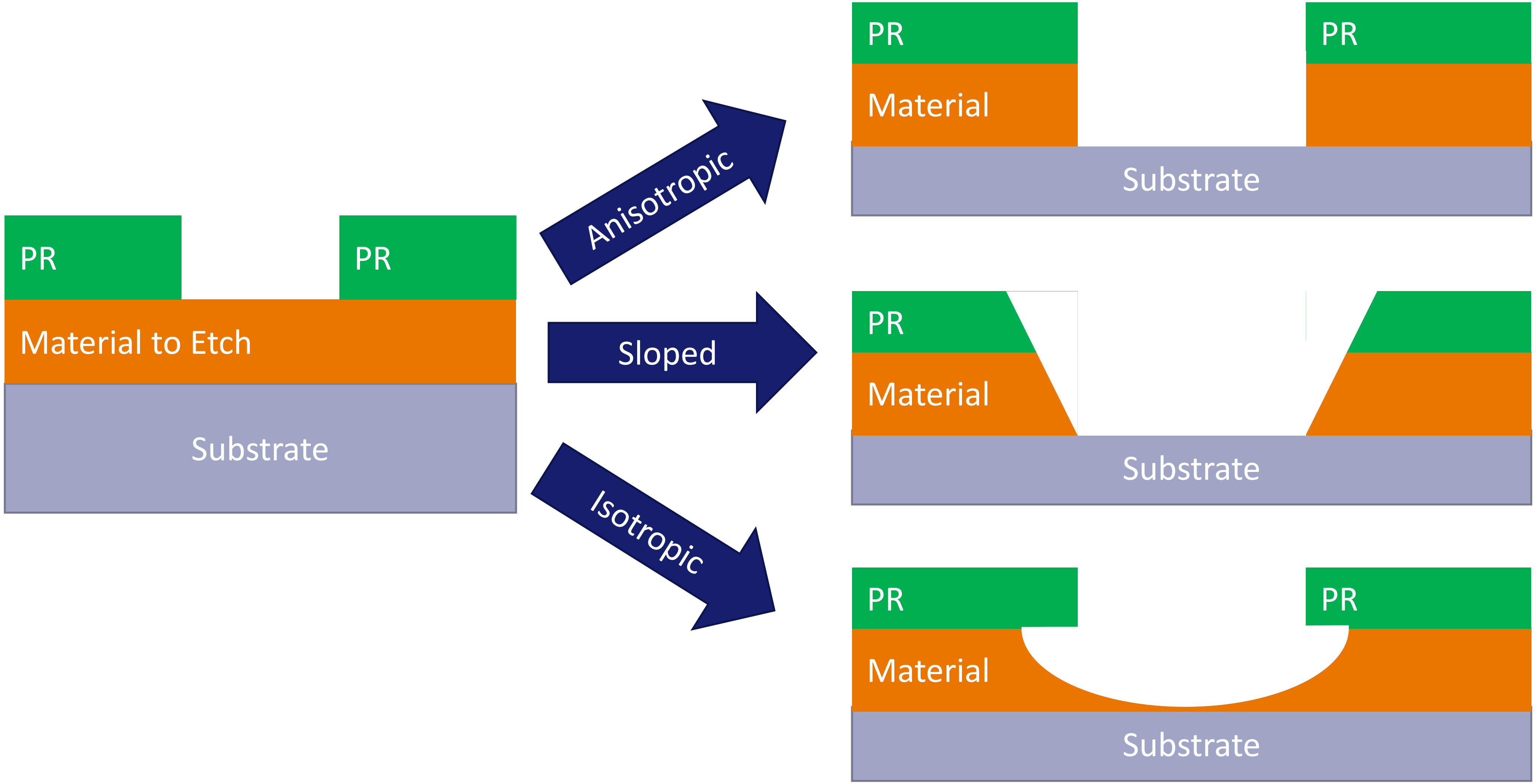
$\text{Etchants}_{(g)} + \text{Material}_{(s)} \rightarrow \text{Products}_{(g)}$

- Chemical Component
  - O_2 for organics → $CO_{2(g)}$
  - SF_6 for Nb, Si → $NbF_{5(g)}$, $SiF_{4(g)}$
  - Cl_2 for Al → $AlCl_{3(g)}$
  - Selectivity, passivation, safety also affect choice
  - Less sensitive to bias (more isotropic)
- Physical Component (Argon)
  - Physically blast material and/or products off
  - Non-reacting
  - More sensitive to bias (more anisotropic)



Chamber Cleaning & Conditioning ensure process stability over time

Profile Control with RIE



- Bias
- Physical and/or passivation

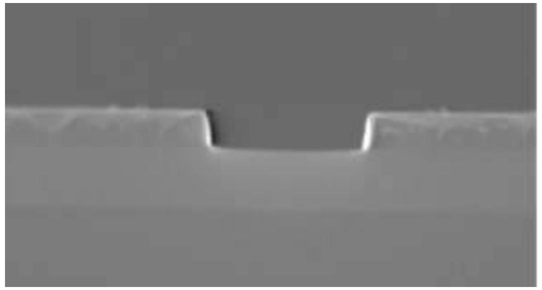
- Exploit PR erosion & selectivity

- Less bias
- Chemical etch

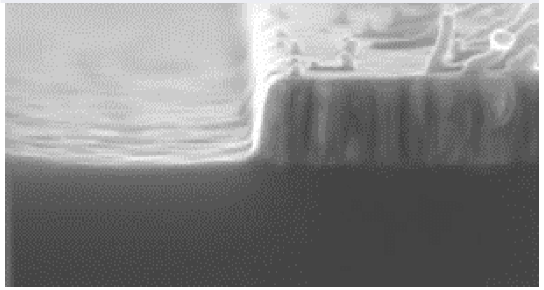
Quantum Materials Etched

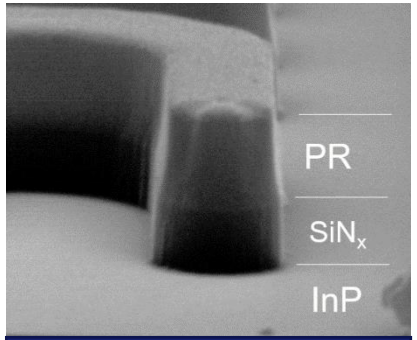
Application	Material
Superconducting	Al
	TiN
	Nb
	NbN
	WSi
	Ta
Color Center	Diamond
	SiC
Photonic	GaAs
	GaN
	SiN
	InP
	$LiNbO_3$

200 nm Nb etch
Resist mask fully stripped



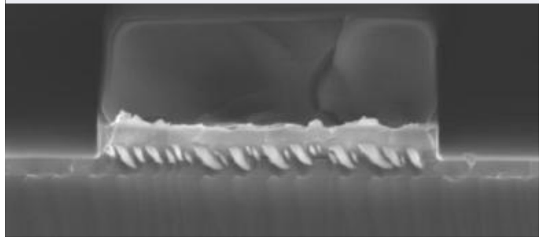
200 nm Mo etch
Resist mask partly stripped



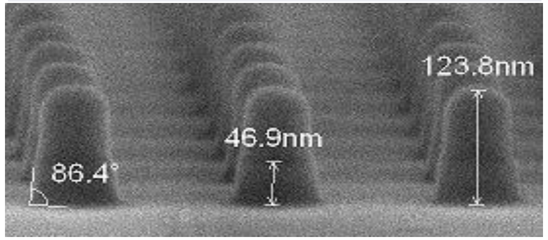


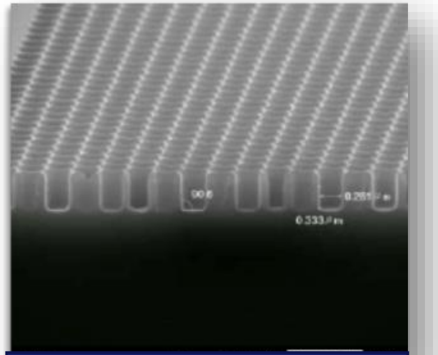
SiN_x on InP

Vertical $Al/Al_2O_3/Al$ tunnel junction stack etch



60 nm wide Ta features





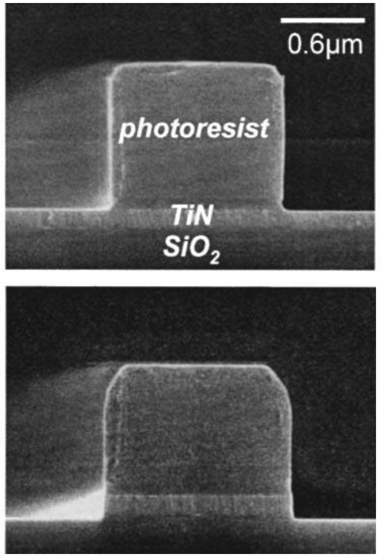
GaAs / AlGaAs

Superconductor Etch Detailed Examples

TiN Etch Profile Control

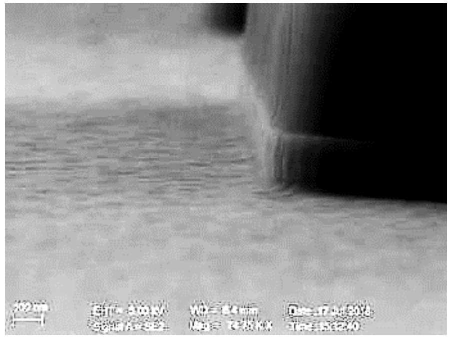
Gas chemistry	Etch rate [nm/min]	Profile [°]
Ar	0	-
Ar-CHF_3	10	70
Ar-BCl_3	35	45
Ar-Cl_2	230	88

J. Tonotani et al, J. Vac. Sci. Technol. B 21.5., Sep-Oct 2003
doi: 10.1116/1.1612517

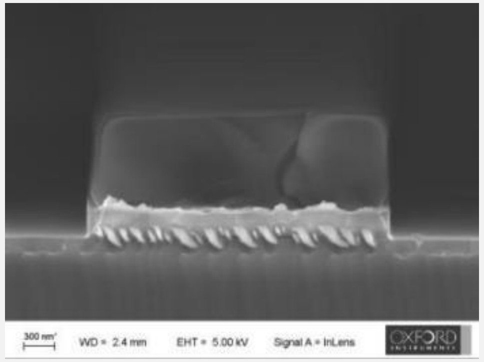


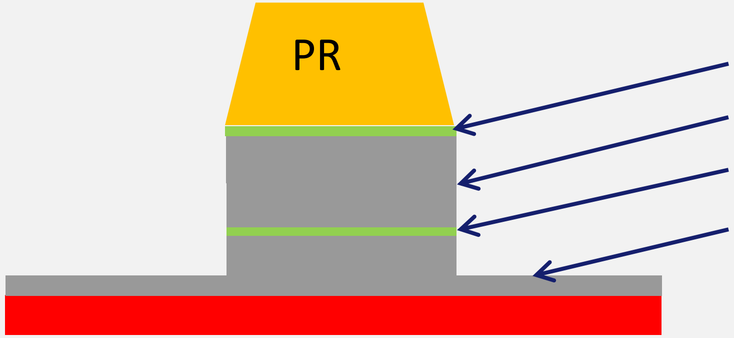
Vertical Nb profile

System	PlasmaPro 100 ICP
Process gases	CF_4-Ar
Depth	330nm
Etch rate	29nm/min
Uniformity	±1.4% (100mm wafer)
Selectivity PR mask	0.8:1
Selectivity SiO_2 underlayer	1.2:1



Al/Al_2O_3/Al Stack Etch





Step 1. Pure BCl_3 native Al_2O_3 removal. Stops on top Al

Step 2. Pure HBr Al etch. Stops on Al_2O_3

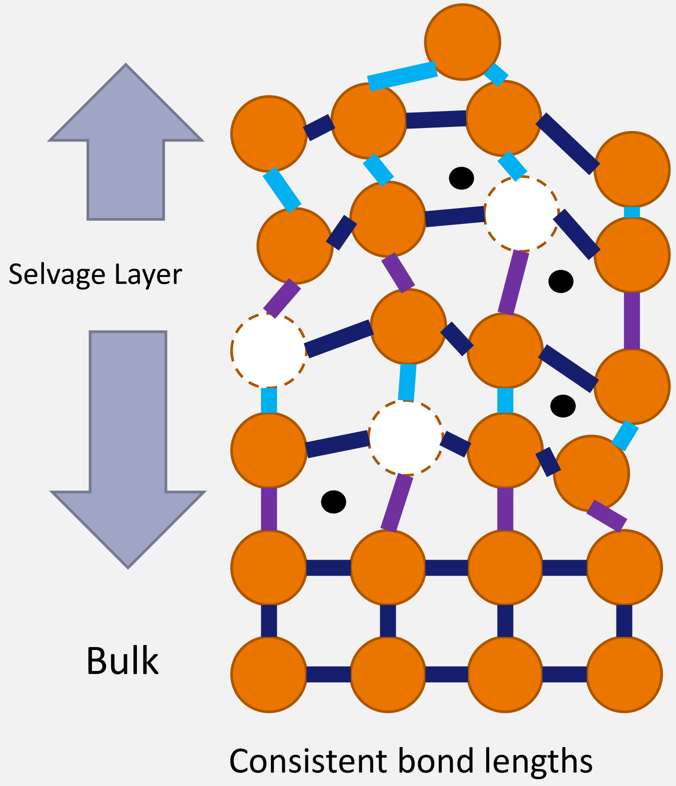
Step 3. Pure BCl_3 Al_2O_3 barrier. Stops on bottom Al

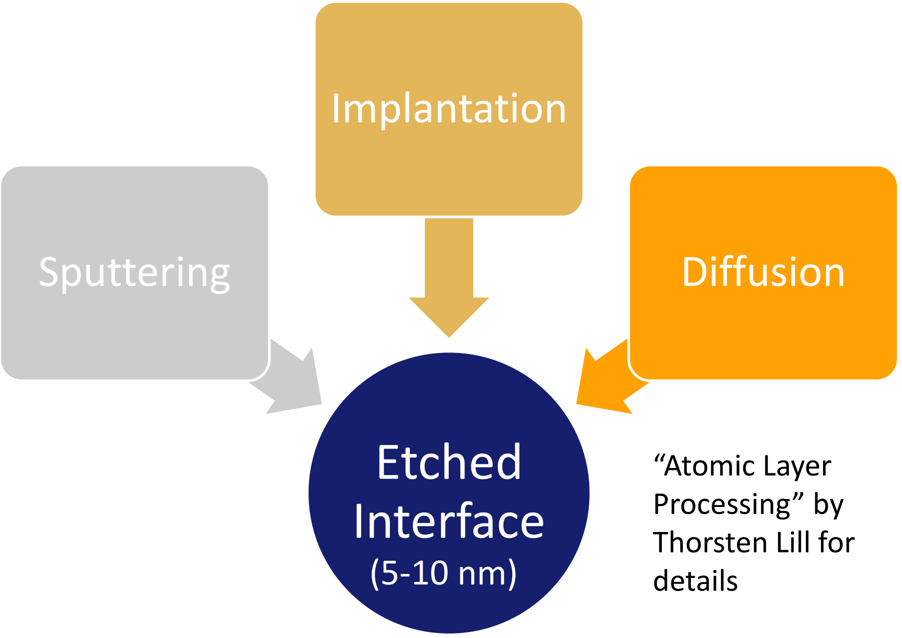
Step 4. Pure HBr Al etch. Stops <u>in</u> bottom Al controllably

Surface Damage in RIE

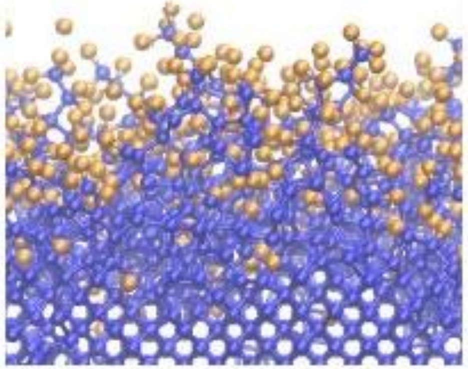
Post-Etch Surface

Defective Surface Layers





“Atomic Layer Processing” by Thorsten Lill for details



Crystal structure under continuous dry etching

From O. Joubert, SEMATECH Workshop on Atomic-Layer-ETch (ALET) and - Clean (ALC) Technology, April 21, 2014

BOE Si Reference

- $N_c = 7 \times 10^{14}$ cm^{-3}

Wet-etched Al resonators

- $N_c = 1 \times 10^{16}$ cm^{-3}

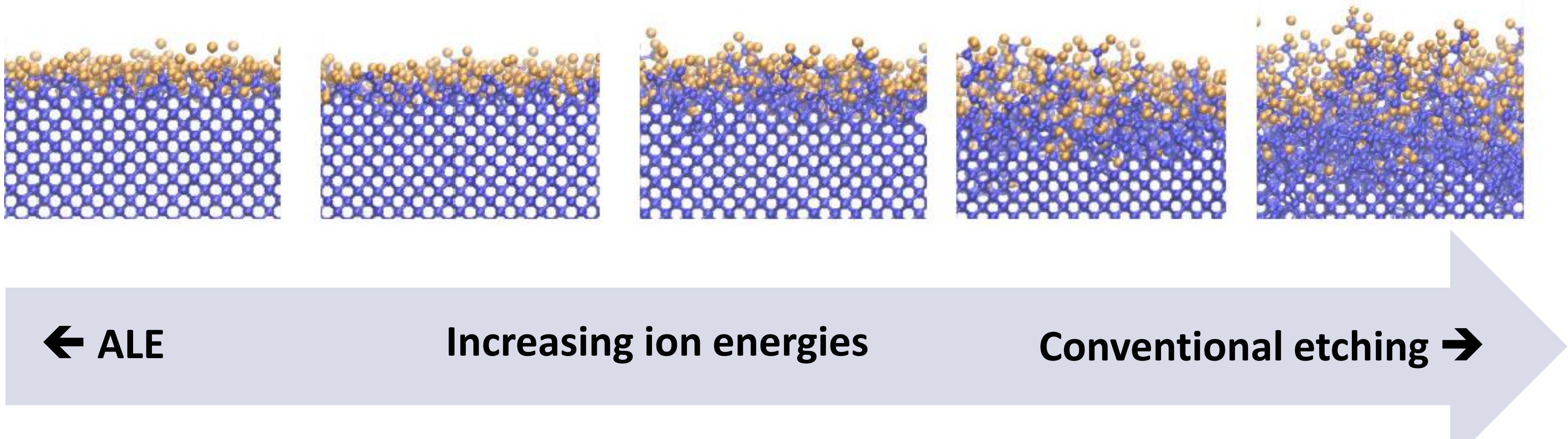
22-sec BOE post-etch

- $N_c = 3 \times 10^{15}$ cm^{-3}

*p-type dopant carrier concentrations, adapted from Table I from Guo, Xiao, et al. “Near-field terahertz nanoscopy of coplanar microwave resonators." *Applied Physics Letters* (2021).

How to remove defects & TLS from etched surfaces?

Low damage for minimal influence top layers



← ALE

Increasing ion energies

Conventional etching →

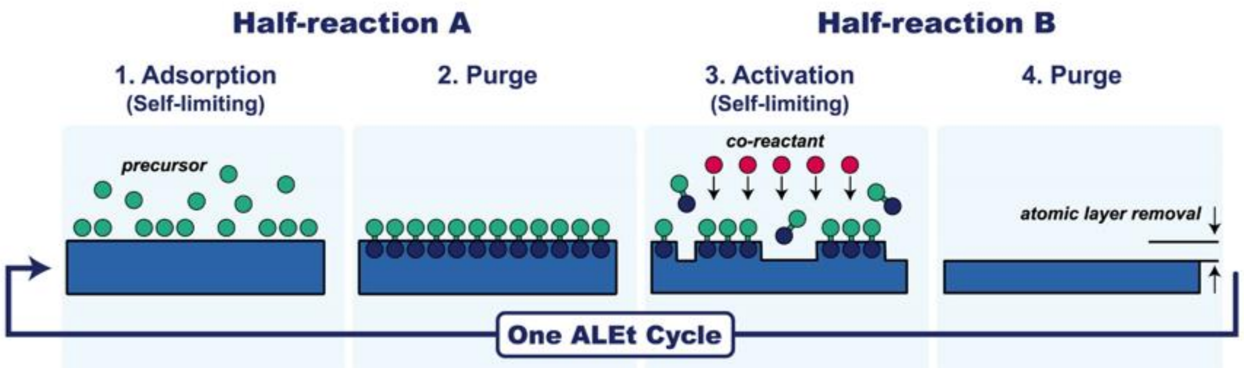
From O. Joubert, SEMATECH Workshop on Atomic-Layer-ETch (ALET) and - Clean (ALC) Technology, April 21, 2014

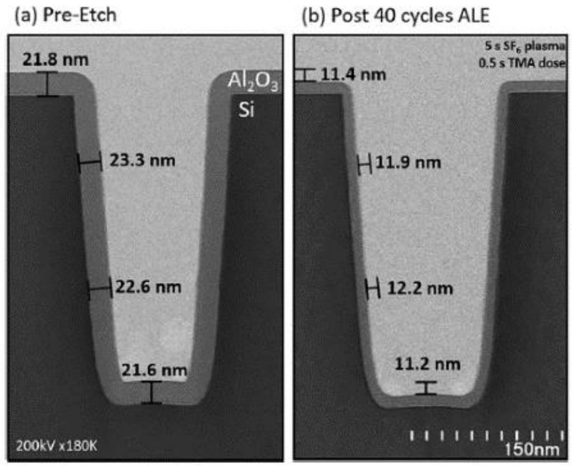
- ALD and ALE provide control and low damage options to allow minimal influence on sensitive surfaces.

Two Types of ALE

Reduced Subsurface Damage

Isotropic ALE (FlexAL ALD)





Chittock, Nicholas J., et al. "Isotropic plasma atomic layer etching of Al2O3 using a fluorine containing plasma and Al (CH3) 3." *Applied Physics Letters* 117.16 (2020): 162107.

Faraz et al., *J. Solid State Sci. Technol.* **4**, N5023 (2015)

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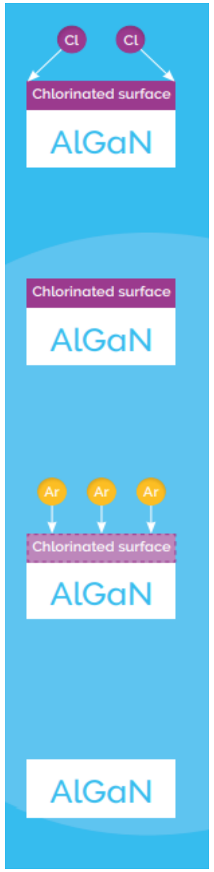
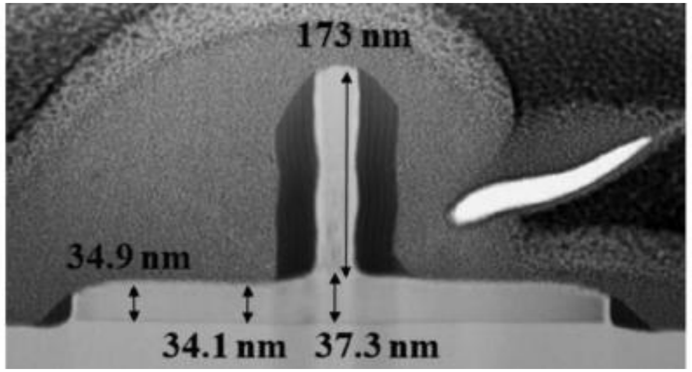
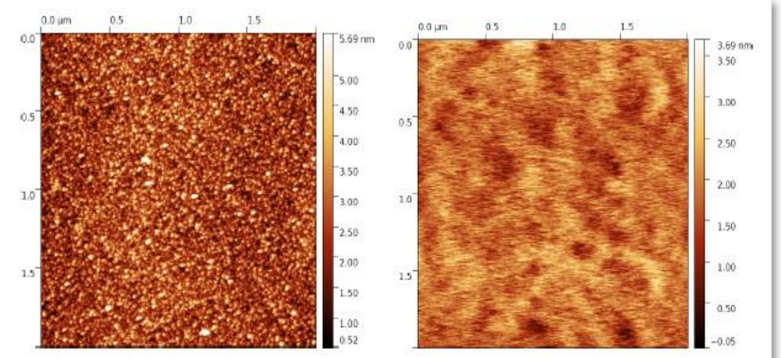
Directional ALE (Cobra ICP RIE)



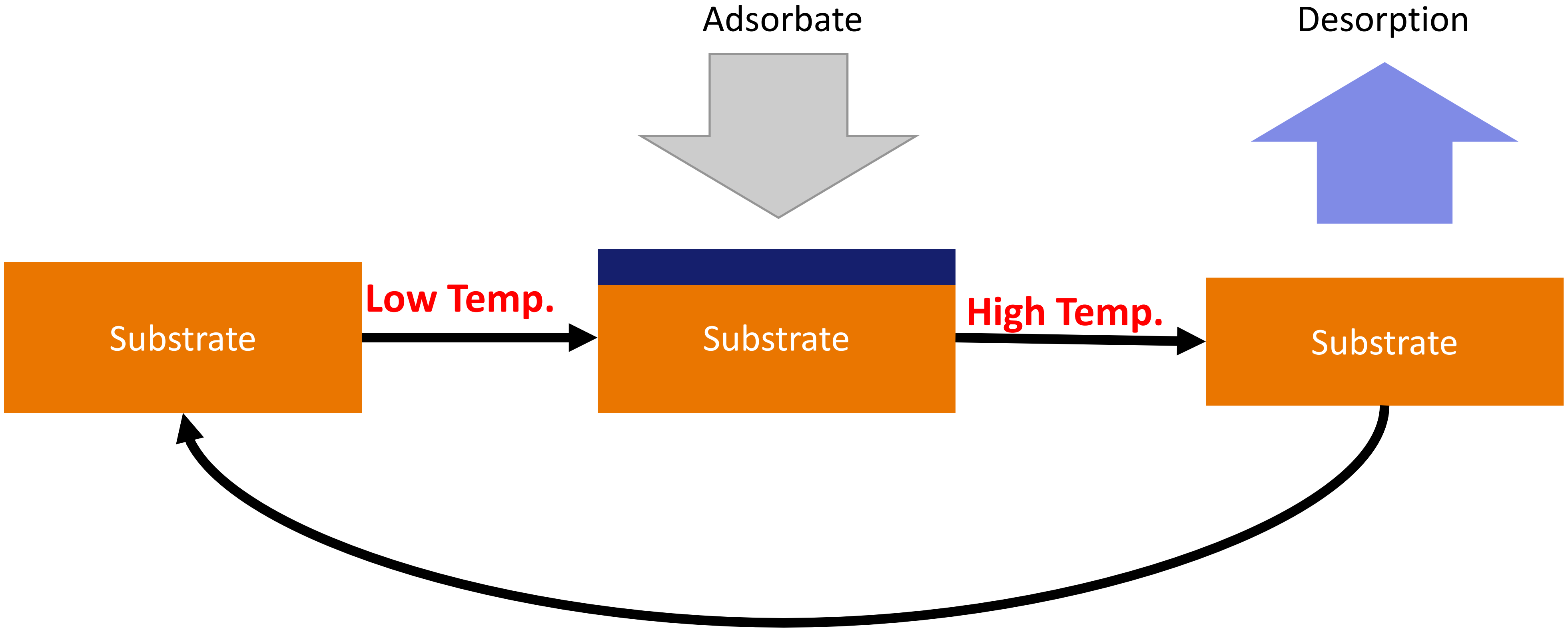


Jaffal, Moustapha, et al. *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* 39.3 (2021): 030402.



AlGaN surface roughness decreased from 650 pm to 350 pm after 200 cycles

Basic Thermal Desorption ALE



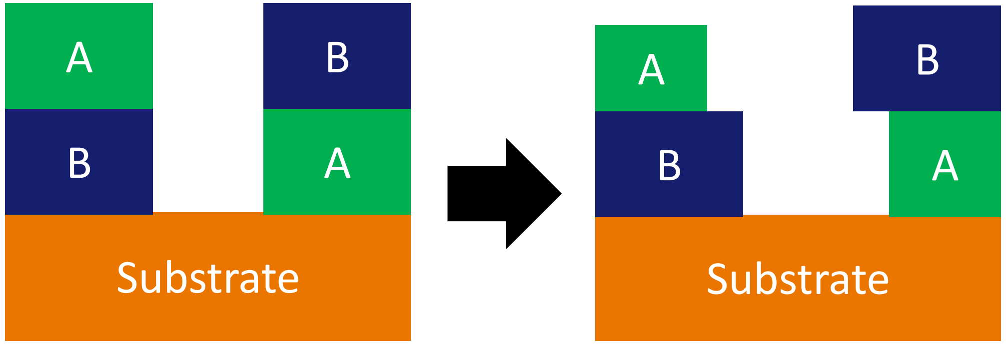
Demonstrated with O_2 ALE of Germanium
(Paeng et al. 2019)

Reaction-Assisted Thermal ALE

Use Chemistry to Engineer Volatile Species

- Chelation (oxidize and remove)
  - Form surface oxide, chelate oxide to form volatiles
- Ligand Exchange
  - Form metal fluoride, remove via ligand exchange with selective precursor, all products volatile
- Conversion
  - Exchange metallic element with one that's amenable to other ALE methods (e.g. SiO_2 to Al_2O_3)
- Oxidation/Fluorination
  - Form surface oxide, react with F to form volatiles

Isotropic ALE

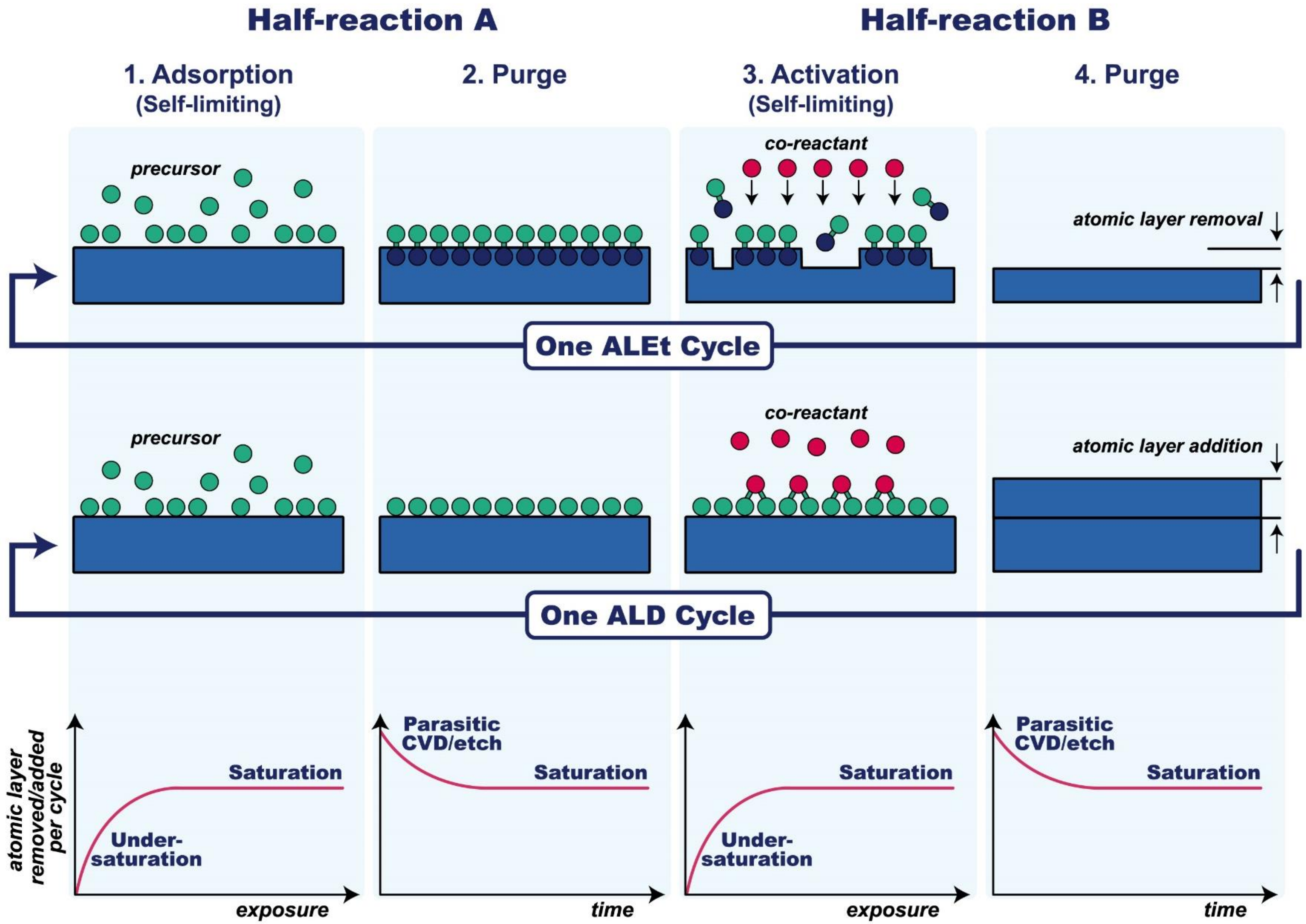


BUT

1. Frequently requires HF
2. Thermal ALD deposition less flexible

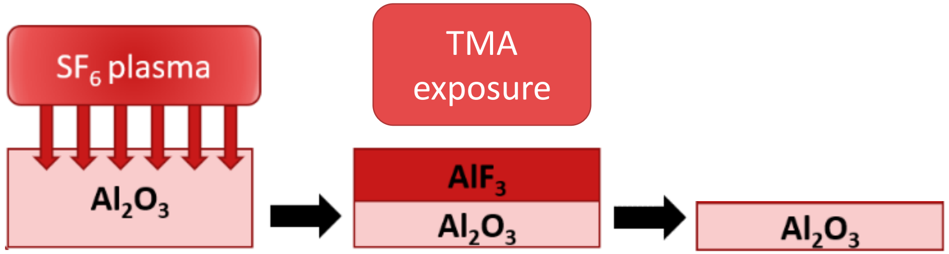
See "Atomic Layer Processing" by Thorsten Lill for more

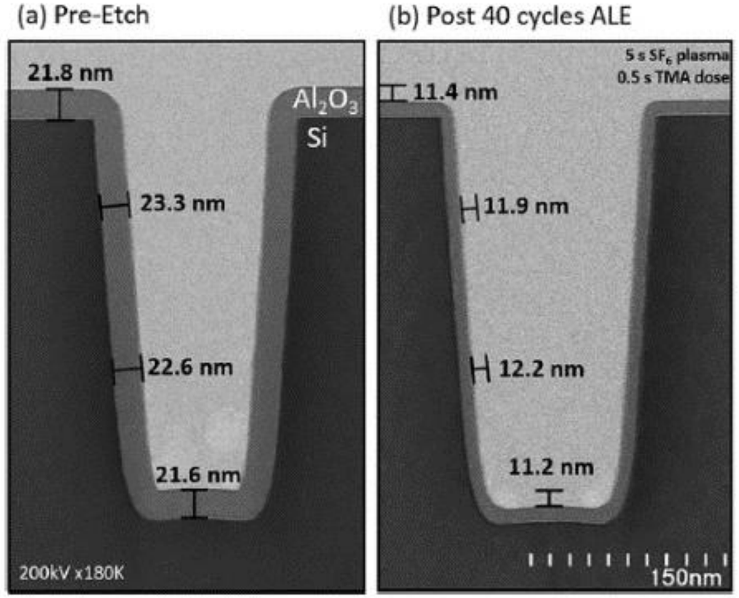
Generalized ALE/ALD cycle



Faraz et al., *J. Solid State Sci. Technol.* **4**, N5023 (2015)

Isotropic ALE using TMA and SF_6 plasma





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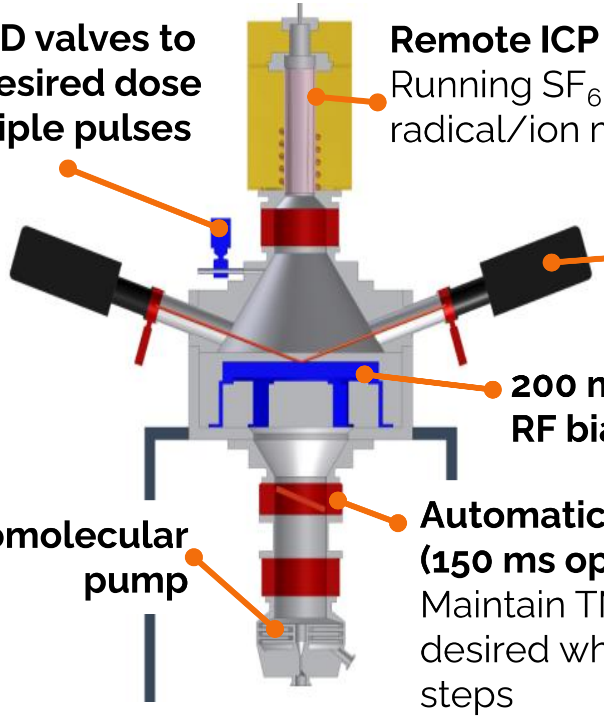
FlexAL ALD for Isotropic ALE



Fast ALD valves to pulse desired dose in multiple pulses

Remote ICP plasma source
Running SF_6 at chosen pressure for desired radical/ion mix

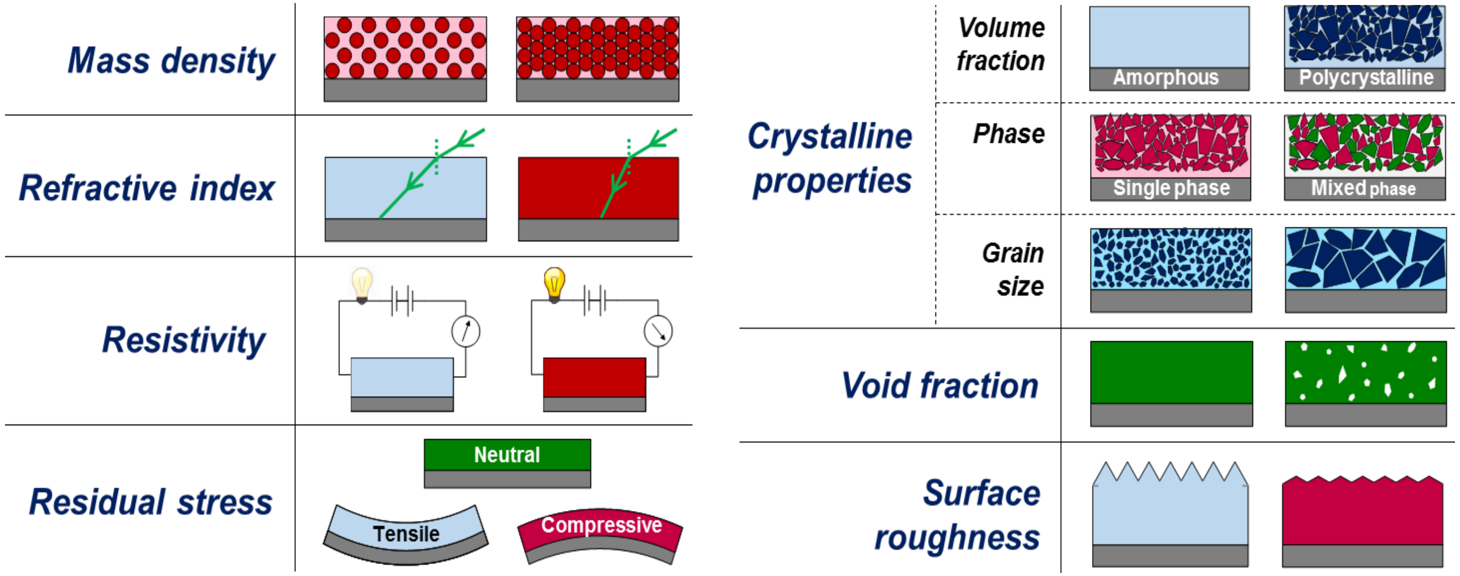
In-situ ellipsometry and other techniques to monitor process

200 mm wafer electrode, up to 400 °C RF biased 550 ° C electrode optional

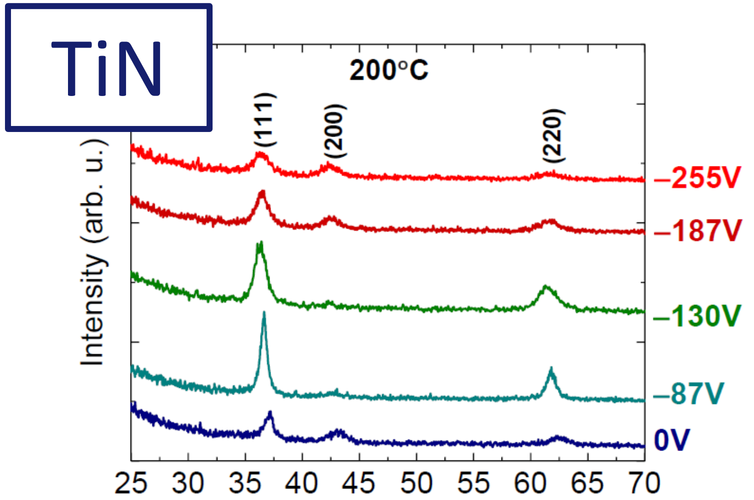
Turbomolecular pump

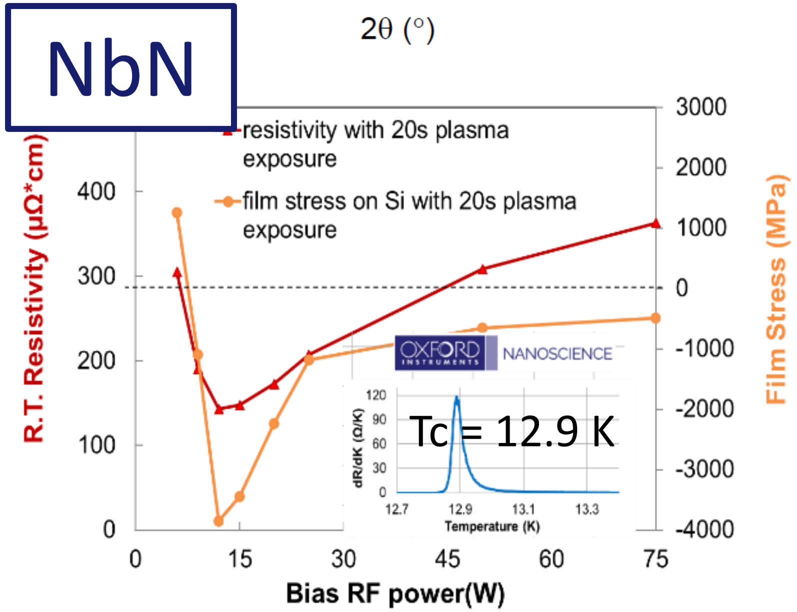
Automatic Pressure Control (APC) valve (150 ms open and close during ALD cycle)
Maintain TMA at high concentration when desired while strong pumping in purge steps

SC Nitride ALD also in FlexAL



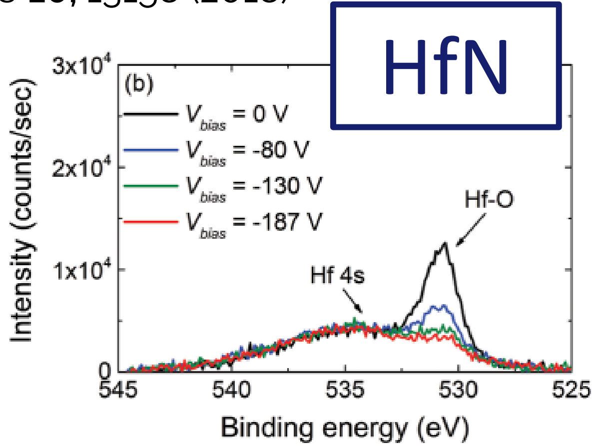
Faraz et al., *ACS Appl. Mater. Interfaces* **10,** 13158 (2018)





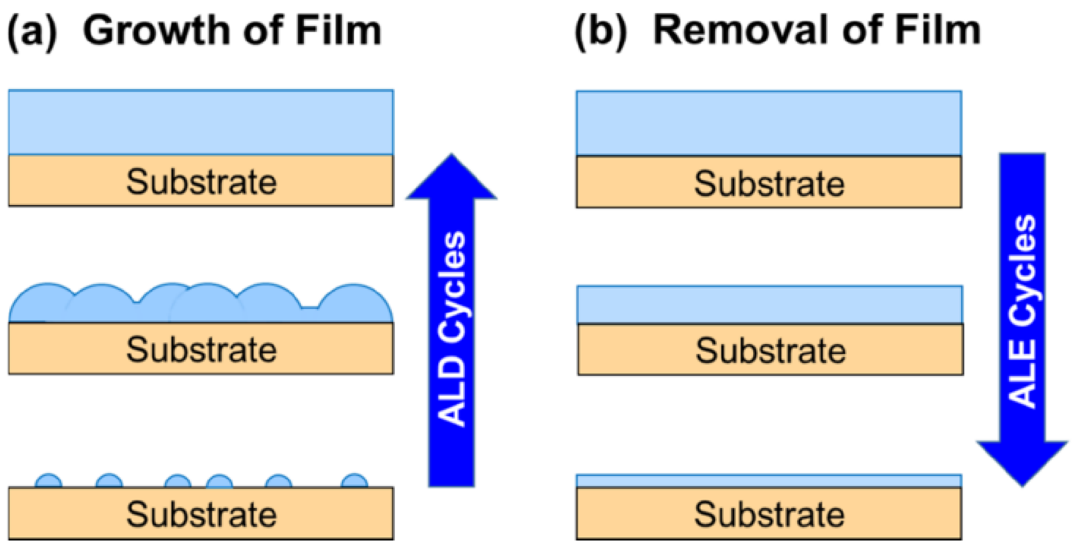
Bias improves conductive nitrides

- Shorter plasma exposure times
- Lower deposition temperatures
- Crystallinity & O-content control
- Faster Deposition Rate

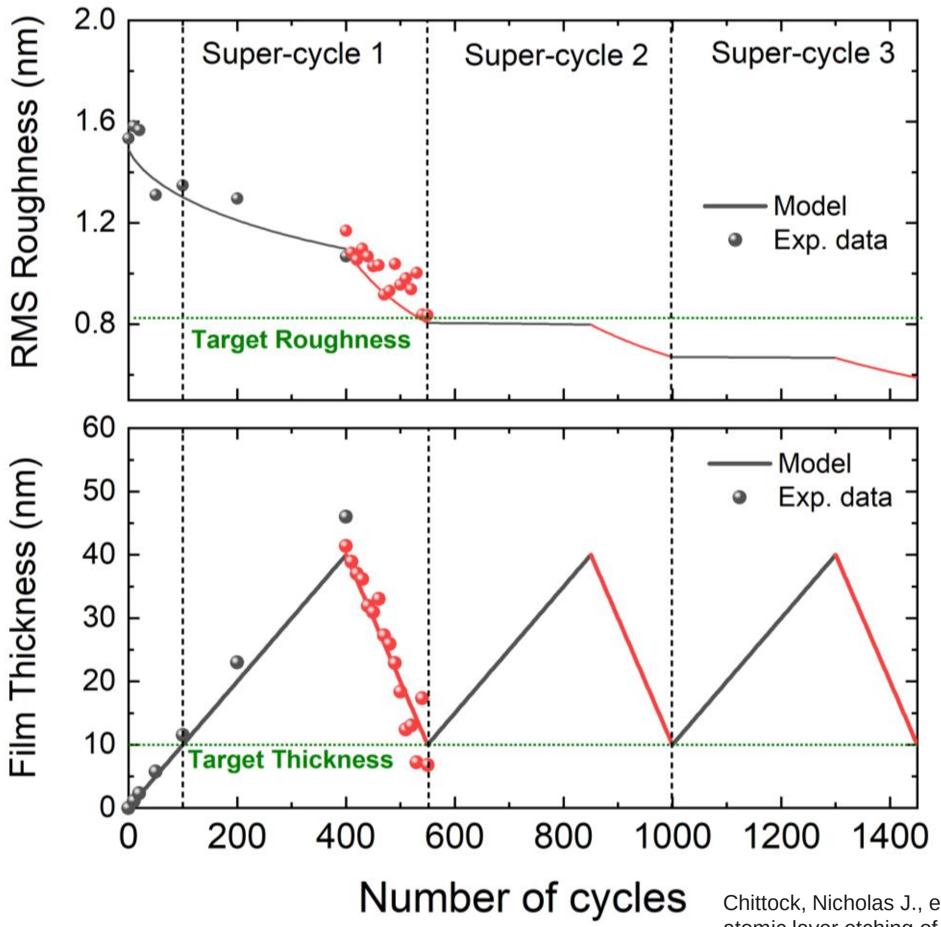


Karwal et al., *Nanoscale* (2021)

ALD/i-ALE Supercycles (Al_2O_3)



Gerritsen, Sven, and Ir AJM Mackus. "Surface smoothing using atomic layer deposition and etching." (2020).

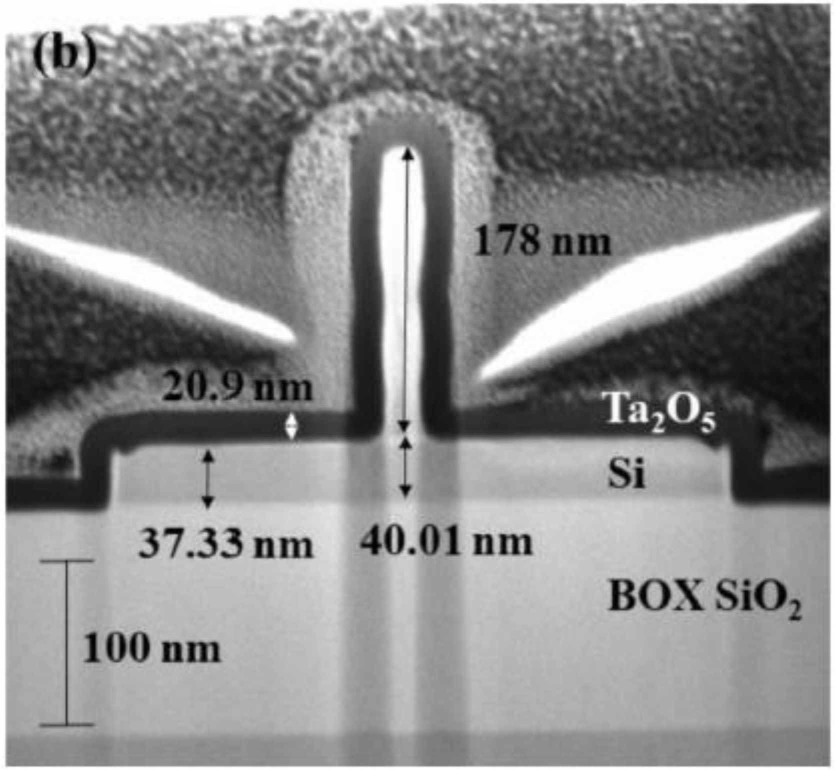


Chittock, Nicholas J., et al. "Isotropic plasma atomic layer etching of Al2O3 using a fluorine containing plasma and Al (CH3) 3." *Applied Physics Letters* 117.16 (2020): 162107.

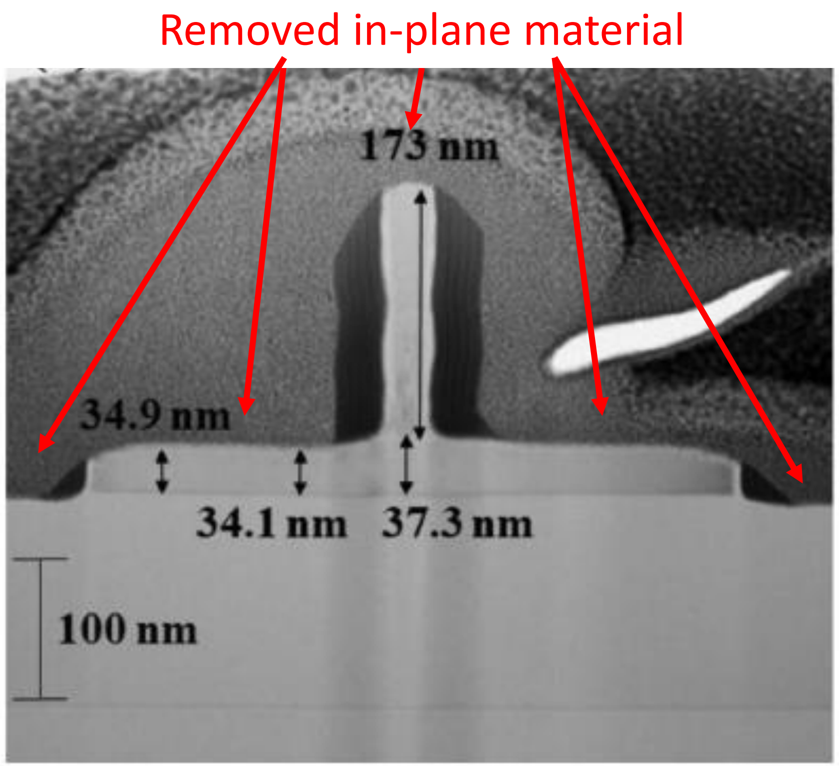
ALD/ALE Supercycles Enable Ultra-Smooth Ultra-Thin Dielectrics

What about Directional ALE?

Conformal Ta_2O_5 ALD



Directional ALE

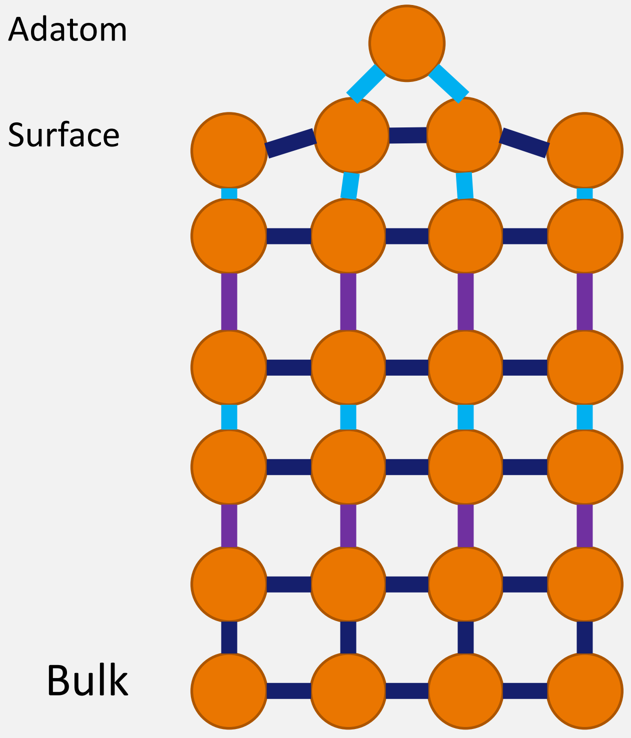

Removed in-plane material

Jaffal, Moustapha, et al. "Topographical selective deposition: A comparison between plasma-enhanced atomic layer deposition/sputtering and plasma-enhanced atomic layer deposition/quasi-atomic layer etching approaches." *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films* 39.3 (2021): 030402.

Directional ALE: How it Works

Bonds adjust to minimize energy

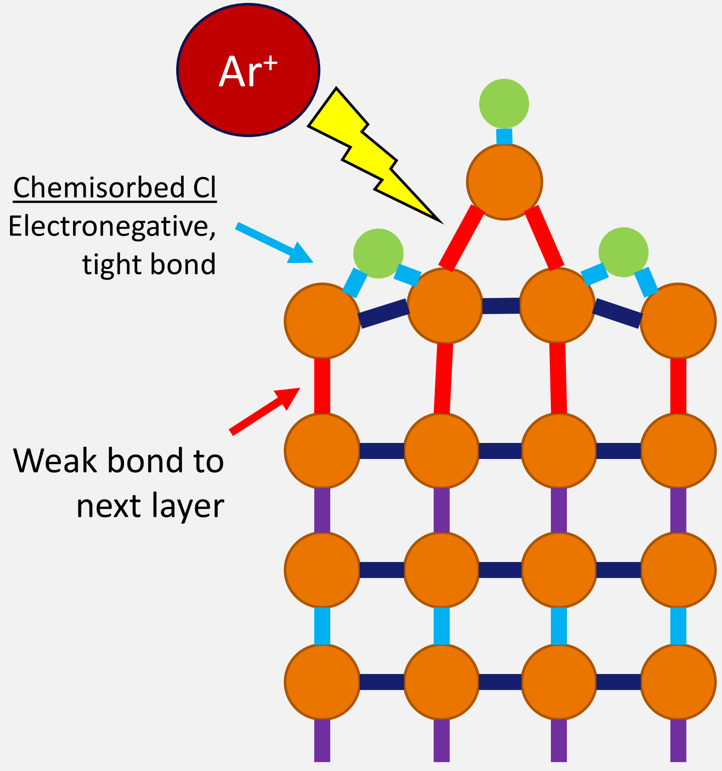
Energy difference too small for surface-selective sputtering



Consistent bond lengths

Chemisorption Weakens 2nd Layer Bonds

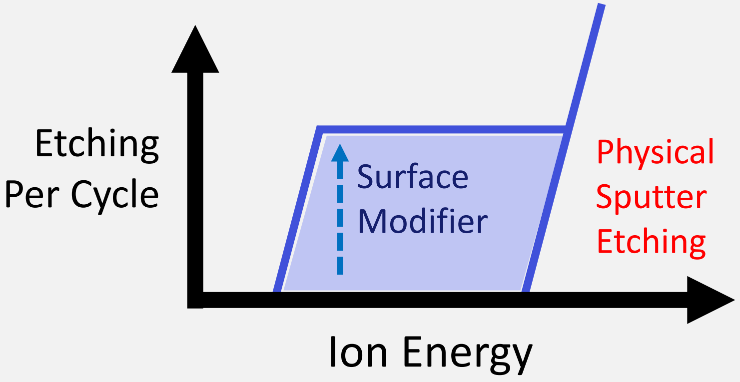
Large energy difference = surface-selective sputtering



Bias Voltage

Synergy and the ALE Window

$$Synergy\ (\%) = \frac{EPC\ -(\alpha+\ \beta)}{EPC}$$



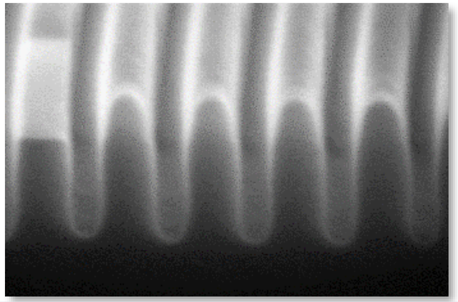
Synergy Requirement

- $E_{\text{modification}} < E_{\text{StepA}} < E_{\text{desorption}}$
- $E_{\text{desorption}} < E_{\text{StepB}} < E_{\text{bulksputter}}$

Kanarik et. al. 2017

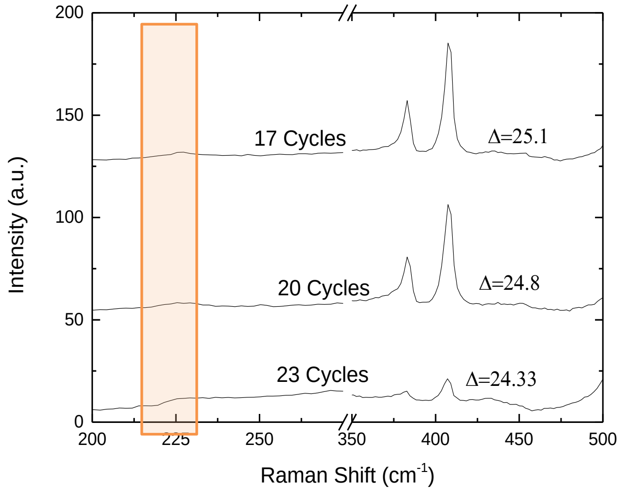
Directional ALE Process Examples

- Si
  - Etch rate 2 to 7Å/cycle (up to 70Å/min)
  - Cl_2 dose step, Ar etchant



25nm wide Si trenches etched to 110nm depth by ALE, HSQ mask still in place

- MoS_2
  - Small shift in peaks per 3ALE cycle
  - 40 ALE cycles removed all material
  - Starting thickness 18nm
  - Cl_2 dose step, Ar etchant
  - Low damage with no defect induced peak at 227 cm-1

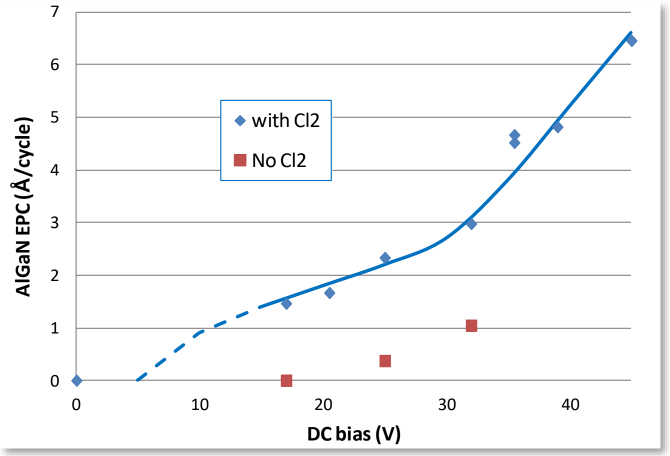


Raman spectra after 17, 20 and 23 ALE cycles

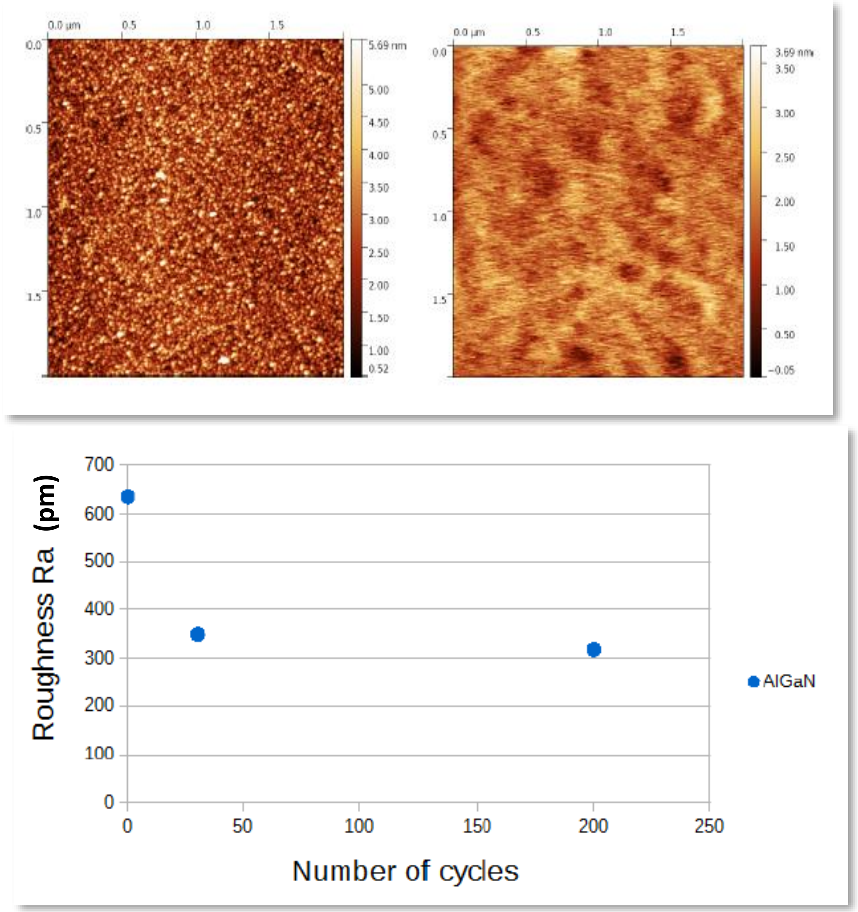
Directional ALE Process Example

AlGaN/GaN ALE with Ar/Cl_2

- Etch rate 1.5-3 Å/cycle
  - up to 18 Å/min
- Added roughness <<1nm
  - AFM data indicates a smoothing effect



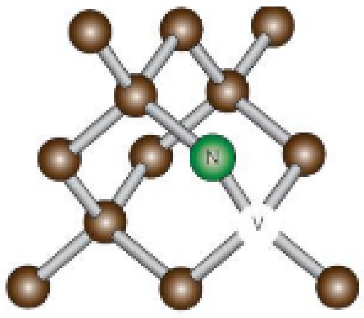
AlGaN etching rate per cycle

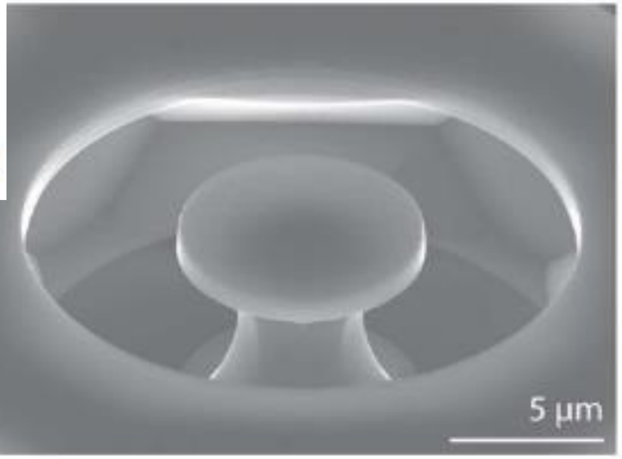


AlGaN surface roughness after 200 cycles (bottom), before etching (*top left)* and after etching *(top right)*

AFM data courtesy of Paolo Abrami in Collaboration with Bristol Uni

Directional ALE for Color Centers





Paul Barclay and group, Calgary

DOI: 10.1021/acs.nanolett.5b01346, Nano Lett. 2015, 15, 5131–5136

Si	SiC	Diamond
Telecom	Near IR (Bio Apps)	Visible

$$\eta_{dipole} \sim \frac{r^3}{e^{(-\tau/T_2)}}$$

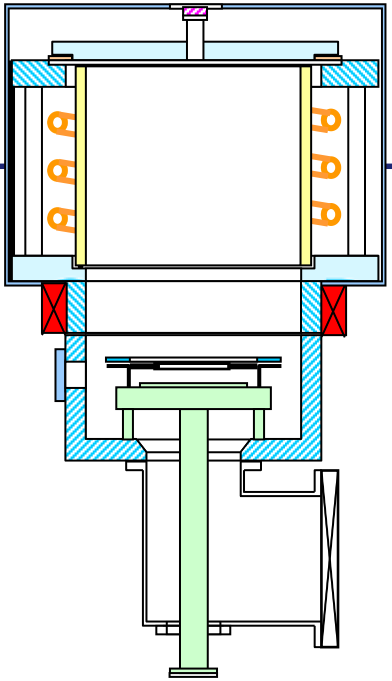
Sensitivity scales with distance to NV center (r) and spin coherence time (T_2)

Many Defect Hosts and Types

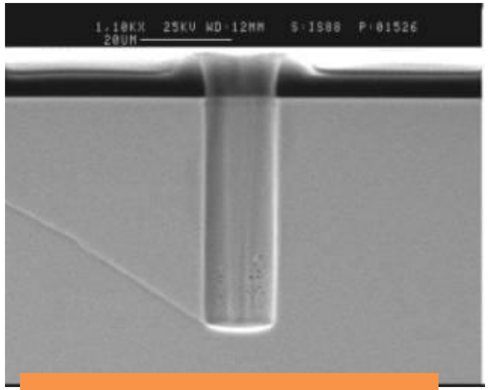
T_2 Strongly Impacted by Surface Condition

Will ALE enable higher-sensitivity quantum sensors?

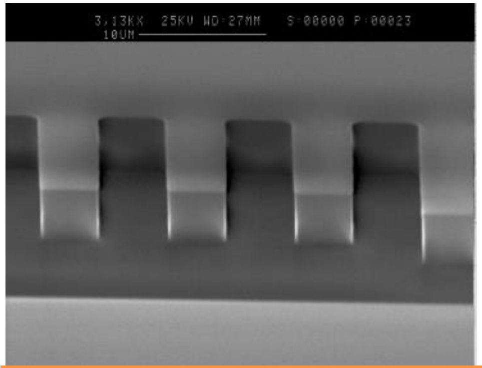
Premium ICP Etcher



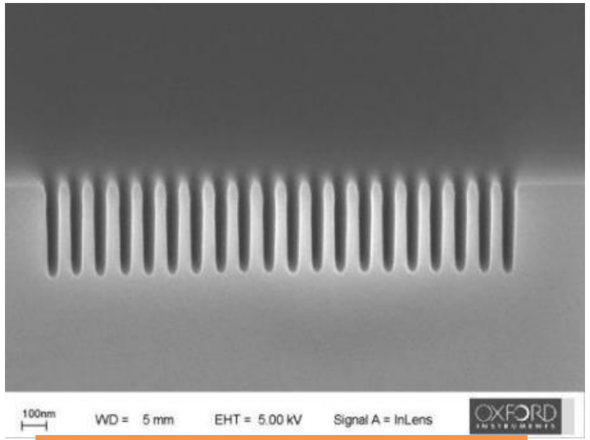
- PlasmaPro 100 Cobra
  - Loadlocked, clusterable, up to 200 mm wafers
  - Wide power range: 5-1000 V bias, 3/6kW ICP
  - 300 mm ICP source, available heated liners
  - Compatible with ALE, Turbo, Active Uniformity Control
  - Large process library at OIPT apps labs & in literature



GaAs Via etch



High Rate (>2.5µm/min) polyimide etch

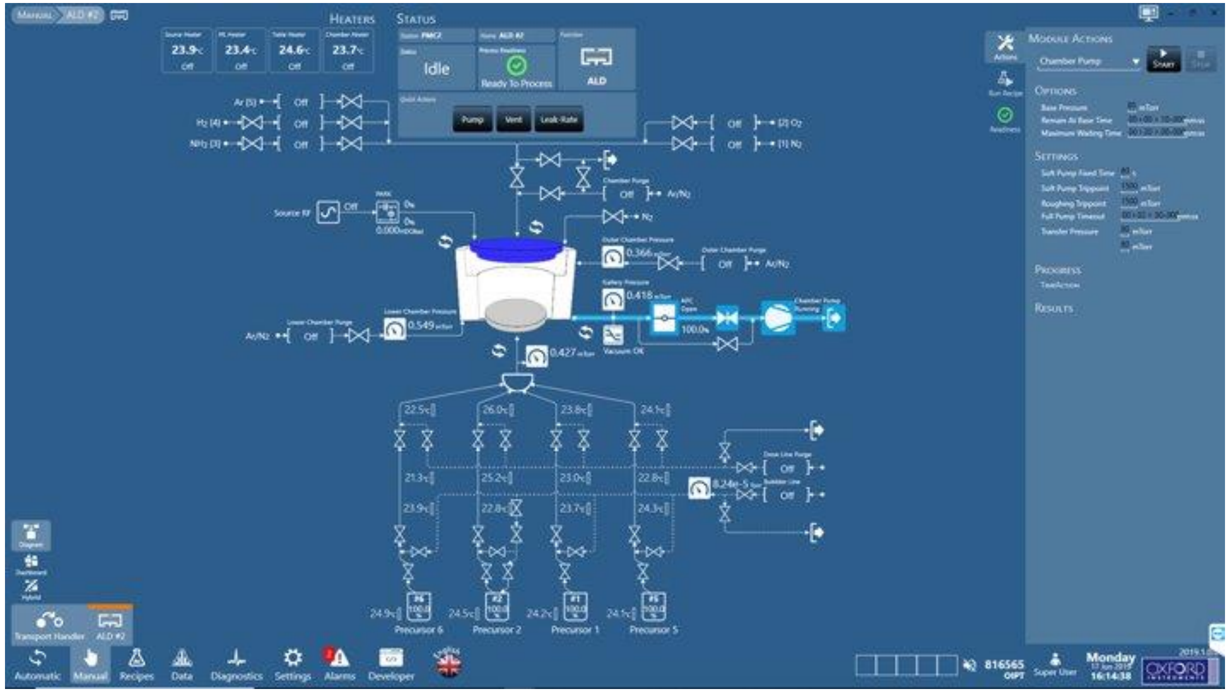


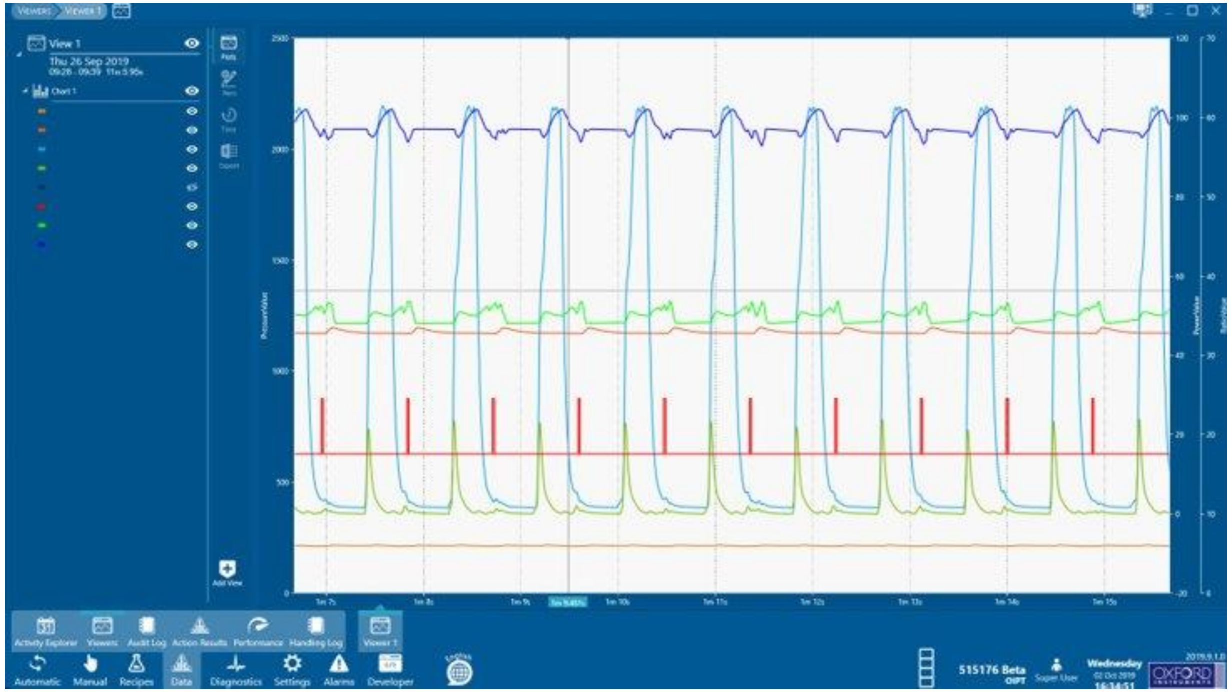
Cryo Si etch

PTIQ

+ Major Software Upgrade

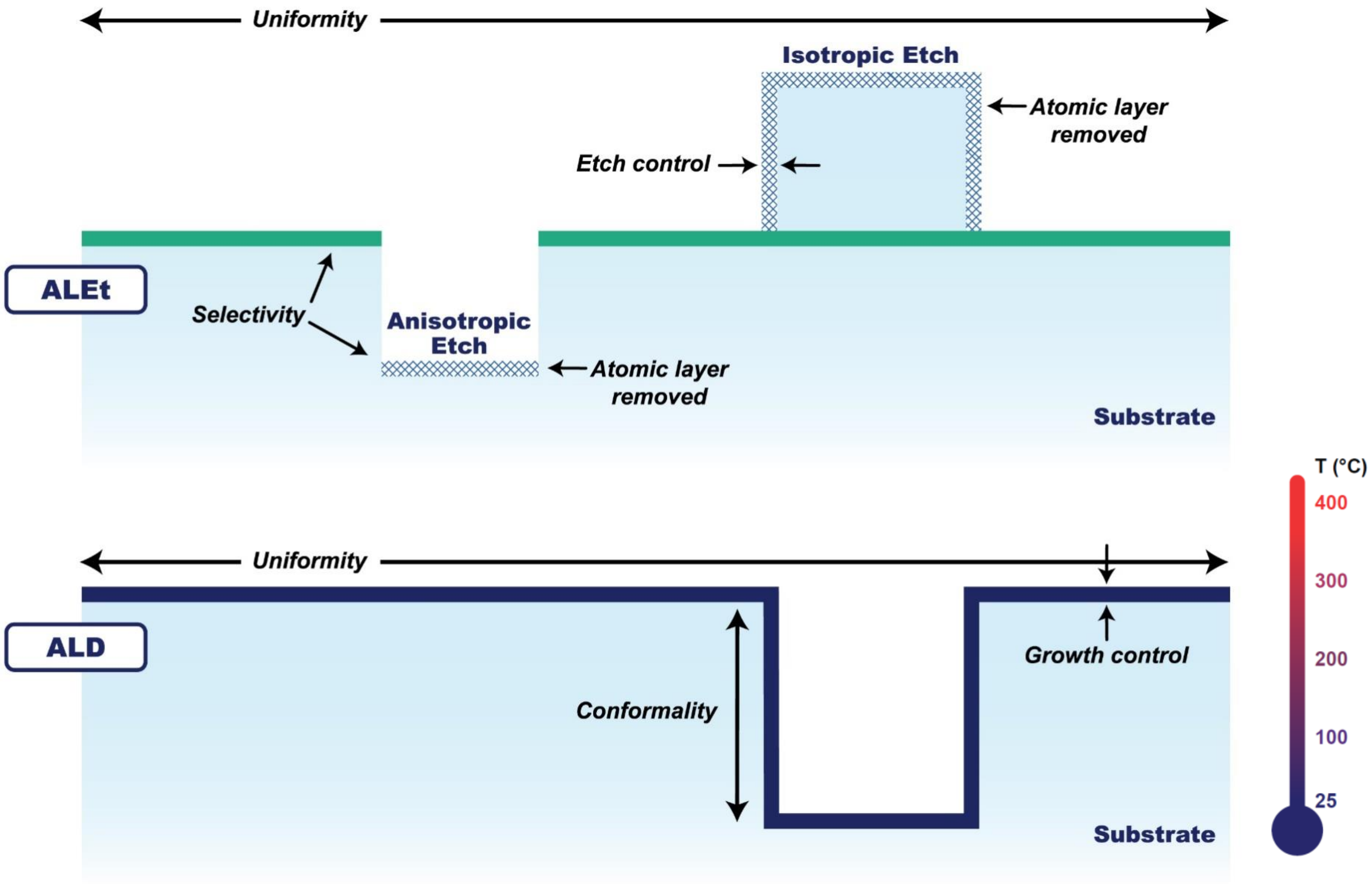
- Intuitive GUI
- uSec accuracy
- Constant monitoring
- Role-based security
- Sophisticated datalogging





Switch from RIE to ALE during recipe

ALE vs. ALD



Faraz et al., *J. Solid State Sci. Technol.* 4, N5023 (2015)

Make Better Devices with Oxford Instruments

- Surface Losses are major issue
  - Superconducting: SA effect on Q_i. TLS, T_1, T_1 fluctuations
  - Color centers: T_2 decrease for near-surface NVs. ZPL fluctuations
  - Photonics: Waveguide scattering loss. SPE linewidth broadening

- Conventional RIE can damage surfaces
  - Sputtering damage (straggle), implantation, diffusion

- Low damage etches offer path to lower loss
  - ICP-RIE optimized for low-damage
  - Atomic layer etch
    - Bulk etch with ICP-RIE, remove damaged layer with in-situ ALE

OI Quantum Technology Solutions portfolio

Plasma Technology
Device Fab

Improving Qubit performance

NanoScience
Cryogenics

Measuring Qubit performance

Asylum
AFM

Reducing losses at interfaces

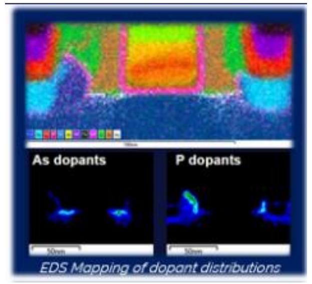
Andor
Quantum Optics

Detect each photon with confidence

WITec
Raman & Correlative

Vibrational Spectroscopy

NanoAnalysis
EDS, WDS, EBSD



Composition and Crystallinity

Russ Renzas, Ph.D.

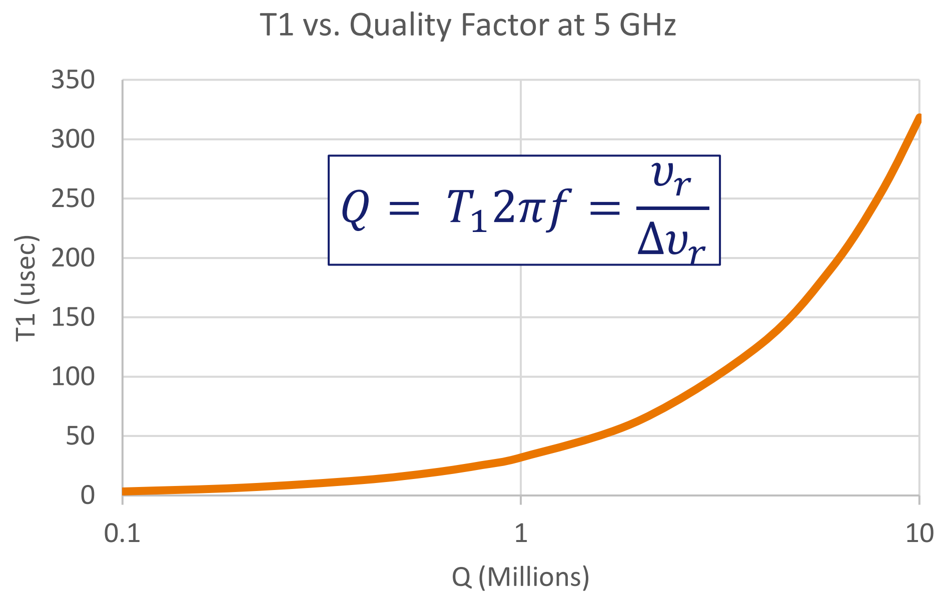
Quantum Technology Manager

Oxford Instruments Plasma Technology

Russ.Renzas@oxinst.com

Thanks for Listening!

Q_i = Device Fab Metric



$$Q = T_1 2\pi f = \frac{\upsilon_r}{\Delta\upsilon_r}$$

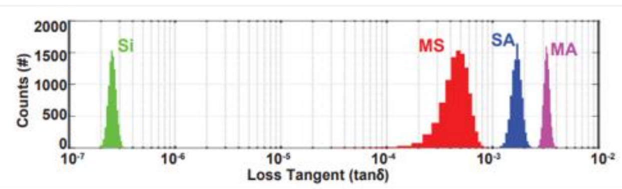
$$\frac{1}{Q} = \frac{1}{Q_i} + \frac{1}{Q_c}$$

Materials & Process

Design

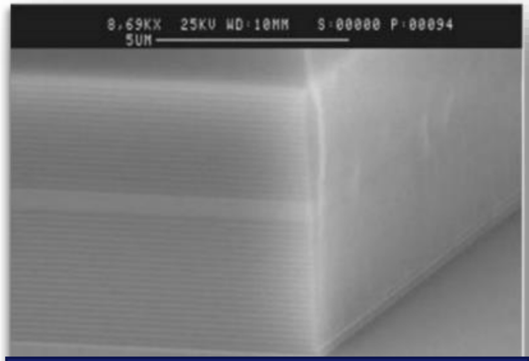
$$\frac{1}{Q_i} = \frac{p_{substrate}}{q_{substrate}} + \frac{p_{SC}}{q_{SC}} + \boxed{\frac{p_{surface}}{q_{surface}}} \nearrow \frac{p_{MA}}{q_{MA}} + \frac{p_{SA}}{q_{SA}} + \frac{p_{MS}}{q_{MS}}$$

Log Loss Tangent (1/q) vs. Interface

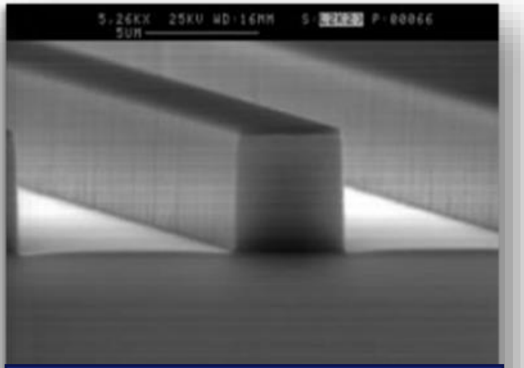


Woods, Wayne, et al. "Determining interface dielectric losses in superconducting coplanar-waveguide resonators." *Physical Review Applied* 12.1 (2019): 014012.

Huge Range of Photonic Materials Etched

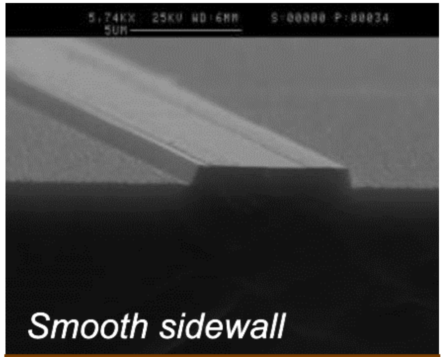


GaAs / AlGaAs heterostructures



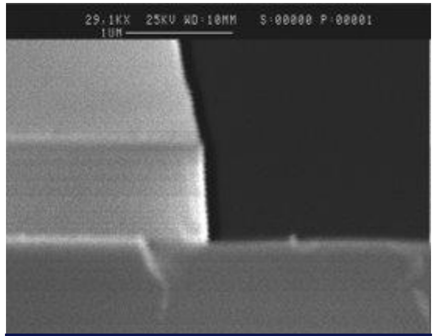
InP

SiO_2

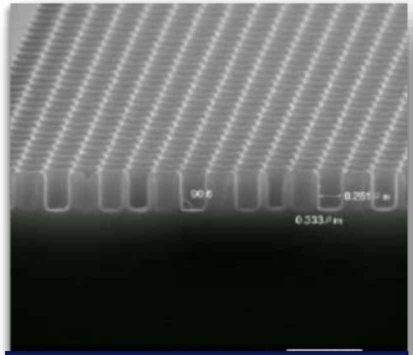


Smooth sidewall

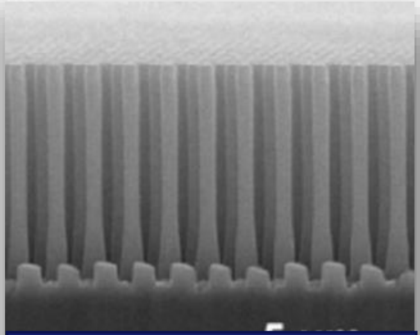
$LiNbO_3$



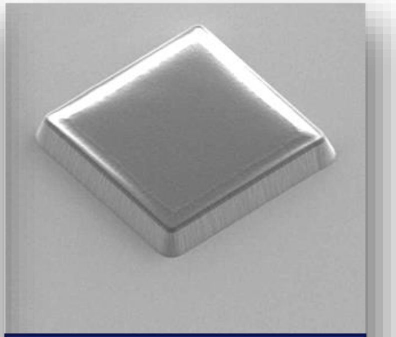
WSi



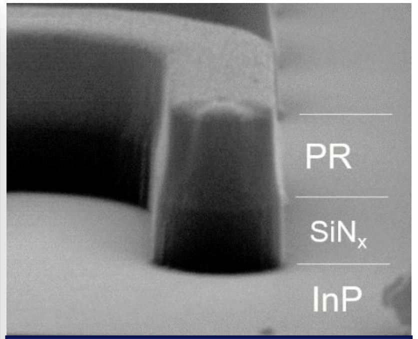
GaAs / AlGaAs



GaN

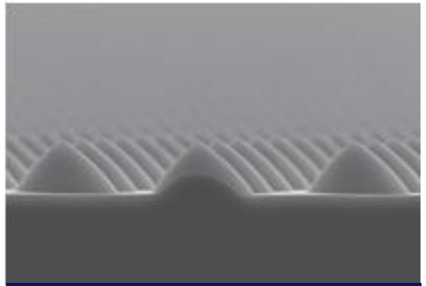


InSb/InSbAs



SiN_x on InP

Si (Cryo)

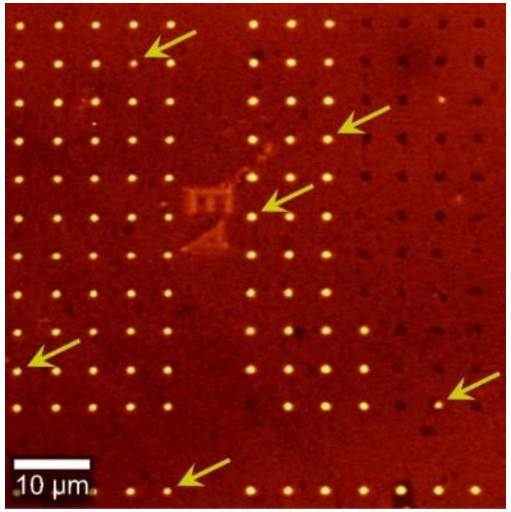


Sapphire

Color Center Characterization (WITec)

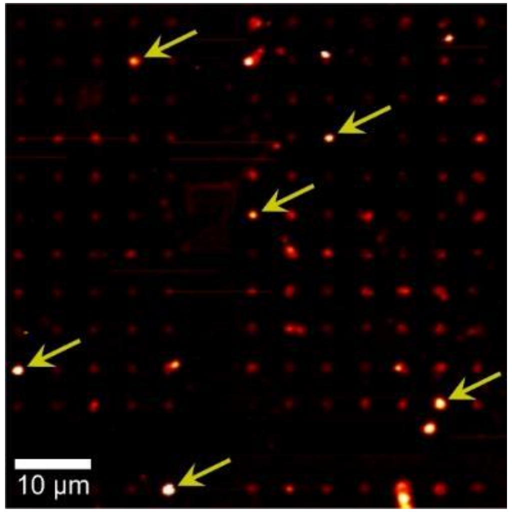
Correlative imaging identifies structures of interest

Raman image (1330 cm^{-1})



Intact diamond pillars

Photoluminescence image

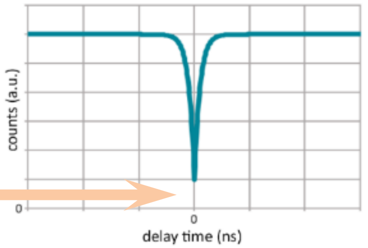


NV centers or contaminations

Signal in both pictures: micropillars with NV centers (arrows)

Single-photon emitter:
Histogram of inter-photon times shows dip around zero

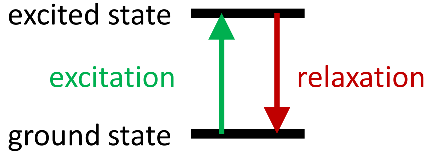
dip = antibunching



- Sample: diamond micropillars with NV centers
- Aim: identify structures of interest (single NV centers)

Sample courtesy of Dr. Rainer Stöhr and Prof. Dr. Jörg Wrachtrup from the 3rd Physics Institute at the University of Stuttgart, Germany.

Single-photon emitter:
Minimum inter-photon time depends on excited-state lifetime

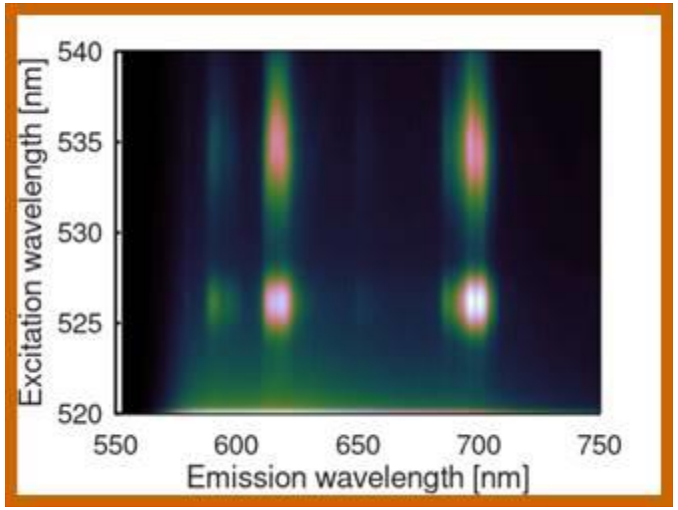

excited state

excitation

relaxation

ground state

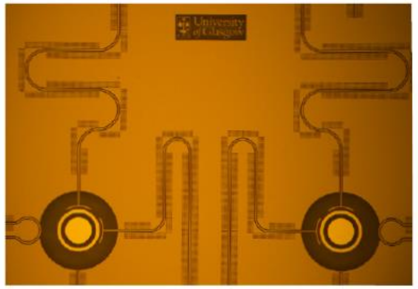
Heat Map
Excitation vs. Emission



Developed for other applications, useful for color center characterization.

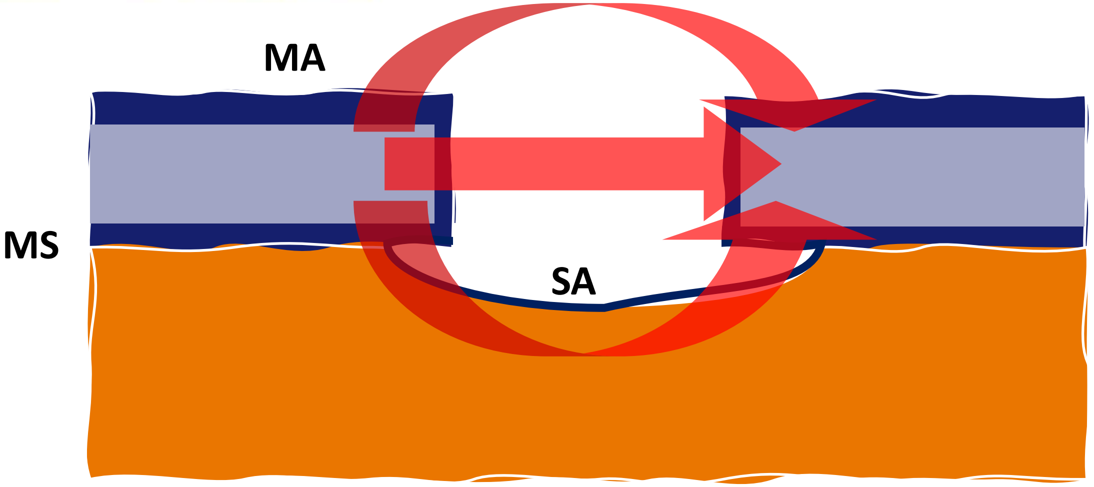
AFM-Confocal correlative microscope also available.

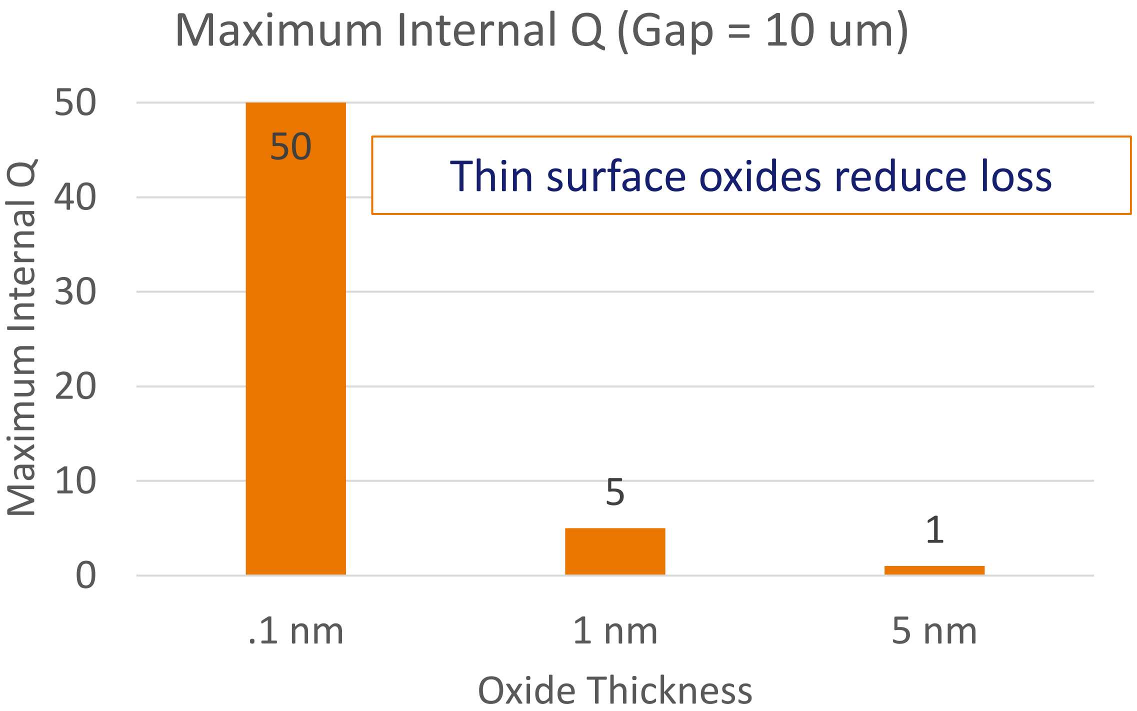
Bad Surfaces are Lossy



- Oxides
- Roughness
- Defects

} LOSS



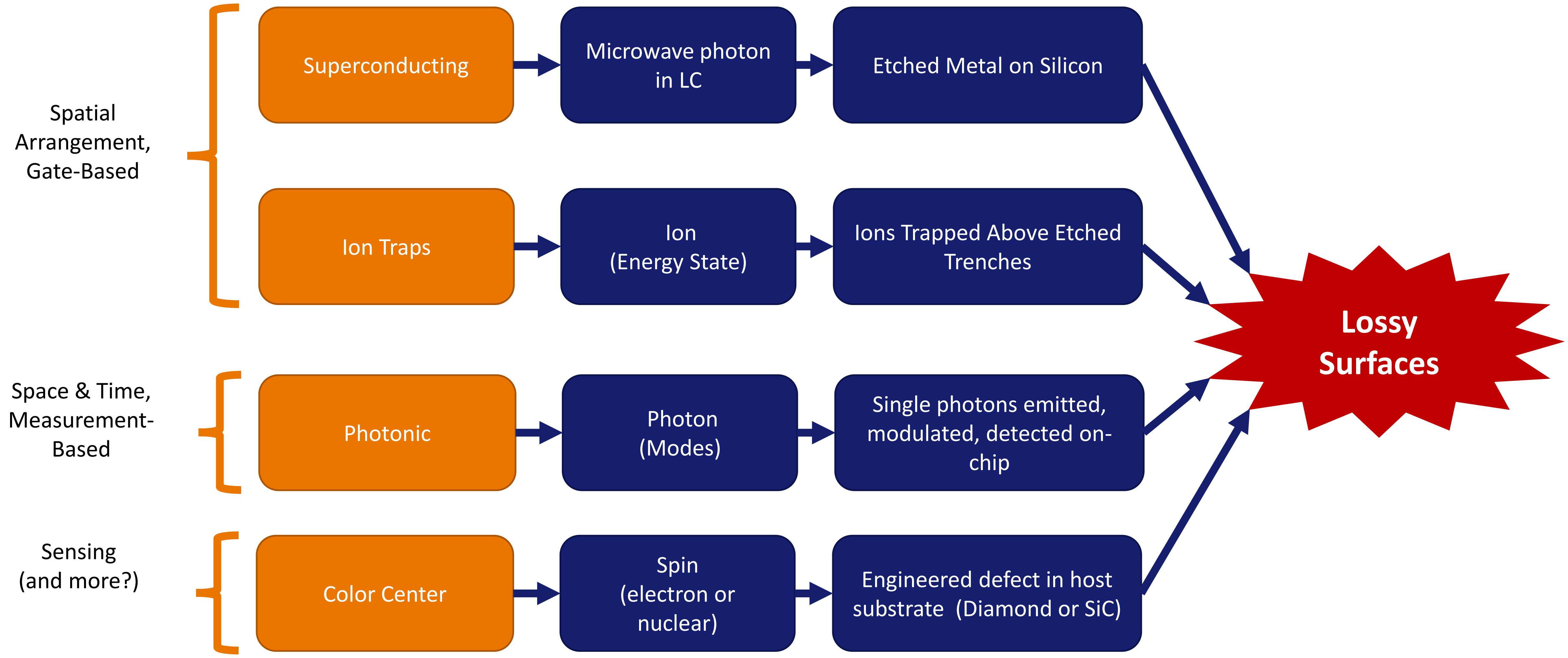


Thin surface oxides reduce loss

Q↓ as devices shrink → **Loss Impedes Scaling**

$$Q_{surf} = \frac{q_{surf}}{p_{surf}}, \mathbf{p_{surf}} \sim {}^{\mathbf{t}}/_{\mathbf{L}}, q_{surf} \sim 500$$

Surface Loss Common Across Modalities



Spatial Arrangement, Gate-Based

Superconducting → Microwave photon in LC → Etched Metal on Silicon

Ion Traps → Ion (Energy State) → Ions Trapped Above Etched Trenches

Space & Time, Measurement-Based

Photonic → Photon (Modes) → Single photons emitted, modulated, detected on-chip

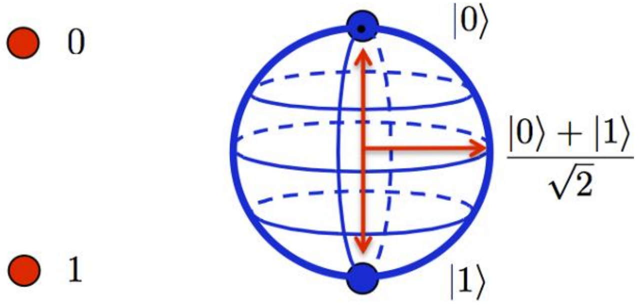
Sensing (and more?)

Color Center → Spin (electron or nuclear) → Engineered defect in host substrate (Diamond or SiC)

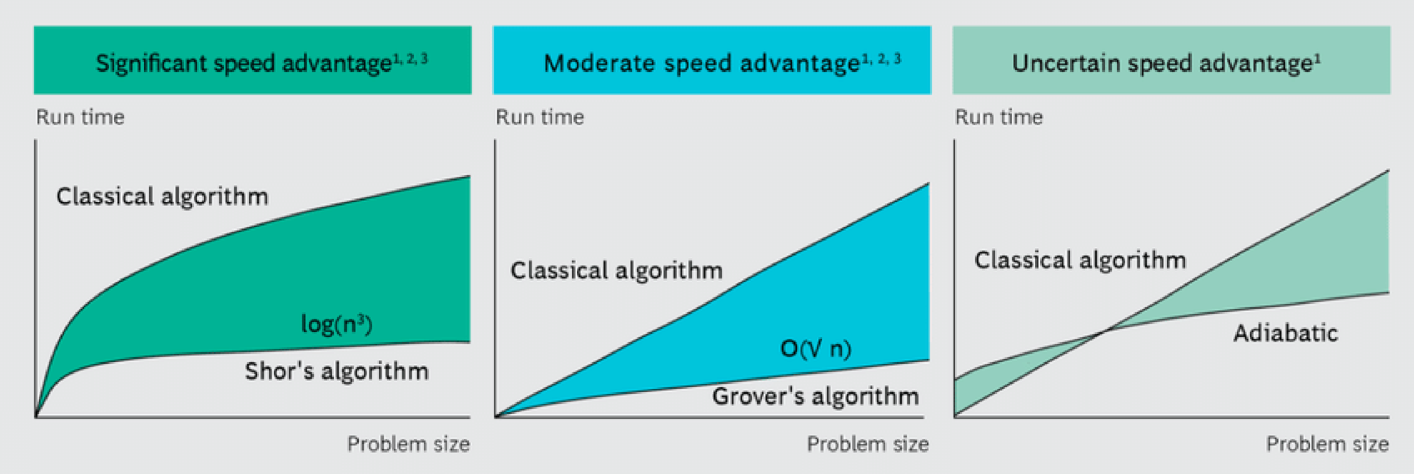
Lossy Surfaces

Exploit Quantum Properties for New Computation

- Classical Computing = AND, OR, NOT, NAND, flipflops…
  - Capacitors/RAM = Memory element (Binary)
  - Transistor = Switching element (logical gate operations)
- QC = Entanglement, interference
  - Qubit = Memory element (Complex Number)
  - Microwaves or lasers = Switching element (quantum gate operations)



Classical Bit **Qubit**



Silvestri, Riccardo. (2020). Business Value of Quantum Computers: analyzing its business potentials and identifying needed capabilities for the healthcare industry.