Atomic Layer Processes to Enable the Atomic Scale Era

August 20, 2018

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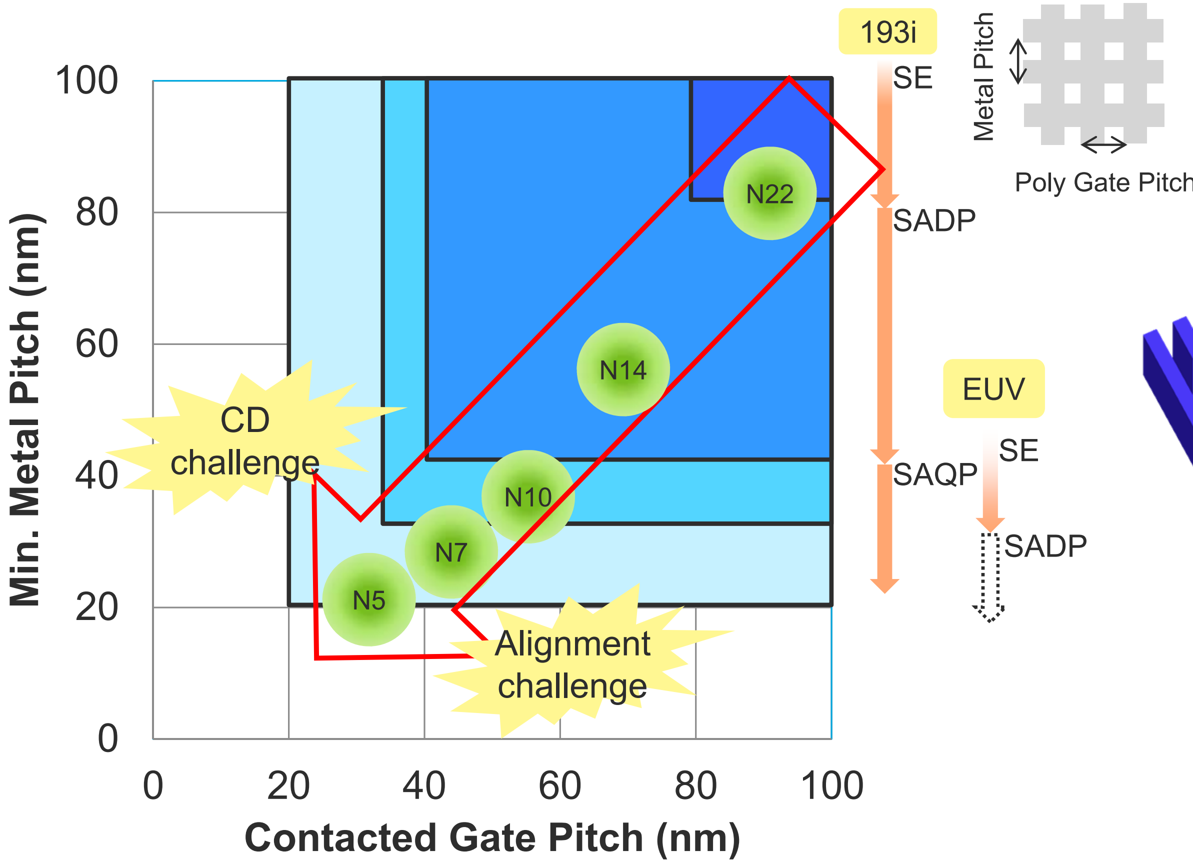
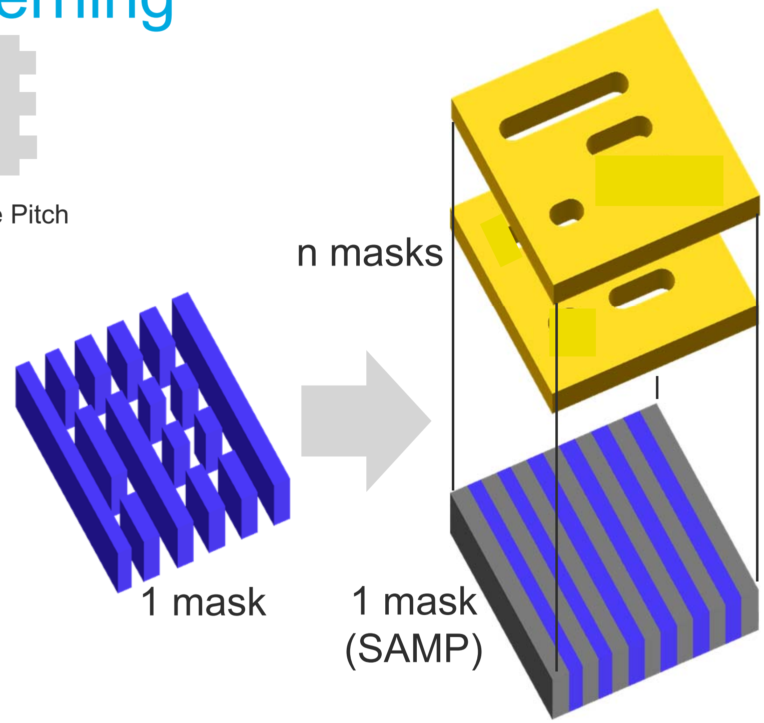
TEL Technology Center, America, LLC

Scaling Trend – Sub-lithographic Patterning





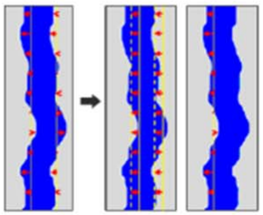
Design layout change from 2D to 1D

Complex and fine patterning technology is required for further scaling

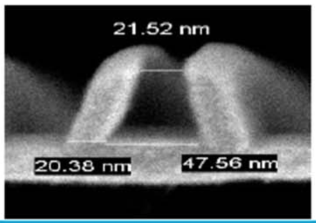
Patterning Challenges

CD variation

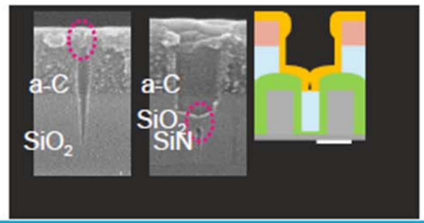
Line Roughness
(LER / LWR)



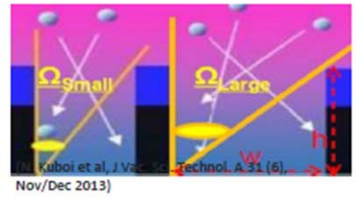
Pattern profile
(leaning)



Etch clogging

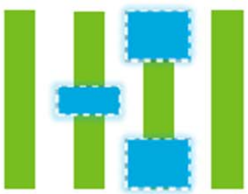


Loading effect

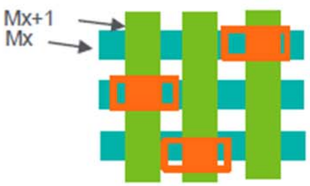


Overlay

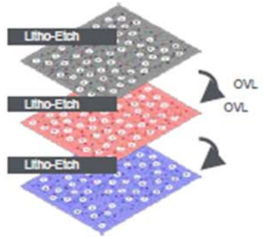
Alignment of
cut/block to grid



Alignment of via to
metal lines



Alignment of holes
at multiple LE

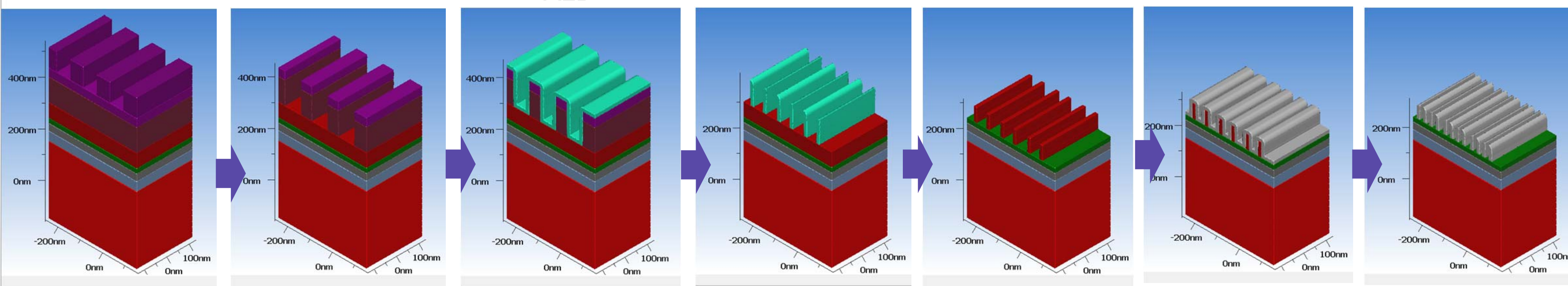


Numerous factors impact EPE

What is Enabling Patterning?

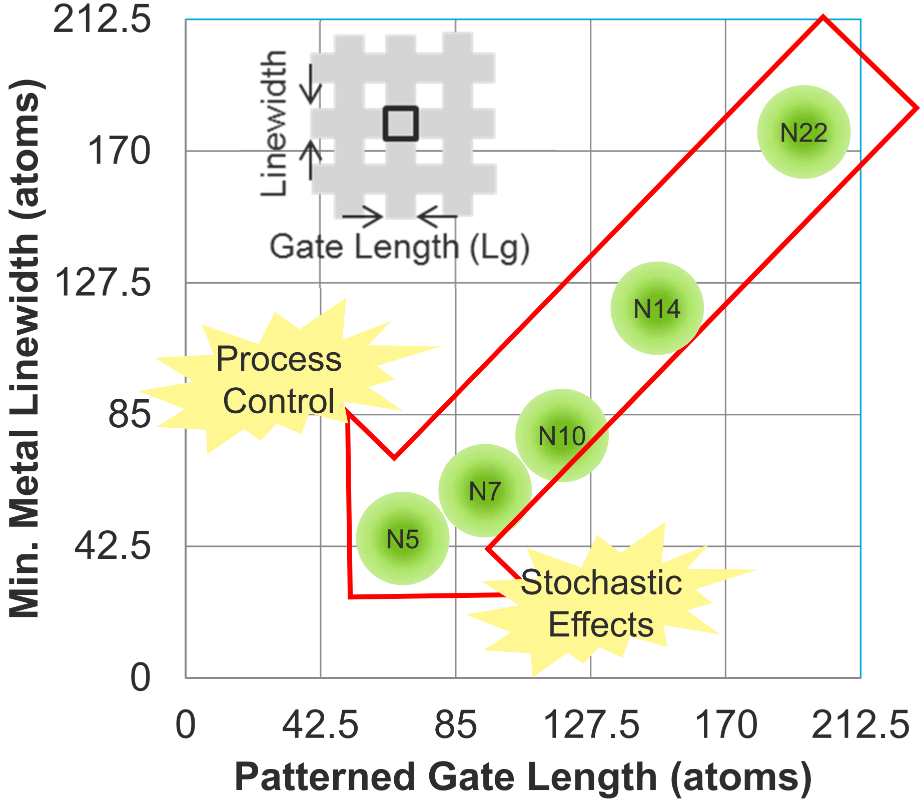
SAQP

Litho | Etch | ALD | Etch | Etch | ALD | Etch

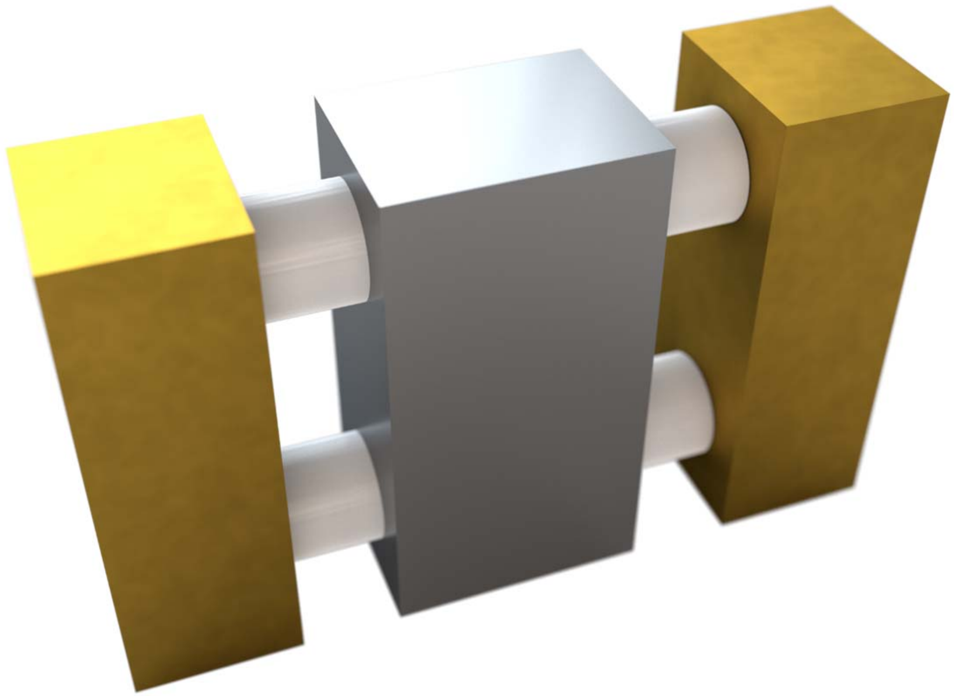


Plasma **trim** and self-aligned multiple patterning (**Etch, ALD**) are foundation for cost effective scaling in foreseeable future

Process Implications of Scaling

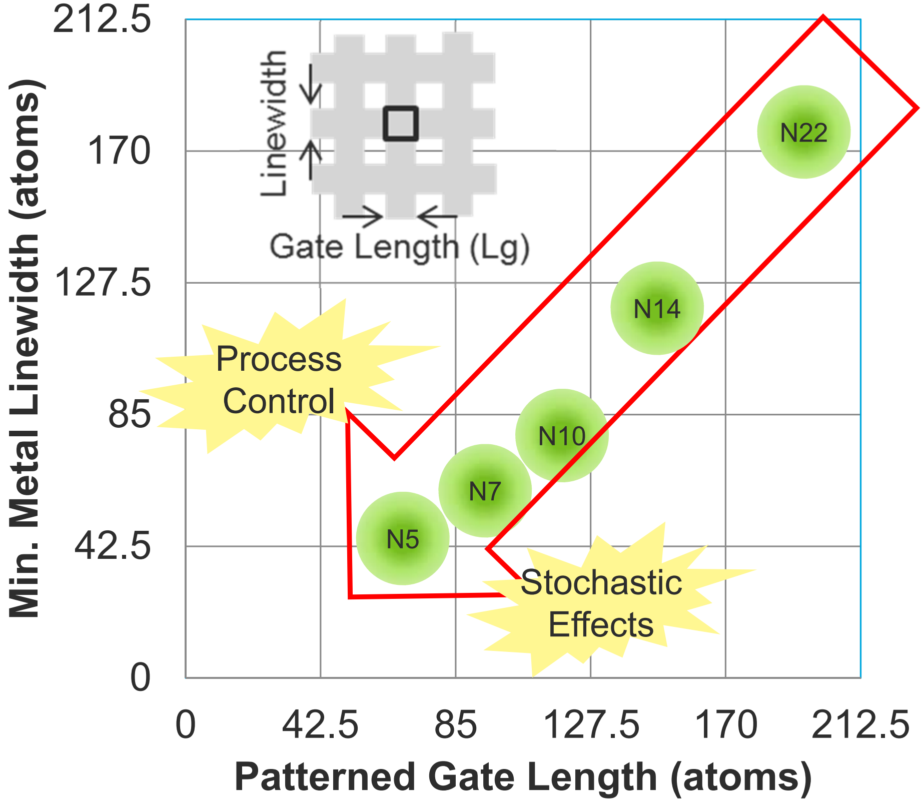


The way we have been thinking, and…

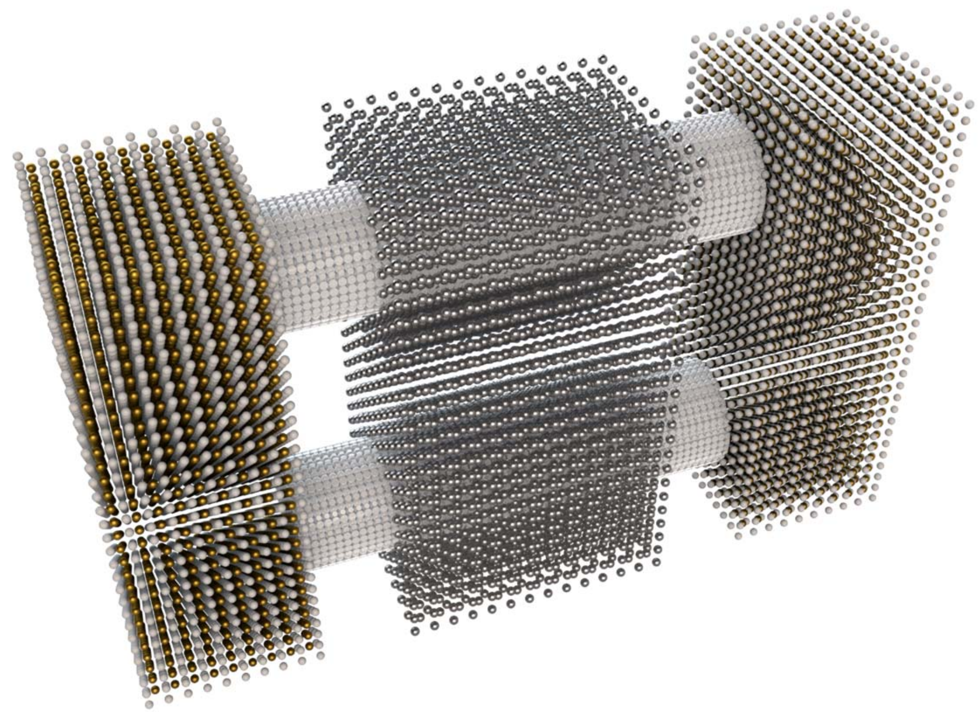


As the available device area continues to shrink, we are approaching fundamental limits

Process Implications of Scaling

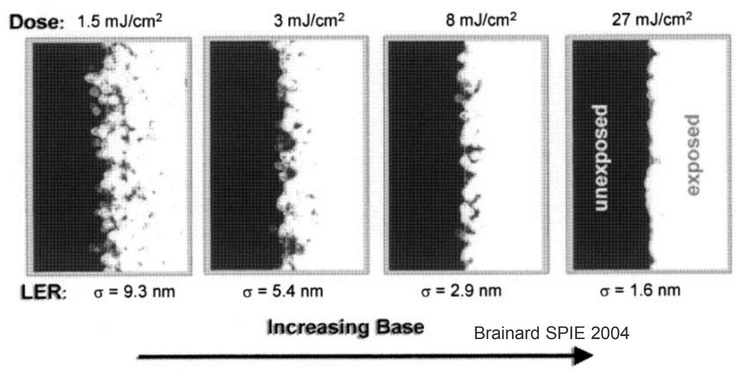


the way we will need to start thinking.

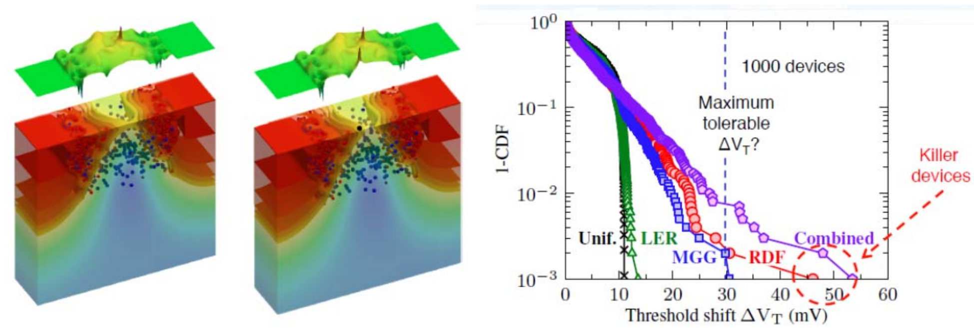


As the available device area continues to shrink, we are approaching fundamental limits

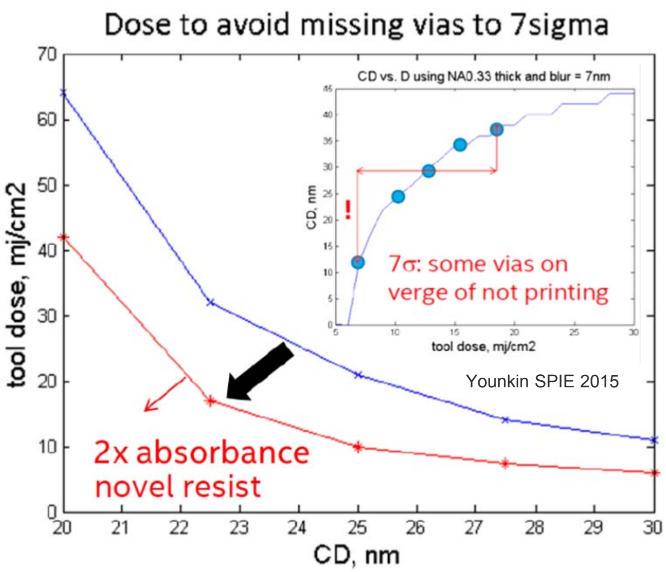
Increasing Number of Stochastic Variability Problems



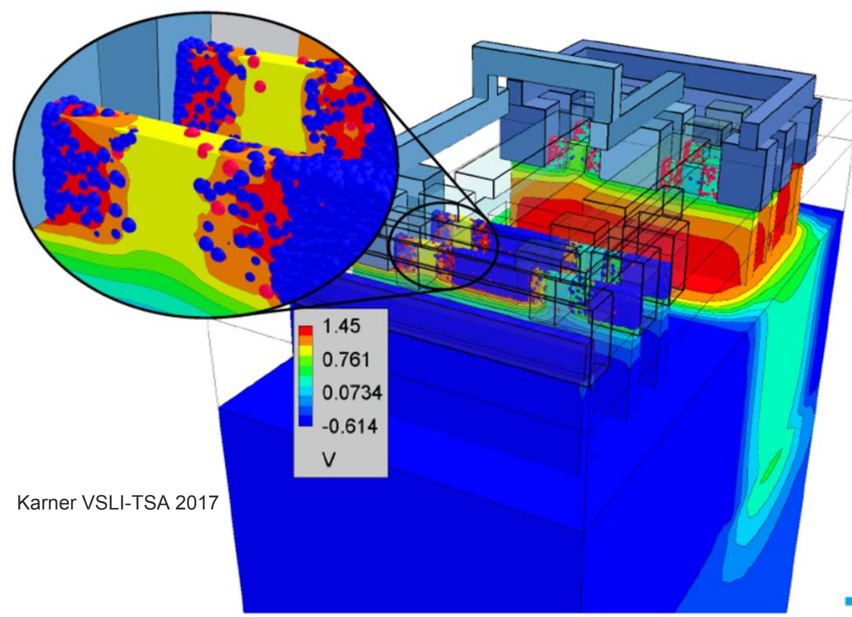
Brainard SPIE 2004



Asenov VLSI-TSA 2017

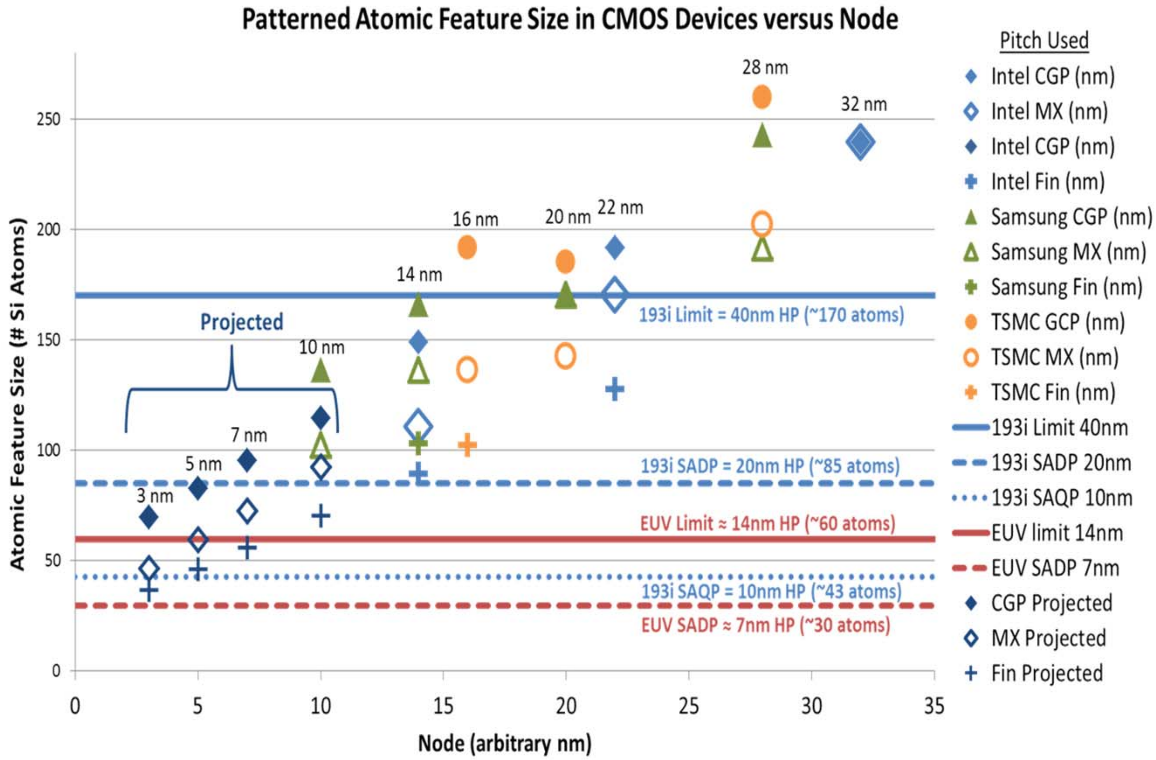


Younkin SPIE 2015



Karner VSLI-TSA 2017

Welcome to the Atomic Scale Era- There's No Longer Plenty of Room at the Bottom.

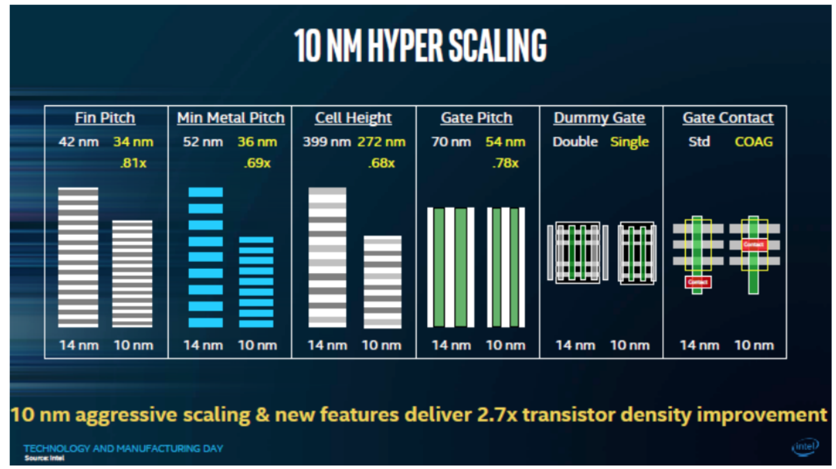


Historical and Projected Atomic Feature Sizes (half pitch/0.235 nm/Si atom) in CMOS High Volume Manufacturing. Projected feature sizes are based on Intel historical trend through 14nm manufacturing.

Scaling is Taking Longer…

	Projected 10nm	10nm Actual*
CGP	54	54
MX	43	36
Fin	33	34

*Mistry Intel TMD March 28, 2017



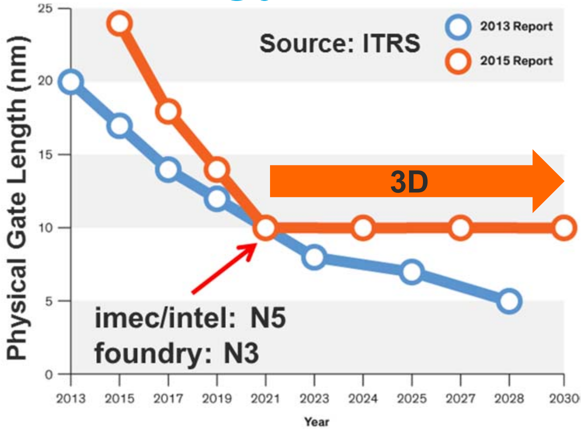
But So Far it is Still Delivering.

So What Happens When We Run out of Room at the Bottom?

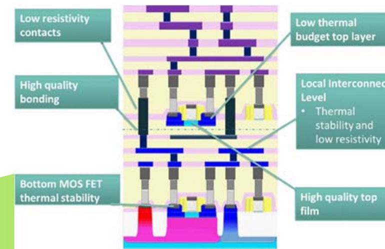
Source: dailymail.co.uk

We Do What We've Always Done: We Go Up

Technology Trend: Going Vertical

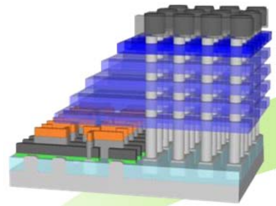


Monolithic 3D



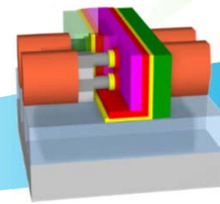
Vinet, M. ESSDERC 2016

3D NAND large stack

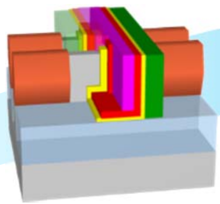


3D Architectures

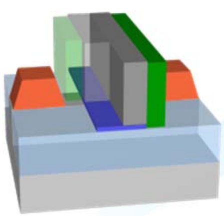
Nano-wire



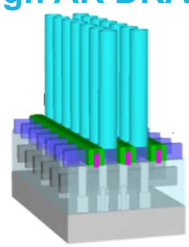
FinFET

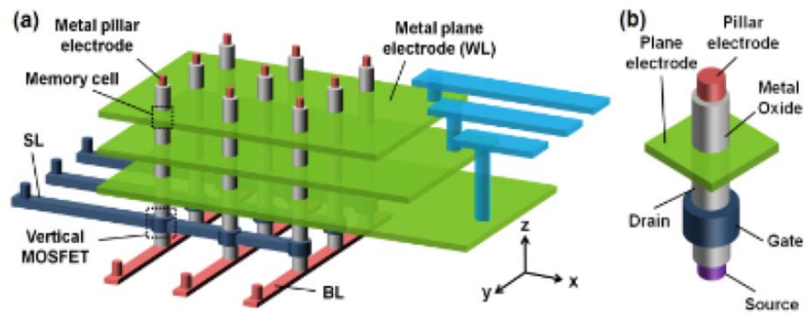


Planar



High AR DRAM





2016 IRDS More Moore

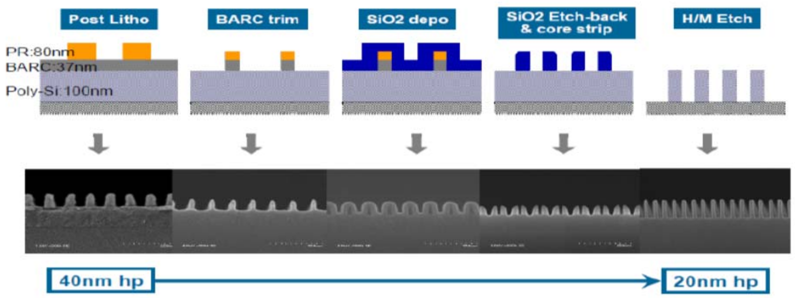
3D Devices

Vertical utilization is the key approach to future Moore's Law Style Scaling

Technology Trend: Self-(Something) Revolution

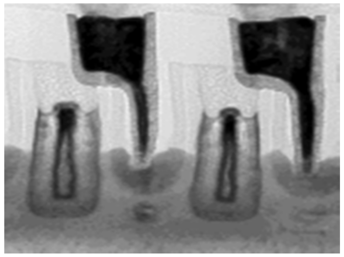
Self-Aligned

Self-Aligned Double Patterning



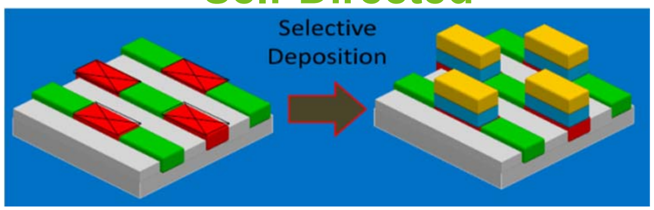
Mircea and Hsu MPT Short Course SPIE 2015

Self-Aligned Contact

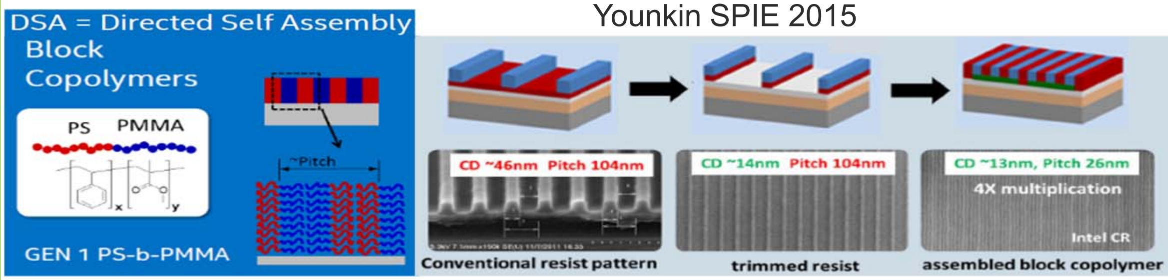


Auth VLSI 2014

Self-Directed

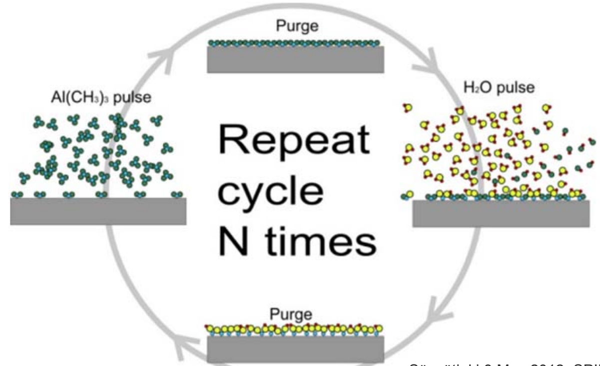


Younkin SPIE 2015



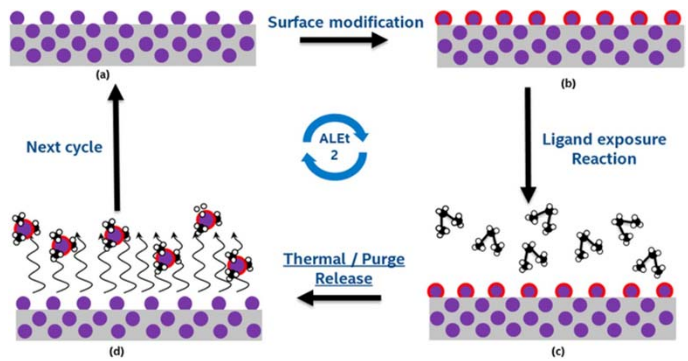
Self-Limited

Atomic Layer Deposition



Säynätjoki 8 May 2012, SPIE Newsroom
DOI: 10.1117/2.1201204.004218

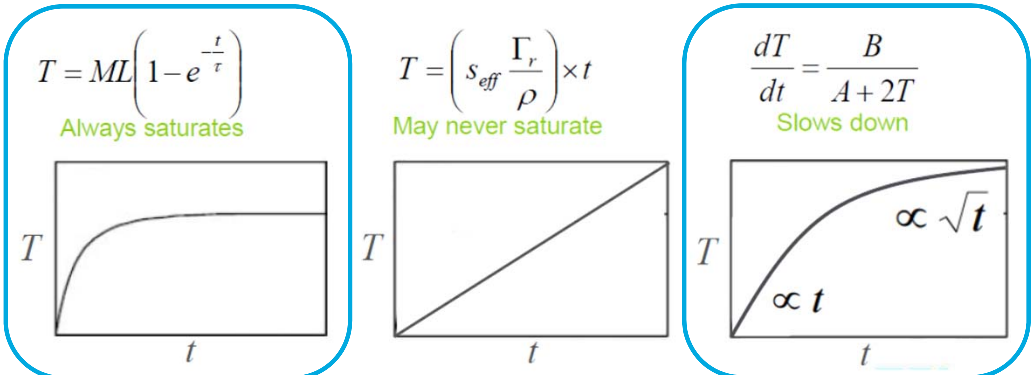
Atomic Layer Etching



Carver, T. *ECS J. Solid State Sci. Technol. 2015 volume 4, issue 6, N5005-N5009.* . doi: 10.1149/2.0021506jss

Sequential Self-Limited Processes (SSP's) – e.g. ALD and ALE

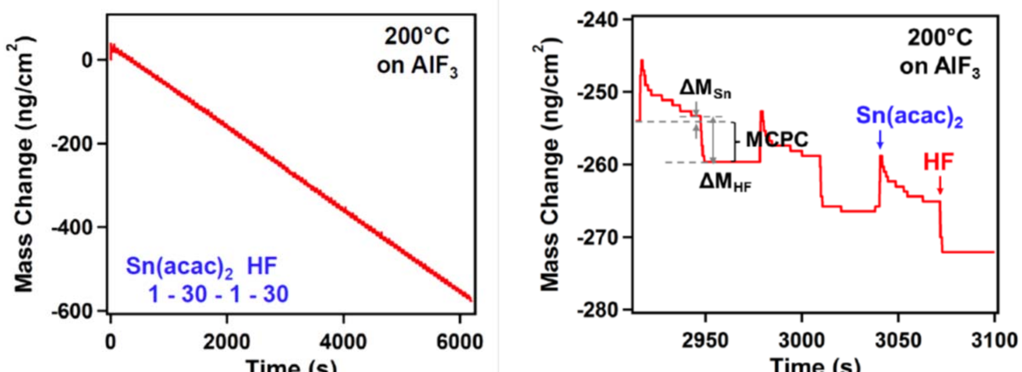
- Kinetics of Adsorption/Desorption (T can be +/- for any given half cycle)



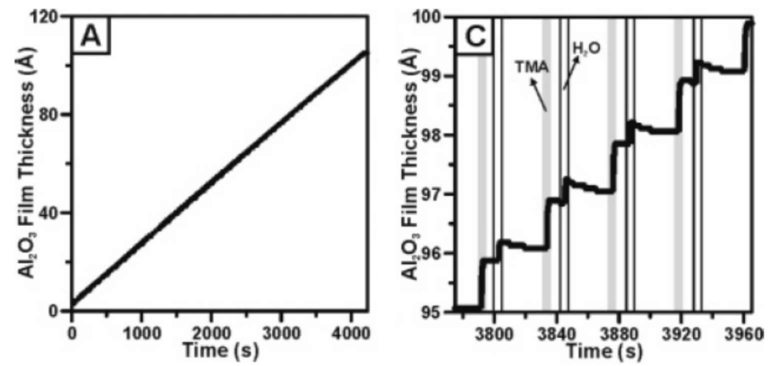
Ranjan AVS 2015

Rate Limiting Half Cycle must saturate in some manner

- Net Change in thickness for each A+B cycle determines Etching/Deposition



George AVS 2015



Whitney J. Phys. Chem. B 2005, 109, 20522-20528.

Contacts – A universal problem

Area Effects – Contacts -Theory

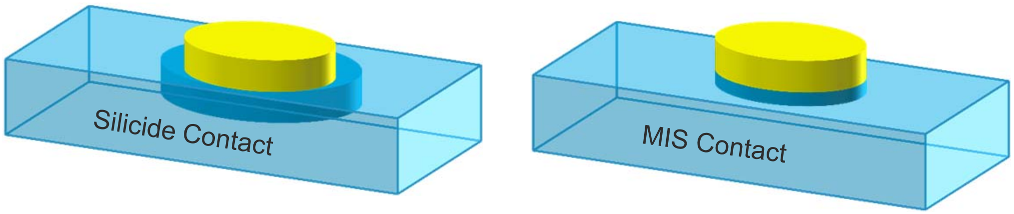
Planar Bulk

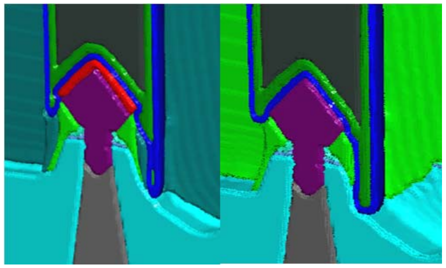
$A_{silicide} > A_{MIS}$

$R_c = \rho_c/A$

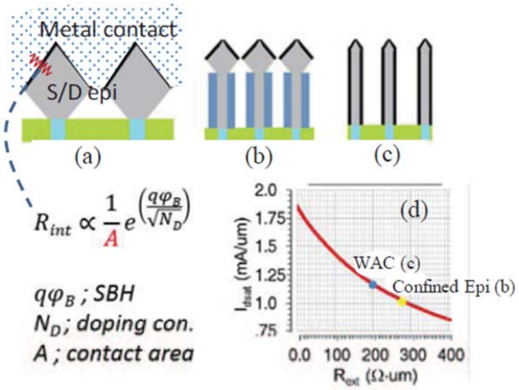
Thin Body/Fin

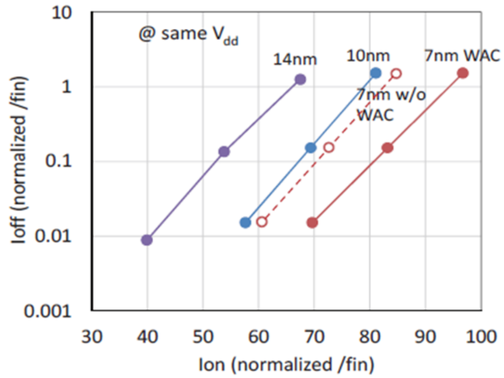
$A_{silicide} < A_{MIS}$





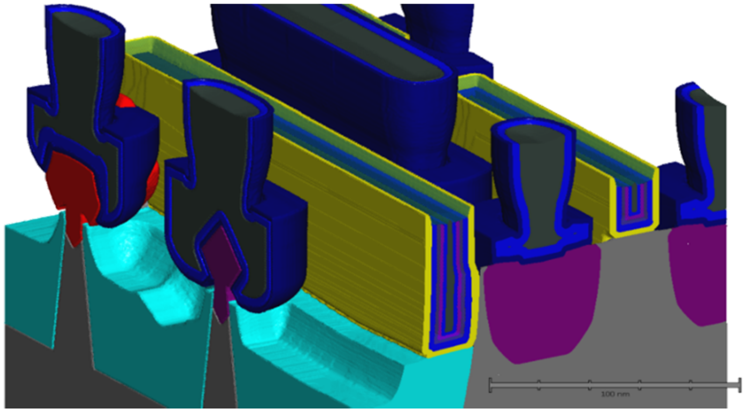
For 3D Devices Wrap Around Contacts have a clear performance and area advantage over traditional silicide contacts to the top of the fin





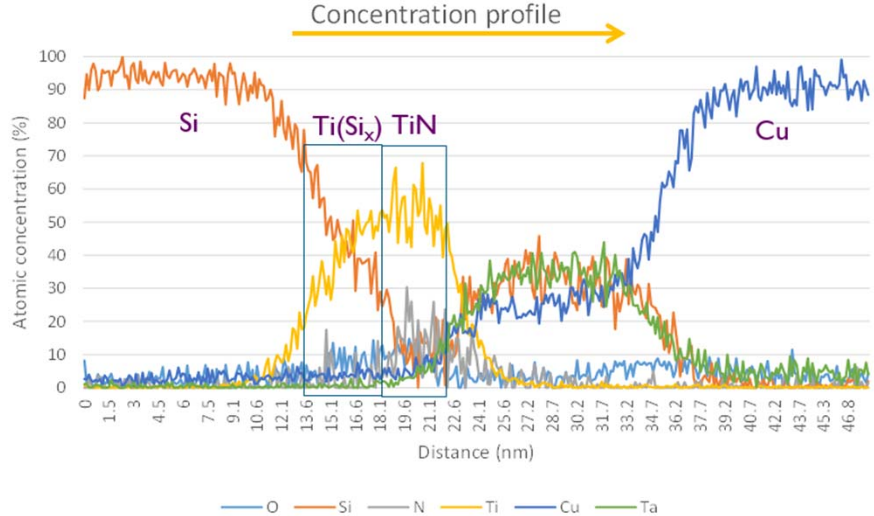
Traditional diamond shape regrown S/D with large Contact area; (b) Confined S/D epi regrowth with smaller Contact area; and (c) Wrap-Around Contact (WAC) on entire S/D surface with large Contact area. (d) WAC show significantly lower Rext and thus higher Idsat.

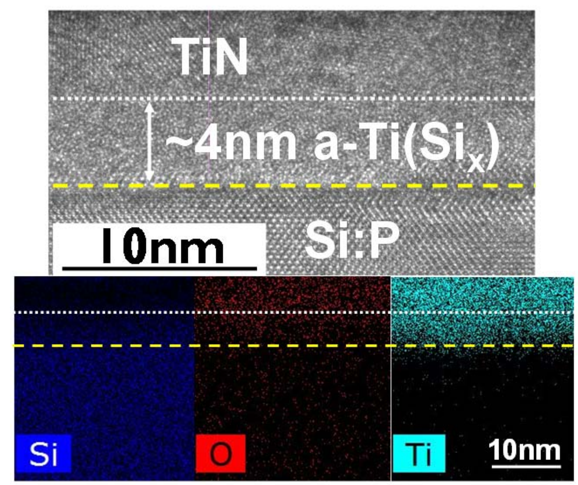
S.C. Song et al, VLSI 2015



Elements of a Low Rs Contact

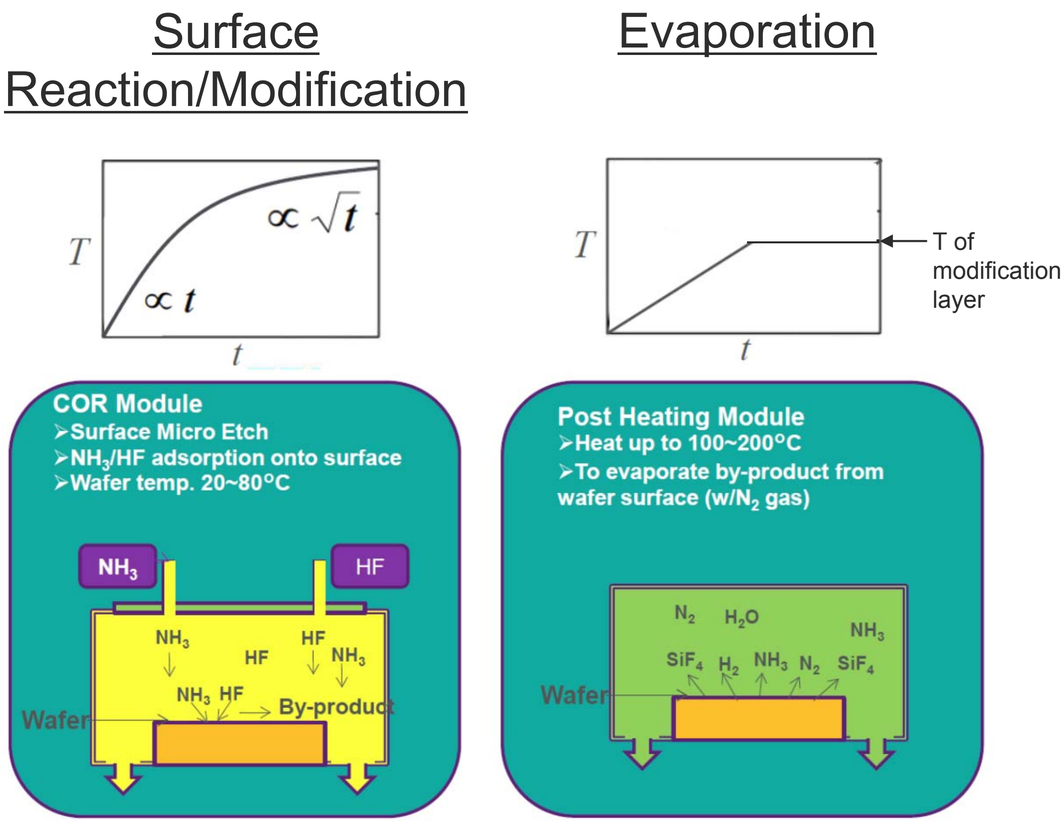
- Maximize Doping
  - In situ doped Epi + Implant + LSA
- Maximize Area → WAC
  - Processes need to be Conformal!
  - Note Doping is Done Earlier
- Clean Interface → SSP
  - Without blowing up the contact CD
- Workfunction Metal → ALD Ti
- Controlled Silicide Formation
  - Area Detriment
  - Dopant Segregation
  - Interface quality
- Minimize Liner → ALD





Adapted from S.A. Chew *et. al. IITC May 16, 2017 Hsinchu, Taiwan*

Chemical Oxide Removal



$SiO_2 + 6HF + 2NH_3 \rightarrow (NH_4)_2SiF_6 + 2H_2O$

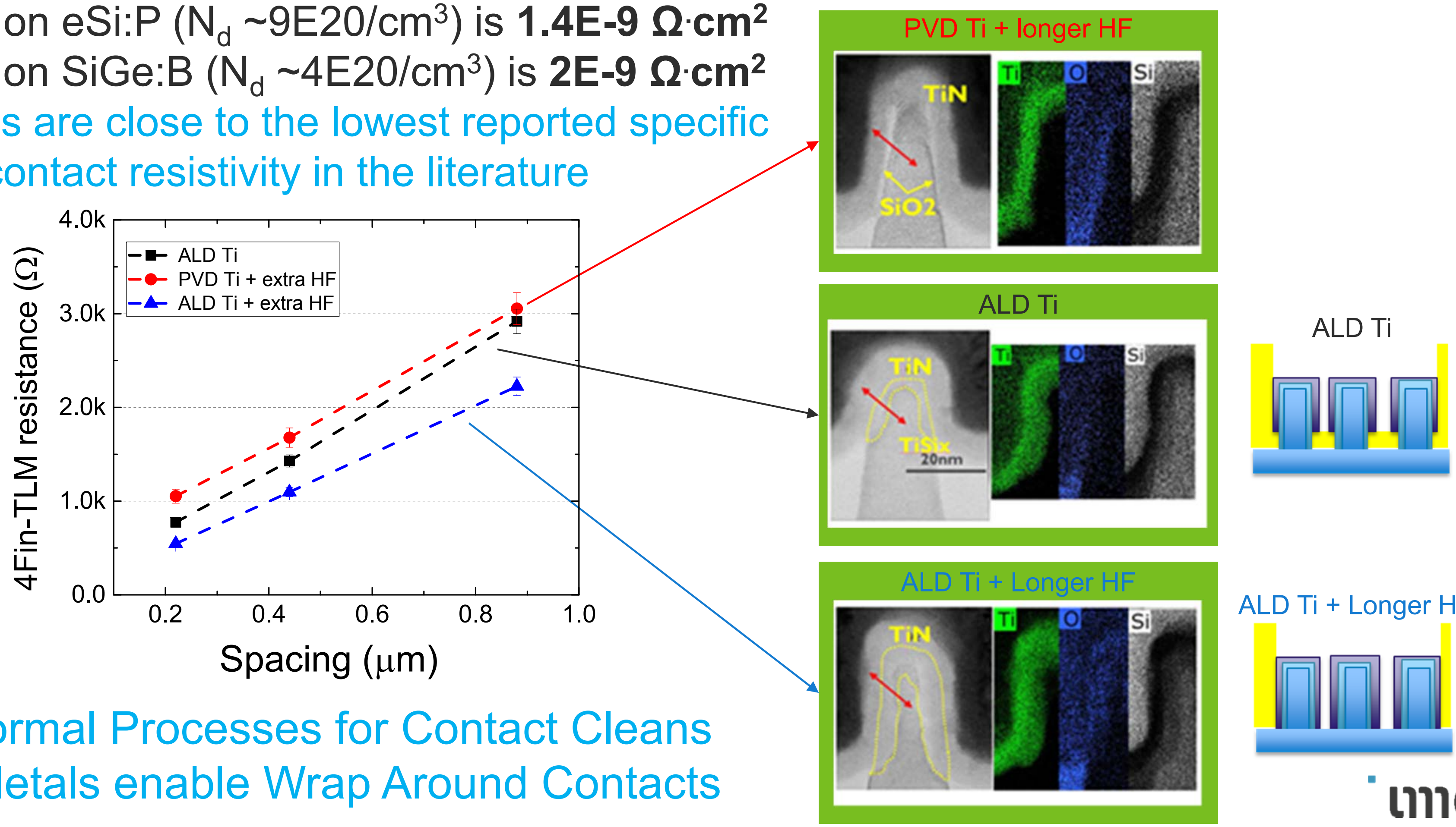
- Surface Reaction is Diffusion Limited
- Evaporation is limited by the amount of material
- Near infinite selectivity for SiO_2/Si
- Si and Ge Oxide can both be cleaned
- Plasma free
- Dry → Can be Clustered with deposition

Tapily ECS Spring 2014

ALD Ti for Ultra Low Rs Wrap Around Contacts

N-Type ρ_c on eSi:P (N_d ~9E20/cm^3) is **1.4E-9 Ω·cm²**
P-Type ρ_c on SiGe:B (N_d ~4E20/cm^3) is **2E-9 Ω·cm²**

Both values are close to the lowest reported specific contact resistivity in the literature

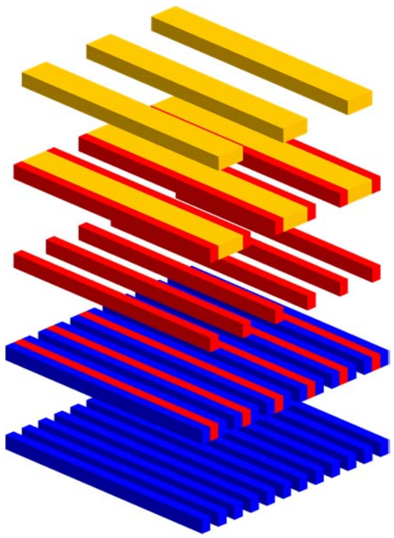


Conformal Processes for Contact Cleans and Metals enable Wrap Around Contacts

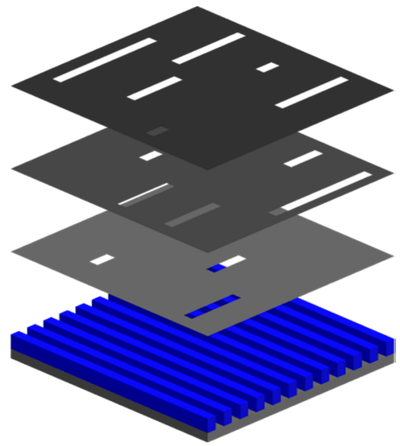
More about Patterning Challenges

Patterning challenges to EPE

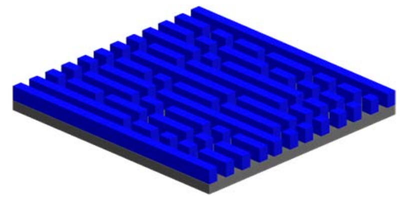
SAQP



Line cutting with LELELE



Final Pattern



$$EPE = f(\text{CD variation}, \text{Pattern OL})$$

(EPE : Edge Placement Error)

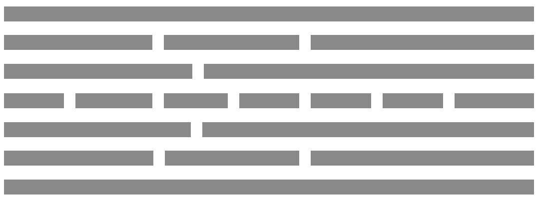
- Mandrel, spacer, cuts
- Traditional sources of CD variation
- Roughness

- Previous Pattern
- Cuts to the grid
- Cuts to each other

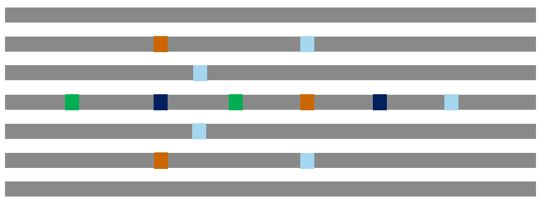
EPE control is critical for further extension

New Colors enable self-aligned integration schemes

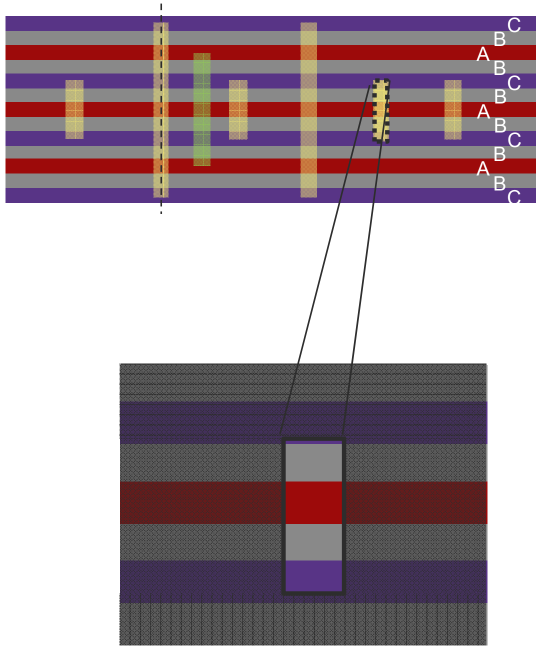
Intended Design



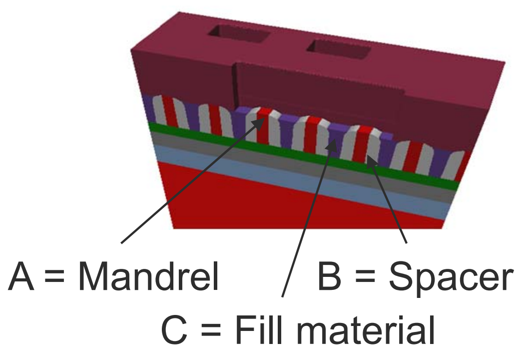
Conventional approach
(using L/S grid)

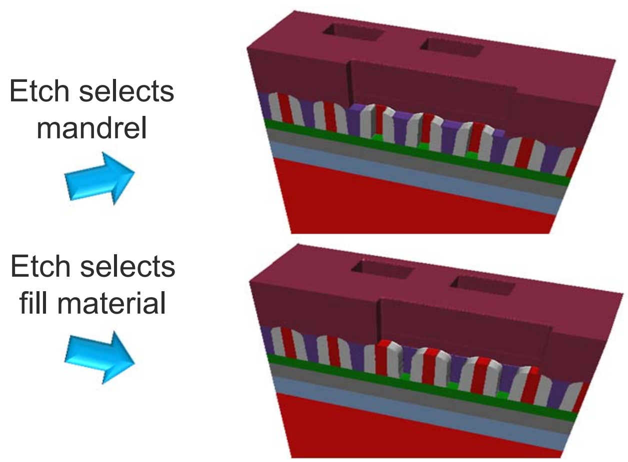


Self-aligned approach
(using three grid colors)



SAB (Self-aligned Block)





self-alignment of cut/block is enabled by SAB, using etch selectivity

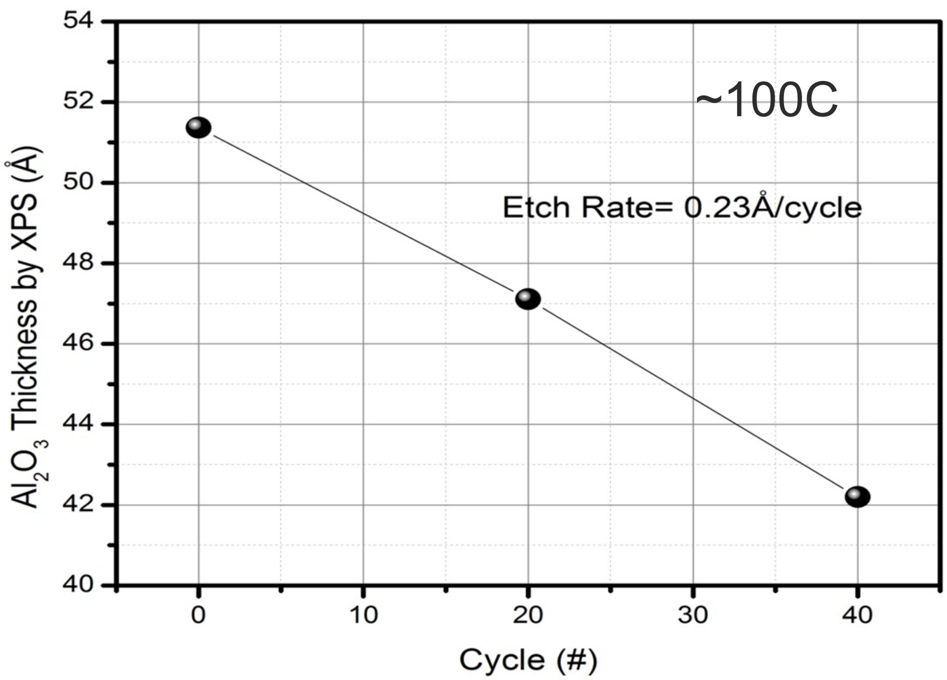
Patterning Challenges and Approaches

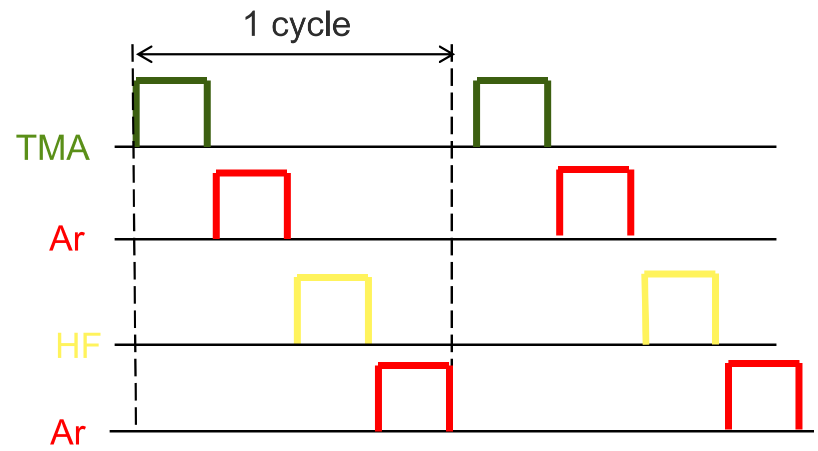
	Typical Scheme	Challenge	Potential Approach
Grid formation	SADP SAQP	LER, LWR, local CDU	• Etch smoothing (DCS) • Spacer reshape
		Spacer leaning	• Dep / cure and trim
		Cost	• PR mandrel
Cut / Block	LEx	CD, CDU, CER	• Healing, shrink
		Alignment with grid (within layer)	• SAB
		Cost and complexity mitigation	• EUV
Via/Contact formation	LEx	CD, CDU, CER	• Healing, shrink
		Alignment with metal lines (inter layers)	• FSAV, SAC, SAGC
		Cost and complexity mitigation	• EUV
New process development		Atomic level process	• ALE / ALD
		Bottom up lithography	• Selective deposition

Self-Something

New Solutions from ALE

Isotropic Thermal ALE of Al_2O_3 at TEL Technology Center, America (TTCA)

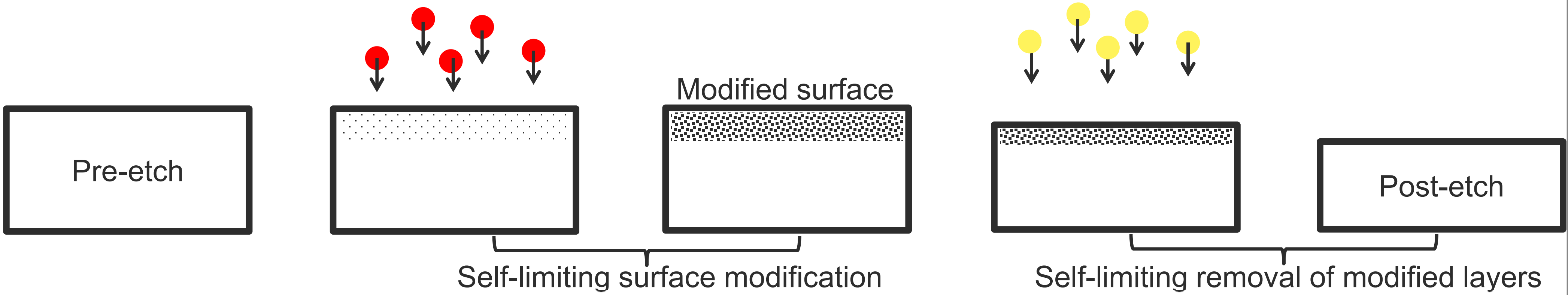


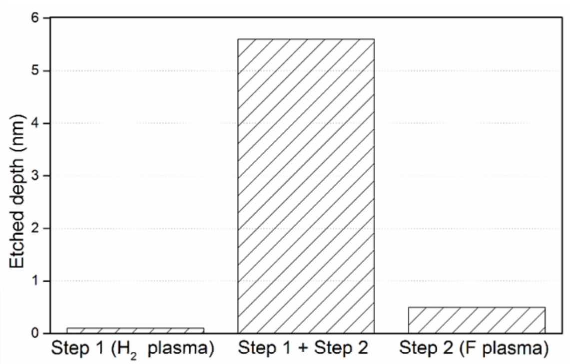


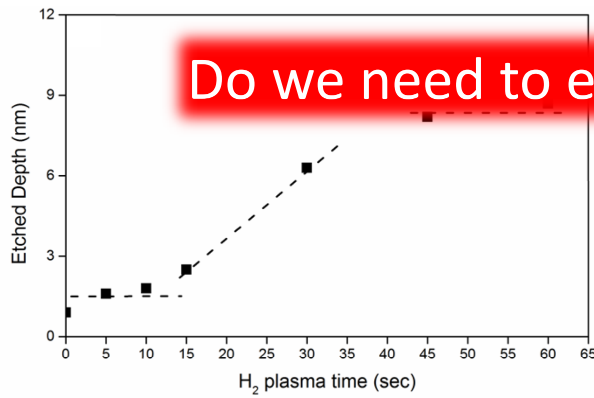
See also: George, S. AVS 2015 and ALD 2016

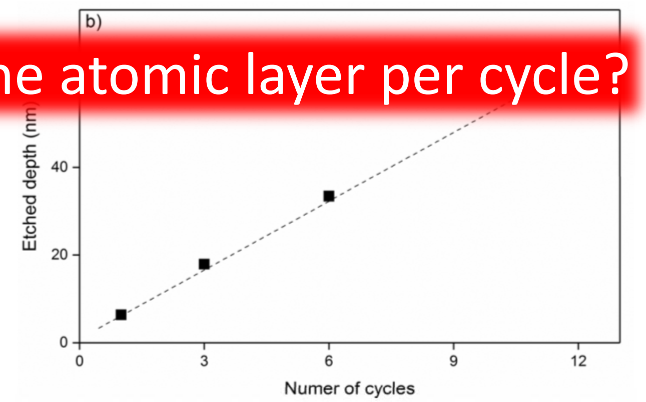
- Etch rate ~0.2A/cycle obtained at 100C

ALE: Temporal Separation of Ions and Radicals









Do we need to etch one atomic layer per cycle?

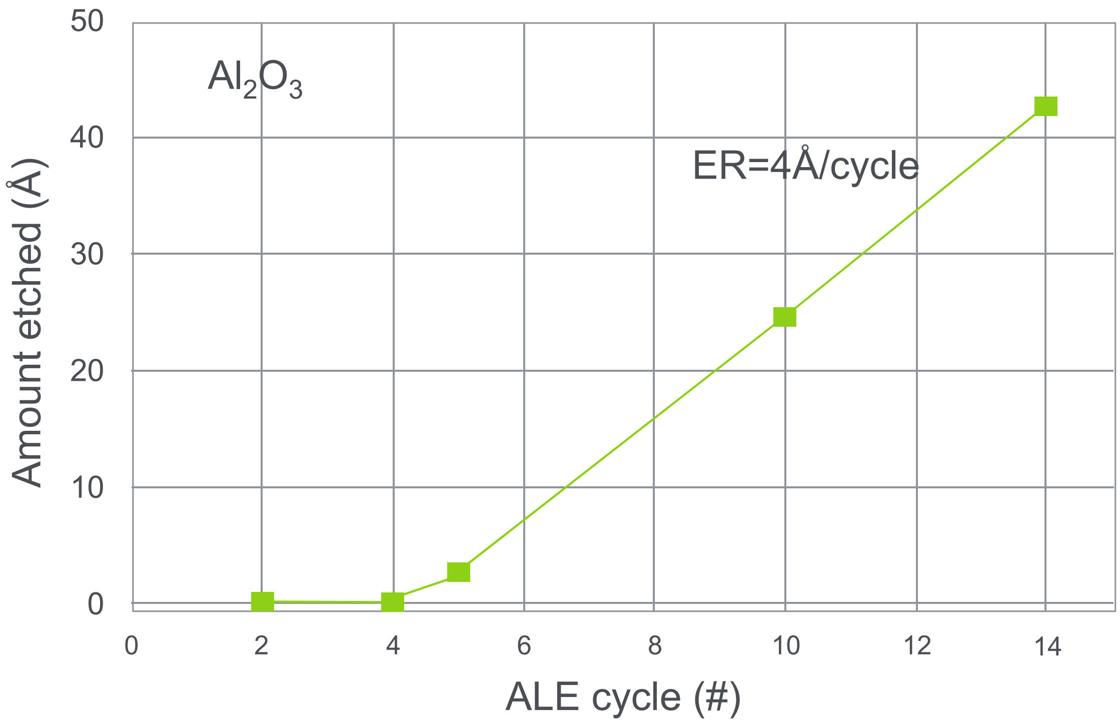
Synergy

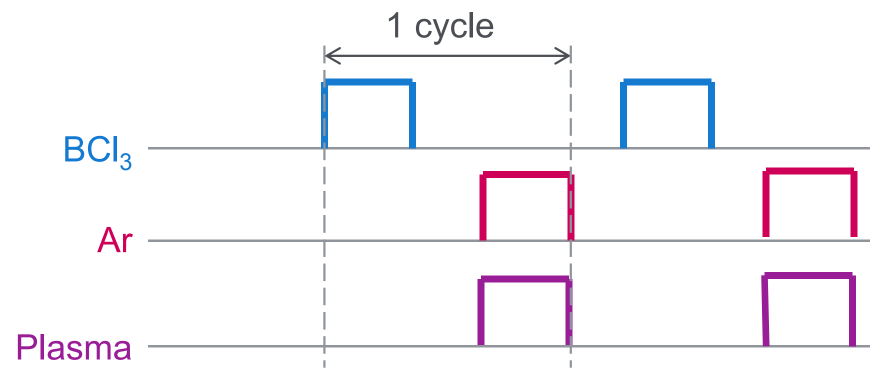
Etch rate saturation

Etch rate $\neq f(\tau_{rad})$ or $f(\tau_{ion})$

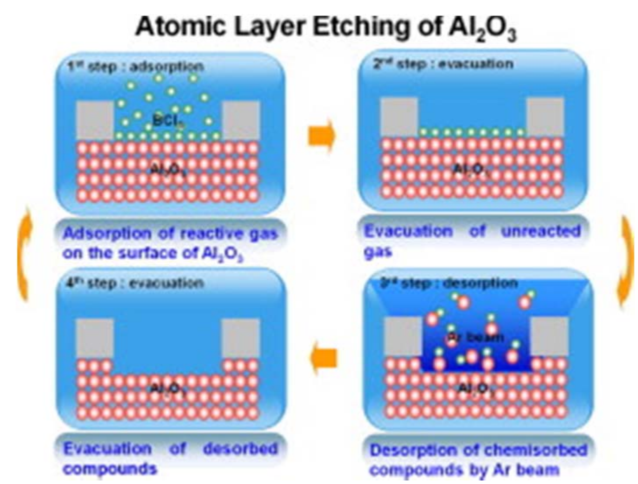
Etched depth α number of cycles

Anisotropic atomic layer etching of high K films



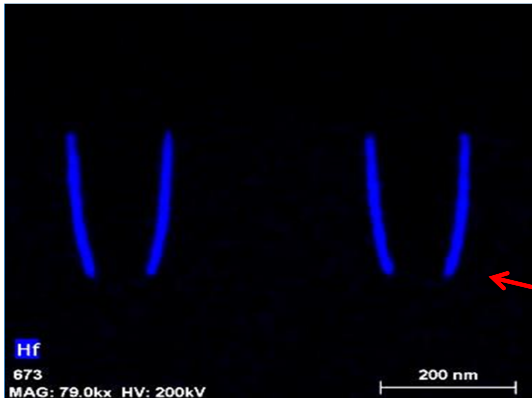


Min *Microelectronic Eng.* 110 (**2013**) 457–460

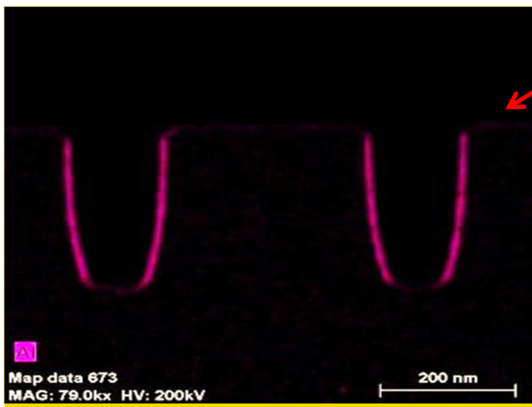


Area Selective Deposition by Combining ALD and Etching

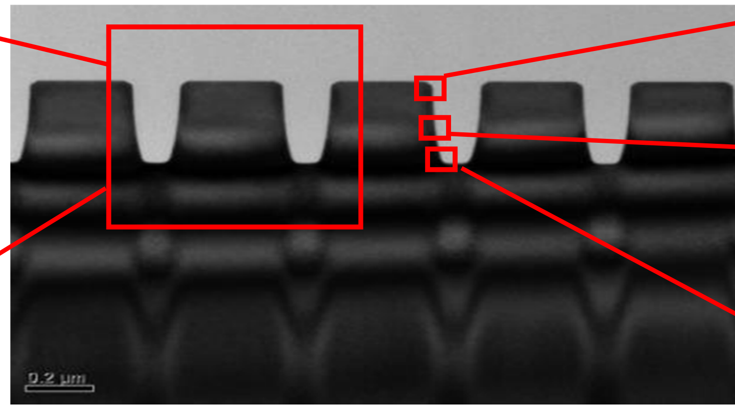
ALD High K Dielectrics followed by Anisotropic Etching enables Ultra-Thin ALD Sidewall Spacers



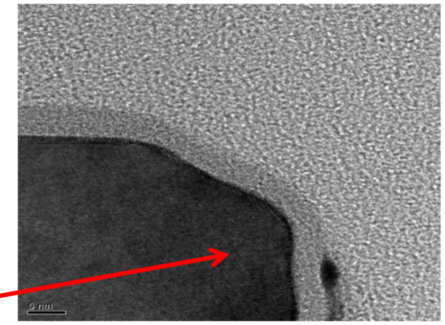
HfO_2

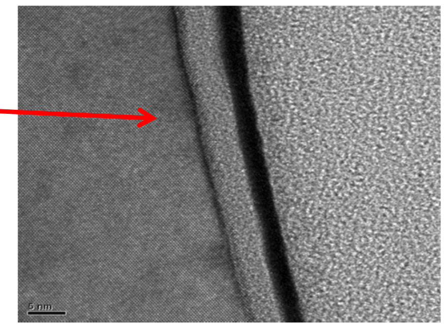


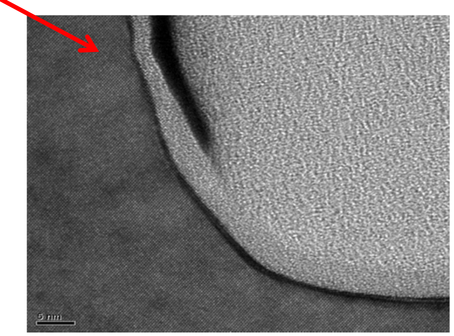
Al_2O_3



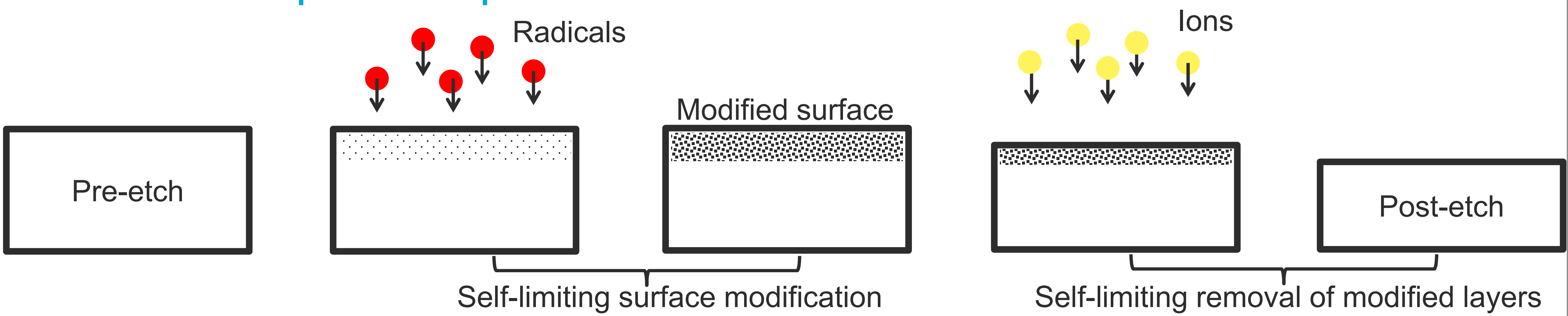
Note: Very good selectivity to SiO_2







ALE: Temporal Separation of Ions and Radicals

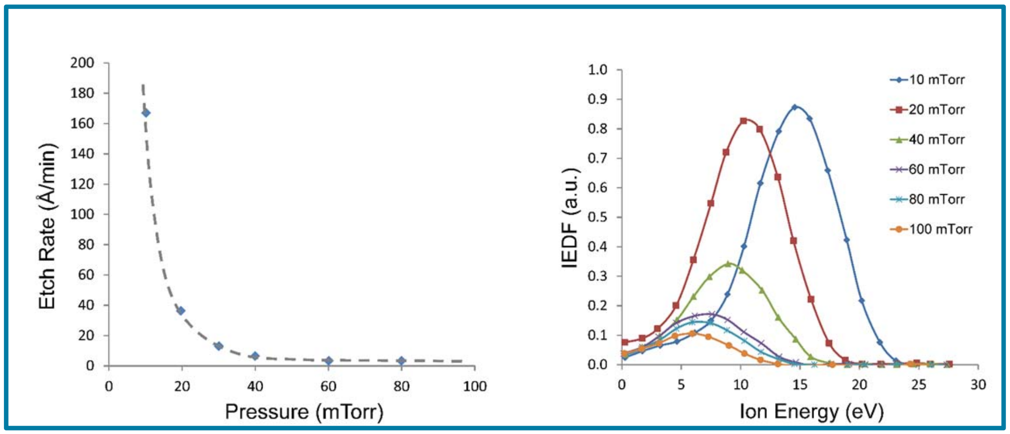


- ALE provides
  - Aspect Ratio Independent etching
    - Self-limiting steps of ALE
  - Uniform etching
    - Self-limiting steps of ALE

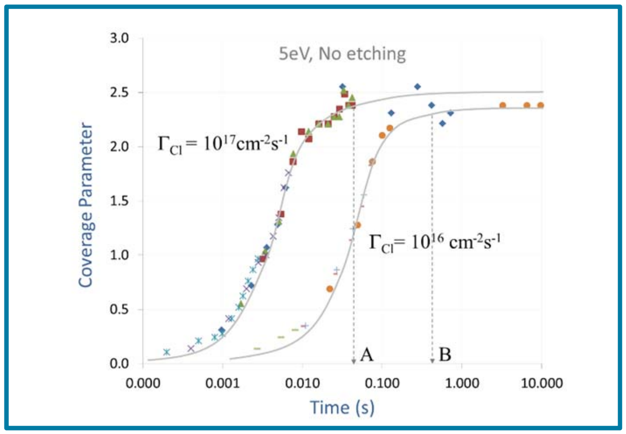
- ALE is <u>engineered</u> to provide
  - High Selectivity
    - Tuned ion energy
  - Profile Control
    - IAED in desorption step

Si ALE: Adsorption

- High pressure to achieve halogenation only (no etching)
- Surface coverage "nearly" saturates quickly (~10ms -100ms)



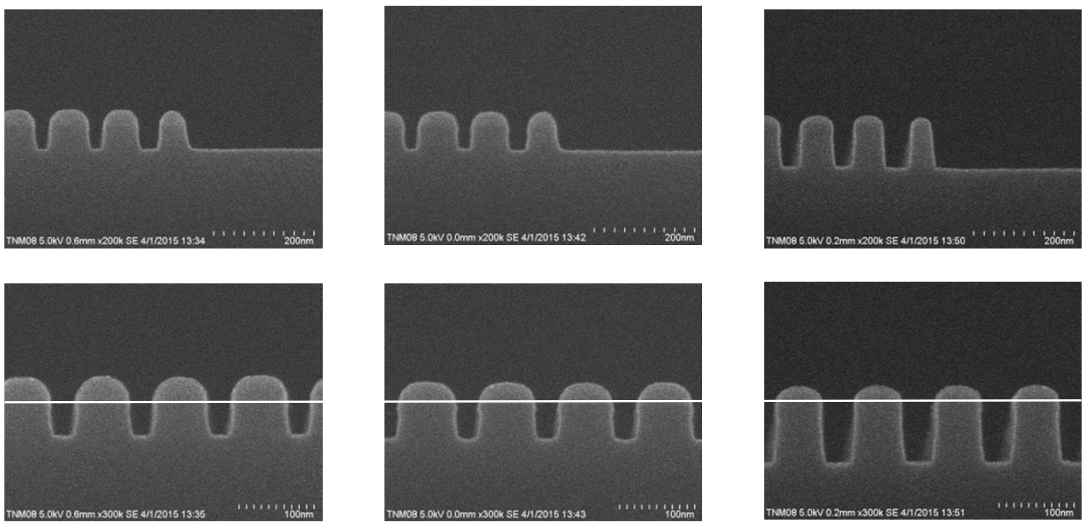
Experiments



MCFPM Simulation

Atomic Layer Etching: Escape from Trade-offs

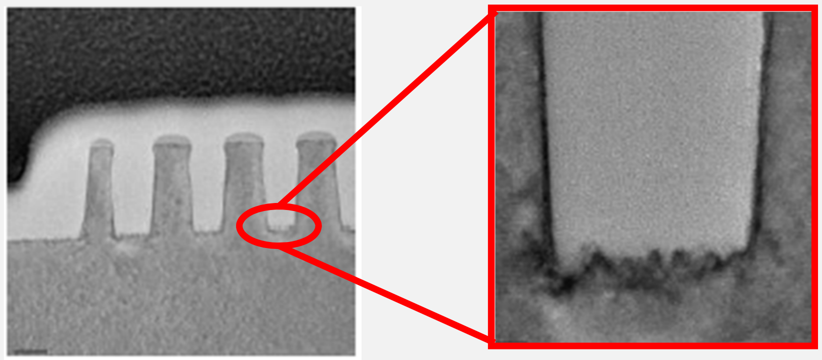
$16eV < E_i < 37.5eV$	$E_i < 70.0eV$	$E_i > 70.0eV$



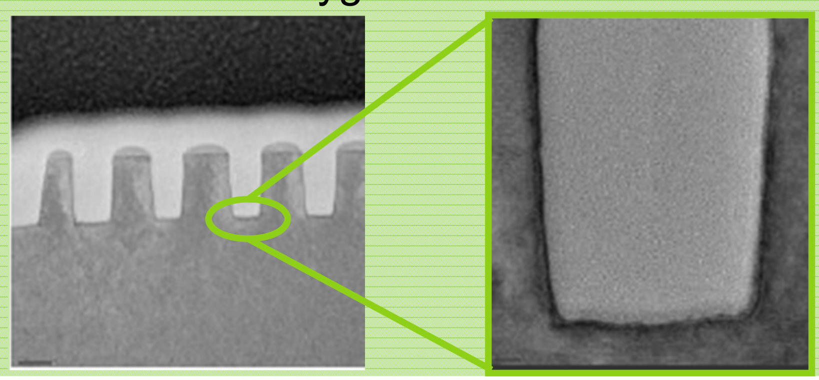
- No ARDE-profile-selectivity trade-off
- Ion energy decides selectivity and etch precision.

Oxidation Effect: Problem of Si-ALE

w/o control of Oxygen from chamber walls



w/ control of Oxygen from chamber walls



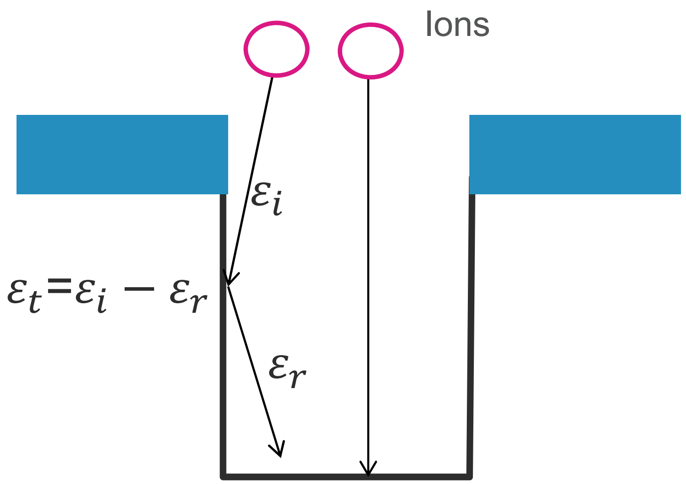
Problem of Si-ALE: Surfaces are not Pristine

Model

Real

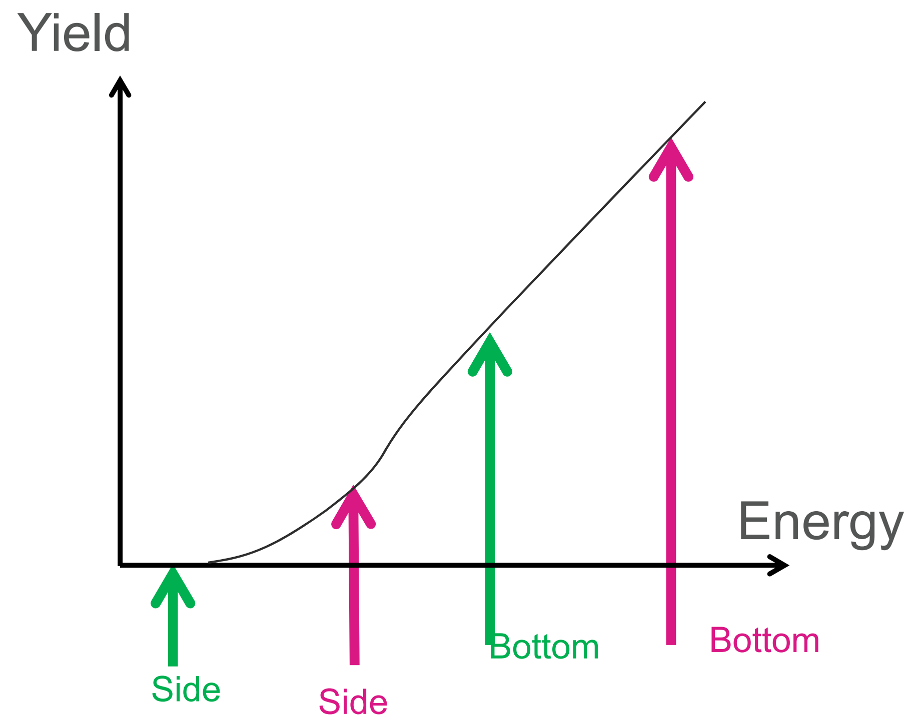
- Models assume ideal surfaces.
- Mask open (Si-F and S-C, possible H termination) and presence of native oxide guarantees anything but pristine surface.
- c-Si is rarely encountered in etch applications. p-Si or amorphous Si are widely used.

Problem of Si-ALE: Ion Angular Distribution Control



$$\sqrt{\frac{\varepsilon_r}{\varepsilon_i}} = \left(\frac{\mu}{\mu+1}\right)^2 \left(\cos\chi_{1/2} + \sqrt{\frac{1}{\mu^2} - \sin^2\chi_{1/2}}\right)^2$$

ε_i = energy of incident ions
ε_r = energy of scattered neutrals
$\mu = m_{ion} / m_{substrate}$
$\chi_{1/2} = \pi/2 - \theta_i$
θ_i is the incident angle of ions



"Correct" Energy Process (Good Profile)

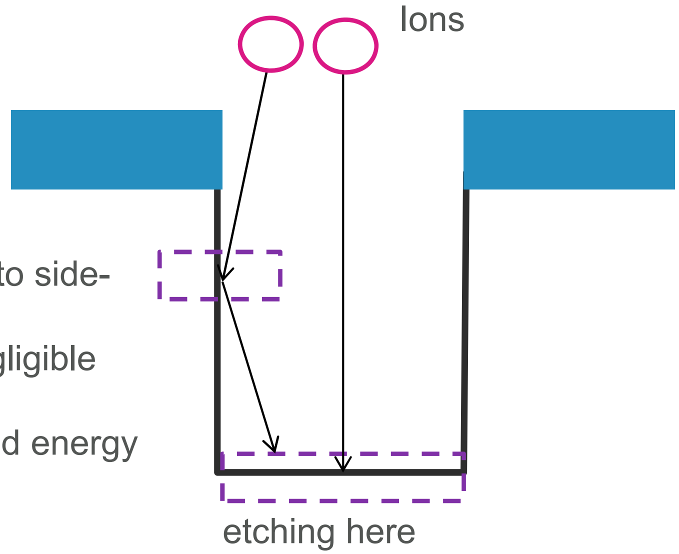
High Energy Process (Poor Profile)

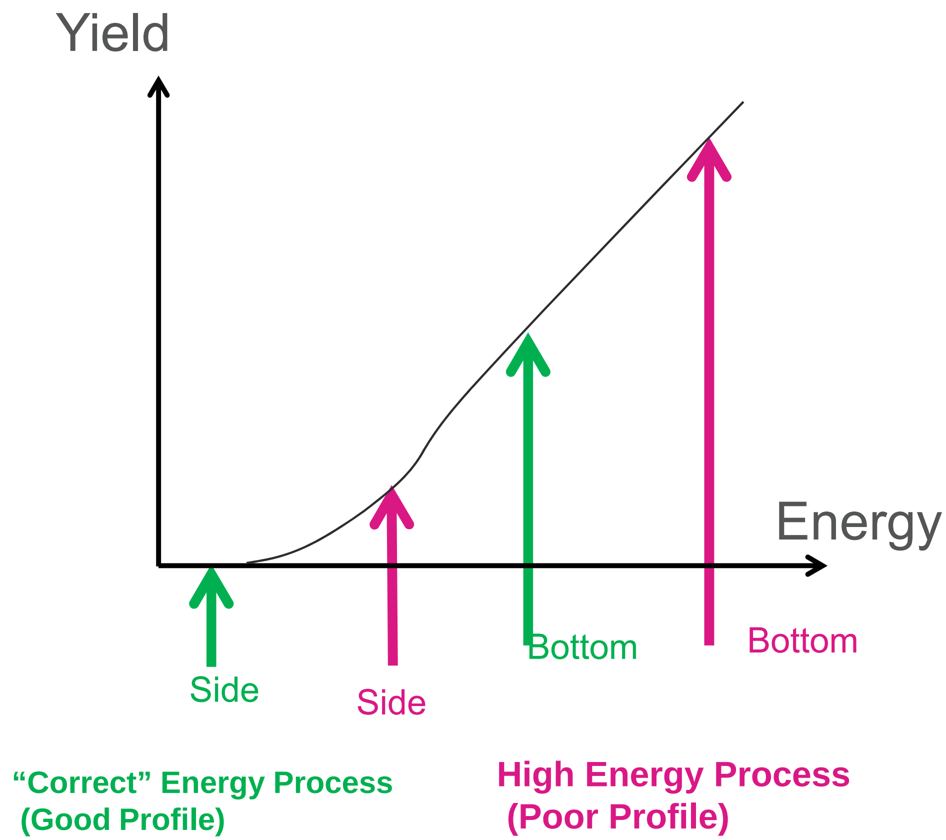
Helmer and Graves, J. Vac. Sci. Technol. A 16, 3502 1998

Problem of Si-ALE: Ion Angular Distribution Control

energy flux to side-wall
must be negligible

=low directed energy

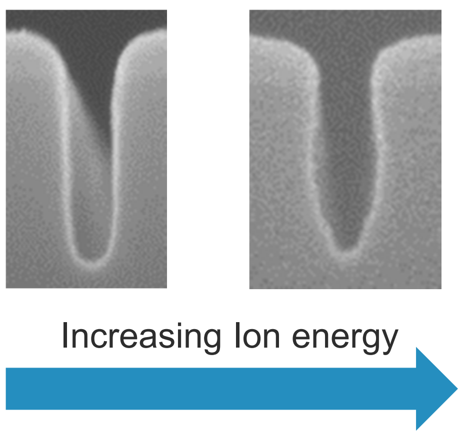


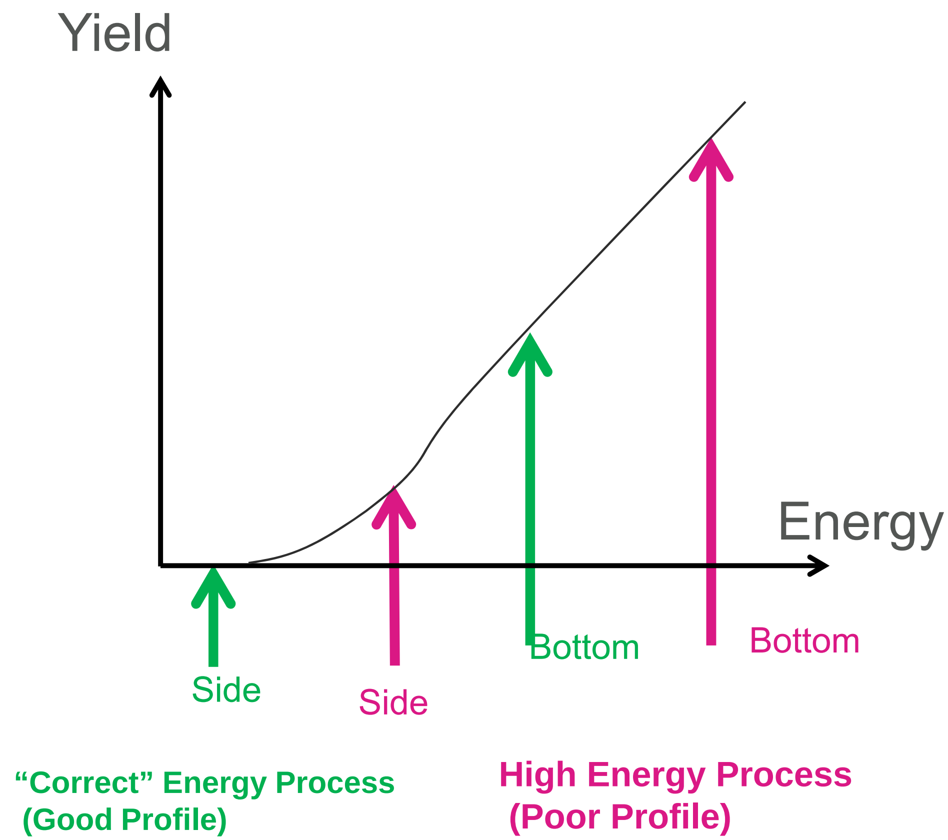


Angle impacted by Ti, Te

$$\theta = \sqrt{\frac{Ti \propto Te}{V}}$$

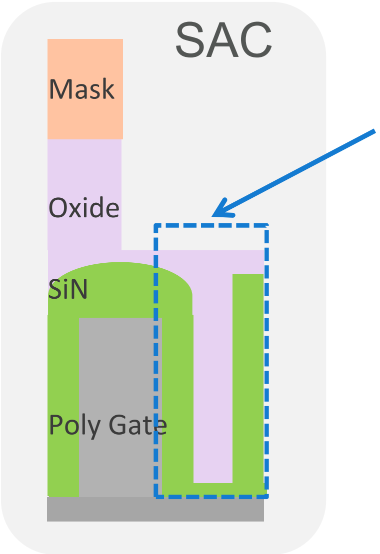
Problem of Si-ALE: Ion Angular Distribution Control





Need for ALE of Oxides and Nitrides

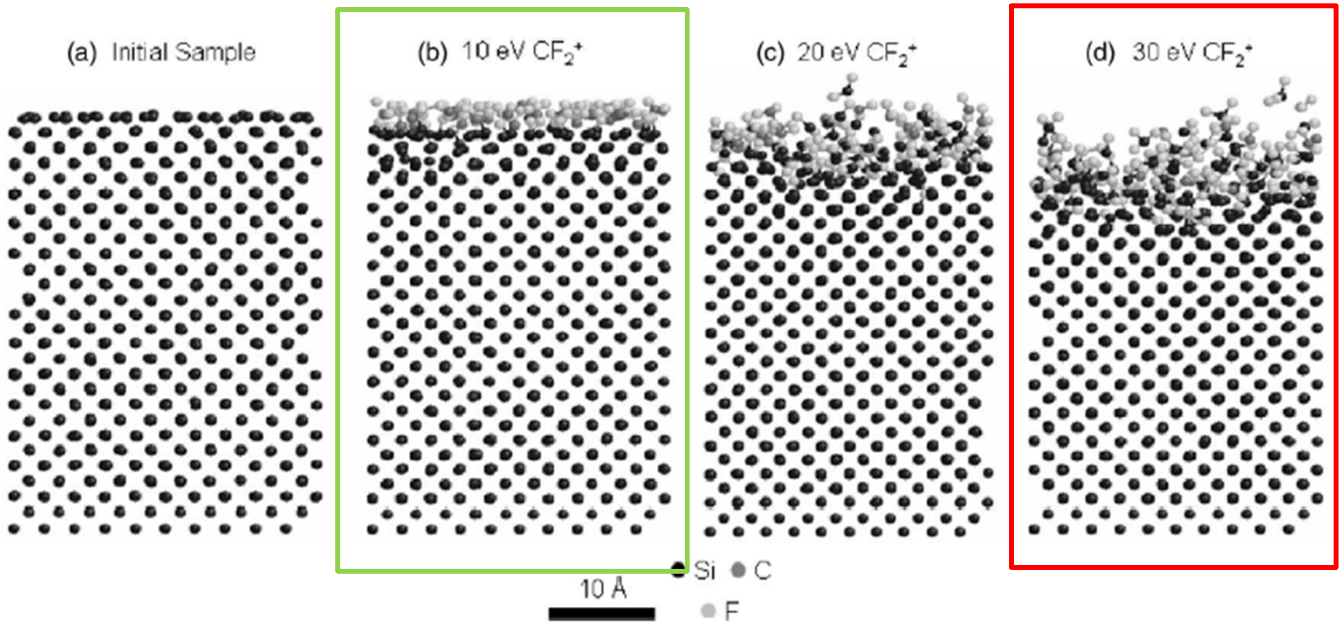
- We used Si to illustrate ANISITROPIC ALE
- Critical applications also include oxides and nitrides
- HARC (in all forms), BEOL/MOL, Patterning



- Example of etching oxide selective to nitride
- Unlike silicon we must grapple with material precursor pairs that are not inherently selective in all aspect

35

Basics of Film Deposition Based ALE



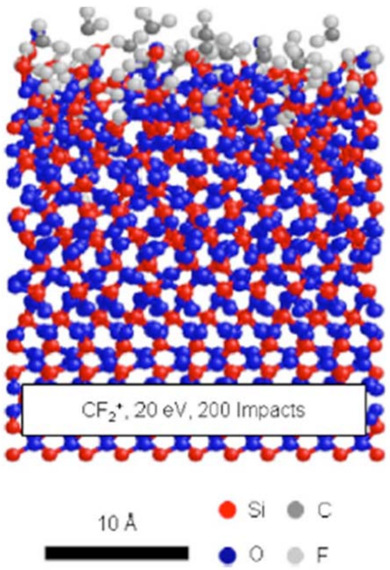
JOURNAL OF APPLIED PHYSICS **101**, 033308 (2007)

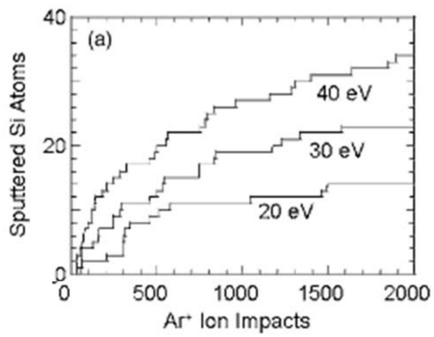
A molecular dynamics investigation of fluorocarbon based layer-by-layer etching of silicon and SiO_2

S. Rauf,[a] T. Sparks, and P. L. G. Ventzek
Freescale Semiconductor, Inc., 3501 Ed Bluestein Bonlevard, MD K-10, Austin, Texas 78721
V. V. Smirnov, A. V. Stengach, K. G. Gaynullin, and V. A. Pavlovsky[b]
SarovLabs, Sarov, Russia

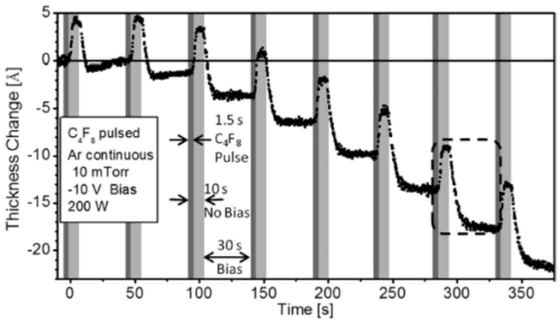
Basics of Film Deposition Based ALE

Simulation to Proof of Principle Experiments





Rauf et al., J. Appl. Phys., (2007)

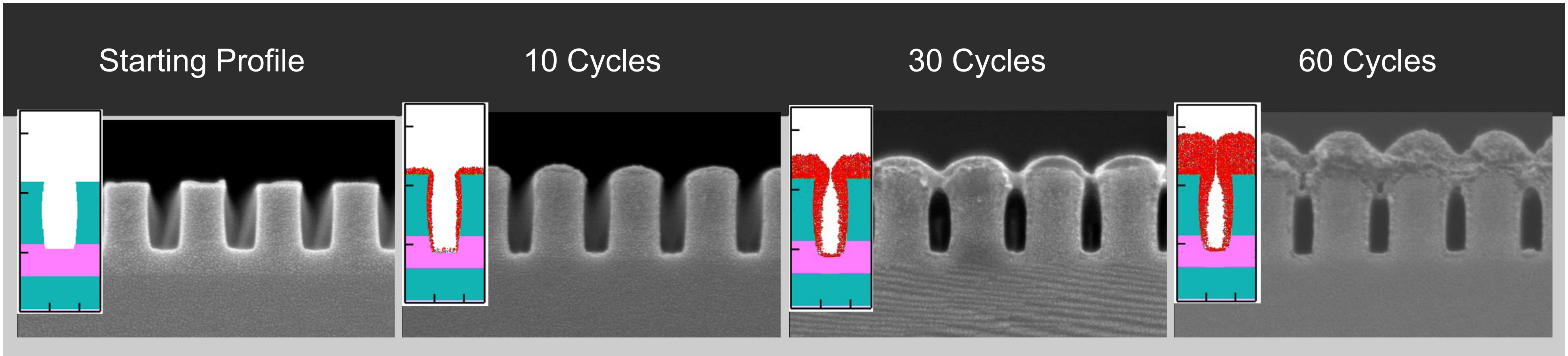


Metzler et al., JVST A 32 (2014)

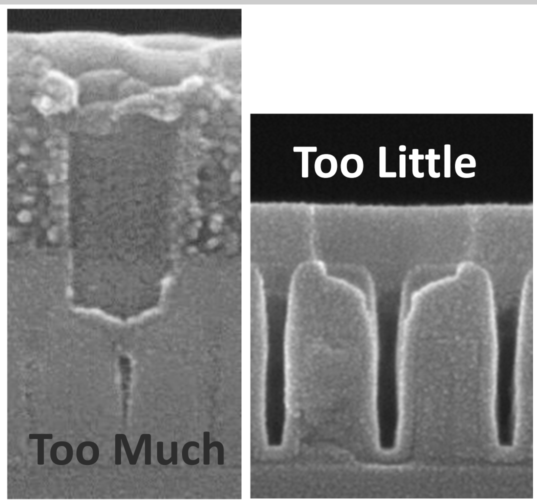
Demonstrated for Self-Aligned Contact Etch by

- Honda et al. AVS 2014
- Tsujii et al. AVS 2015

Fluorocarbon Polymers Build up and Clog Delicate Structures



Simulation: HPEM/MCFPM

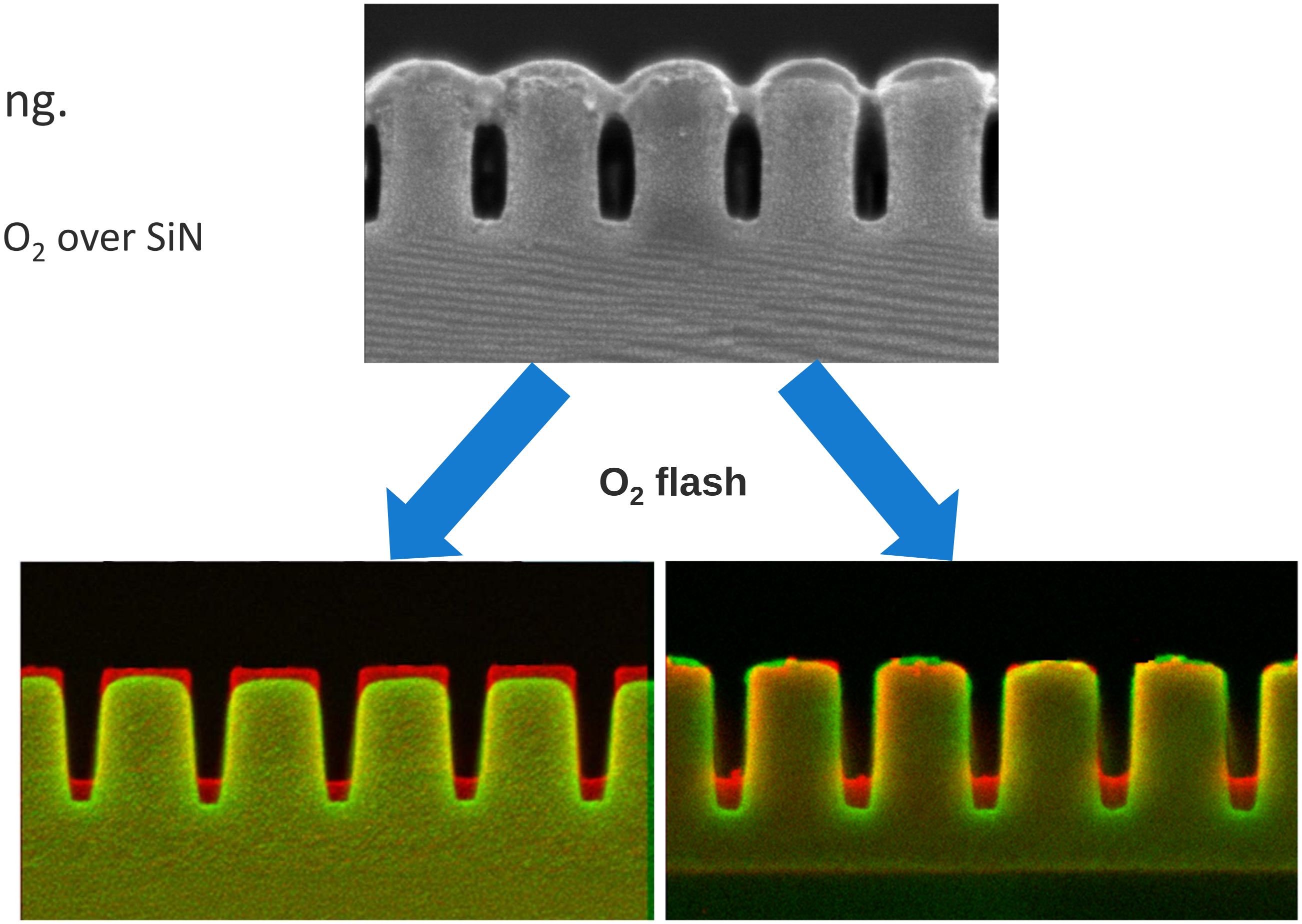


- CF Polymer
- OPL
- Nitride
- Oxide

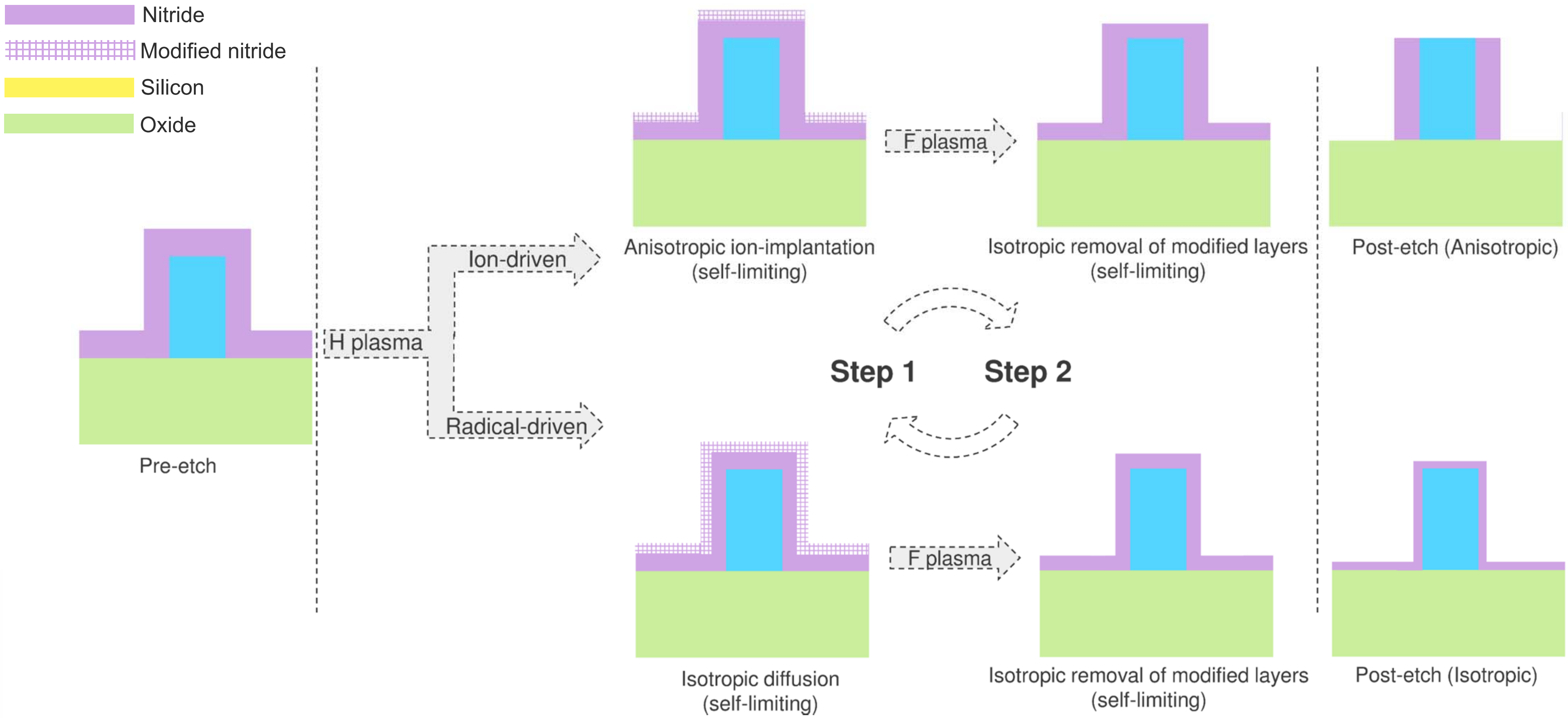
Process solution: Flash

O_2 flash can help avoid clogging.

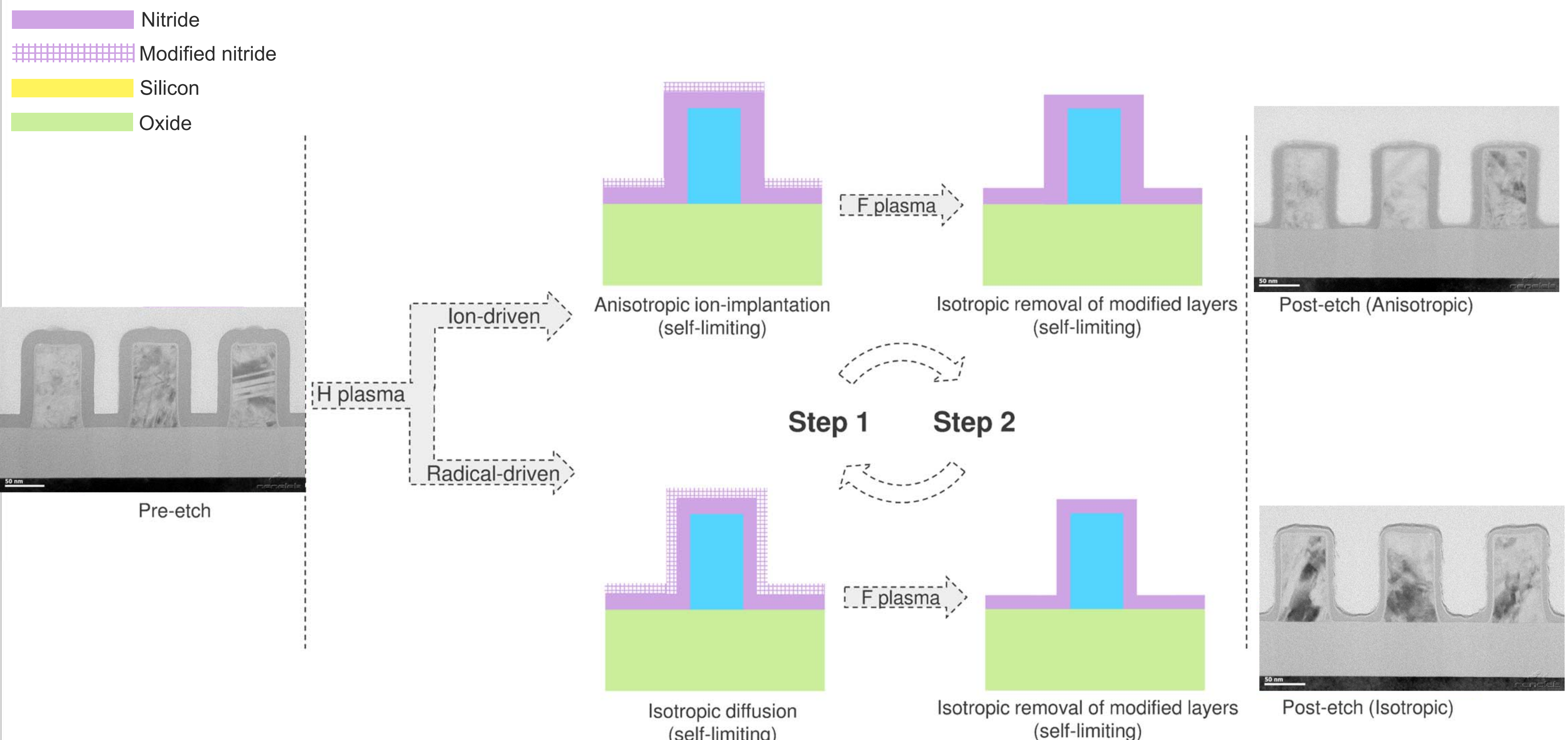
- Not smart: SiN loss
- Smart: infinite selectivity on SiO_2 over SiN



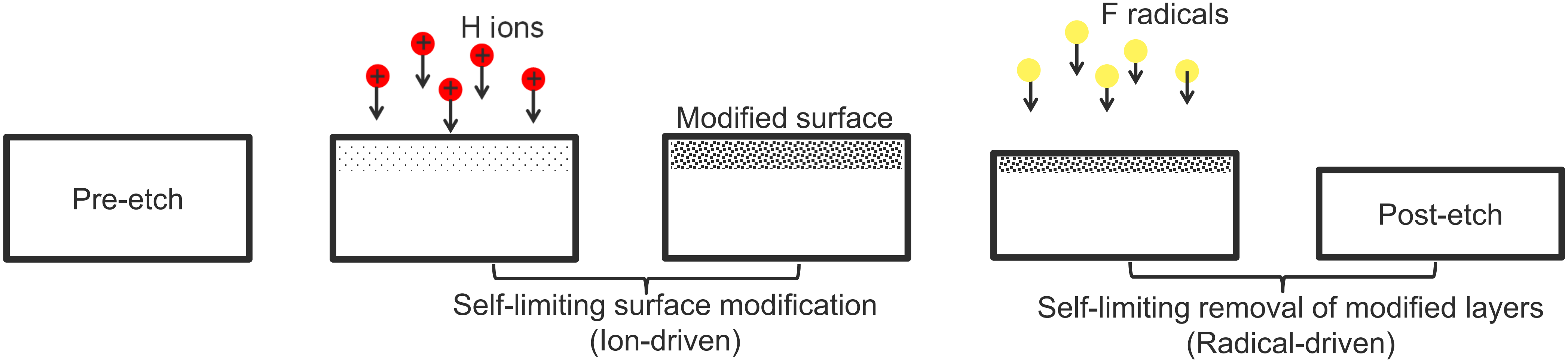
New ALE Advances: Spatially Selective ALE by Modification



New ALE Advances

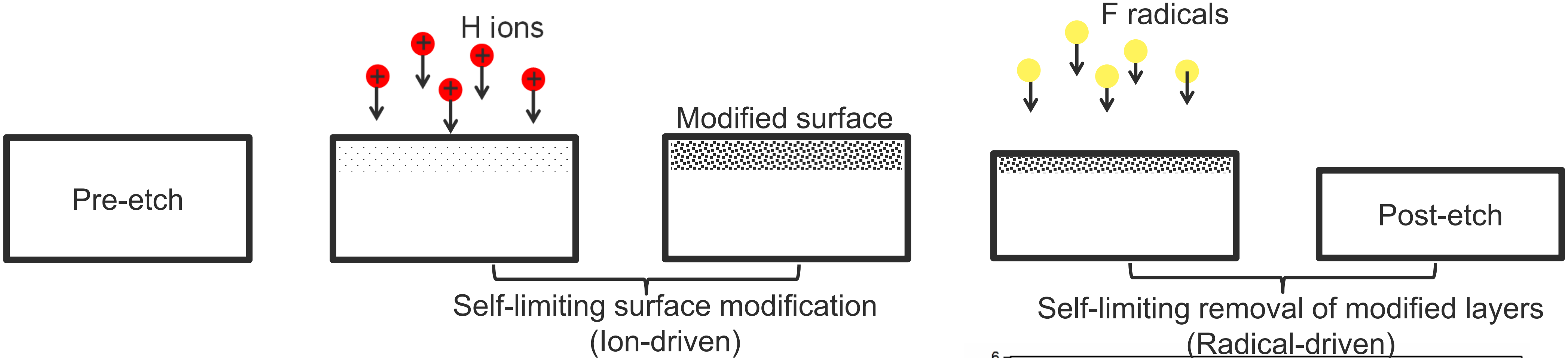


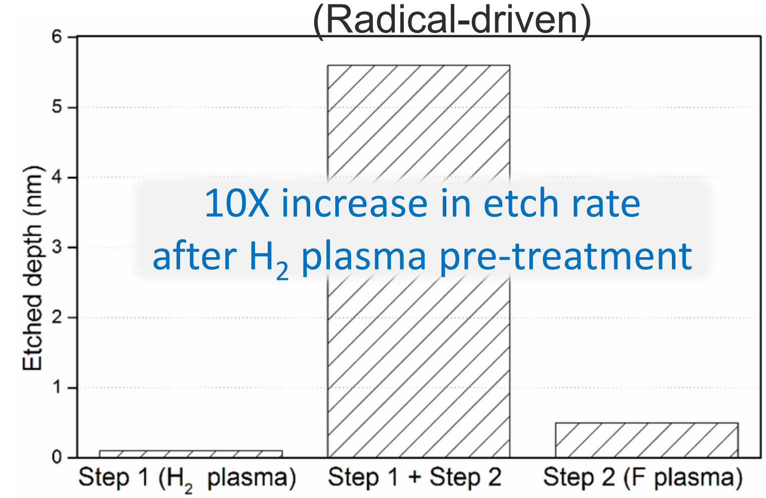
Schematic-Anisotropic SiN QALE



S.D. Sherpa and A. Ranjan, J. Vac. Sci. Technol. A 35, 01A102 (2017)

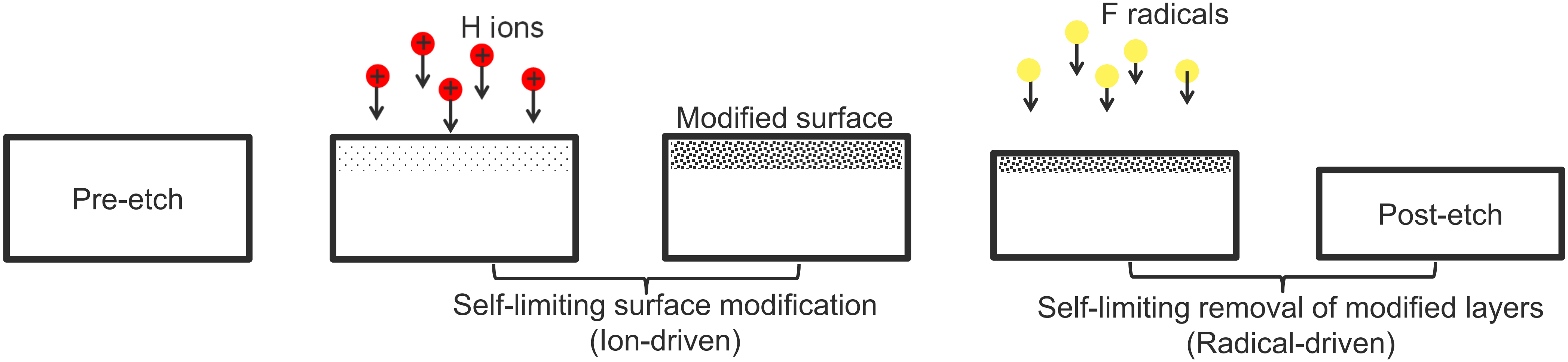
Synergy-Anisotropic SiN QALE





S.D. Sherpa and A. Ranjan, J. Vac. Sci. Technol. A 35, 01A102 (2017)

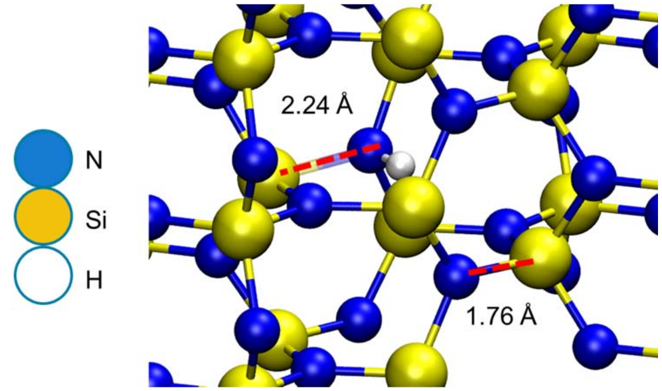
Synergy-Anisotropic SiN QALE



Hypothesis

After insertion of hydrogen,

- Si-N bond length ↑
- Si-N bond energy ↓
- SiN reactivity toward atomic fluorine ↑

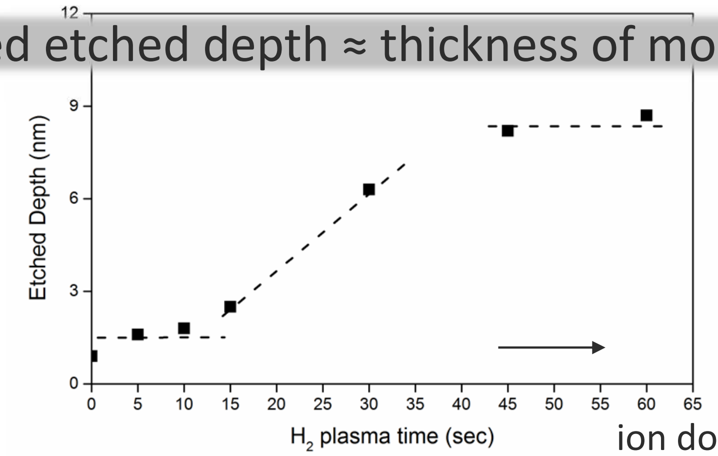


Si-N bond elongation by 0.48 Å

S.D. Sherpa and A. Ranjan, J. Vac. Sci. Technol. A 35, 01A102 (2017)

Self-limiting etch-Anisotropic SiN QALE

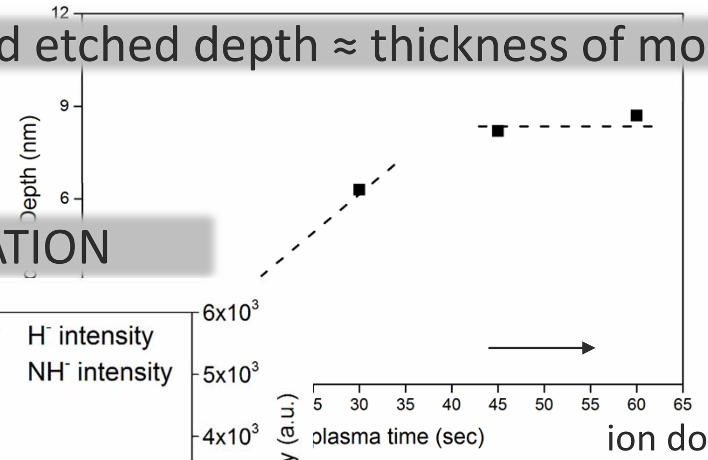
saturated etched depth ≈ thickness of modified nitride



ion dose

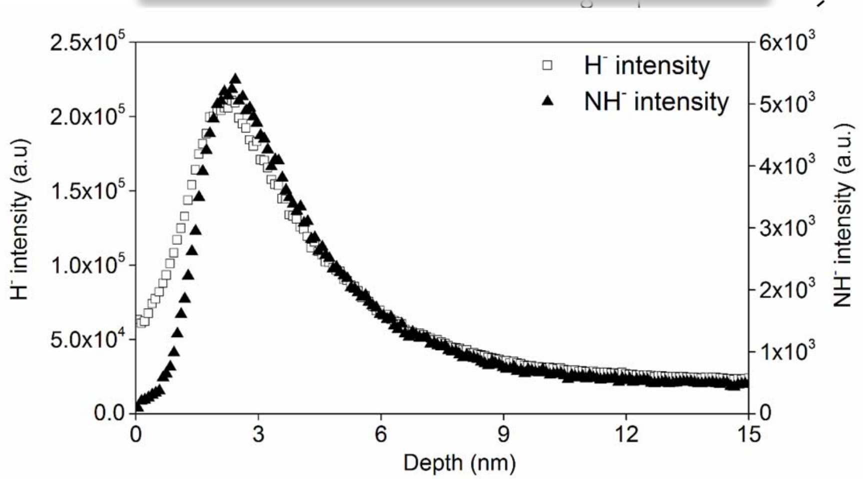
Self-limiting etch-Anisotropic SiN QALE

saturated etched depth ≈ thickness of modified nitride



ion dose

ION-IMPLANTATION

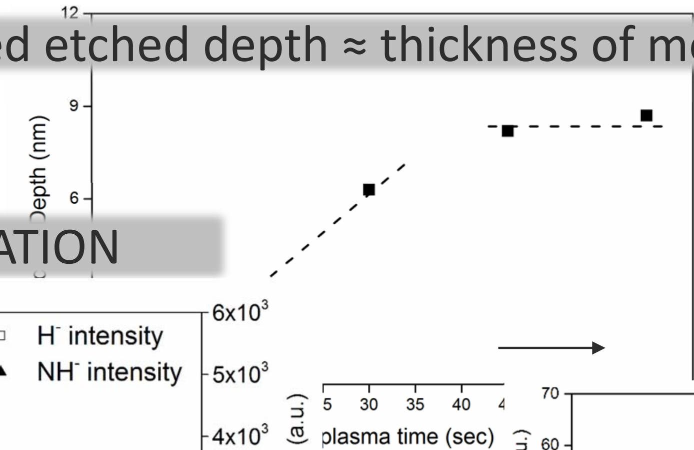


$$n(x) = \frac{S}{\sqrt{2\pi}\sigma_p} \exp[-\frac{(x-R_p)^2}{2{\sigma_p}^2}]$$

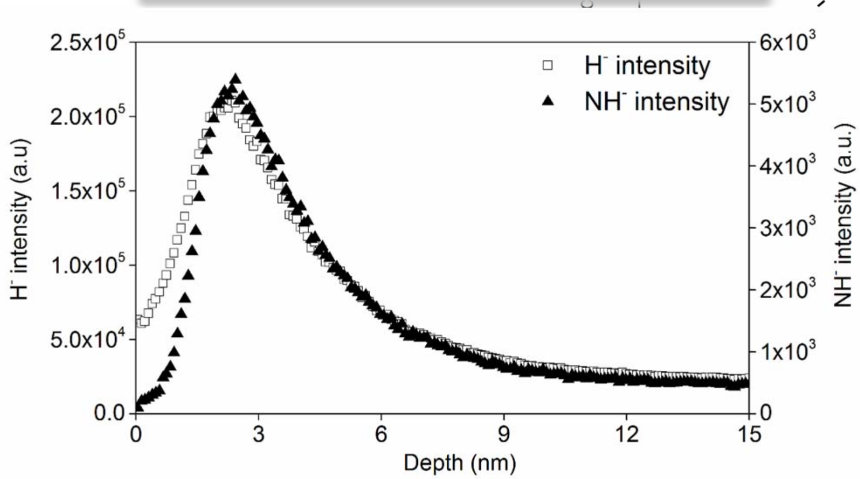
maximum concentration at projected range (R_p)

Self-limiting etch-Anisotropic SiN QALE

saturated etched depth ≈ thickness of modified nitride



ION-IMPLANTATION



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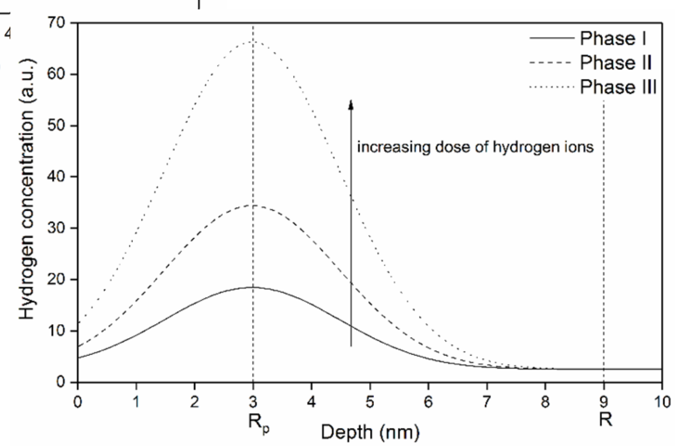
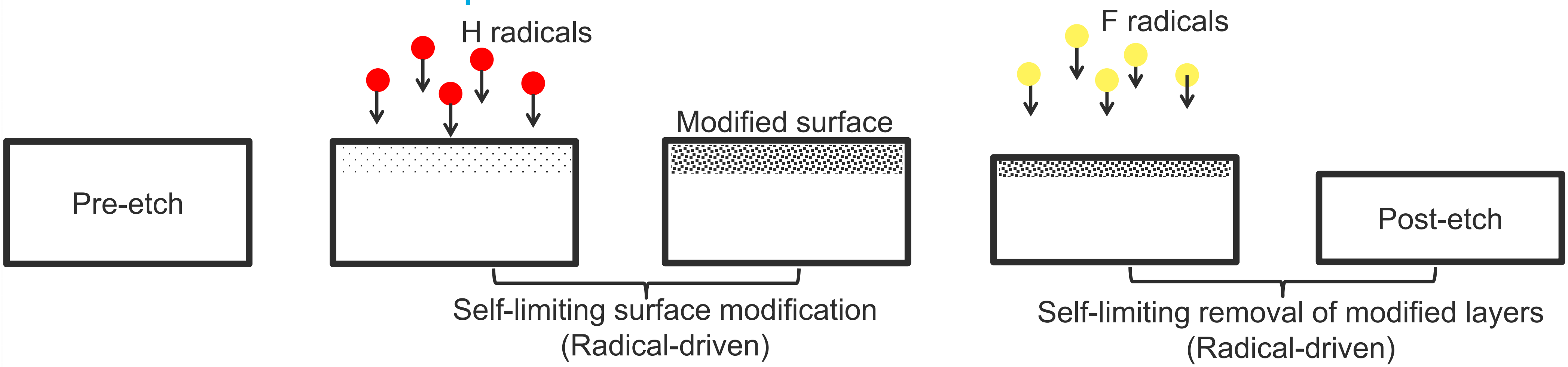


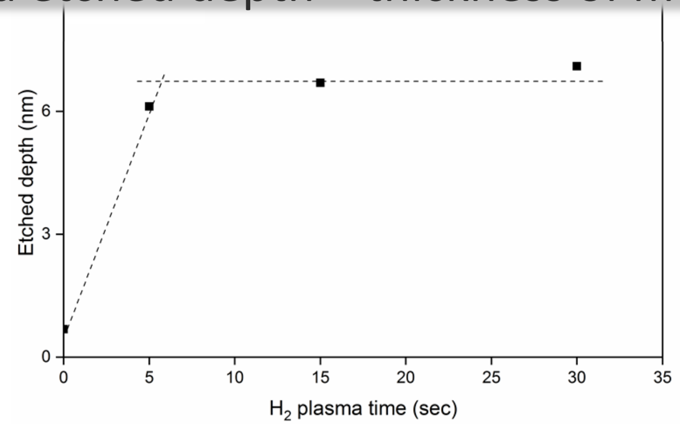
depth of implantation independent of ion dose

Schematic-Isotropic SiN QALE



Self-limiting etch-Isotropic SiN QALE

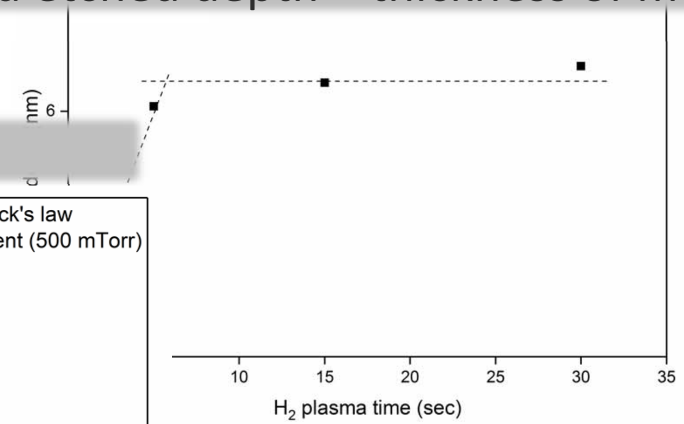
saturated etched depth ≈ thickness of modified nitride



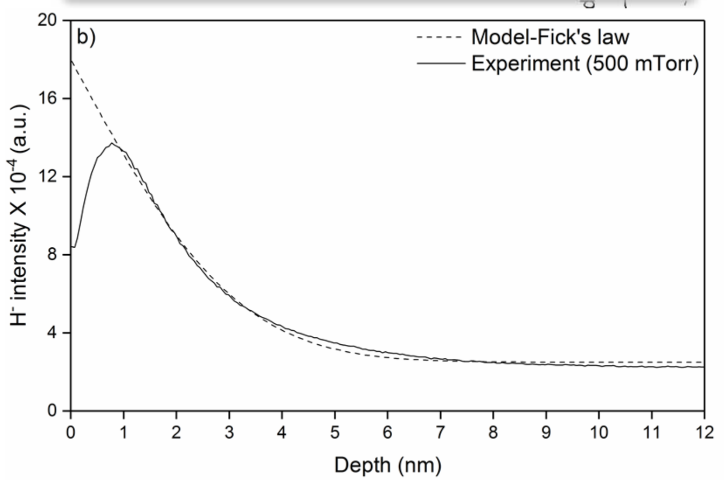
S.D. Sherpa, P.L.G. Ventzek, and A. Ranjan, J. Vac. Sci. Technol. A 35, 05C310 (2017)

Self-limiting etch-Isotropic SiN QALE

saturated etched depth ≈ thickness of modified nitride



DIFFUSION



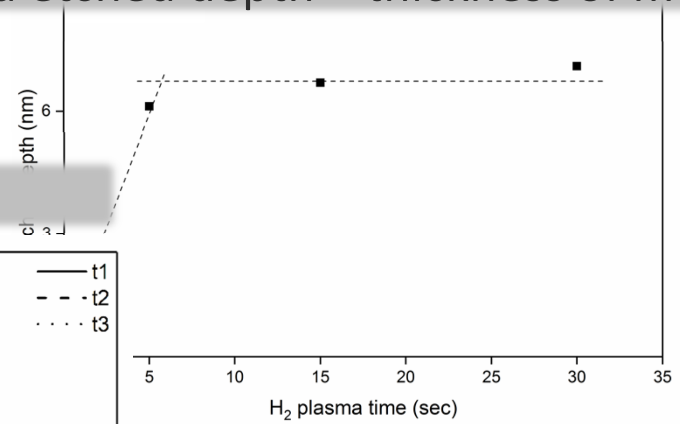
$$C\ (x,t) = C_s - (C_s - C_0)\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

maximum concentration at surface

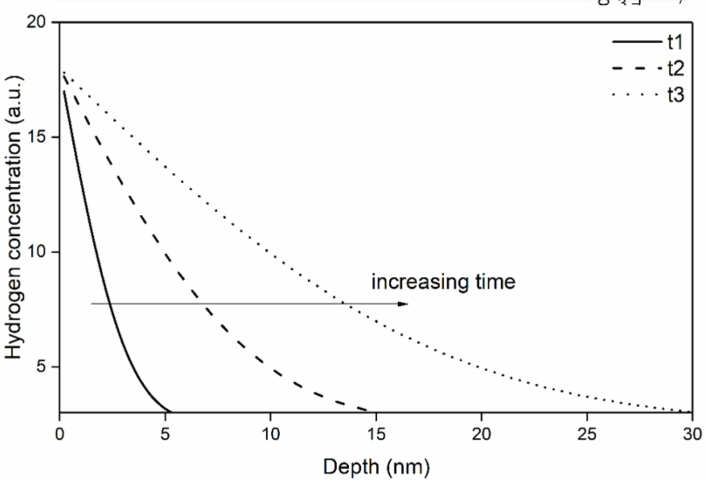
S.D. Sherpa, P.L.G. Ventzek, and A. Ranjan, J. Vac. Sci. Technol. A 35, 05C310 (2017)

Self-limiting etch-Isotropic SiN QALE

saturated etched depth ≈ thickness of modified nitride



DIFFUSION

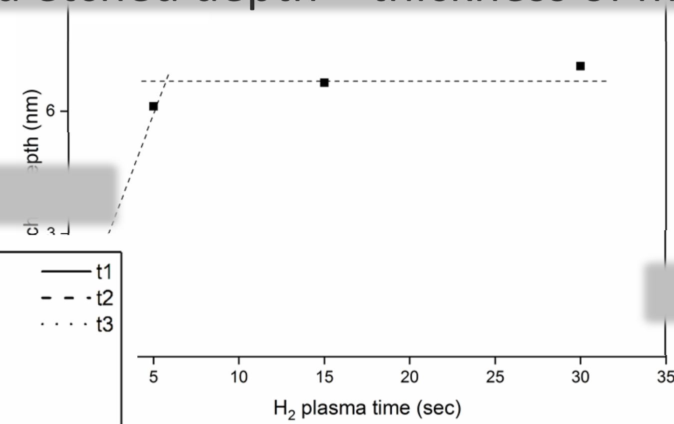


$$C\,(x,t) = C_s - (C_s - C_0)\,\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

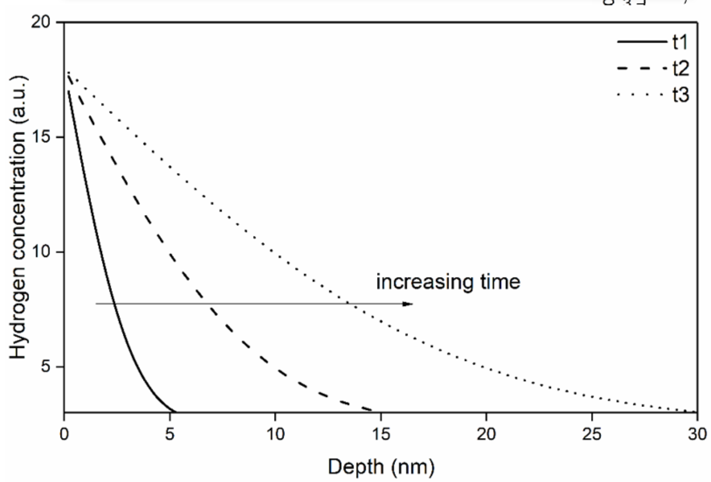
S.D. Sherpa, P.L.G. Ventzek, and A. Ranjan, J. Vac. Sci. Technol. A 35, 05C310 (2017)

Self-limiting etch-Isotropic SiN QALE

saturated etched depth ≈ thickness of modified nitride



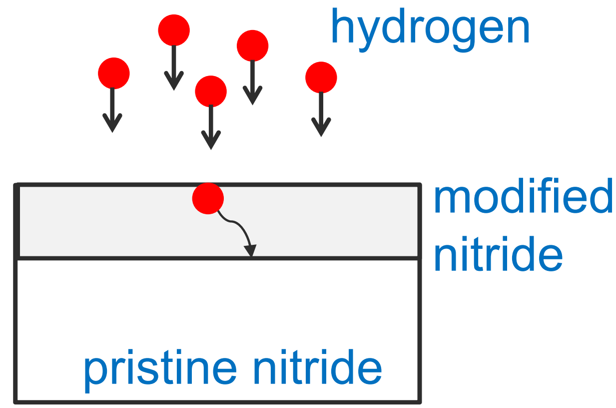
DIFFUSION



$$C\,(x,t) = C_s - (C_s - C_0)\,\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

DEAL-GROVE model

reaction at the interface

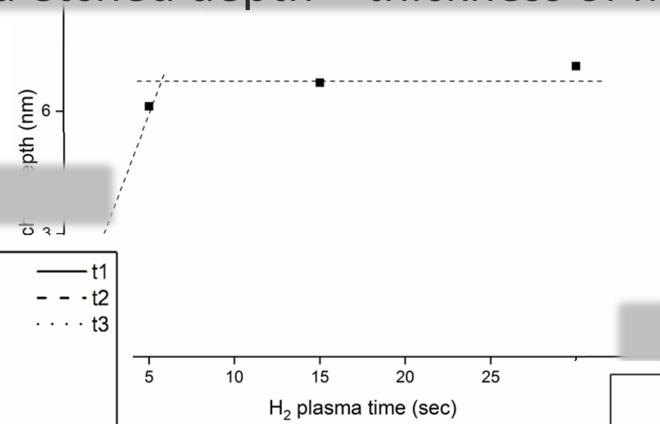


surface modification of silicon nitride

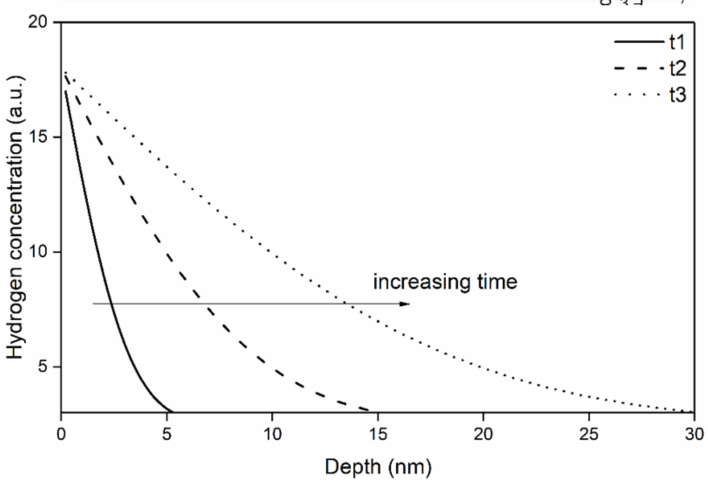
S.D. Sherpa, P.L.G. Ventzek, and A. Ranjan, J. Vac. Sci. Technol. A 35, 05C310 (2017)

Self-limiting etch-Isotropic SiN QALE

saturated etched depth ≈ thickness of modified nitride



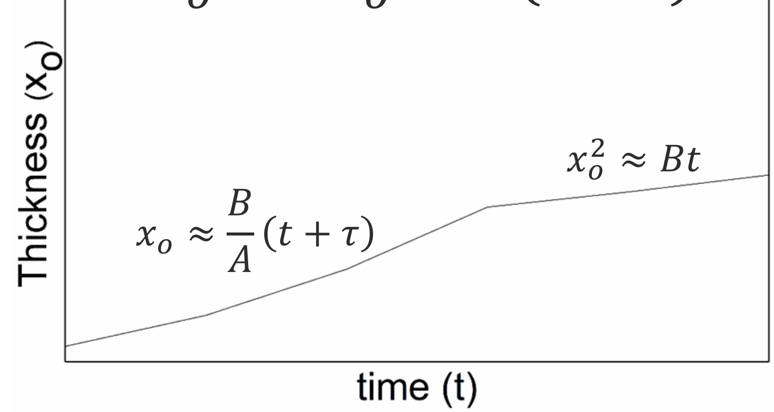
DIFFUSION



$$C\ (x,t) = C_s - (C_s - C_0)\mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)$$

DEAL-GROVE model

$$x_o^2 + Ax_o = B(t+\tau)$$

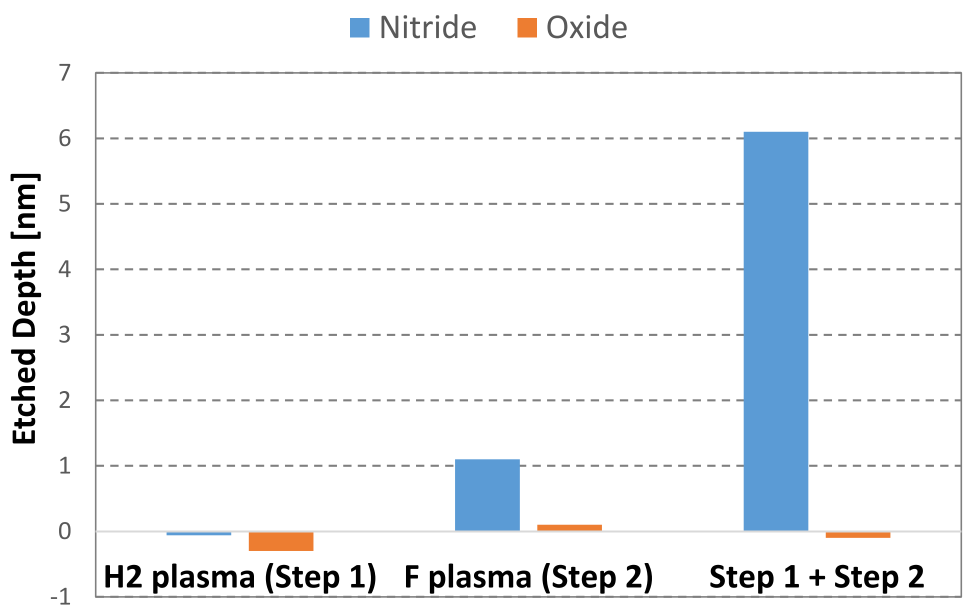


$$x_o \approx \frac{B}{A}(t+\tau)$$

$$x_o^2 \approx Bt$$

S.D. Sherpa, P.L.G. Ventzek, and A. Ranjan, J. Vac. Sci. Technol. A 35, 05C310 (2017)

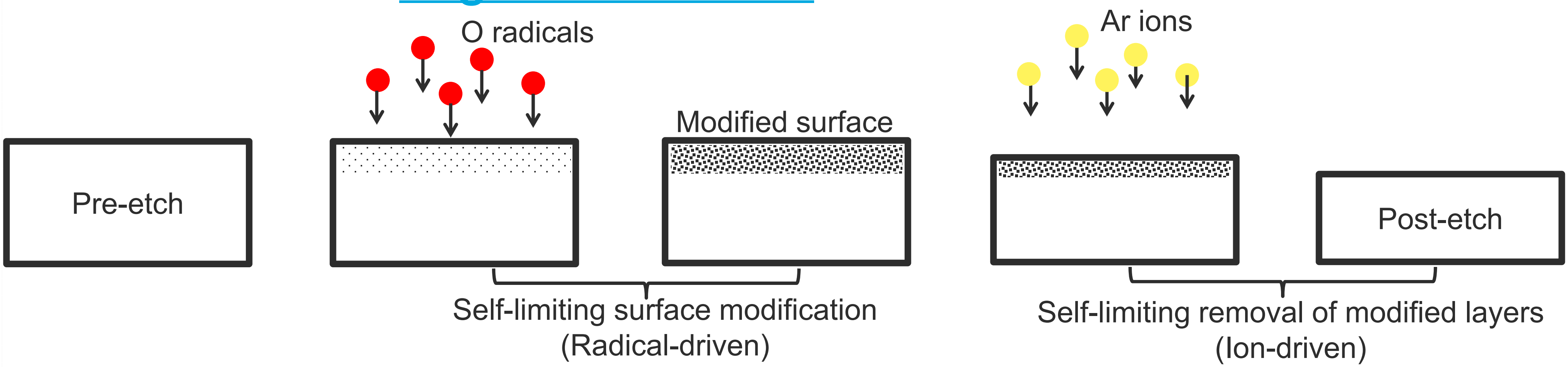
SiN QALE-Ultra-high Selectivity to Oxide



Bond dissociation energy (kJ/mol)		
Si-O	Si-F	Si-N
800	575	435

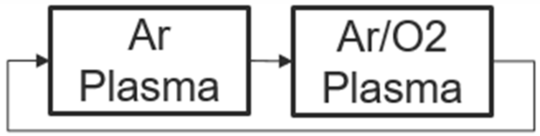
Atomic fluorine the dominant etchant during the exposure to F plasma

Quasi-ALE of **Organic Materials**

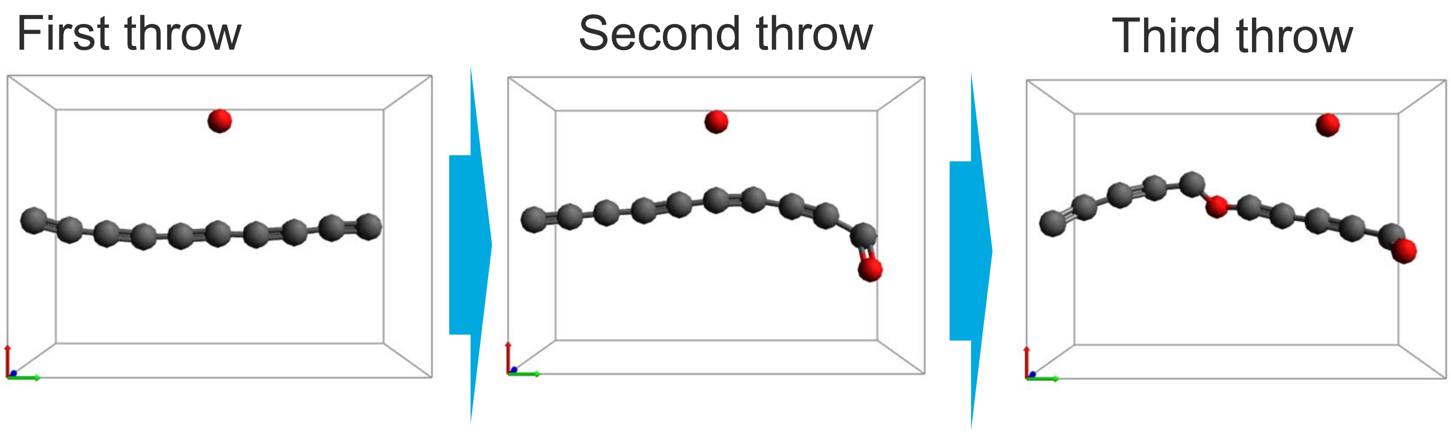


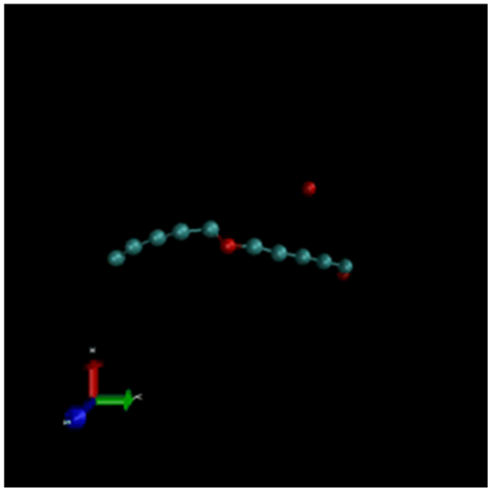
Self-limiting steps for organic materials possible?

O Atoms on a Carbon Strand



- Argon ion bombardment denudes the carbon of its hydrogen

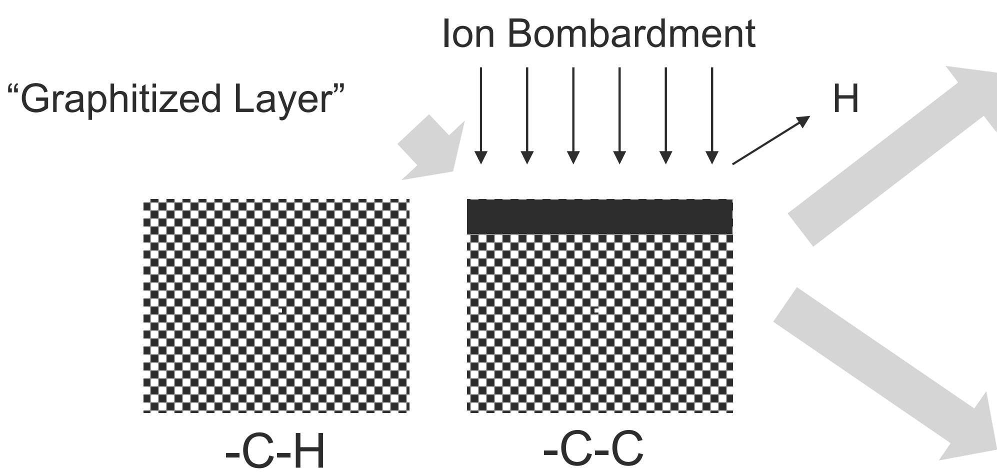


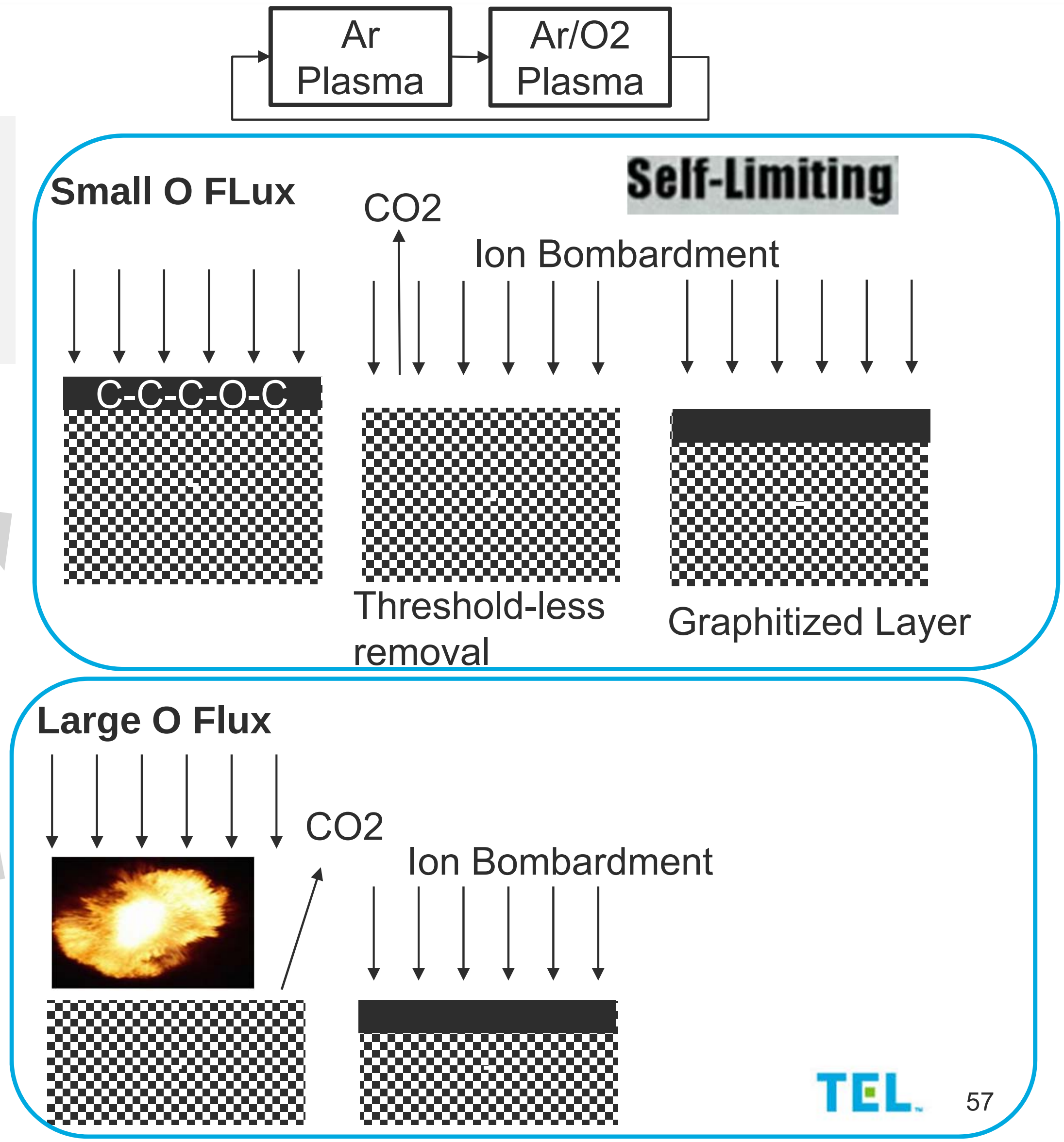


- Repeated oxygen radical exposure to the H denuded surface results in bond breaking.

A viable self-limiting mechanism

- Large oxygen dose results in energy release and no self-limitation
- Small doses gently treat H-free layers.

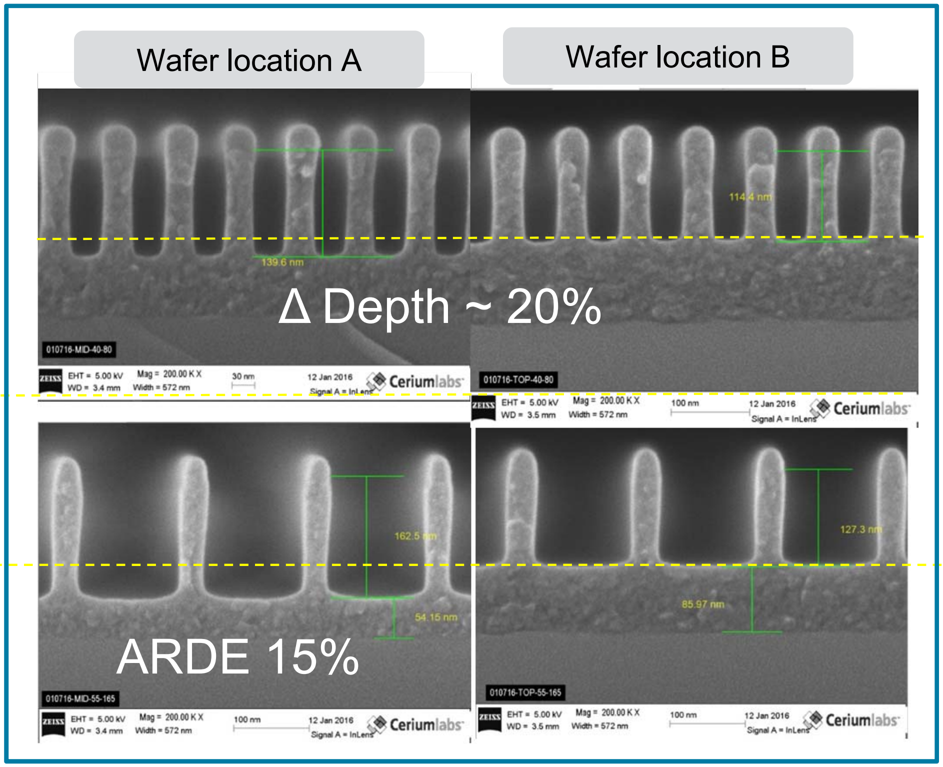




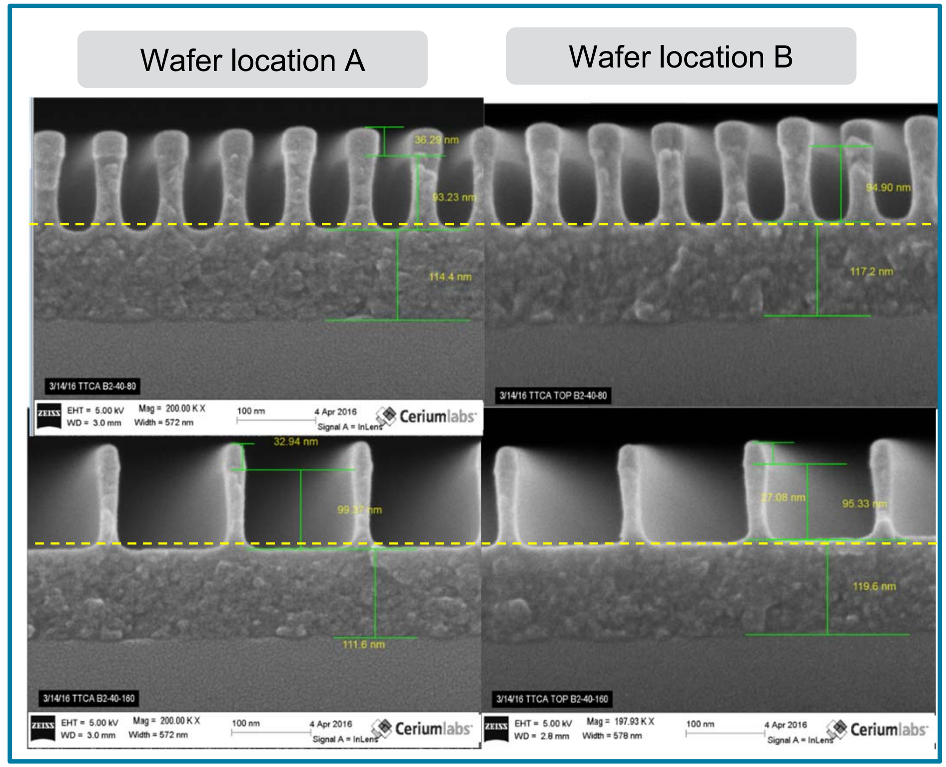
Organic ALE Through Ion Surface Modification

Special Case: Non-Uniform Plasma

RIE Mode

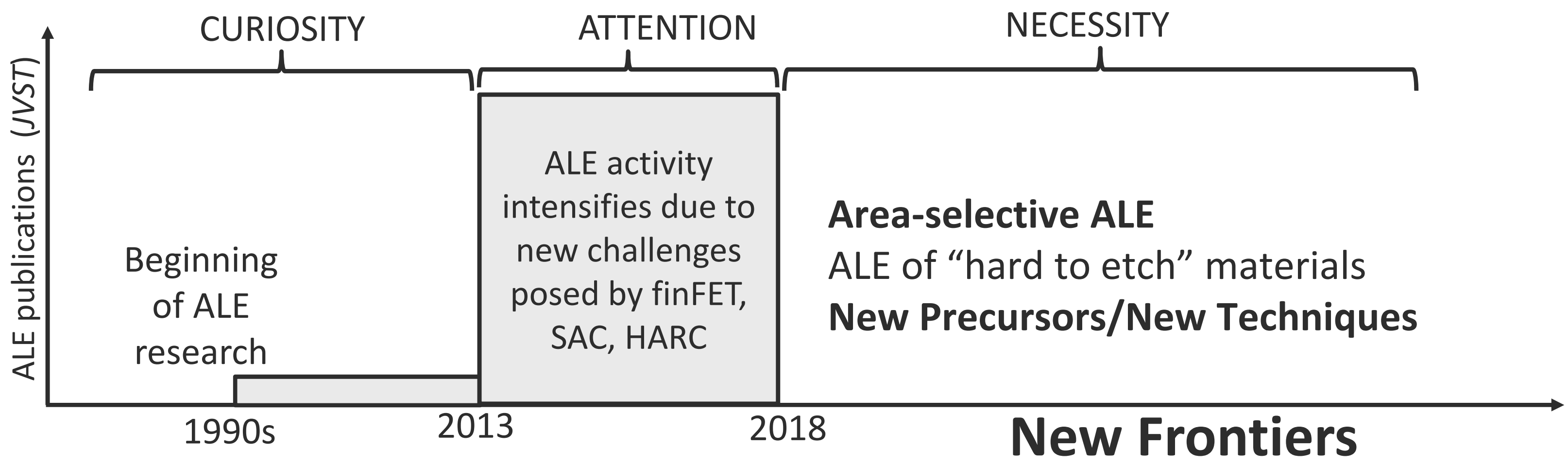


Cyclic Mode (Quasi-ALE)



Quasi-ALE ” virtually eliminates NU and ARDE

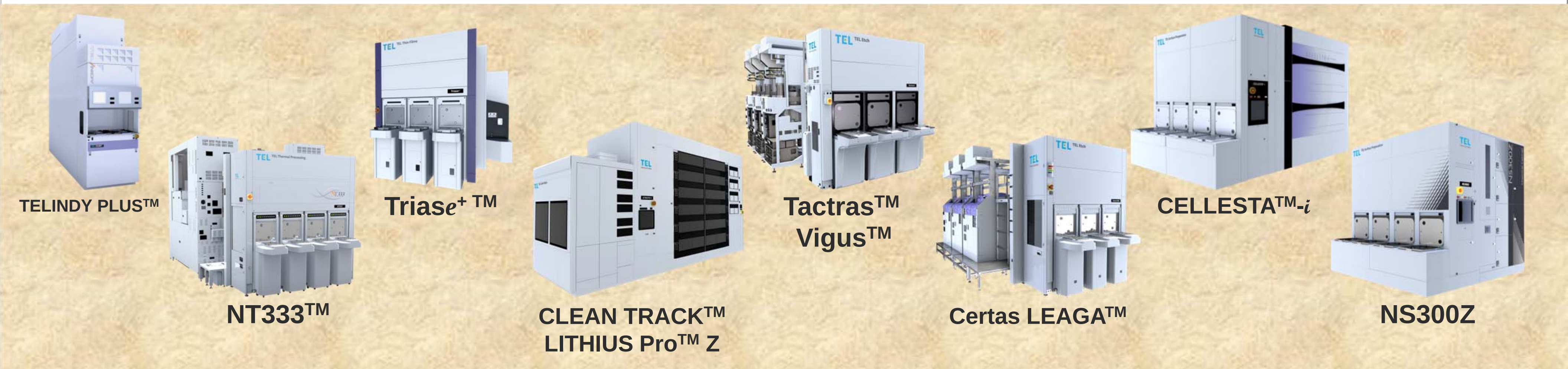
ALE: Where are we and what lies ahead?



- ALEtch requires significant ALEngineering to make it practical.

Summary

- 3D Architectures and Scaling are Required for 10nm and beyond Scaling
- Meeting the challenge of 3D, EPE, New Devices and Contacts Requires New Process Technology and Patterning Paradigms
- TEL is working continuously to develop and improve the New Processes needed to continue scaling beyond the 10nm node and through the next decade.



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