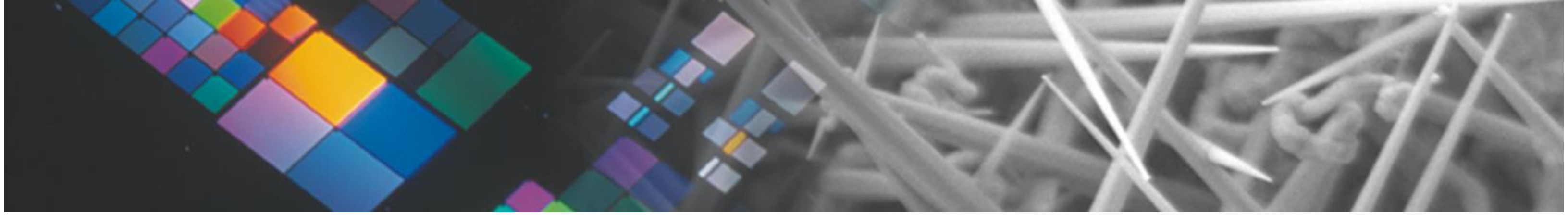


Procédés de dépôt plasma avec injection pulsée de précurseurs (PECVD et PEALD) :

Impact du réacteur et de la pression et développement de dépôts sélectifs

C. Vallée[1,3], R. Gassilloud[2], R. Vallat[1,2], V. Pesce[1,2], S. Belahcen[1], A. Chaker[1], O. Salicio[1], N. Posseme[2], P. Gonon[1], M. Bonvalot[1], and A. Bsiesy[1]

[1]Univ. Grenoble Alpes, Lab. LTM (CEA-LETI/MINATEC) - Grenoble – France

[2]CEA-LETI / MINATEC – Grenoble – France

[3]University of Tsukuba, Faculty of Pure and Applied Physics – Tsukuba – Japan

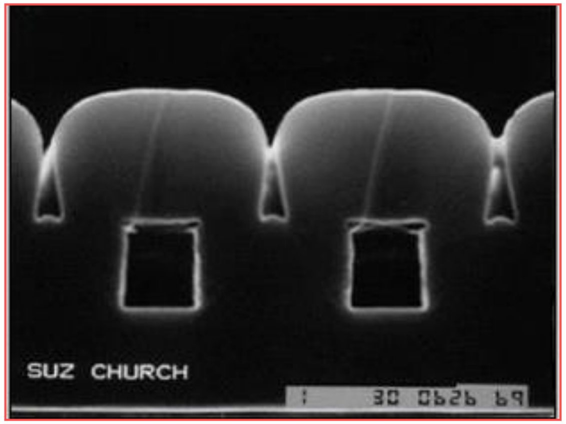
PECVD in microelectronics

- Mainly capacitive discharges working at high pressure (> Torr)
- Plasma damage, no need for ions
- High throughput manufacturing
- Uniformity (2% from center to edge)

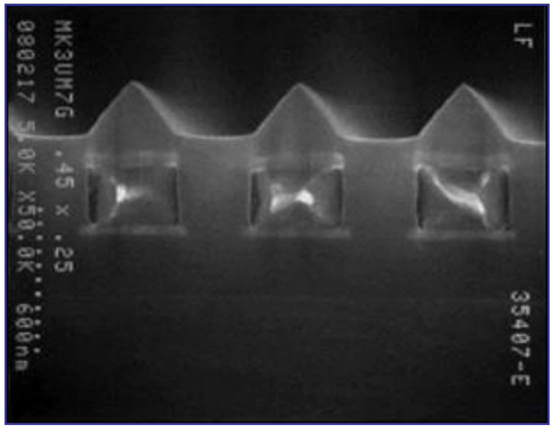
- HDP-CVD process for gap filling is using a low pressure plasma discharge with inductive source

D.R. Cote et al, IBM Journal of Research and Development, Plasma processing, 43 (1/2), 1999

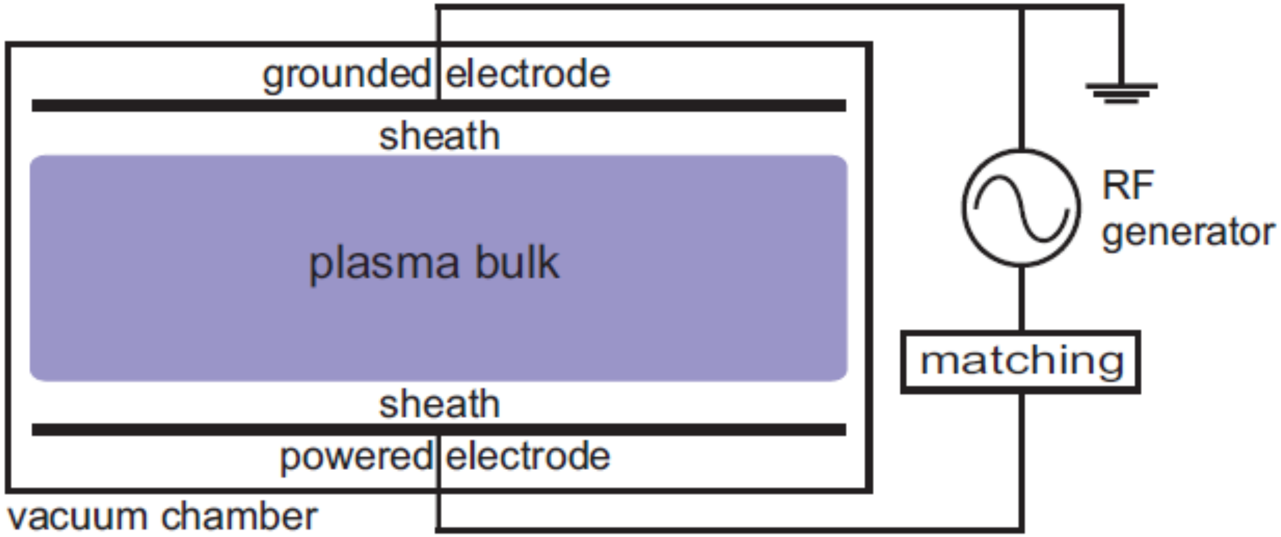
PECVD TEOS



HDP CVD silane



PECVC process with CCP RF reactor



Parameters to turn for the process:

- **Plasma Power**: plasma density, flux, energy
- **Pressure**: reactions in the plasma, T_e, sheath collisionless or not
- **residence time**: plasma/surface interactions

Can we find more parameters to turn?

RF generator frequency

Pulsing the plasma or the precursors

What can be pulsed?

All parameters can be pulsed:

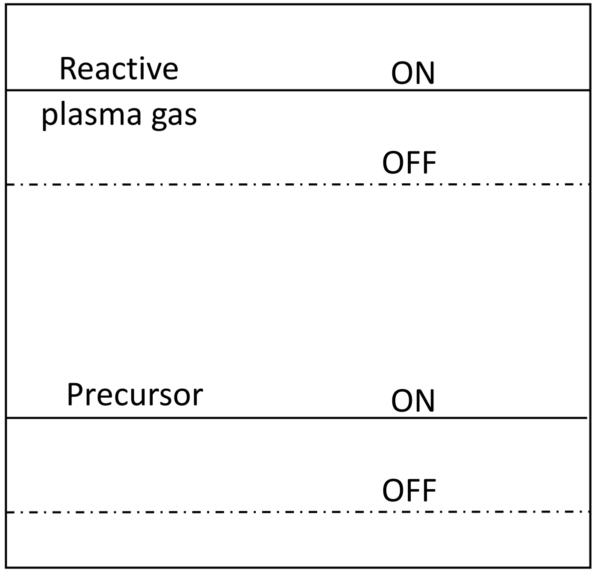
Plasma modulation: modification of discharge chemistry, decrease the ion to neutral flux ratio on the substrate, presence of long life time active species which act as precursors to the film growth, decrease substrate temperature…

Precursors: control of thickness, plasma chemistry, conformality…

→ composition, stress and properties of thin film

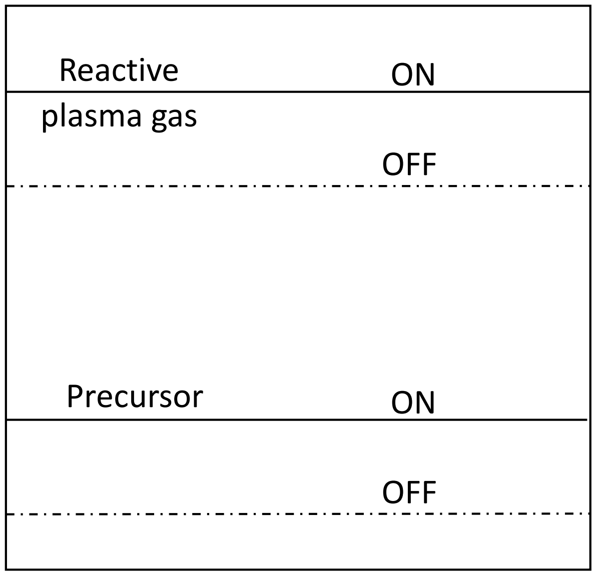
From PECVD to PEALD

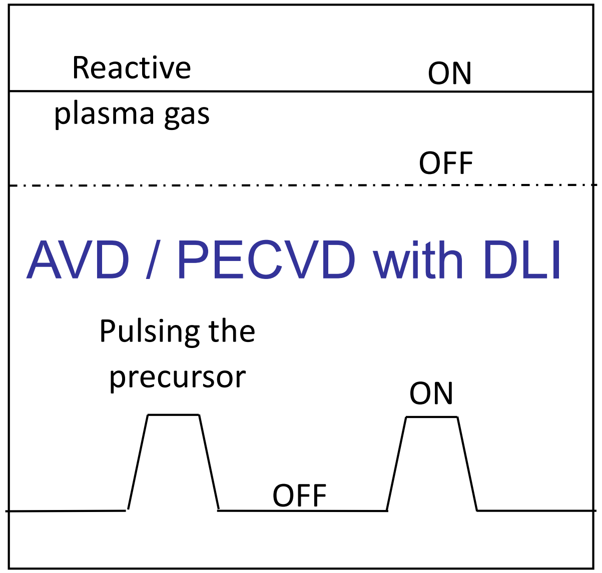
PECVD

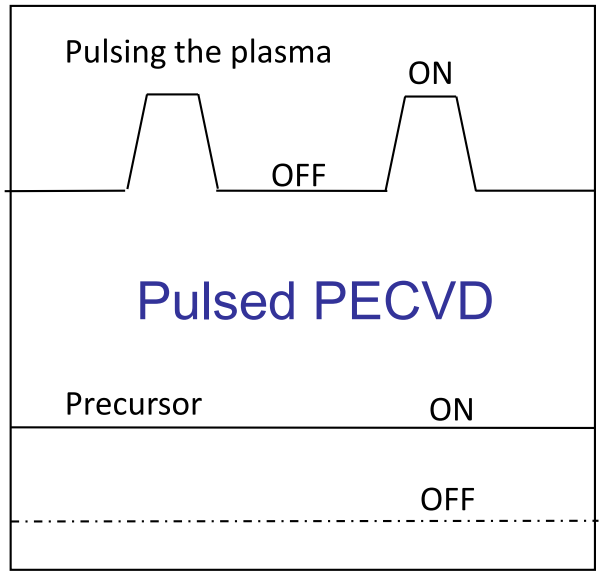


From PECVD to PEALD

PECVD

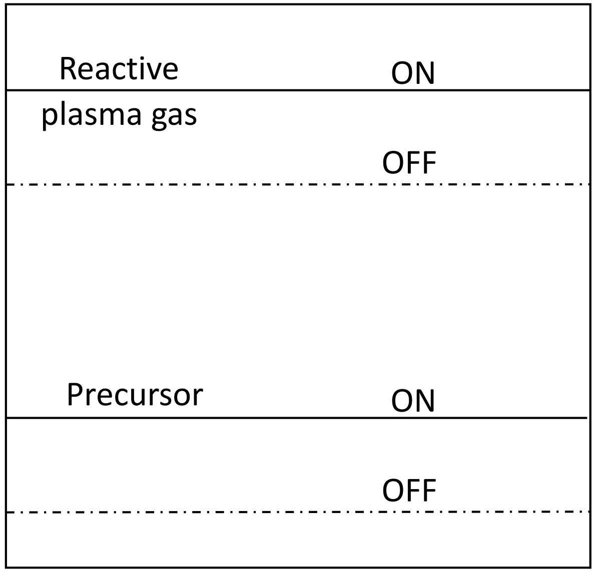


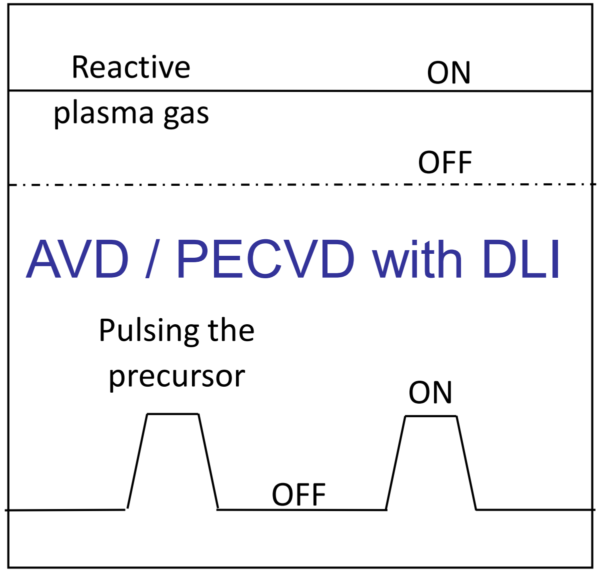


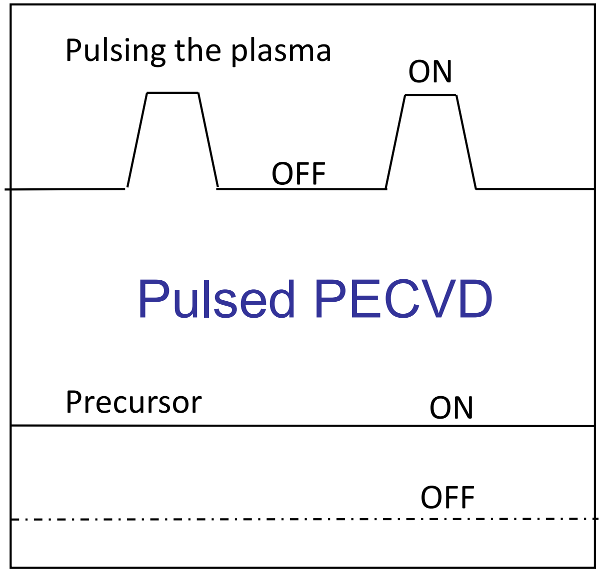


From PECVD to PEALD

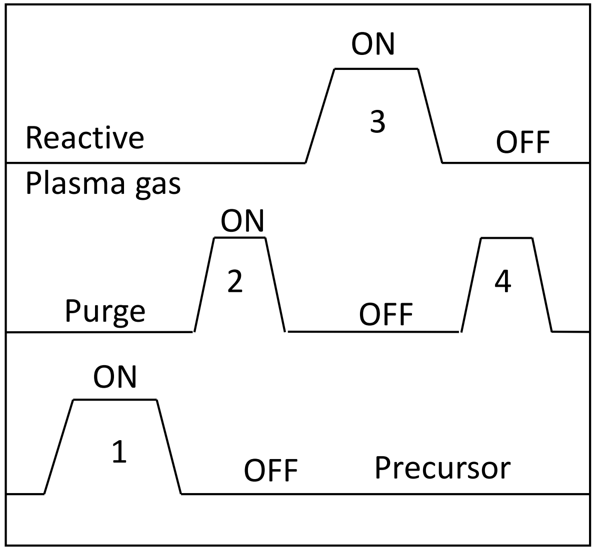
PECVD

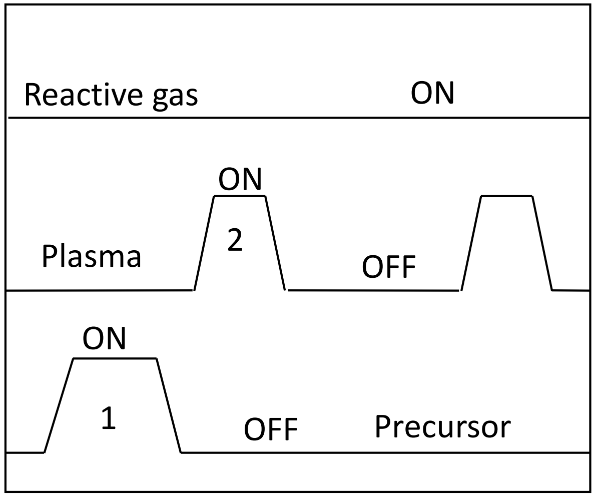






PEALD





ALD

Atomic layer deposition (ALD) is a CVD technique that can achieve unparalleled control at the atomic scale.

ALD achieves ‘bottom-up’ control through chemical reactions with special characteristics:

reactions take place at the surface only

→ gas-phase reactions are inhibited;

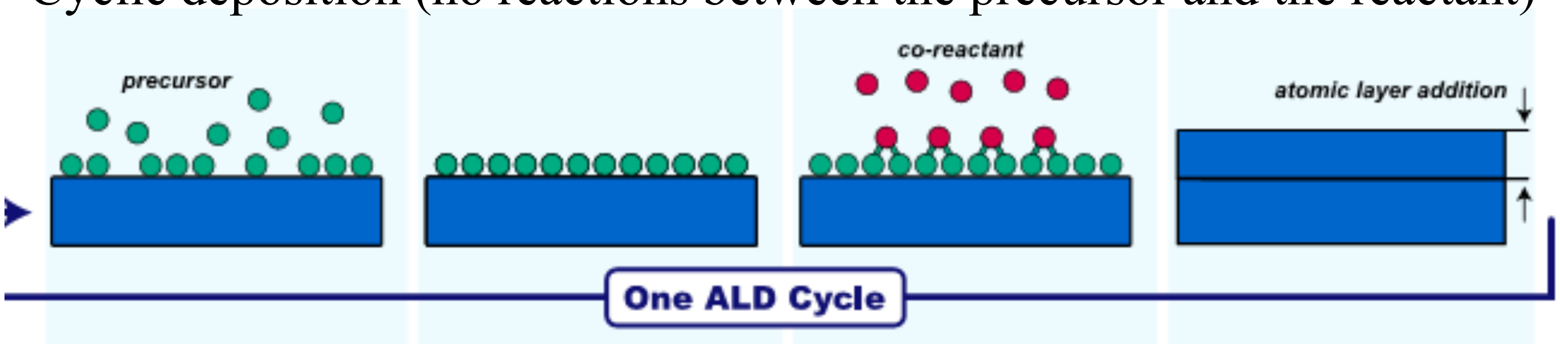
reactions are self-limiting

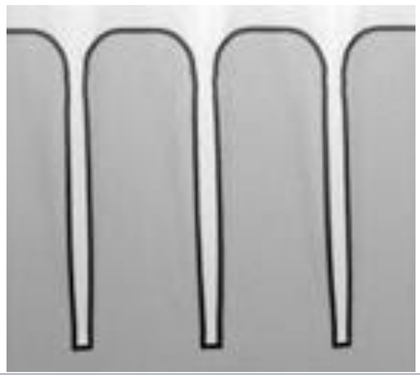
→ but can be re-activated;

reactions take place independent of fluctuations in external conditions

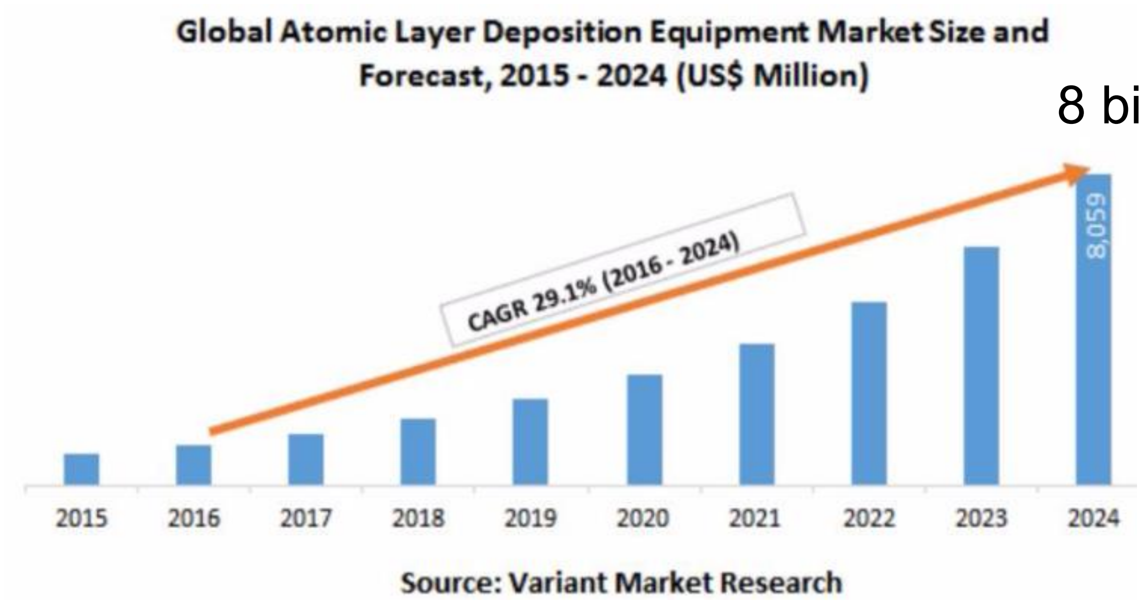
→ the same chemistry thus applies at all scales

Cyclic deposition (no reactions between the precursor and the reactant)

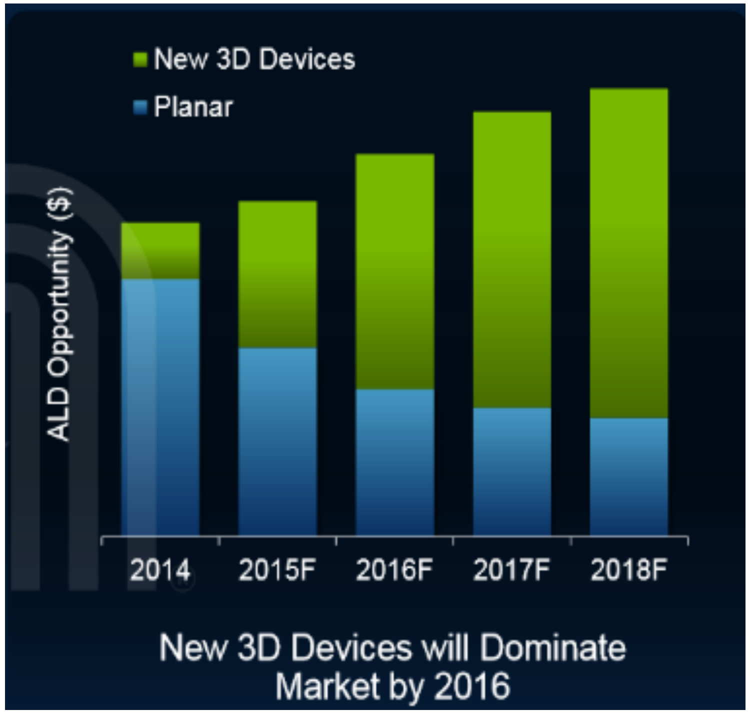




Solid State Technology and Global Industry Analysts (GIA): *the global deposition equipment market will hit $13.6 billion by 2020. Atomic layer deposition (ALD) is forecasted to be the fastest growing segment, with a compound annual growth rate of 19.9 percent, the market research firm estimates.*



8 billions USD



The 3D device inflection is driving growth in ALD with demands for new patterning films, new conformal materials and lower thermal budgets

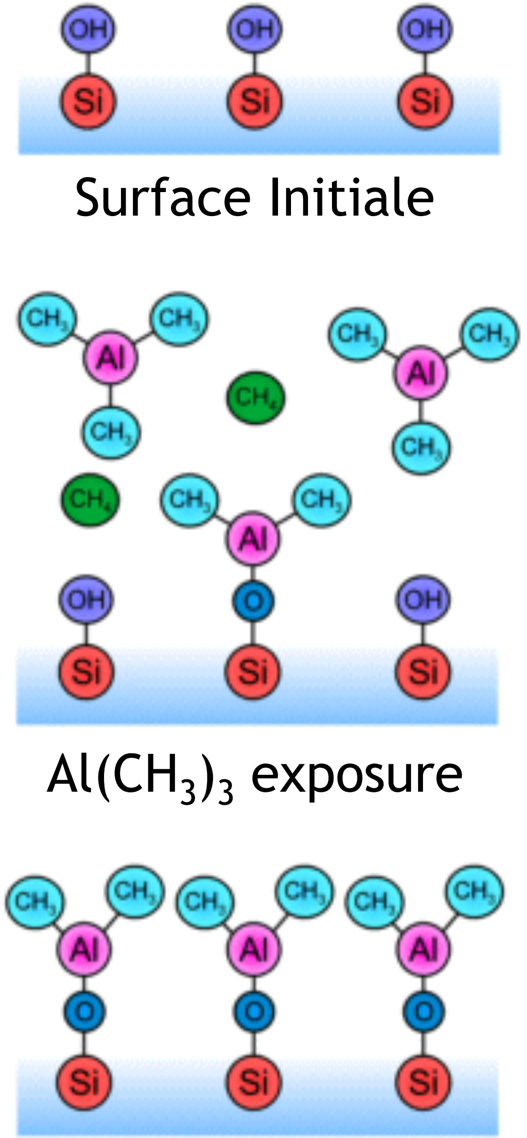
From Oxford instrument

Profijt *et al.*, J. Vac. Sci. Technol. A 29 (5) 050801 (2011)

Comparison between thermal ALD and PE-ALD

Al_2O_3 - $Al(CH_3)_3$ and H_2O

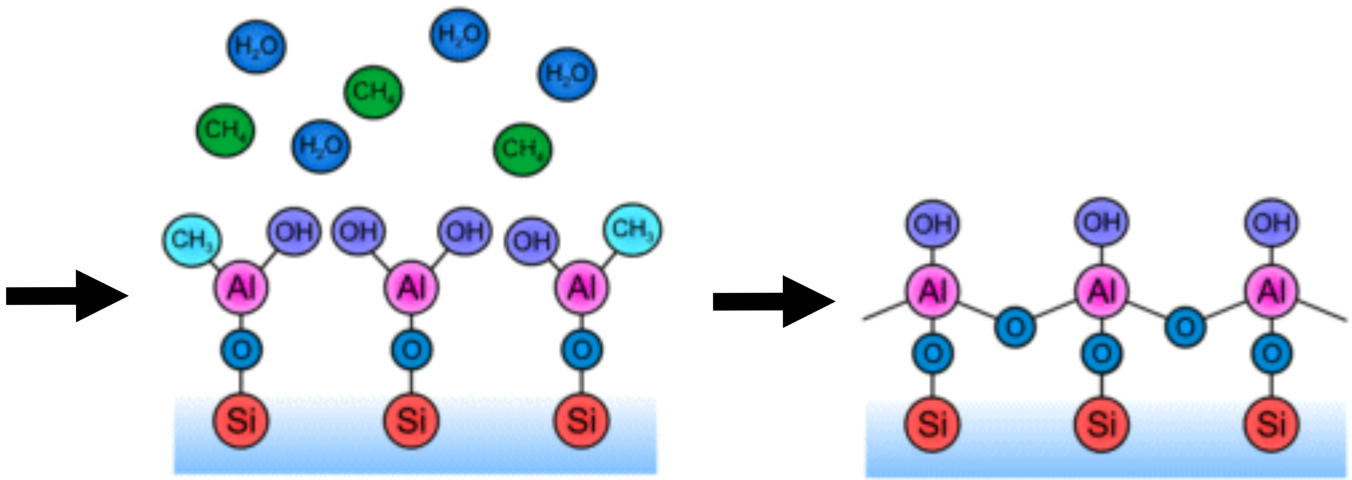
1)



Surface Initiale

2) $Al(CH_3)_3$ exposure

3) Purge



4) H_2O exposure

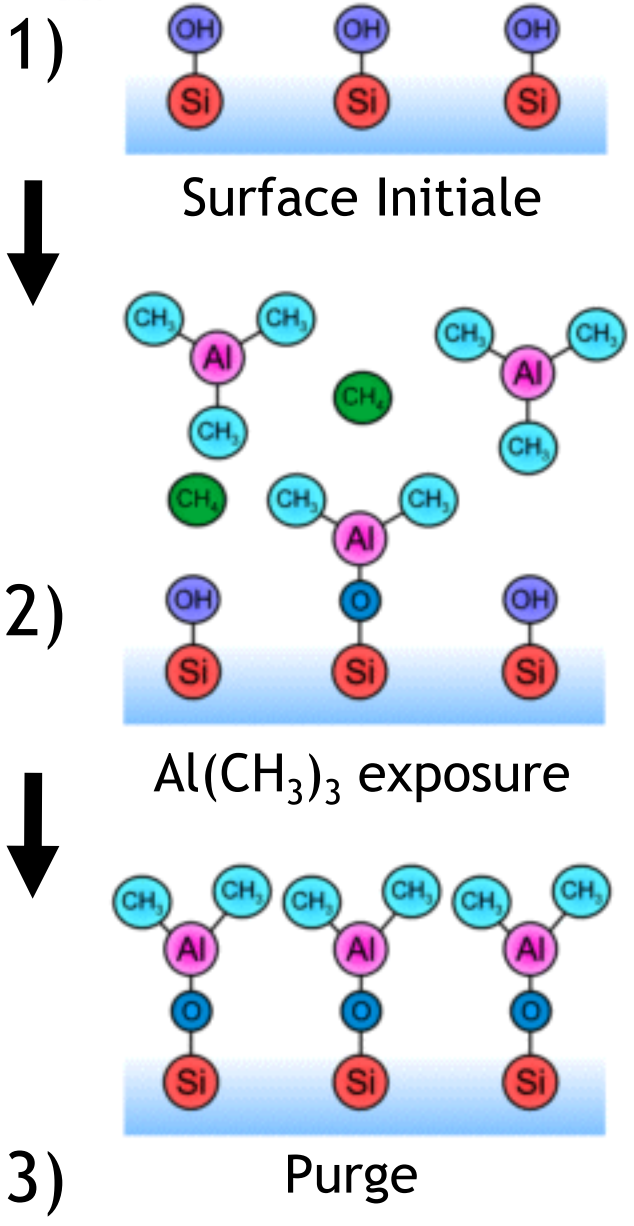
5) Purge

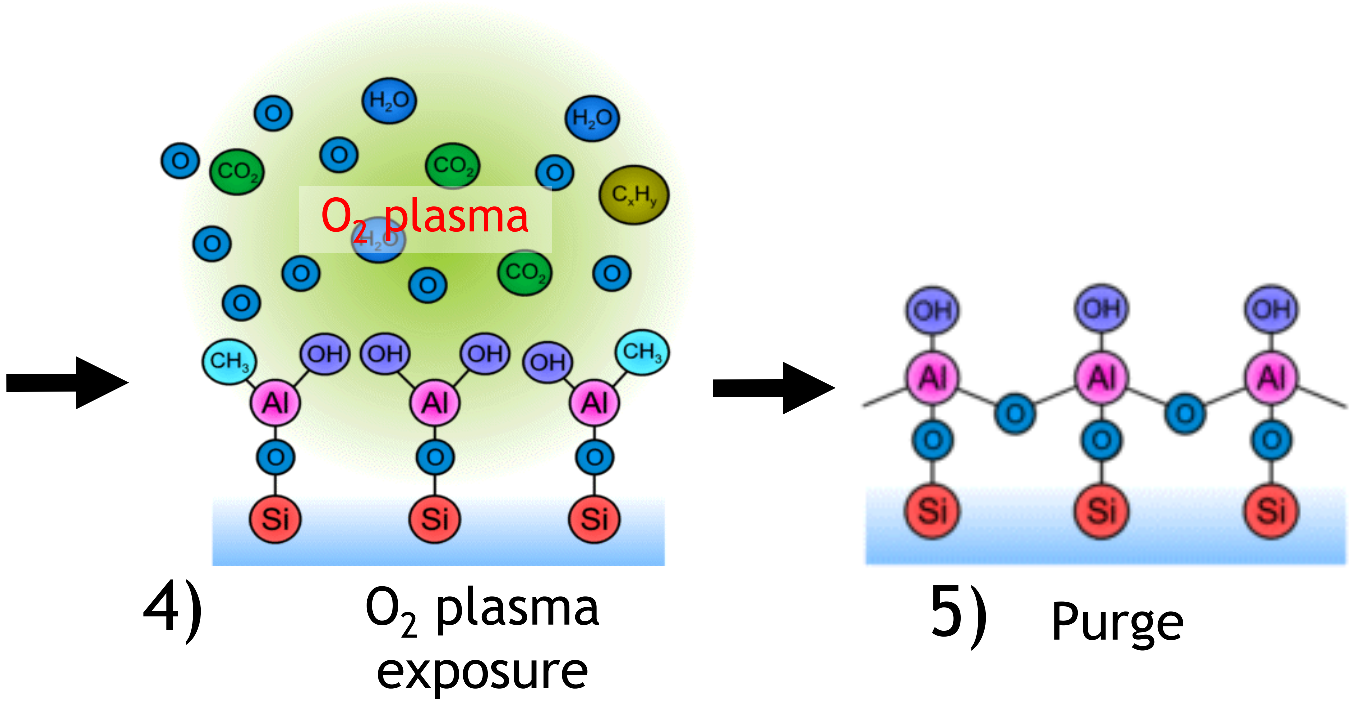
From Oxford instrument

Profijt *et al.*, J. Vac. Sci. Technol. A 29 (5) 050801 (2011)

Comparison between thermal ALD and PE-ALD

Al_2O_3 - $Al(CH_3)_3$ and O_2 plasma





Only used for the activation step. If used during the injection of precursor: PECVD process without self-limited reaction

Cold plasmas reservoir of radicals for oxidation (**O** from O_2 plasma), or reduction (**H** from H_2 or NH_3 plasma) steps

General idea: ions flowing to the surface are too energetic particles for ALD with creation of defects, roughness and not self-limiting step

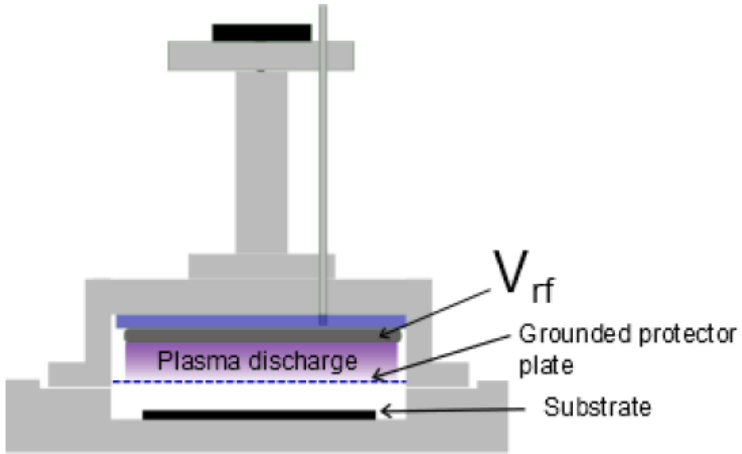
→ they must be removed → specific design of plasma reactors for PEALD

→ capacitive discharge with grids to remove ions

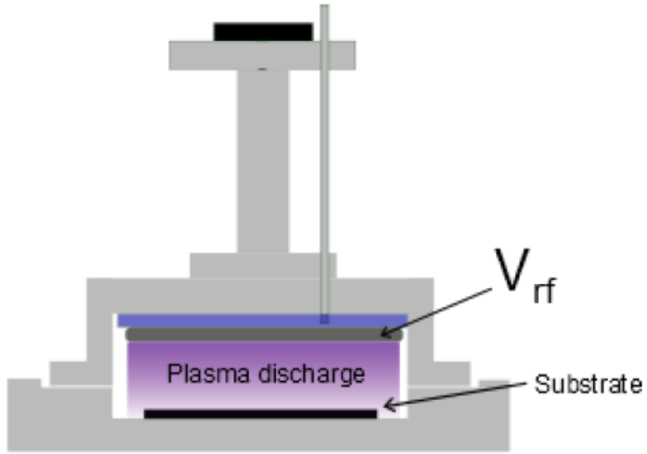
→ high density plasma sources (inductive, microwave) used as a remote discharge: distance between plasma source and substrate is higher than the mean free path of ions ; all ions are loosed when travelling from their creation to the substrate

All reactor have advantages and defaults

ASM / BENEQ / TEL …



- Remote plasma
  - Most common PEALD type
  - No ion bombardment on substrate



- Direct plasma
  - Possible to tune film properties *e.g.* film stress
  - Adhesion pre-treatments etc… possibilities

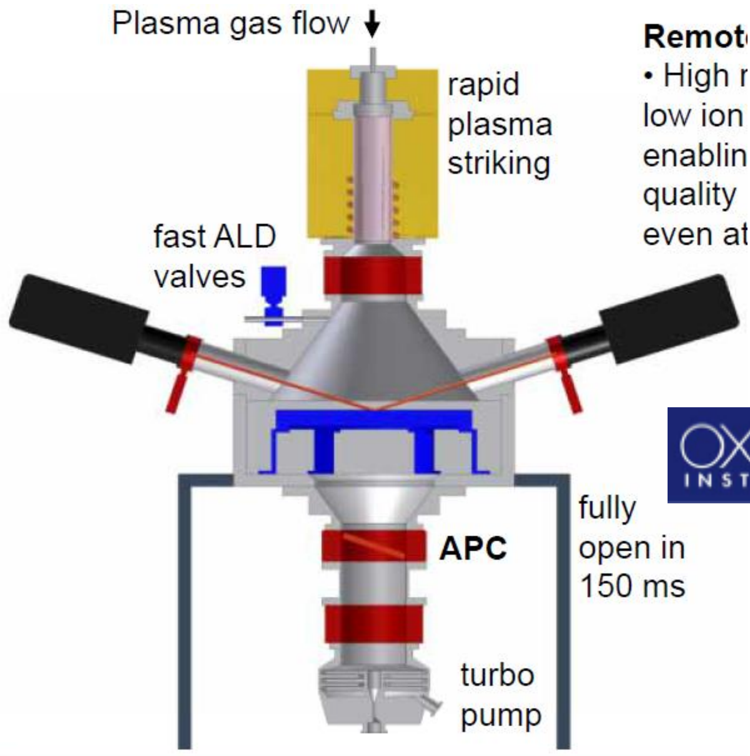
Plasma uniformity / substrate
High flux of radicals (/ions)
Double frequency
High Pressure (collisional sheath)
No ion bombardment (grid)

Substrate where the plasma is ignited
Ion bombardment (direct plasma)
Plasma damage
Substrate heating
No control of ion energy

PEALD plasma reactors

All reactor have advantages and defaults
PICOSUN / OXFORD …

Picosun



OXFORD INSTRUMENTS

Remote plasma
Substrate not in the plasma ignition zone
Control of ion energy may be possible

Plasma uniformity
Plasma damage
Limited to low/moderate pressure

Batch tool

TELINDY PLUS

Si_3N_4 ALD process with dichlorosilane (DCS) and ionized (plasma) ammonia (NH_3) at 500°C in a furnace

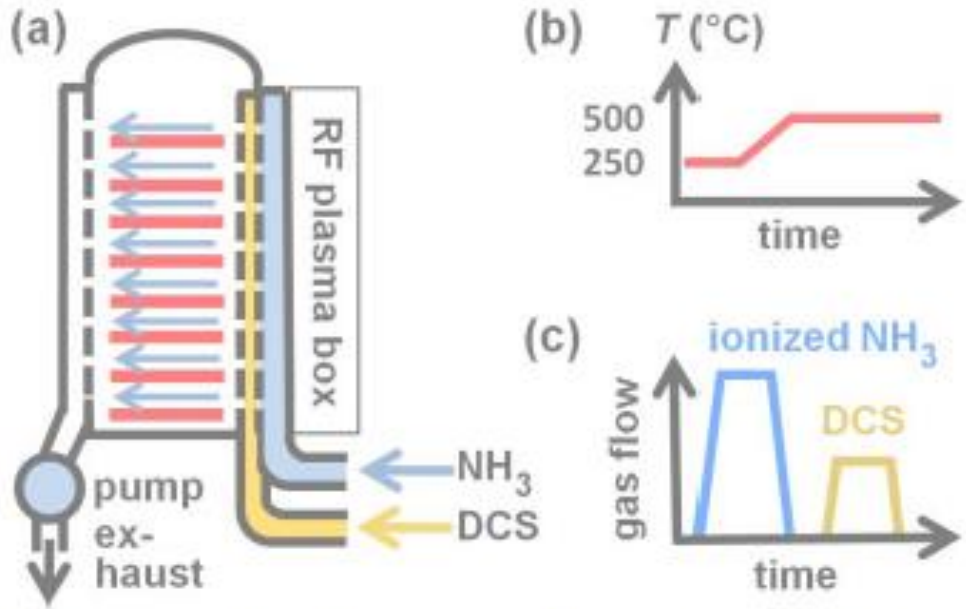


Figure 2 Cross-flow reactor, the red lines symbolize the wafers (a), temperature profile of the reaction chamber (b) and gas flows (c) of one ALD cycle.

A batch furnace can process up to 100 wafers at the same time, which makes the process more cost effective compared to single wafer process. (5nm ~1 hour)

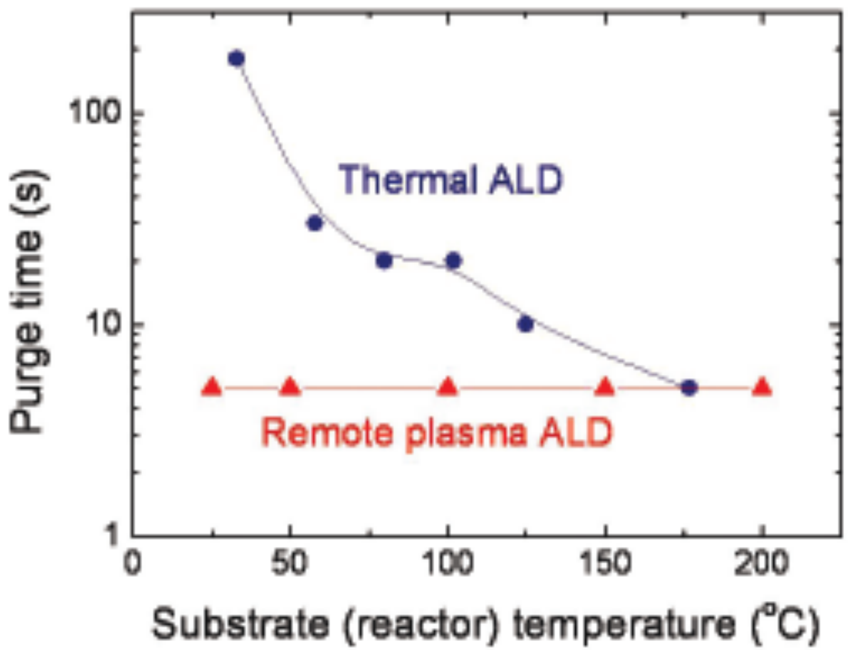
Fabian Koehler*, Dina H. Triyoso, Itasham Hussain**, Bianca Antonioli, and Klaus Hempel
Phys. Status Solidi C **11**, No. 1, 73–76 (2014) / **DOI** 10.1002/pssc.201300157

Plasma ALD is (may) using same precursors than thermal ALD
Only the gas nature of the activation step is modified

Material	**ALD precursor**	**Plasma gas**
Oxide	H_2O ou O_3	O_2
Nitride	NH_3	N_2/H_2
Metal	O_2, N_2/H_2, …	H_2

from Oxford Instrument

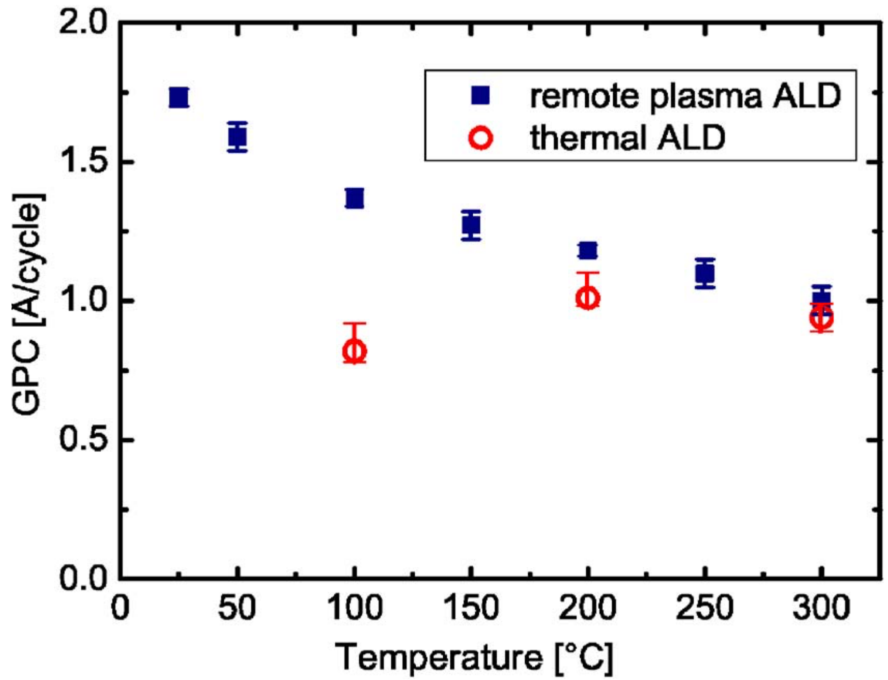
Thermal ALD vs PEALD: Al_2O_3



Purge time for thermal ALD of Al_2O_3 (H_2O) and remote plasma ALD of Al_2O_3 (O_2). *Data courtesy of Eindhoven University of Technology*

Long purge times with H_2O
at low temperature

Source: Oxford instruments

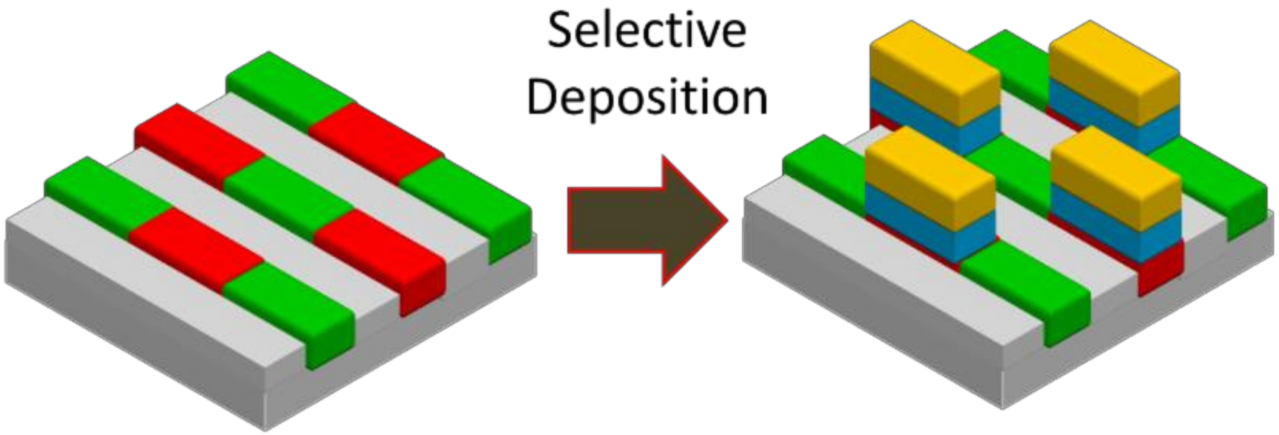


Decrease is attributed to thermally activated recombination reactions of surface hydroxyl groups – OH (dehydroxylation)

J. L. van Hemmen,[a] S. B. S. Heil,[a,*] J. H. Klootwijk,[b] F. Roozeboom,[c,**] C. J. Hodson,[d] M. C. M. van de Sanden,[a] and W. M. M. Kessels[a,**,z]
Journal of The Electrochemical Society, **154** (7) G165-G169 (2007)

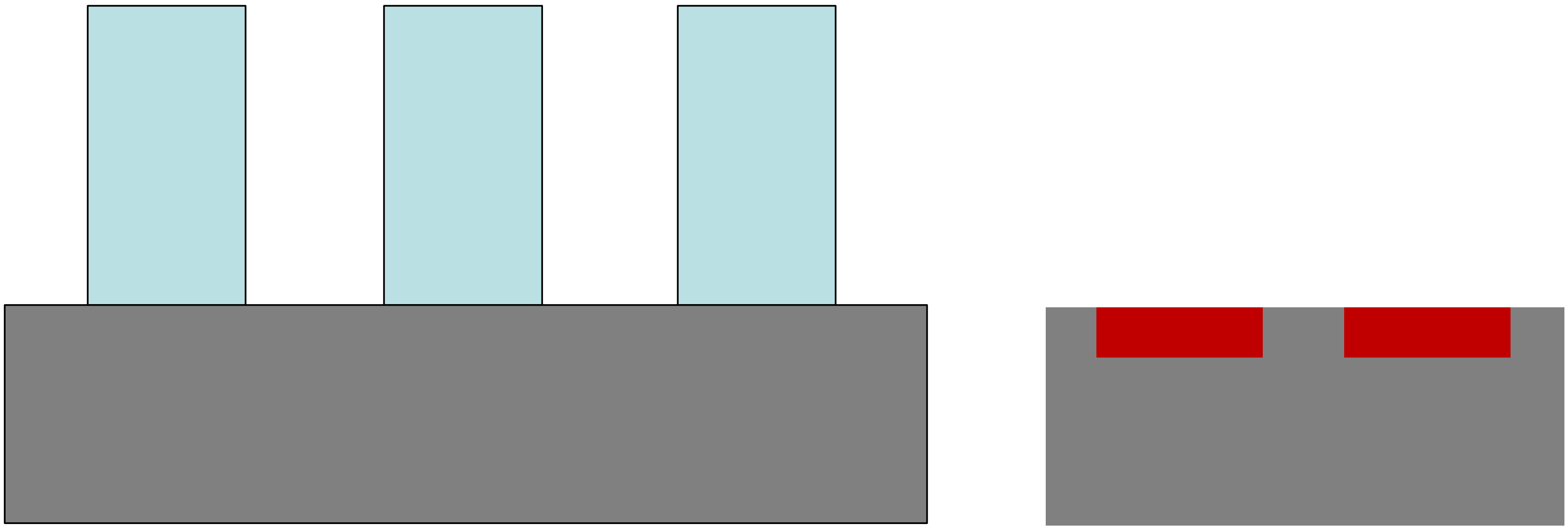
PEALD For Area Selective Deposition

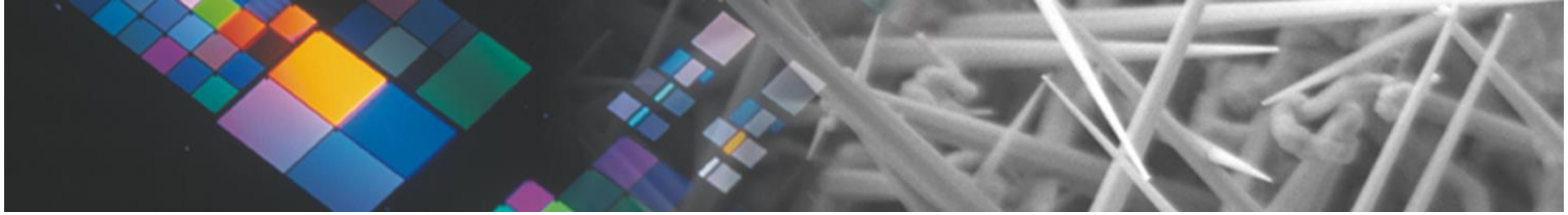
- What is ASD?
- ASD for microelectronics?
- A way to do it: add a plasma etching step in PEALD step



What is Area Selective Deposition?

Hey guys I need a thin oxide deposition on my two wafers

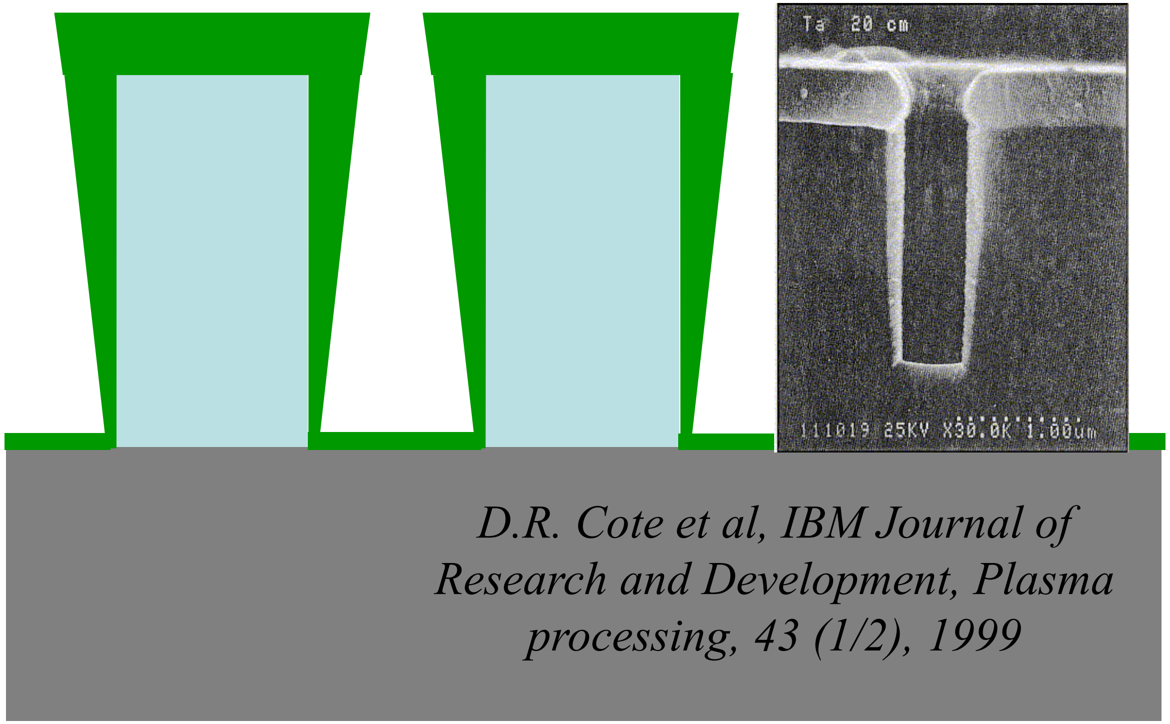




What is Area Selective Deposition?

Hey guys I need a thin oxide deposition on my two wafers

PVD man (70/80's): let's go!

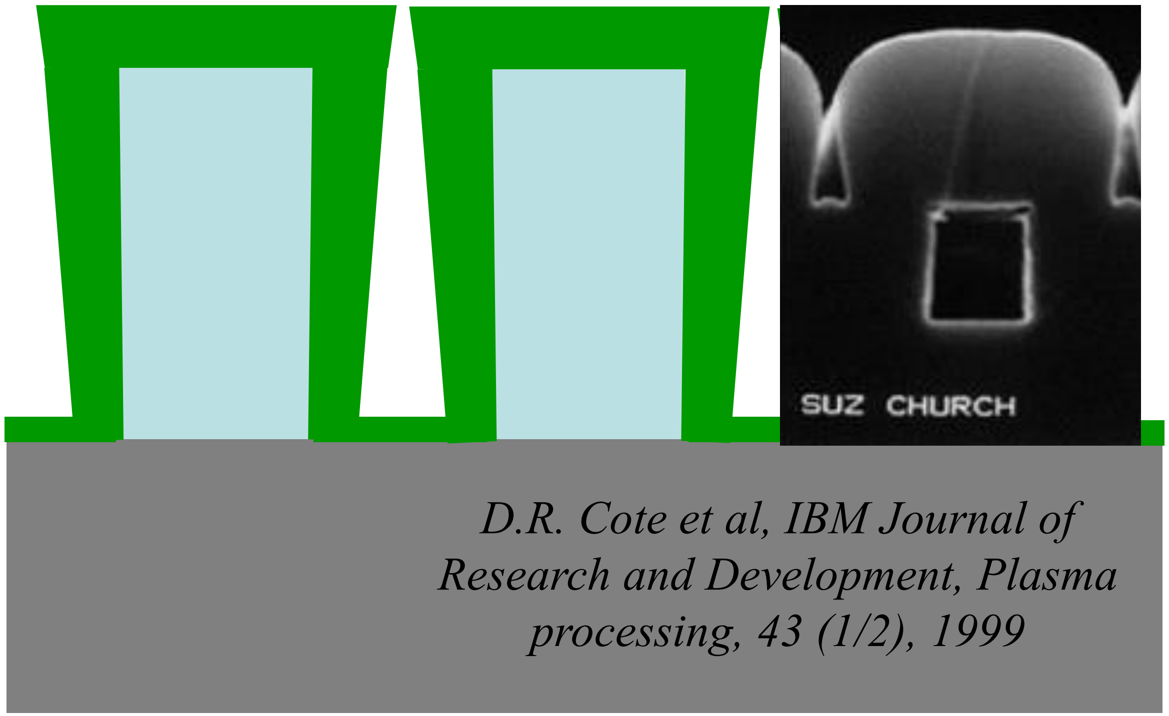


D.R. Cote et al, IBM Journal of Research and Development, Plasma processing, 43 (1/2), 1999

What is Area Selective Deposition?

Hey guys I need a thin oxide deposition on my two wafers

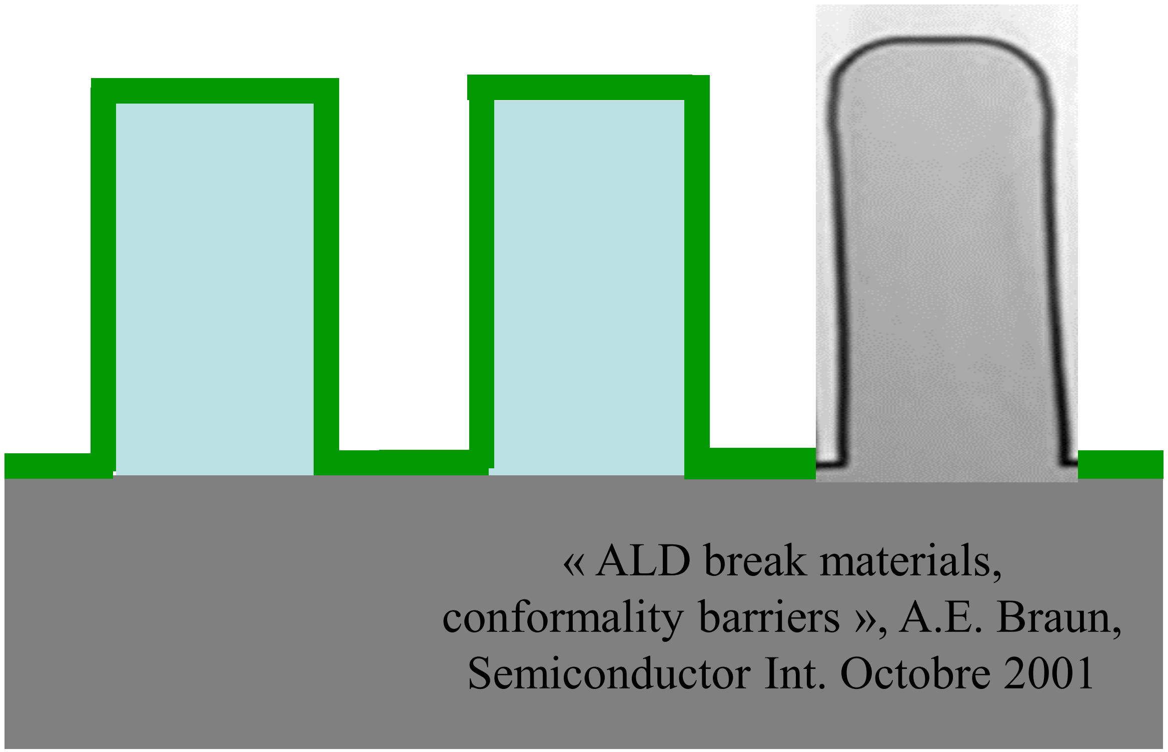
(PE)CVD man (80/90's): In can do better for the 3D substrate!

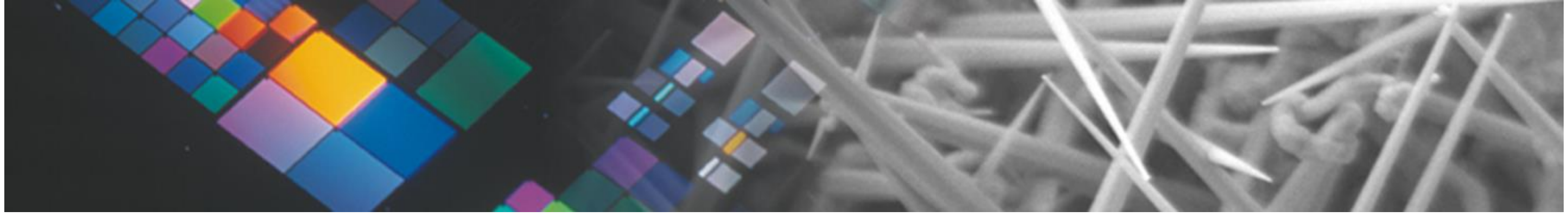


What is Area Selective Deposition?

Hey guys I need a thin oxide deposition on my two wafers

(PE)ALD man (2000’s): No ways, I am the best!

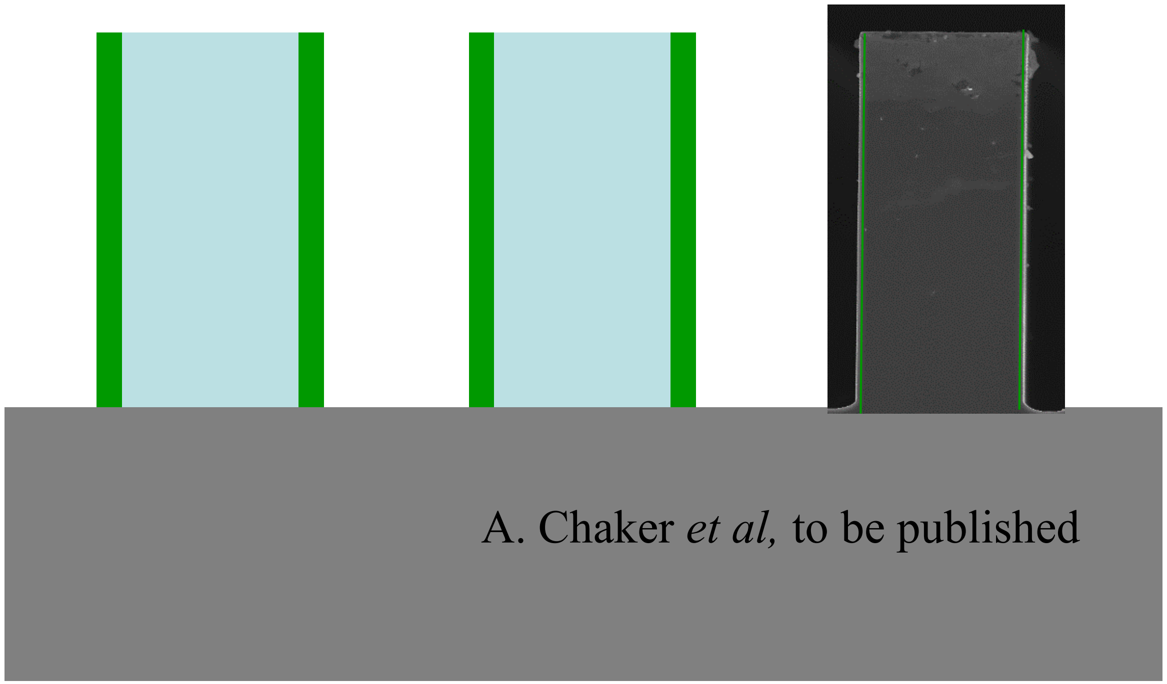


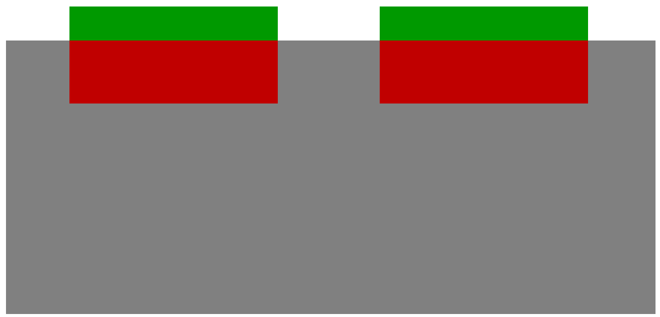


What is Area Selective Deposition?

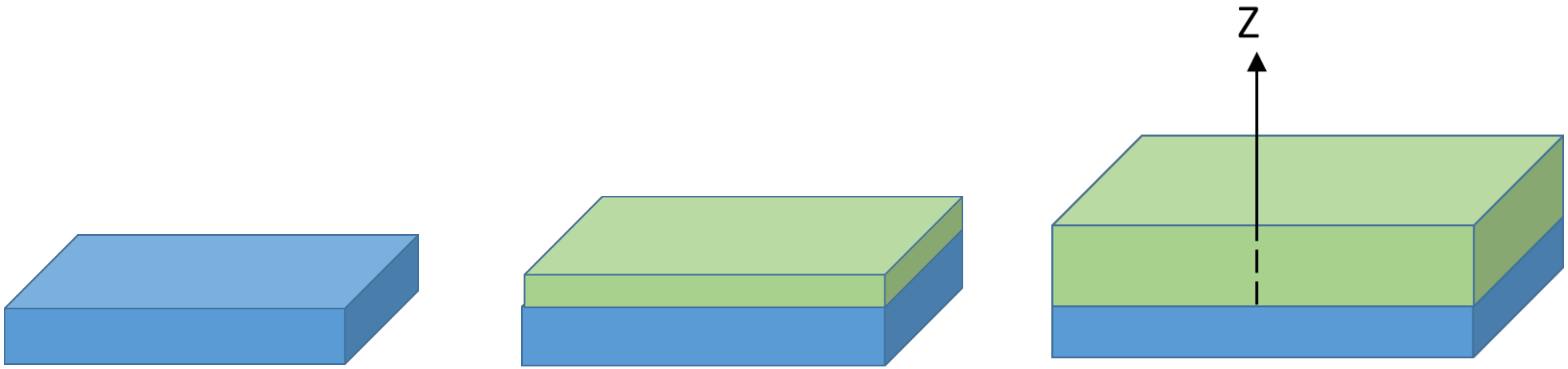
Hey guys I need a thin oxide deposition on my two wafers

ASD man (now to…..): I can select the area!





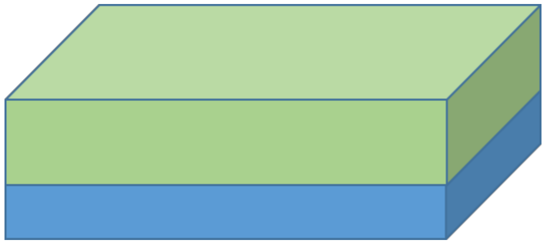
PVD, (PE)CVD, ALD:
Deposition of thin films is made in the z direction
(control of the thickness)

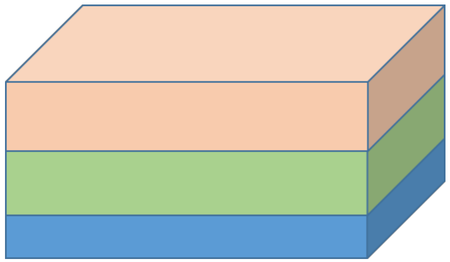


How can we obtain the control of the two other directions (x,y)?

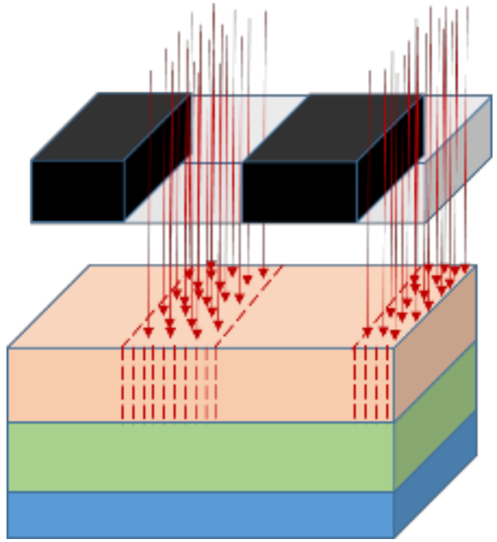
Patterning – top down approach

Patterning steps – TOP DOWN approach

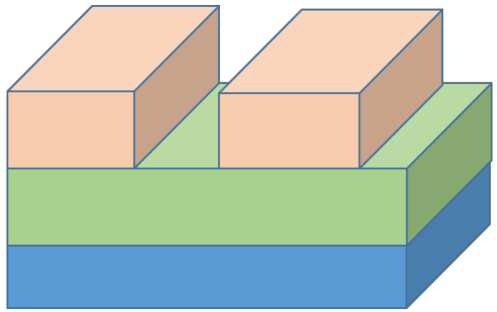


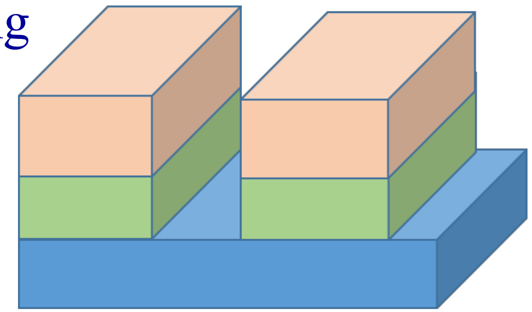


Lithography step: resist deposition
+ mask definition

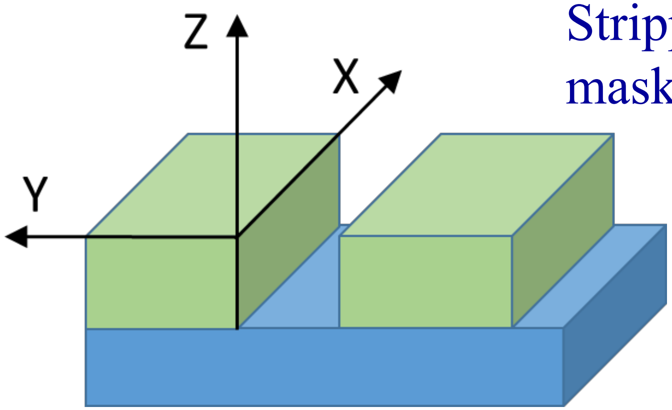


Plasma etching step:
mask transfer



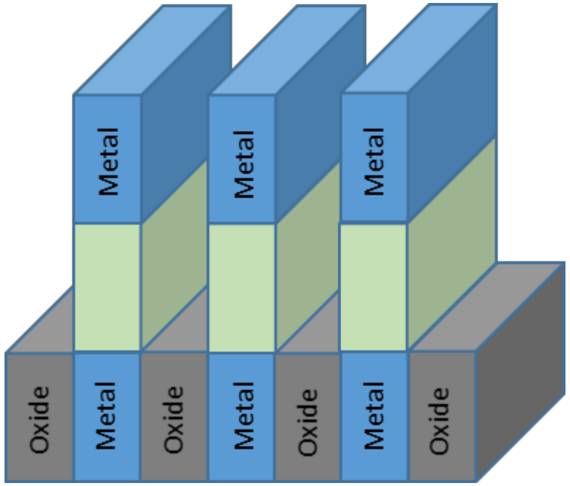


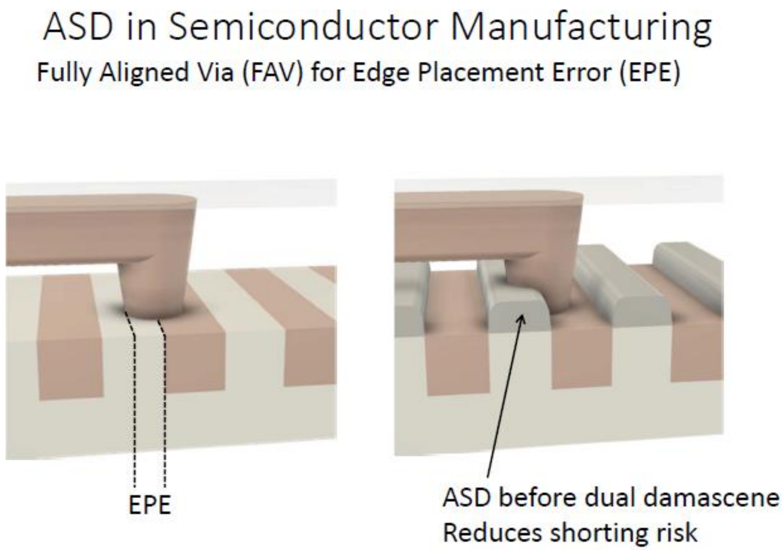
Stripping:
mask etching

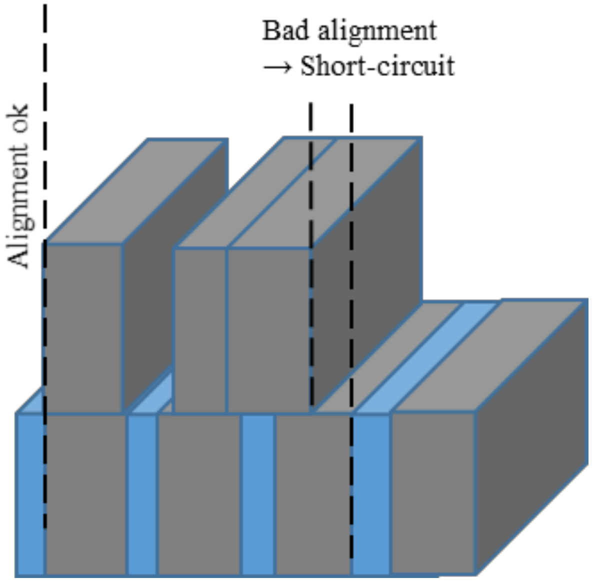


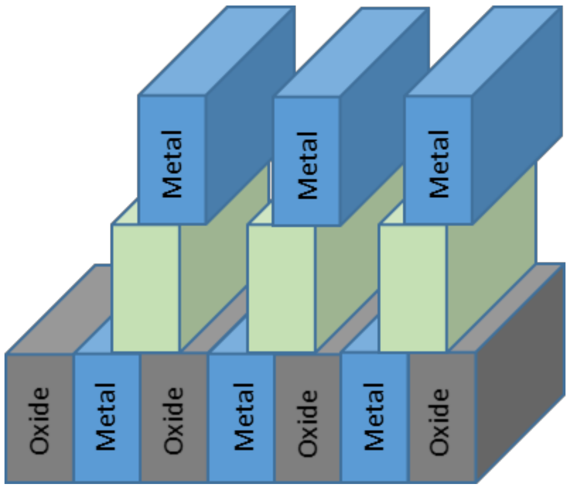
LTM
LABORATOIRE DES TECHNOLOGIES DE LA MICROÉLECTRONIQUE

More an more complex patterning using two of several steps of patterning (masks and exposure) – alignment for is crucial







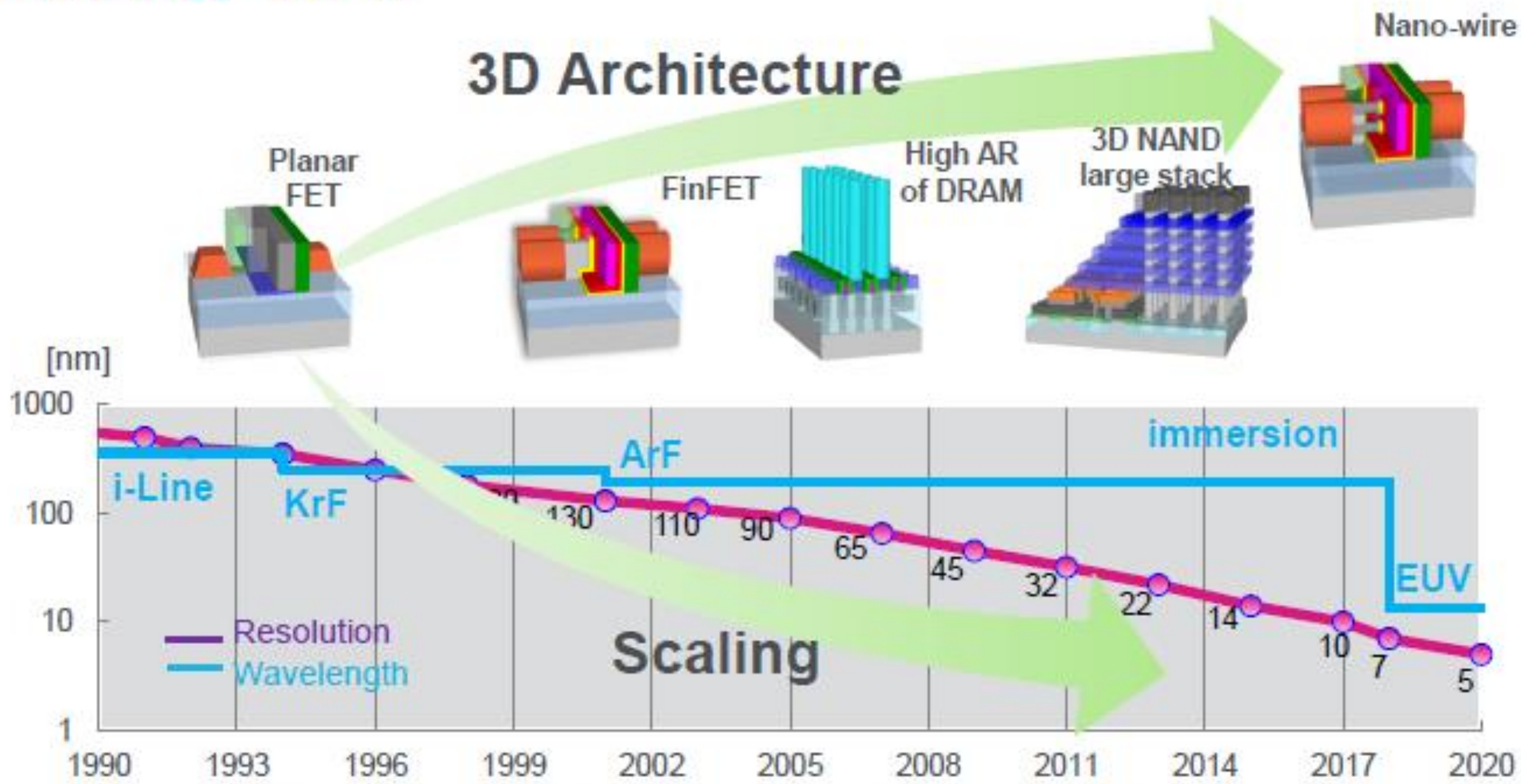


G.N. Parsons
ALD2018 tutorial

LABORATOIRE DES TECHNOLOGIES DE LA MICROÉLECTRONIQUE

Gert Leusink
Director, Thin Films Process Technology & Integration
Sr. Member Technical Staff
TEL Technology Center, America, LLC

Technology trend



Vertical utilization is the key approach towards sub-10nm generation

ASD-2017 Workshop

Resolution needed for the scaling of the pitch is no more following the wavelength of the stepper → introduction of complex **multiple patterning processes**

Self-Aligned Quadruple Patterning: the pitch is reduced by a factor of 4

Material used for spacer »

SiO_2 and Si_3N_4 by PEALD

Low T°

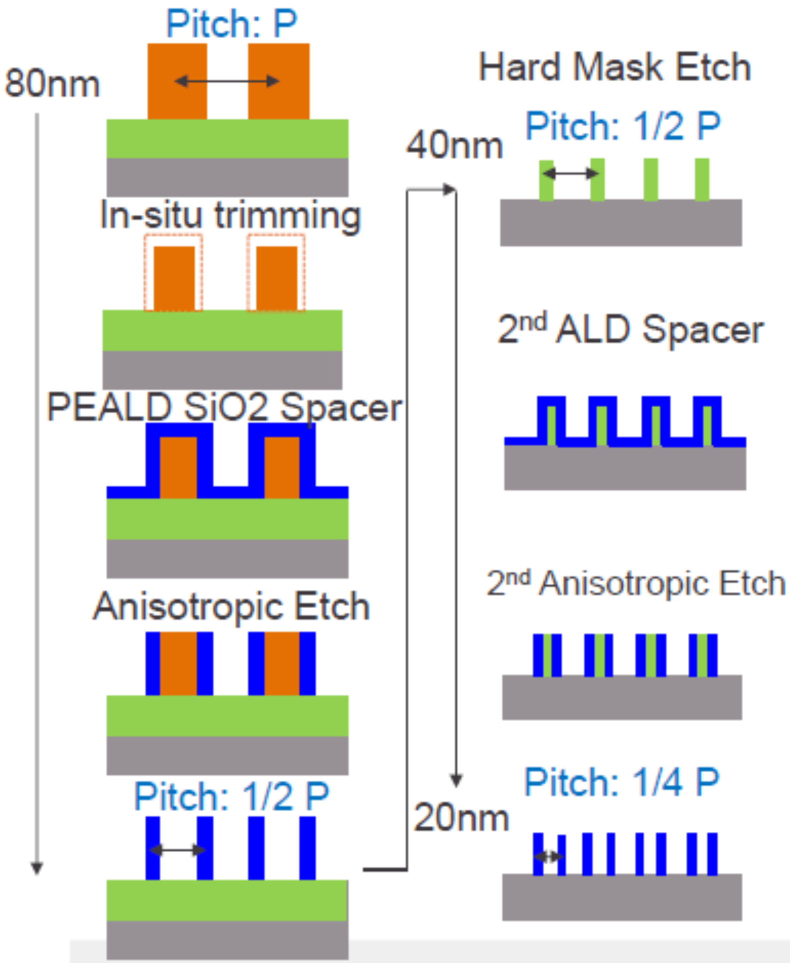
(300 – 500 °C)

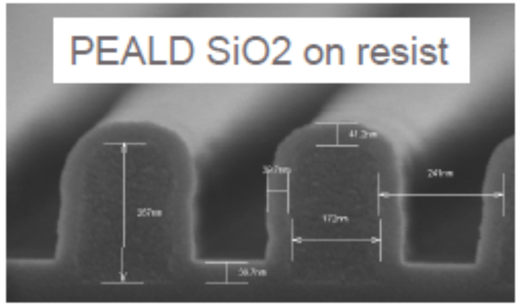
Conformal deposition

High quality

ALD ENABLING SUB-RAYLEIGH LIMIT LITHOGRAPHY WITH SPACER DEFINED DOUBLE/QUADRUPLE PATTERNING

ASM





✓ **Spacer Defined Double Patterning with PEALD in production since 3x nm DRAM and Flash**

✓ **Spacer Defined Quadruple Pattering in production for 1x nm Flash**

Key enablers brought by PEALD

- Uniformity: CD control
- Low temperatures (<100C)
- Good step coverage
- Dense film
- In-situ trimming capability
- Extendible to other materials with high etch selective

| 19

Multipatterning processes is needed for actual and future transistors

→ Increase of wafer cost
→ Misalignment errors

Patterning method	Normalized cost per wafer
Single Exposure (SE)	1
Litho Etch Litho Etch (LELE)	2.5
Litho Etch Litho Etch Litho Etch (LELELE)	3.5
Self-Aligned Double Patterning (SADP)	2
Self-Aligned Quadruple Patterning (SAQP)	3
Extreme UV (EUV) Single Exposure (SE)	4
EUV + SADP	6

A. Raley et al., Proc. SPIE 9782, 97820F (2016)

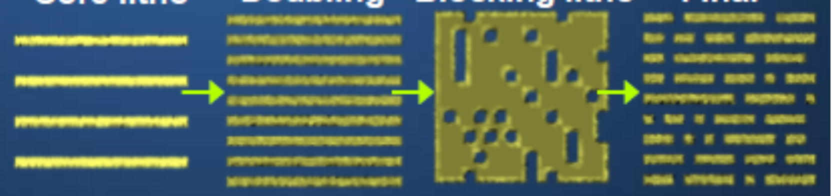
Self-Aligned Multiple Patterning

	32nm		10nm		7nm	
Active	193i	1	SADP + Cut	1+1	SAQP + LE2 Cut	1+2
Gate	193i + Cut	1+1	SADP + Cut	1+1	SADP + Cut	1+1
Contact	193i + 193i	2	LE2+LE2	4	LE2 + LE3	5
Via 0	193i	1	LE2	2	LE3	3
Metal 1	193i + Cut	1+1	LE3	3	SADP + LE3 Block	1+3
Via 1	193i	1	LE2	2	LE4	4
Metal 2	193i + Cut	1+1	SADP + Block	1+1	SAQP + LE3 Block	1+3
	Mask Count	**12**	**Mask Count**	**17**	**Mask Count**	**25**

Source: Julien R, IMEC

Metal 1

Gate



TEL™

SaMP also increase process complexity

Takashi Hayakawa / Tokyo Electron Limited / March 18th, 2015

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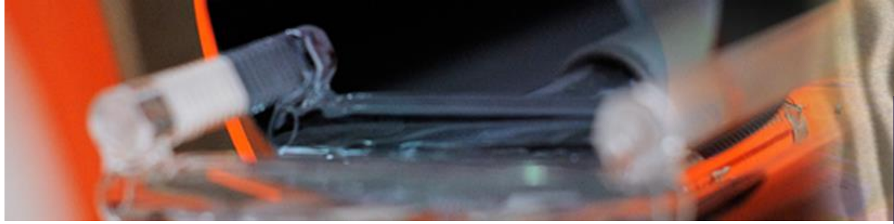
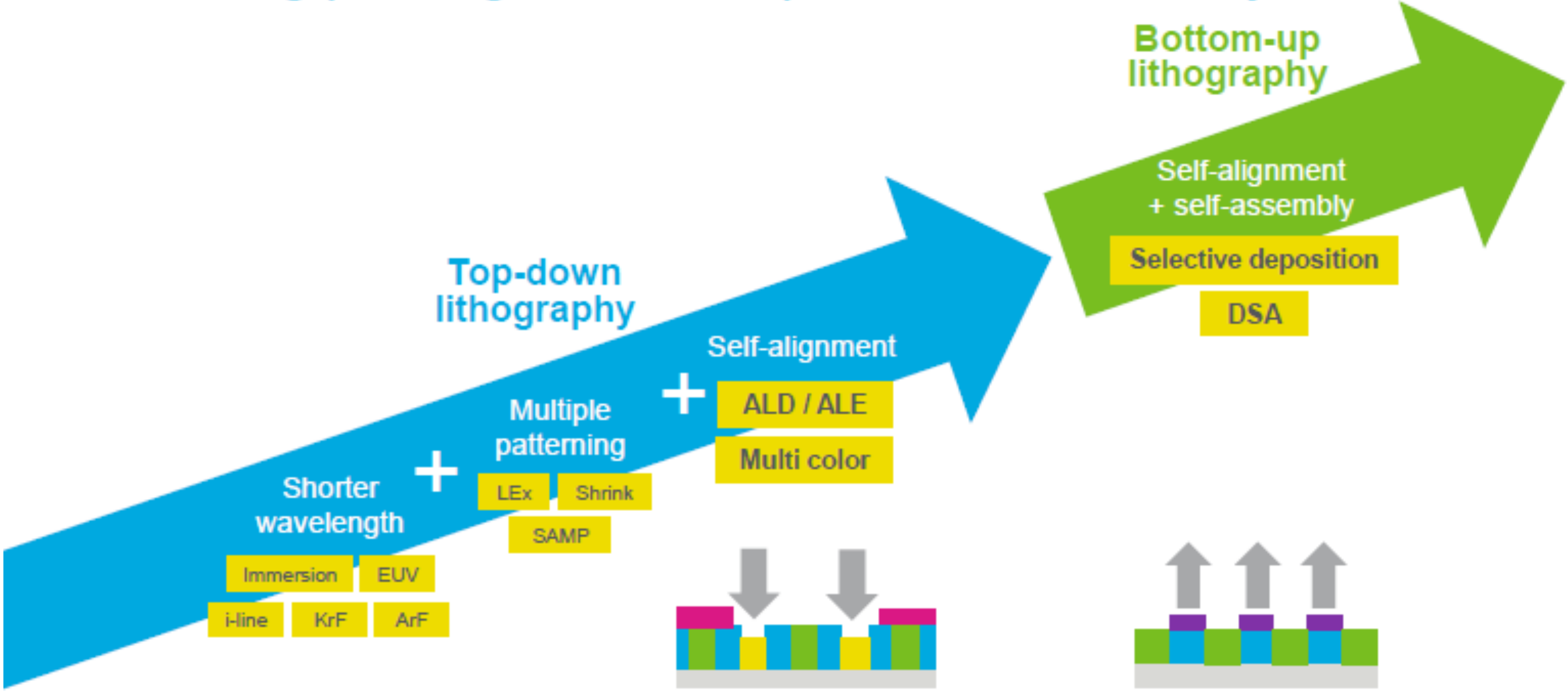


Gert Leusink
Director, Thin Films Process Technology & Integration
Sr. Member Technical Staff
TEL Technology Center, America, LLC

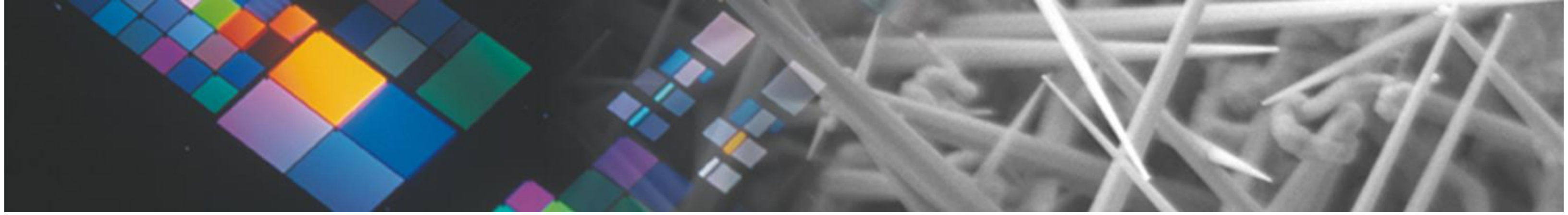
Patterning paradigm towards placement accuracy



The paradigm is expanding to self-alignment and bottom up approach

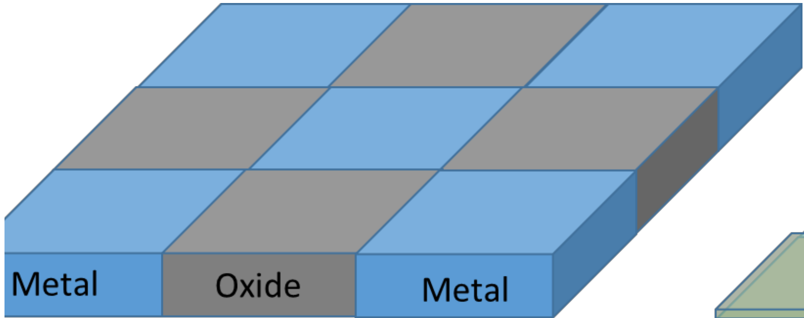
ASD-2017 Workshop

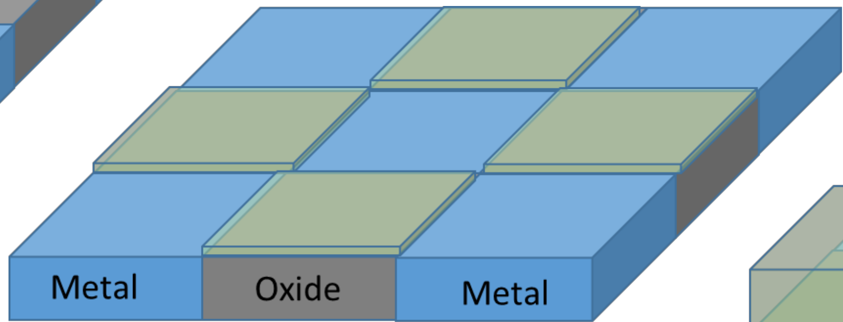
TEL

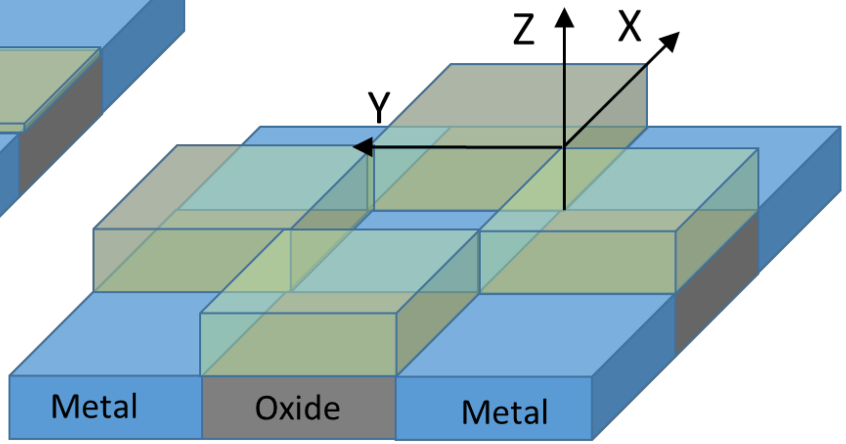


Area Selective Deposition: new bottom-up approach

growth is controlled in the 3 directions

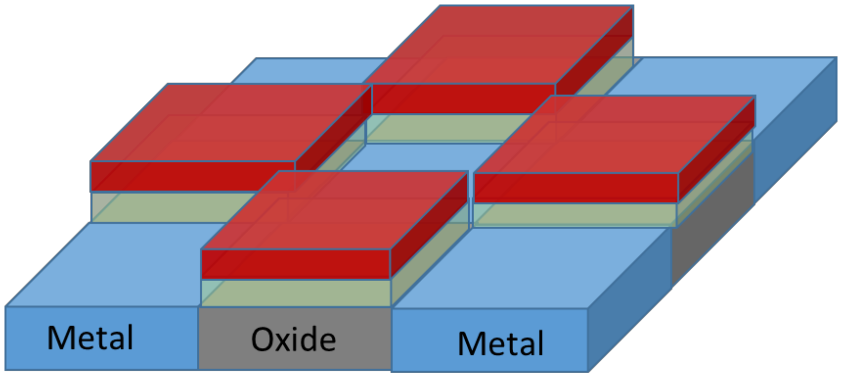


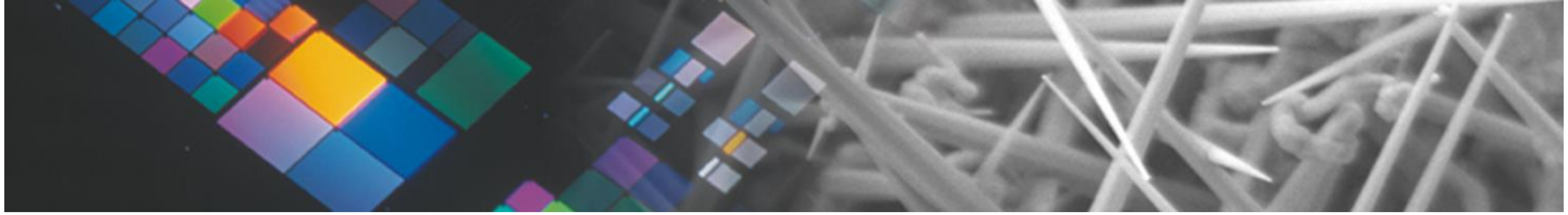




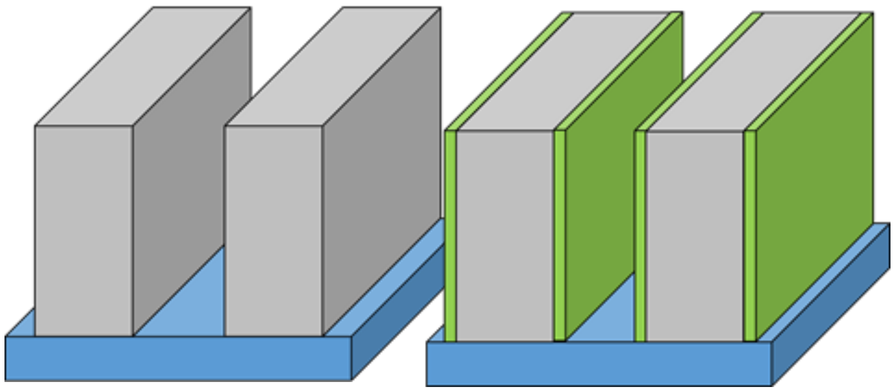
The deposition can depend on the chemical nature of the surface

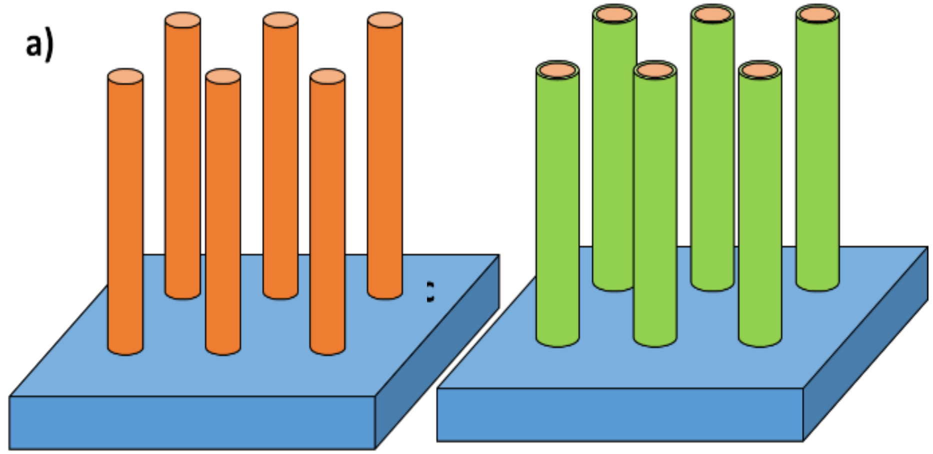
(no deposition on metallic surface)



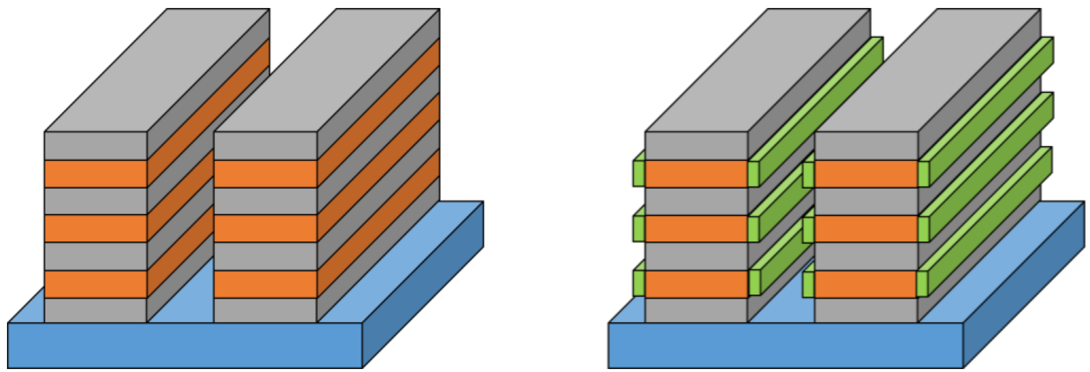


The deposition can also be selective in one direction versus the others



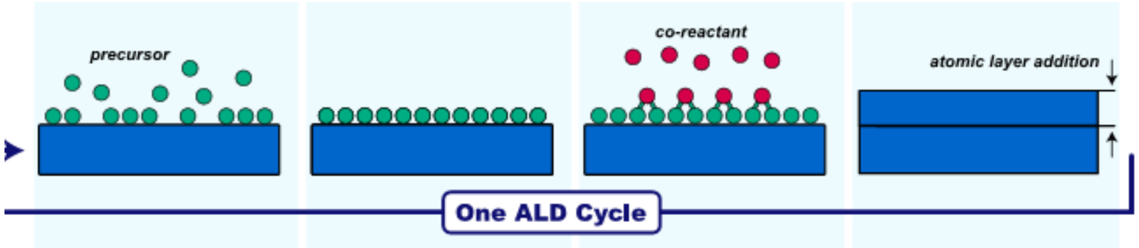


More complex: surface selectivity + directional growth

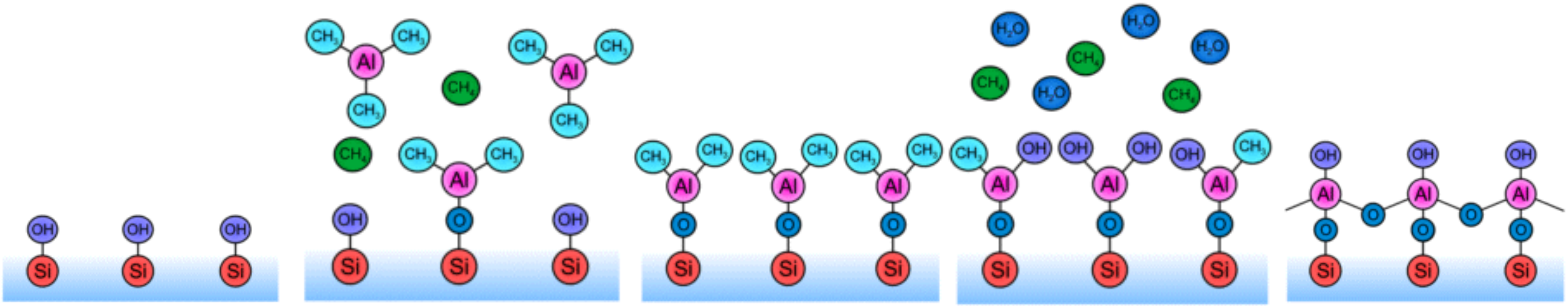


Why using ALD for ASD?

ALD
- Cyclic deposition
- **Self-limiting reactions**
- Very conformal



Very sensitive to the surface

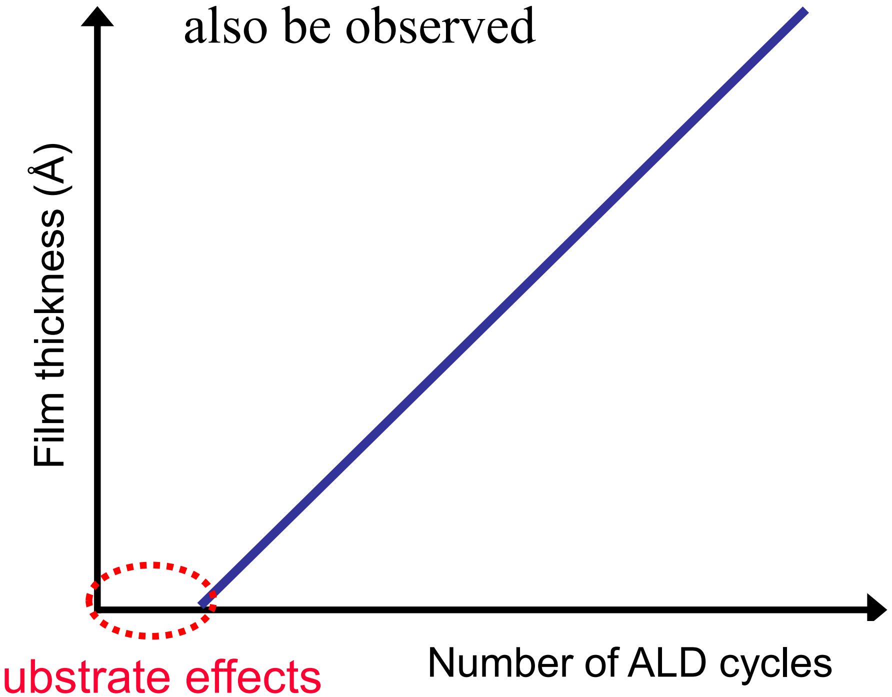


In this ALD example, deposition starts from a –OH terminated surface

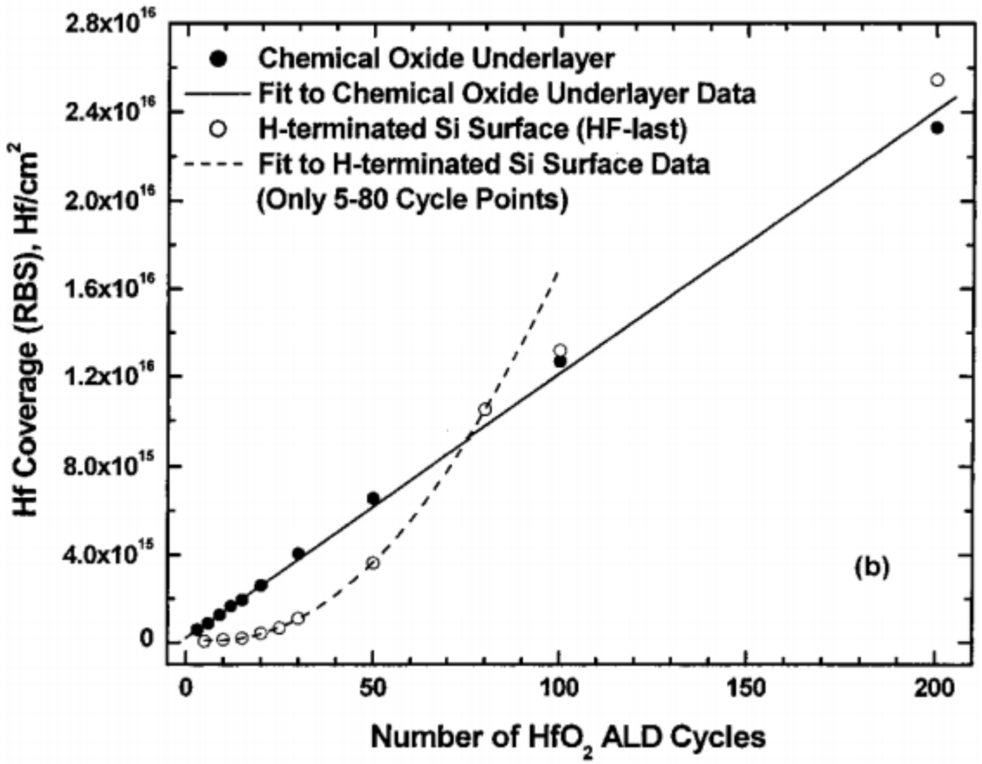
Precursors may react with one substrate, but not with another

A precursor may etch away a substrate or react with subsurface layers. Or a precursor may not react at all on a substrate - such nucleation delays are common, *e.g.* for oxides on H-terminated silicon or for metals on oxides

The ADL growth can start from the first cycle but delays may also be observed



M. A. Alam, and M. L. Green
Journal of Applied Physics, (2003)



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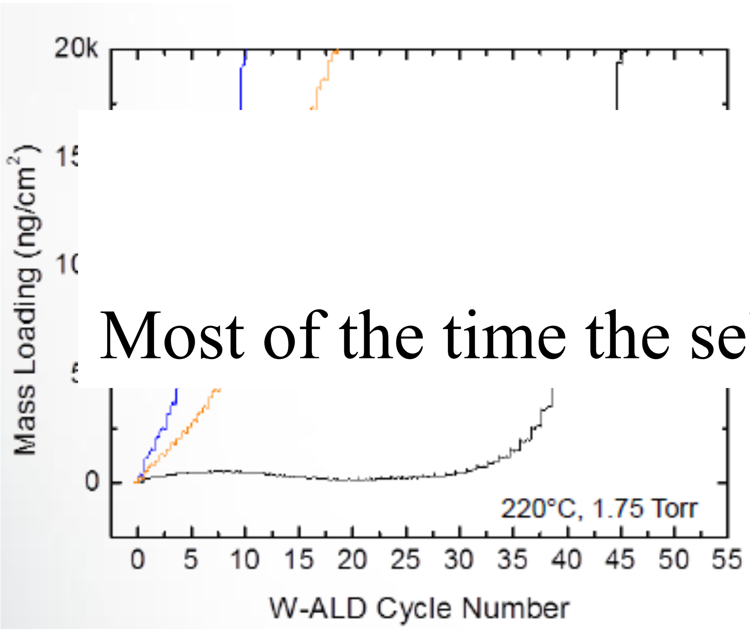
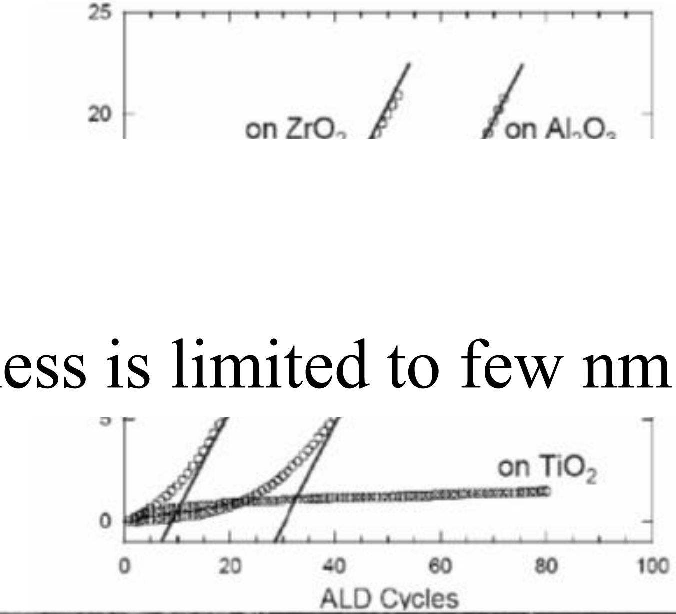
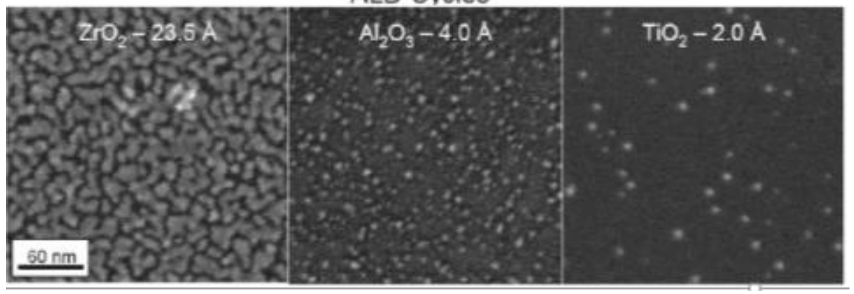
This can be used for ASD, it is ASD by inherent selectivity
- It can be inherent or induced by a post deposition treatment
- Need better understanding between surface and precursors interactions





BUT:

Most of the time the selective thickness is limited to few nm



Tungsten nucleation delay is substrate dependent
- Surface bound water inhibits W-ALD nucleation
- SiH_4 pre-exposure promote nucleation

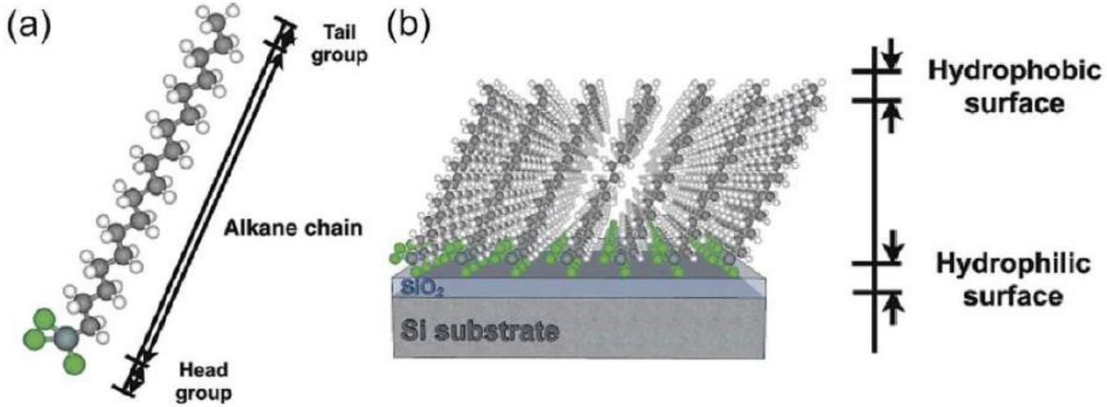
Kalanyan, B.; Lemaire, P. C.; et al. *Chem. Mater.* **2016**.

J. W. Elam ECS Transactions, (2007)

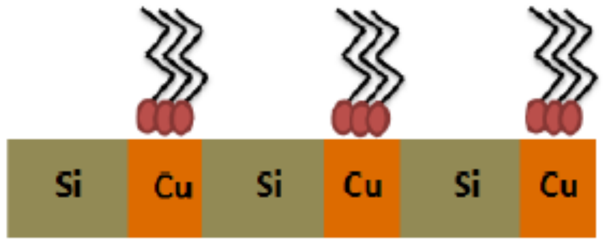
Two strategies to improve the selectivity:

- using an area activation,
- using an area deactivation

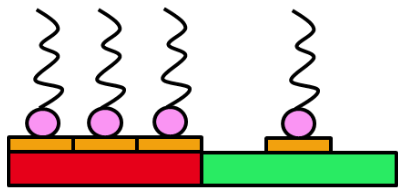
Review paper: *The use of ALD in advanced nanopatterning*
Mackus *et al.*, *Nanoscale* 6, 10941 (2014)



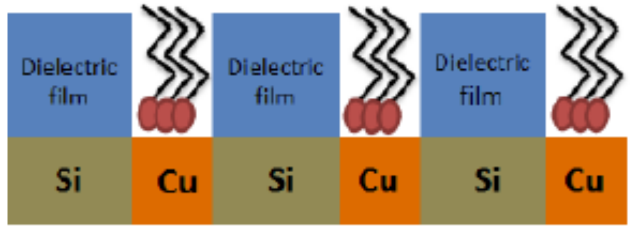
Selective ALD deposition of dielectrics (or metals) using self-assembled monolayers



Types of SAMs	
Thiols	R-SH
Silanes	R-$SiCl_3$
Alkenes	R-C=C
Alkanoic acids	R-COOH
Phosphonic acids	R-PO_3H_3



SAMs



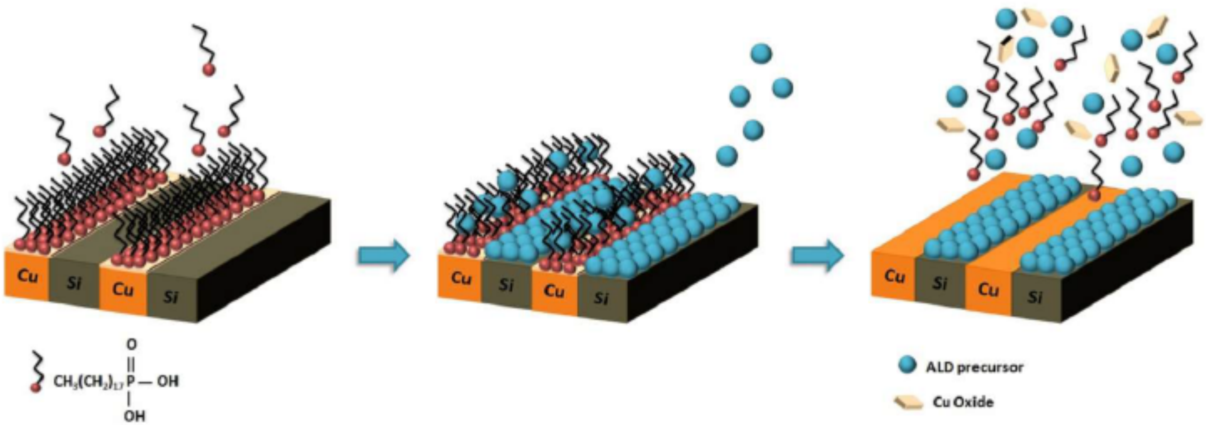
(Bent, et al, Stanford, 2014)

BUT: whatever the choice, a deposition may occur where it is not wanted after a given number of cycles (SAM not dense enough, SAM are reduces/modifies by a plasma,….)

Need to introduce corrective action:

<u>etching of undesired material</u>

Improve selectivity by chemical etching

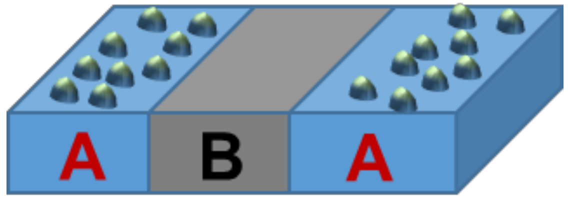


- Use an etchant to attack the underlying CuO_x and consequently remove the dielectric layer deposited on top of that
  - CuO_x etchants: acetic acid, hydrochloric acid, nitric acid

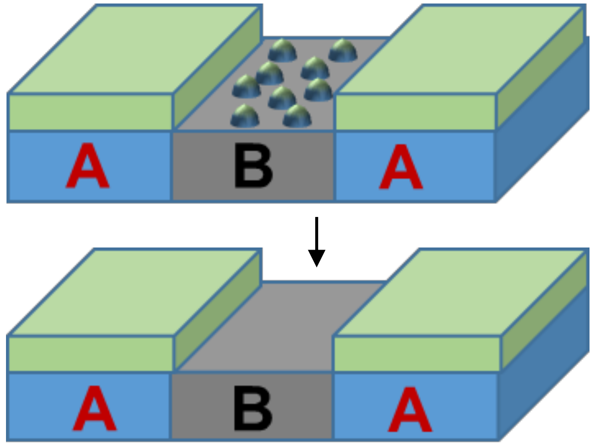
F. S. Minaye Hashemi, C. Prasittichai, and S. F. Bent, ACS Nano 9 (2015) 8710-8717.

Etching will enable a "perfect" ASD?

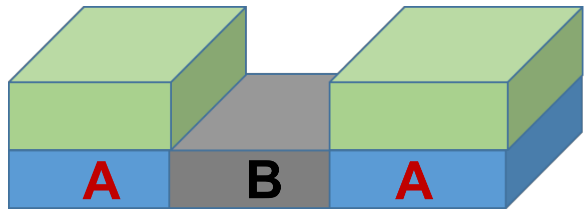
1. Different nucleation time between two surfaces A and B is needed (inherent selectivity, surface treatment…)



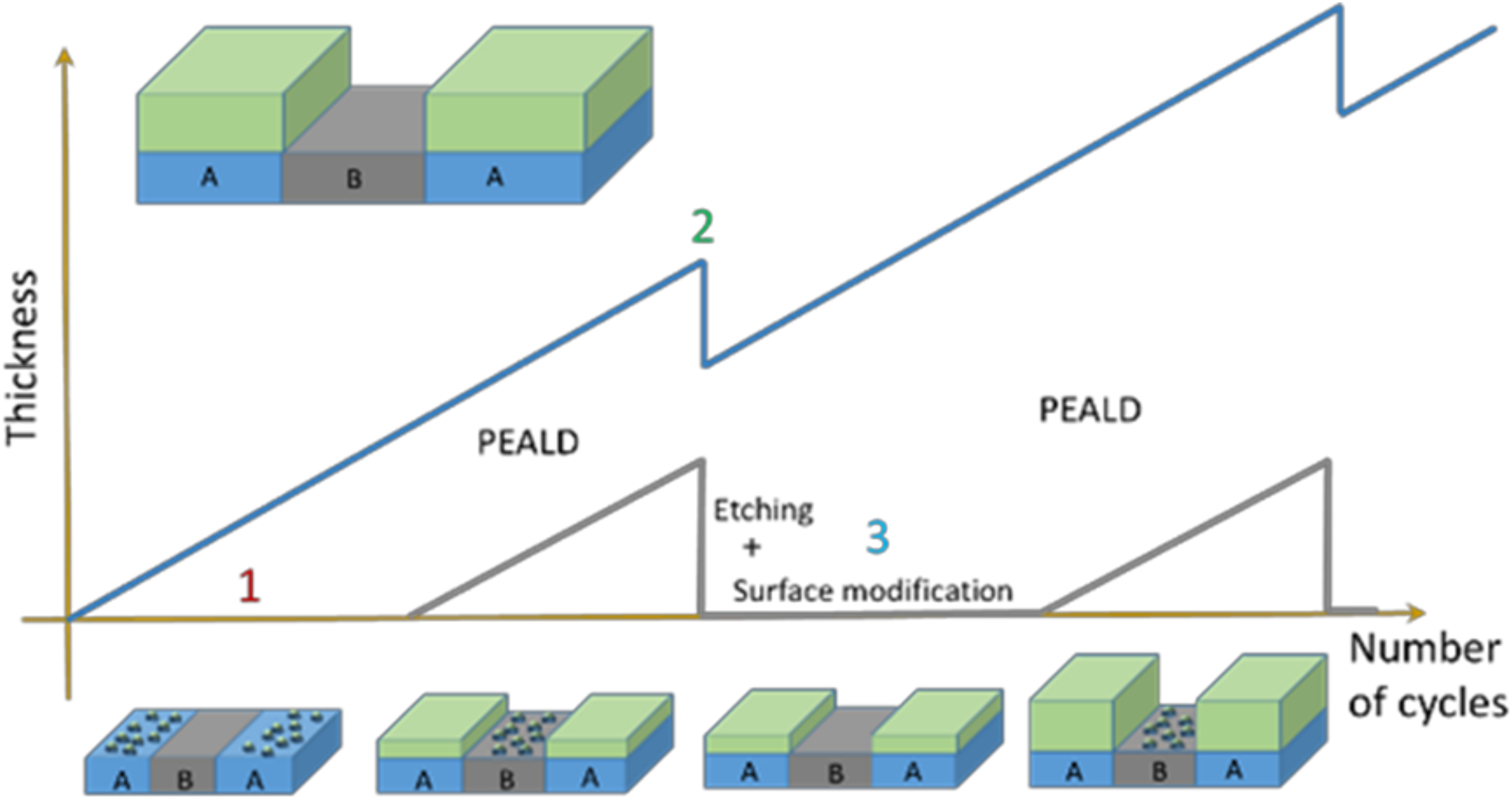
2. Precise etching at the nanometer scale to remove the deposited material from surface B



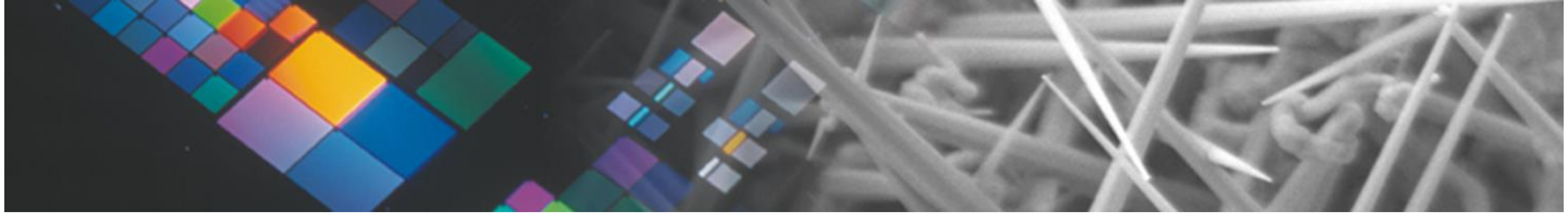
3. Add a new nucleation delay time for the surface B after or during the etching step



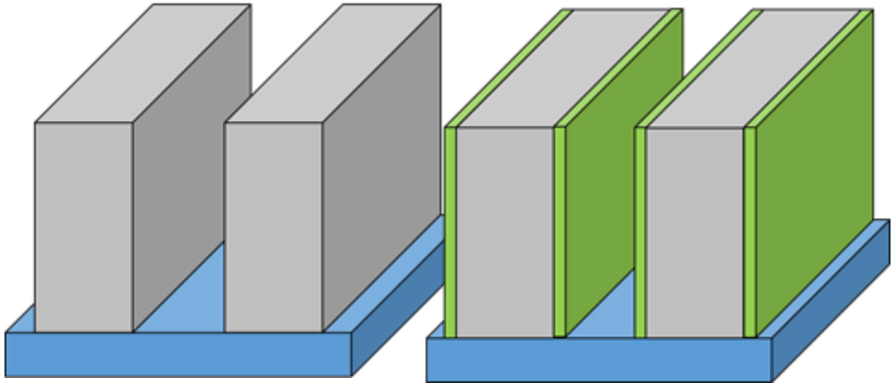
R. Vallat, R. Gassilloud, B. Eychenne, and C. Vallée, J. Vac. Sci Technol. A 35(1) 01B104 (2017)

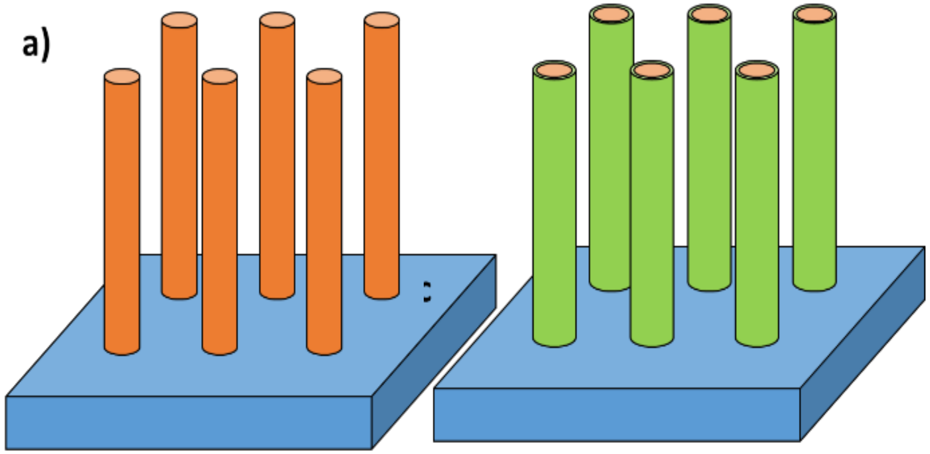


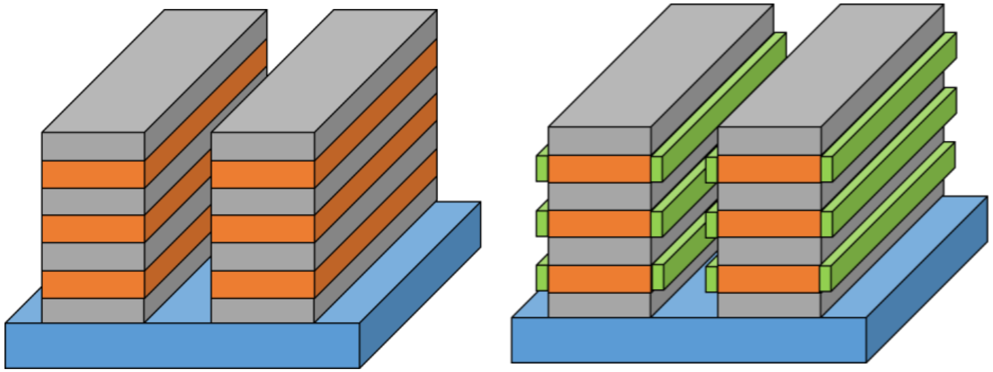
Need to do **both** Deposition (**PEALD**) and Etching (**ALE**…) in the **same tool**

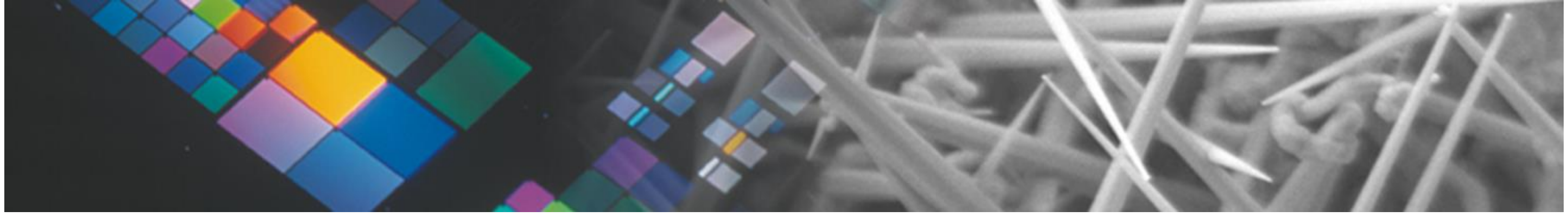


GO BACK TO SLIDE 13: HOW CAN WE DO THAT WITH THIS APPROACH?

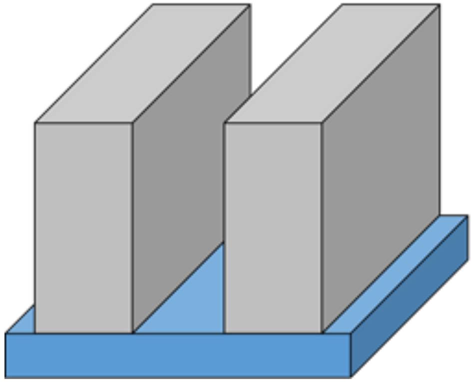




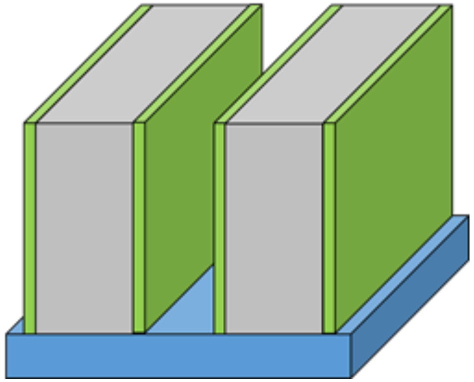


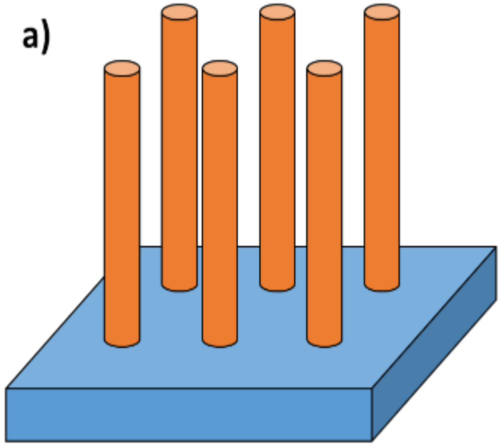


Selective Deposition

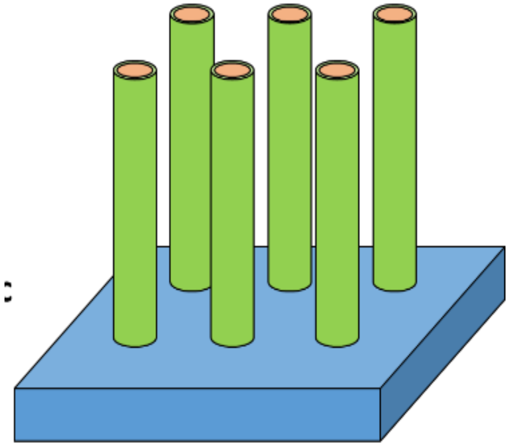


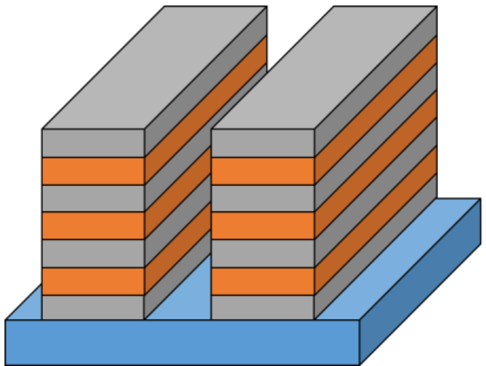
anisotropic etching
ion sputt., RIE, anisotropic ALE



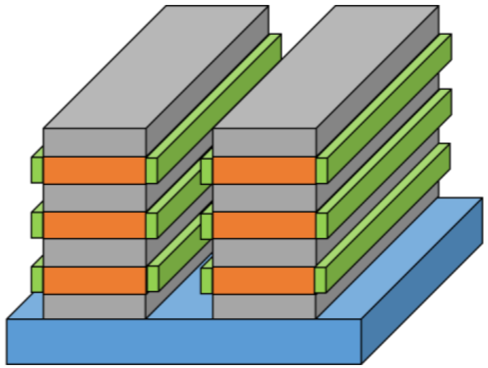


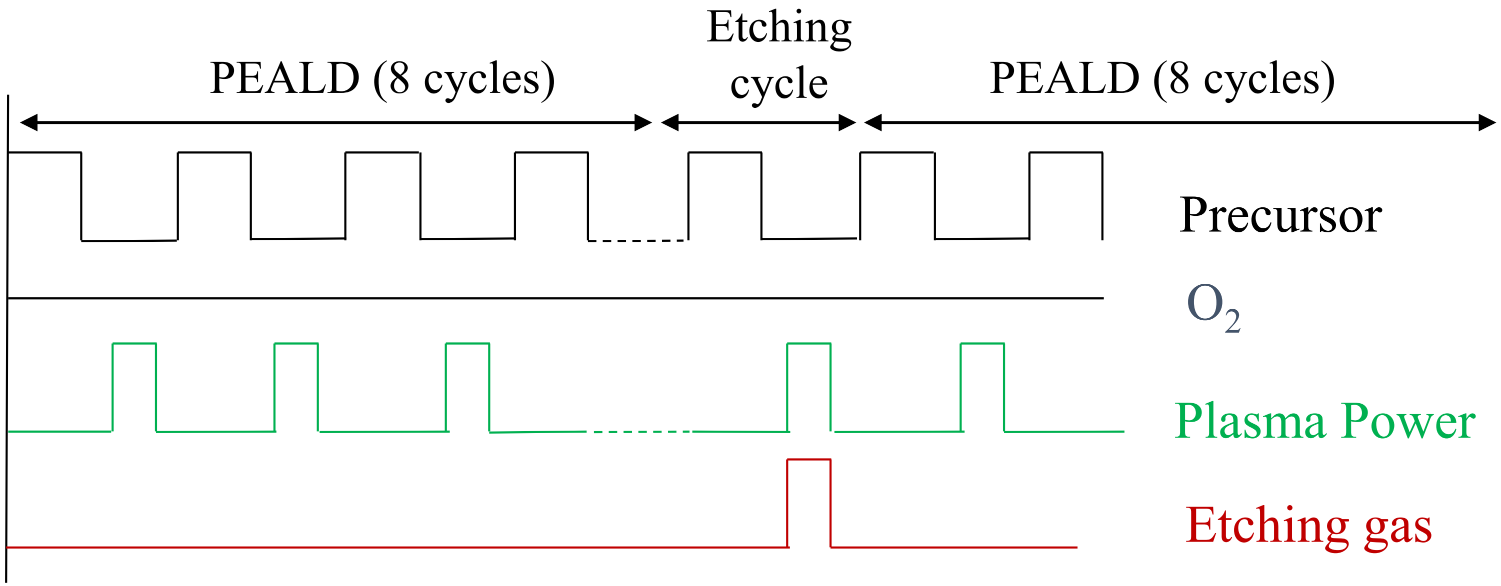
anisotropic etching
ion sputt., RIE, anisotropic ALE





isotropic etching
chem. etching, isotropic ALE



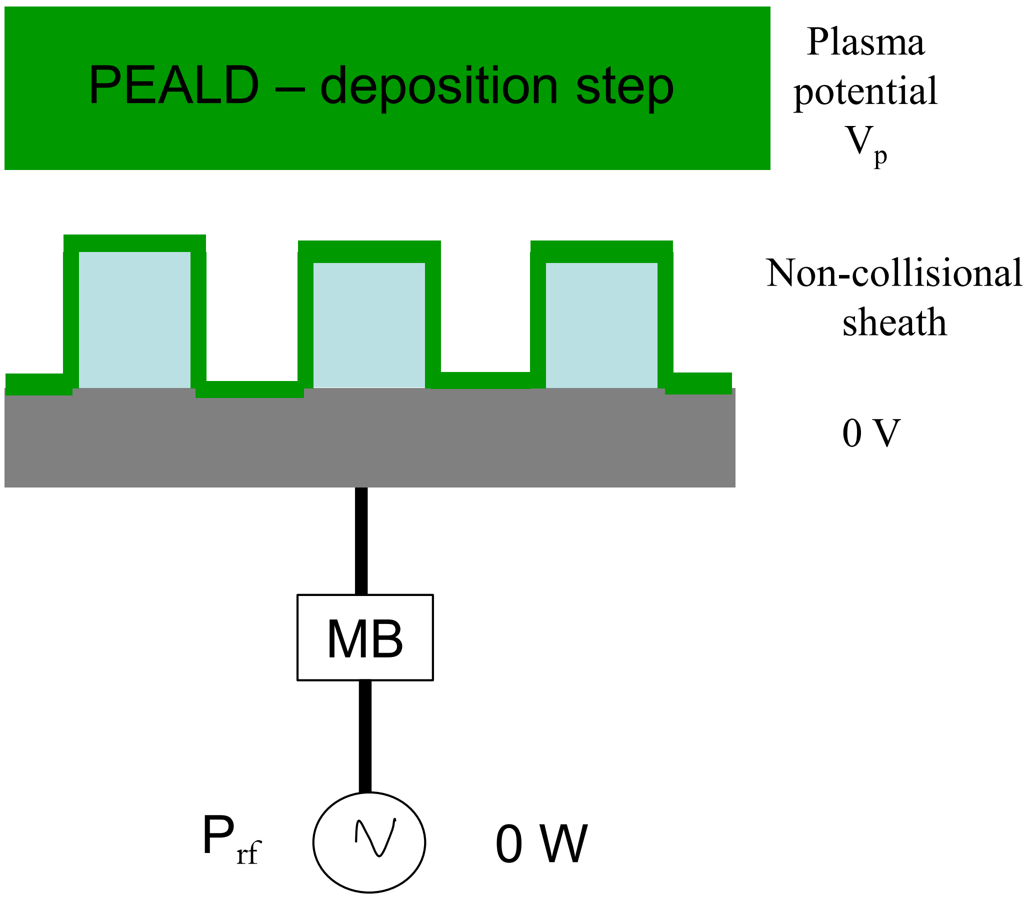


When? Every cycle, every 5 cycles, … → throughput of the process

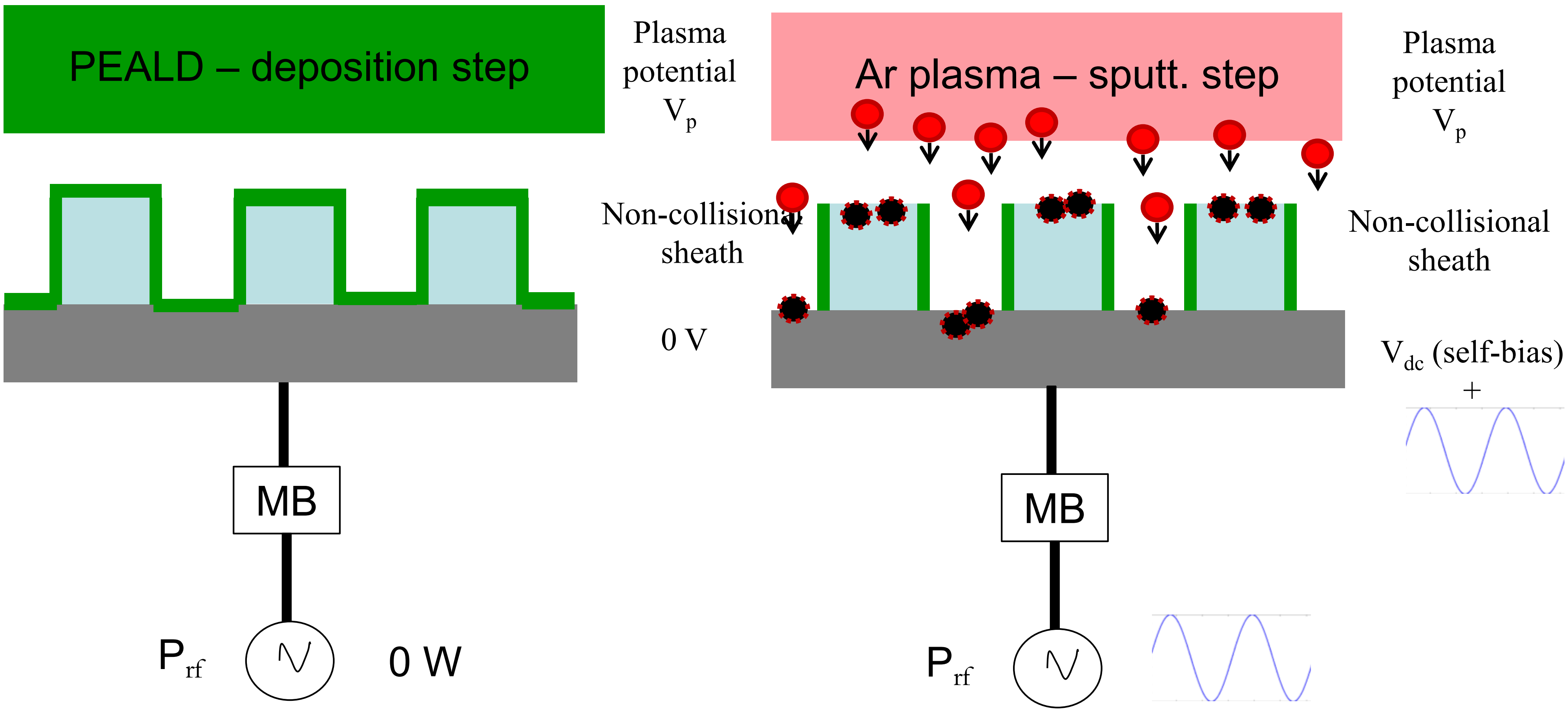
How long? 1s? 3s?... → throughput of the process, not perfect ASD (undesired material not removed / all the desired material is removed)

Why does it work and how improve it? → Plasma and precursor /surface reactions, contamination…

Ta_2O_5 ASD: PEALD Ta_2O_5 + Ar plasma



Ta_2O_5 ASD: PEALD Ta_2O_5 + Ar plasma



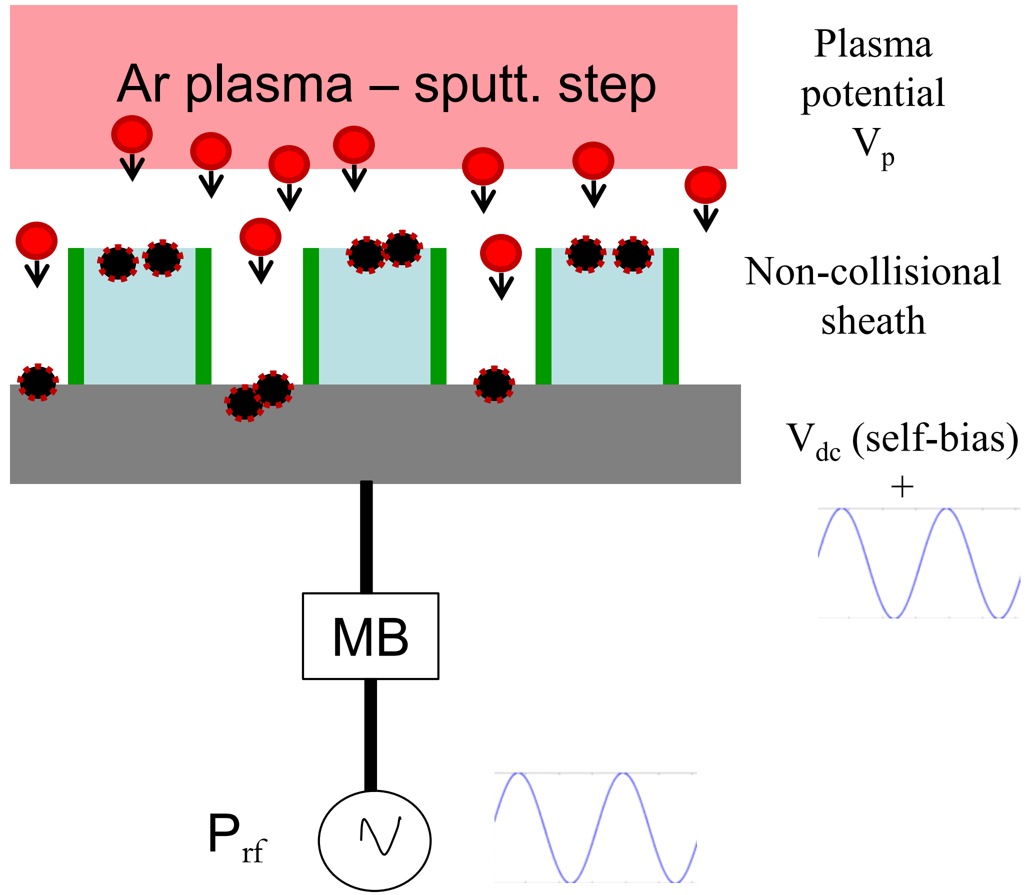
Ta_2O_5 ASD: PEALD Ta_2O_5 + Ar plasma

Need a good control of ion energy

Low pressure plasma (non-collisional sheath)

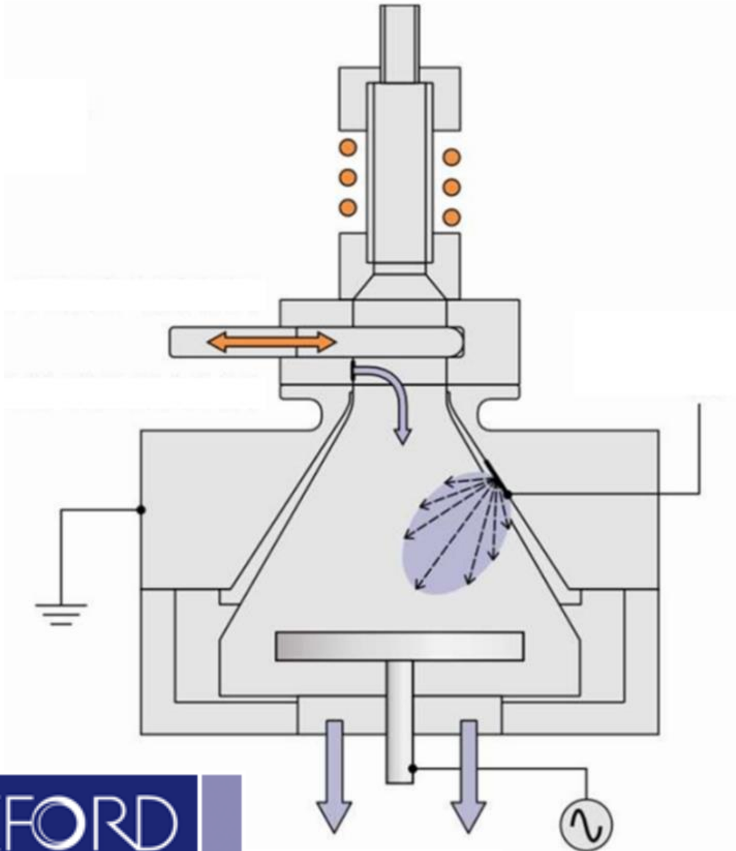
HDP source (inductive…)

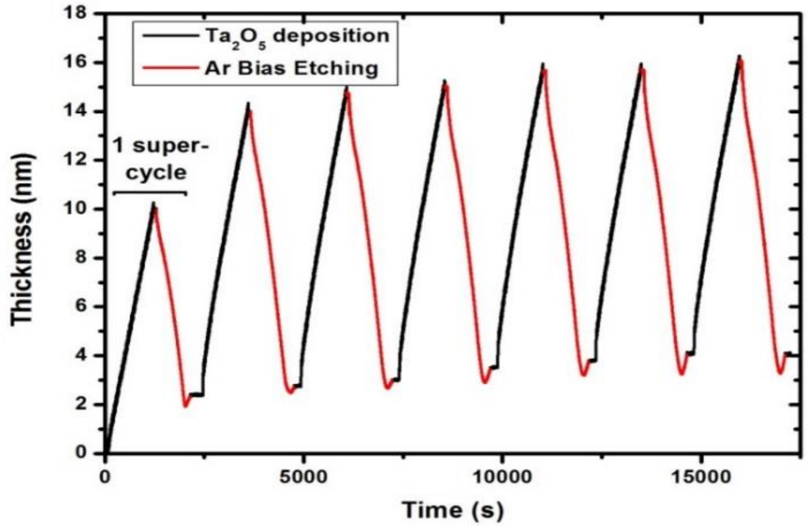
Ion energy = $e(V_p - V_{dc})$



Ta_2O_5 ASD: PEALD Ta_2O_5 + Ar plasma

PEALD tool from Oxford (FLEXAL) with substrate biasing platform and *in situ* ellipsometry (film sense)





OXFORD INSTRUMENTS
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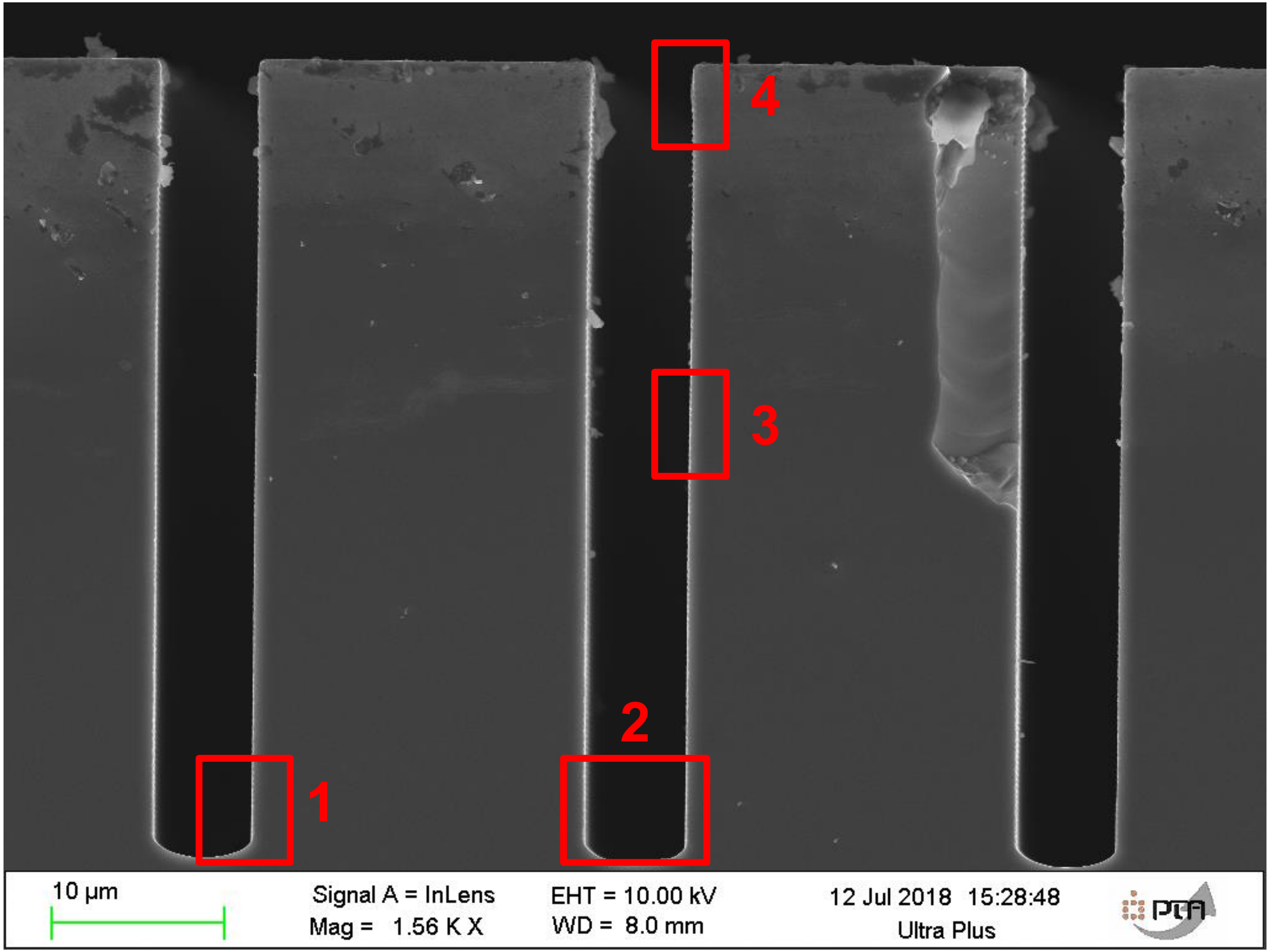
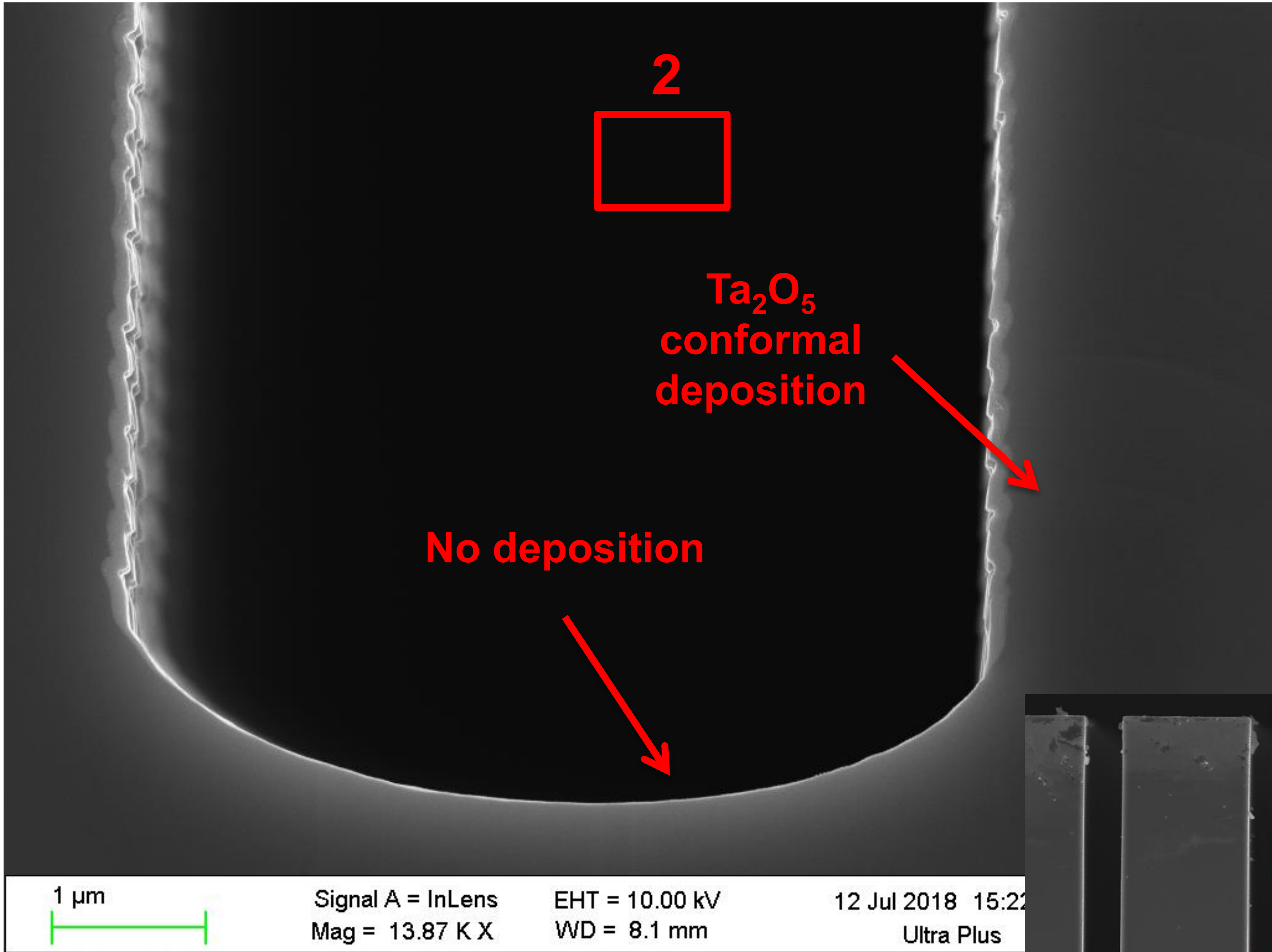
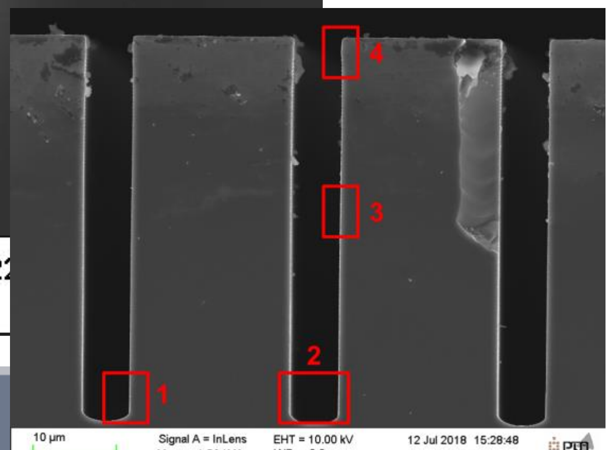
Case 1: Trenches - Aspect Ratio = 8

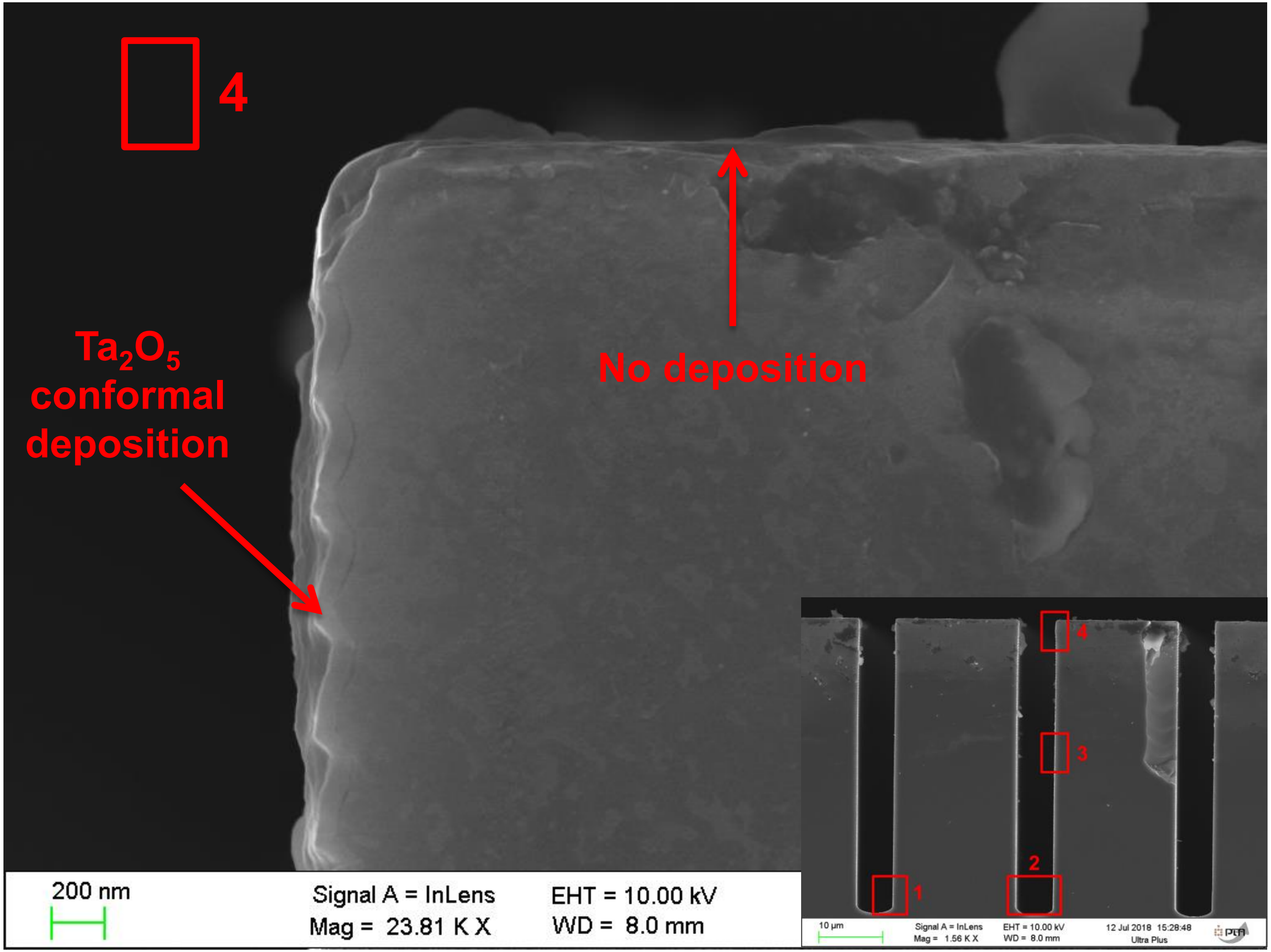


A. Chaker *et al*, to be published

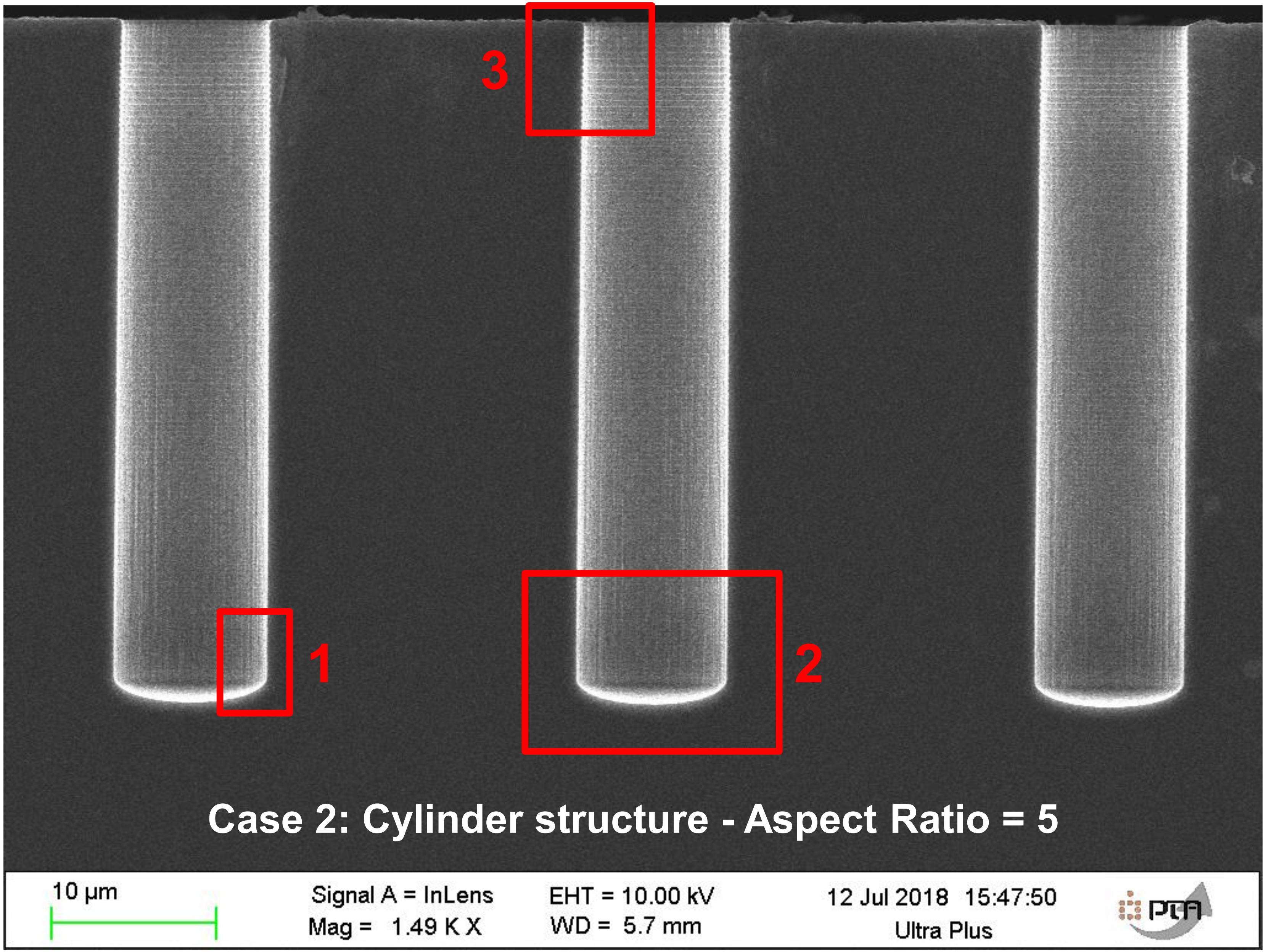




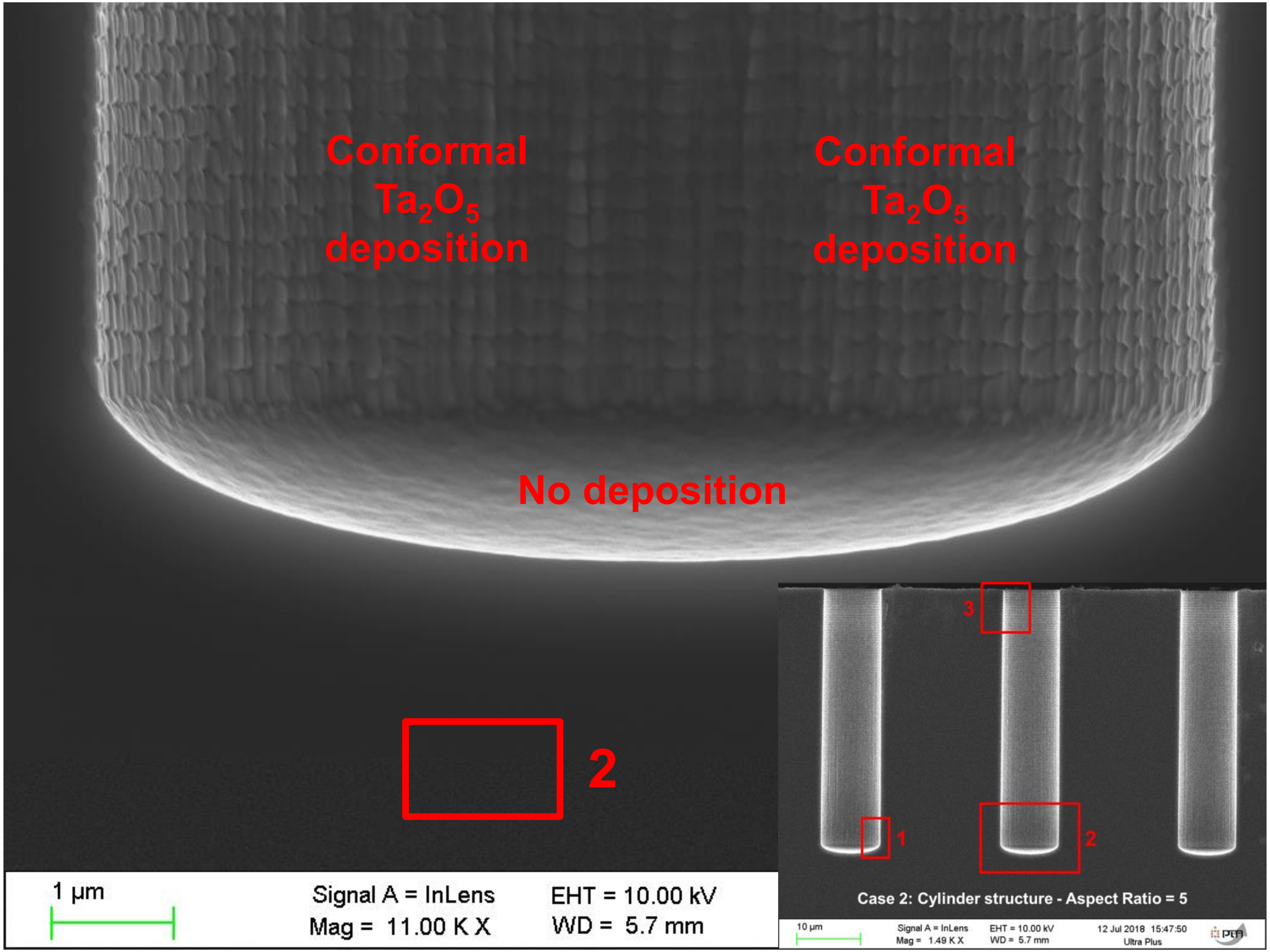
A. Chaker *et al,* to be published



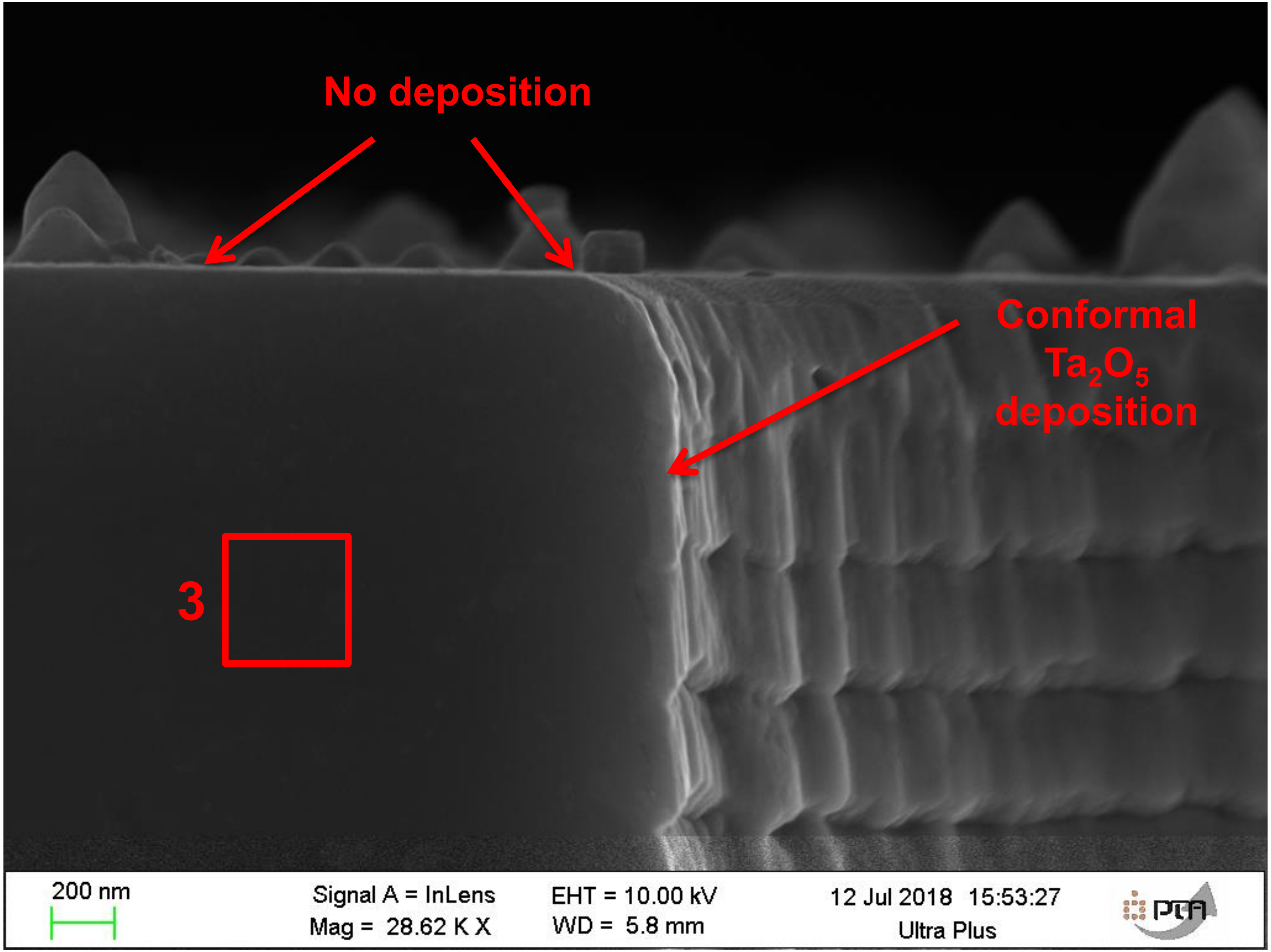
A. Chaker *et al,* to be published



A. Chaker *et al,* to be published

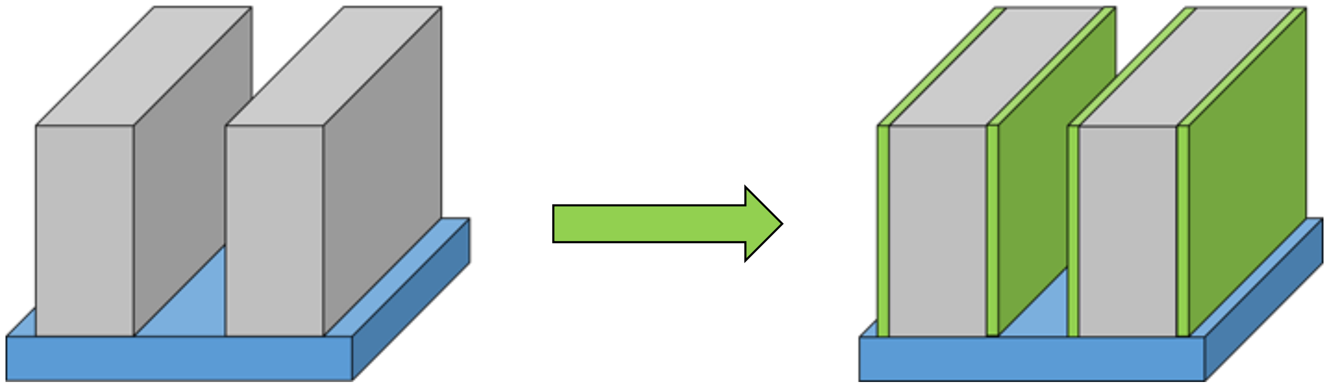


A. Chaker *et al*, to be published

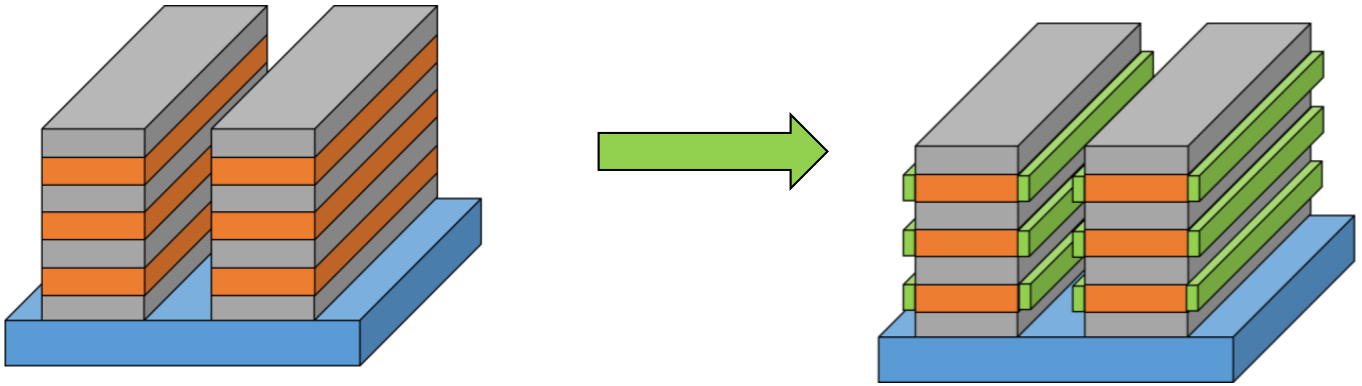


A. Chaker *et al,* to be published

Example 2 of ASD using etching



OK this is done but can we dome something more complicated



directional selective deposition + surface selective deposition using ion sputtering is no more a good solution

Example 2 of ASD using etching

Need of a chemical ISOTROPIC etching
Etching must be done by radicals only

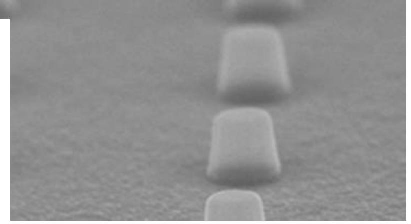
Can be done in CCP discharge at high pressure (collisional sheath)

Process developed in 300 mm tool from KOBUS (capacitive discharge) with in situ XPS

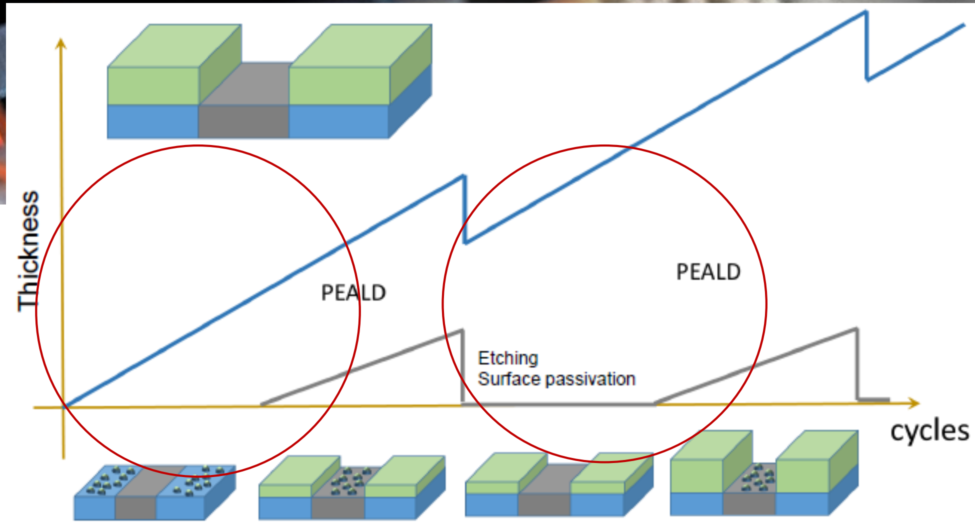
300 mm CCP PEALD tool

KEMSTREAM ADVANCED VAPORIZERS

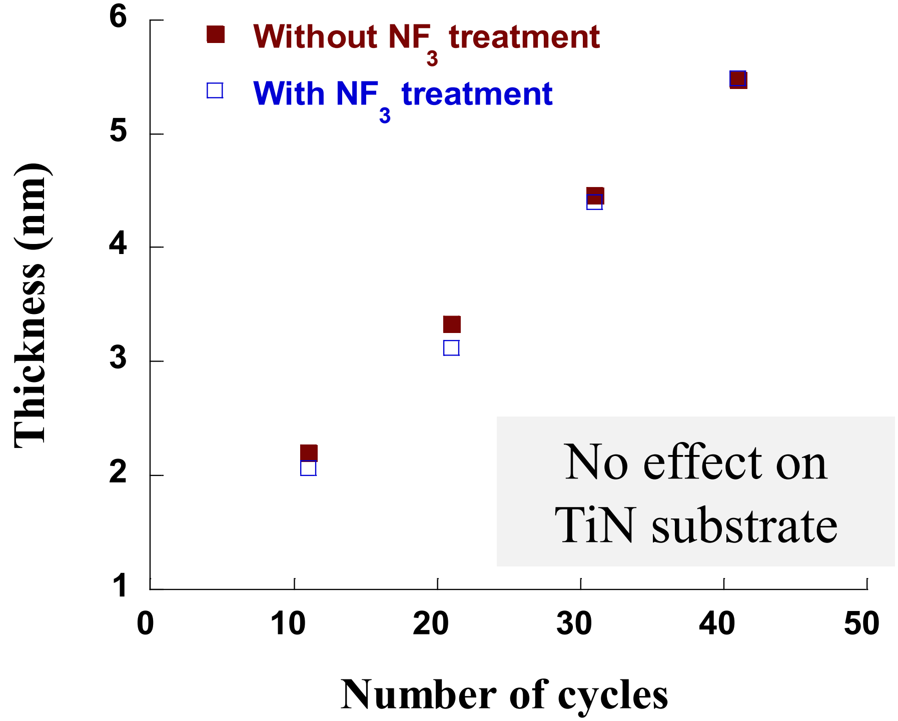
KOBUS Process like no one

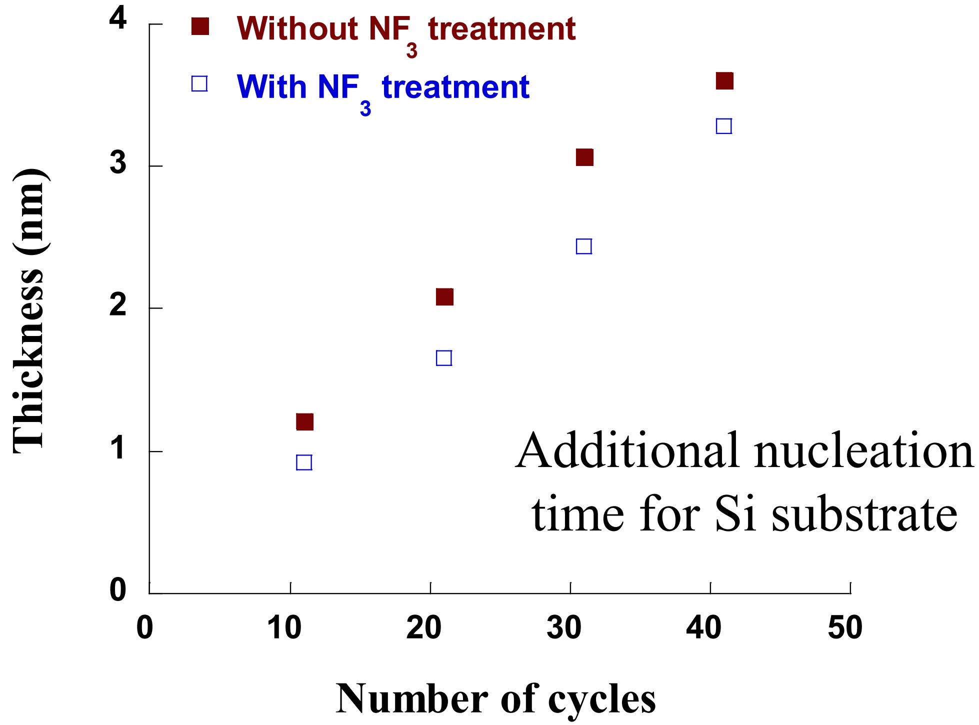


Plasma is used to create delays in nucleation



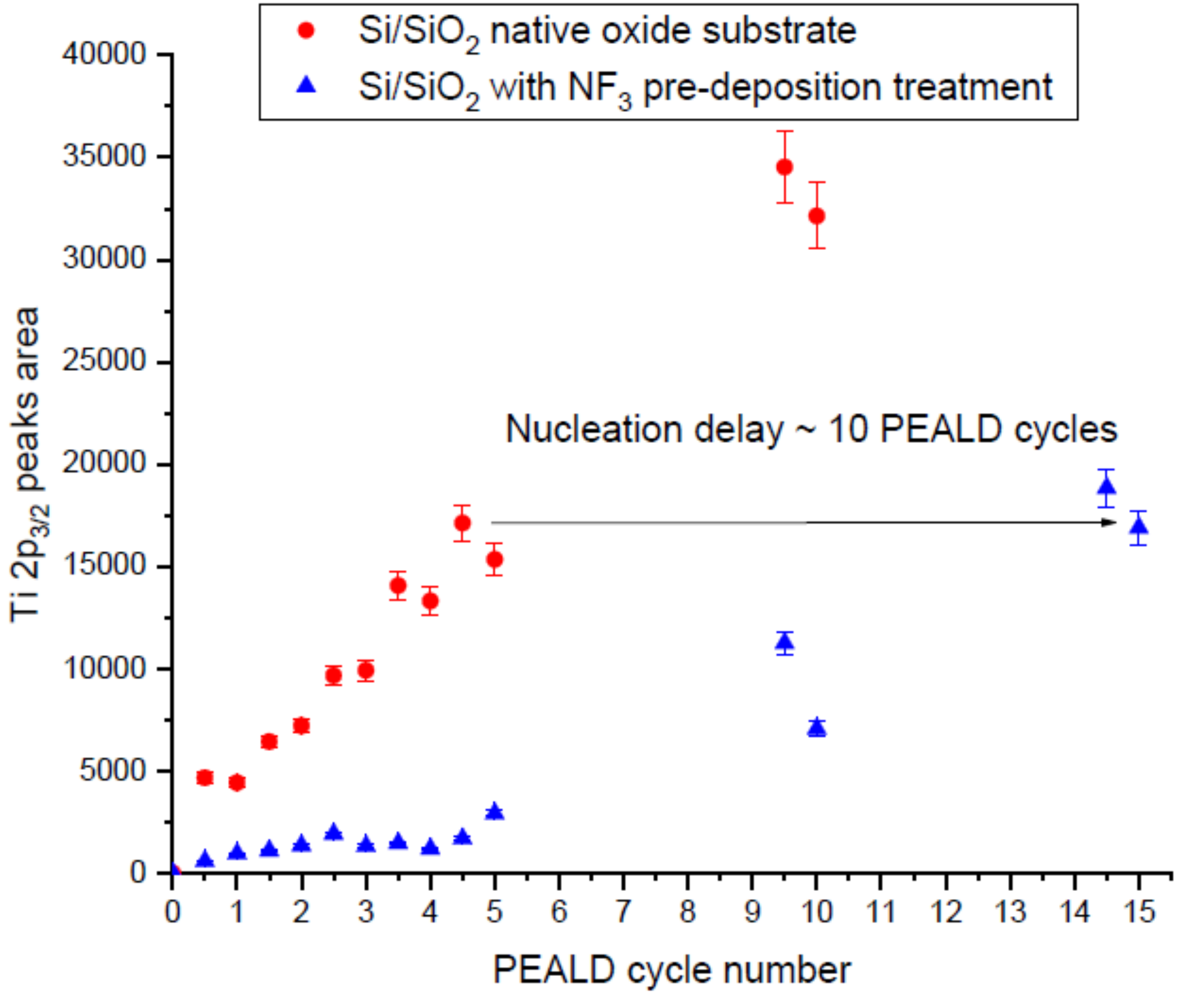
PEALD of TiO_2 before and after NF_3 plasma (Kobus tool)





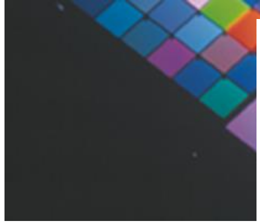
Impact of Fluorine-based plasma? (Example with ASD of TiO_2)

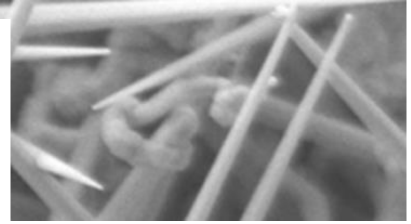
Quasi in situ XPS to understand and optimize the passivation step

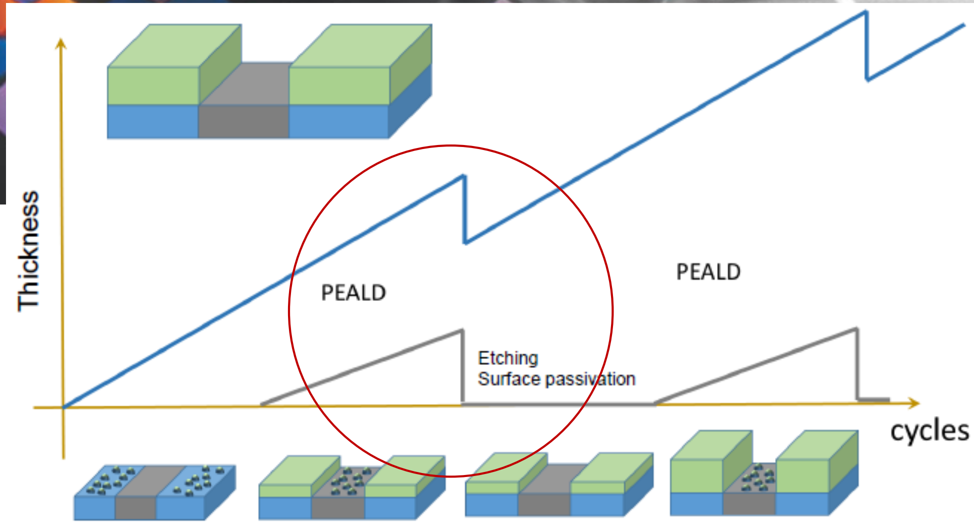


From *quasi in situ* XPS we can estimate the nucleation delay induced by Fluorine-based plasma to be 5-10 PEALD cycles

O. Salicio *et al,* to be published

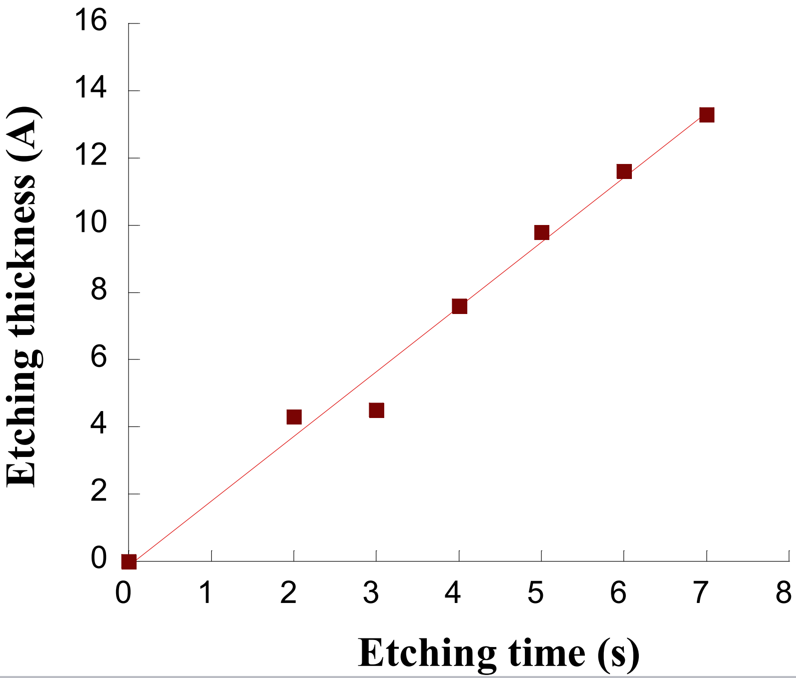






Plasma is also used to etch material

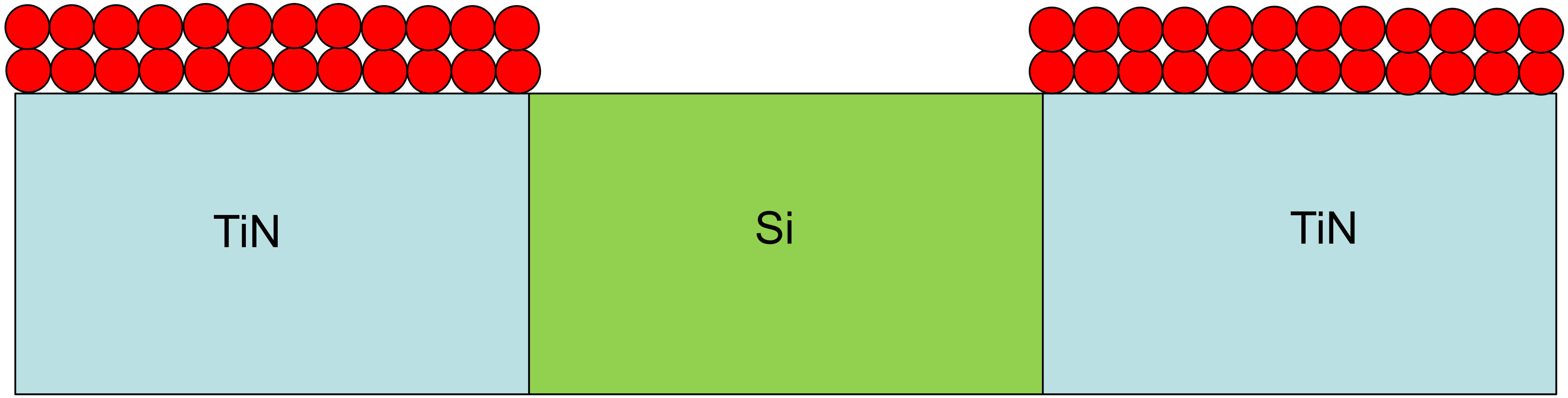
Etching of TiO_2 n $NF_3/O_2/Ar$ plasma



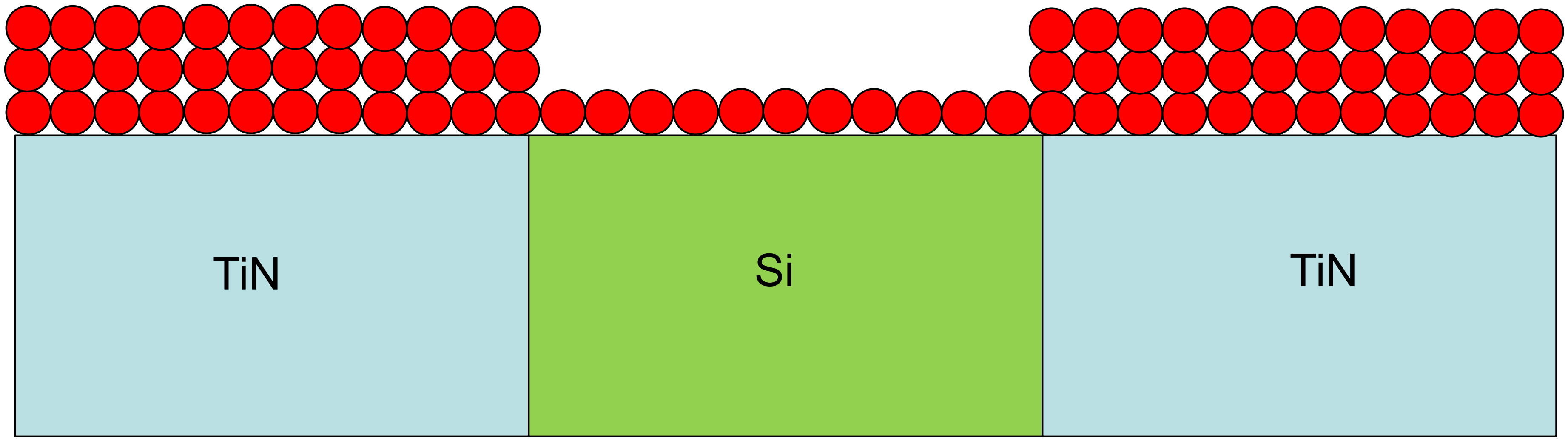
The etching step must be made at the same temperature than the deposition temperature

→ F-based plasma good candidate: TiF_4 volatile at 250°C

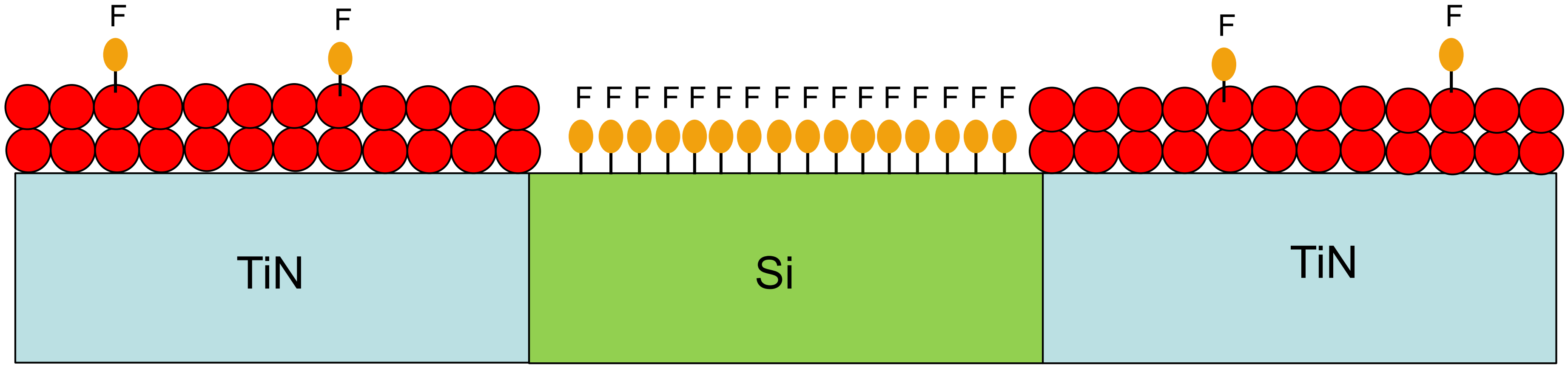
Growth starts faster on TiN substrate (inherent or plasma treatment)



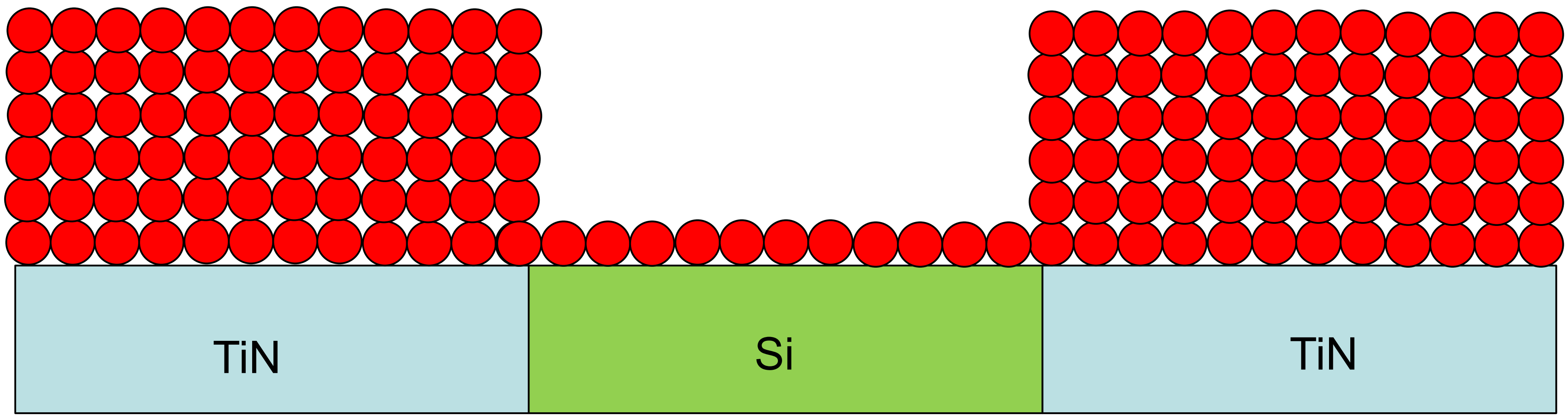
After X cycles TiO_2 starts to growth on both substrates



NF_3 is added to O_2 plasma to etch TiO_2 and create Si-F bonds (few Ti-F bonds)



After a number of PEALD cycles TiO_2 starts to growth on both substrates due to F removal on Si substrate by O_2 plasma: NF_3 again to etch and create new Si-F bonds



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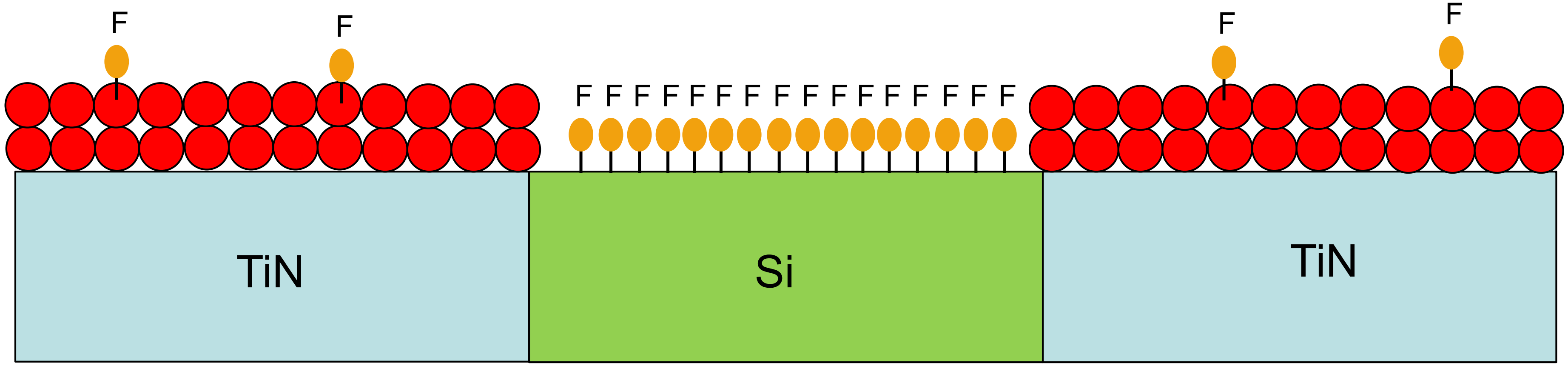

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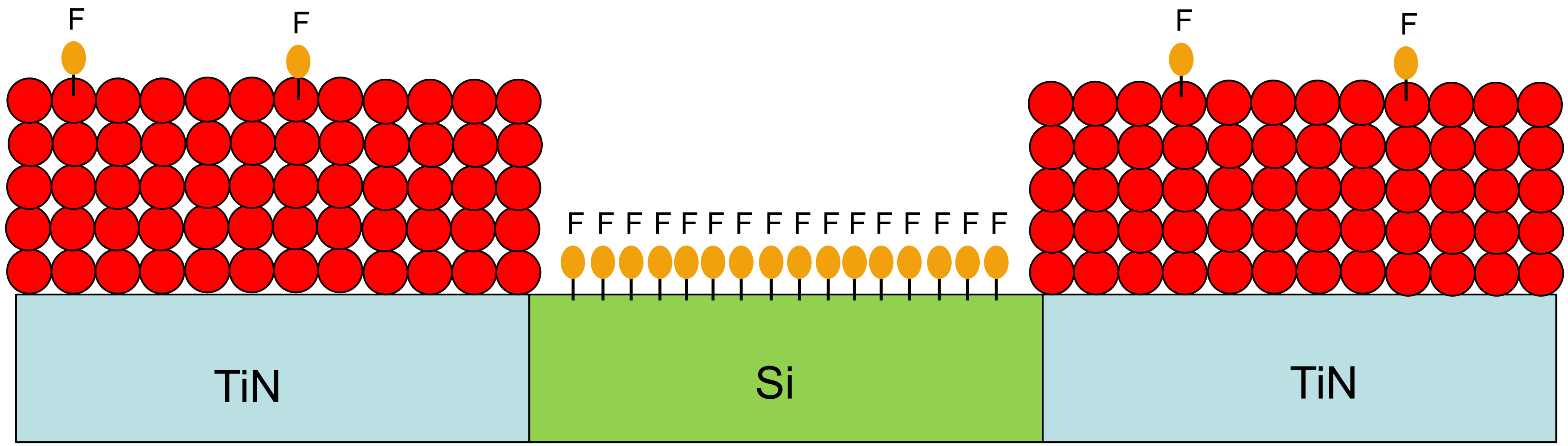
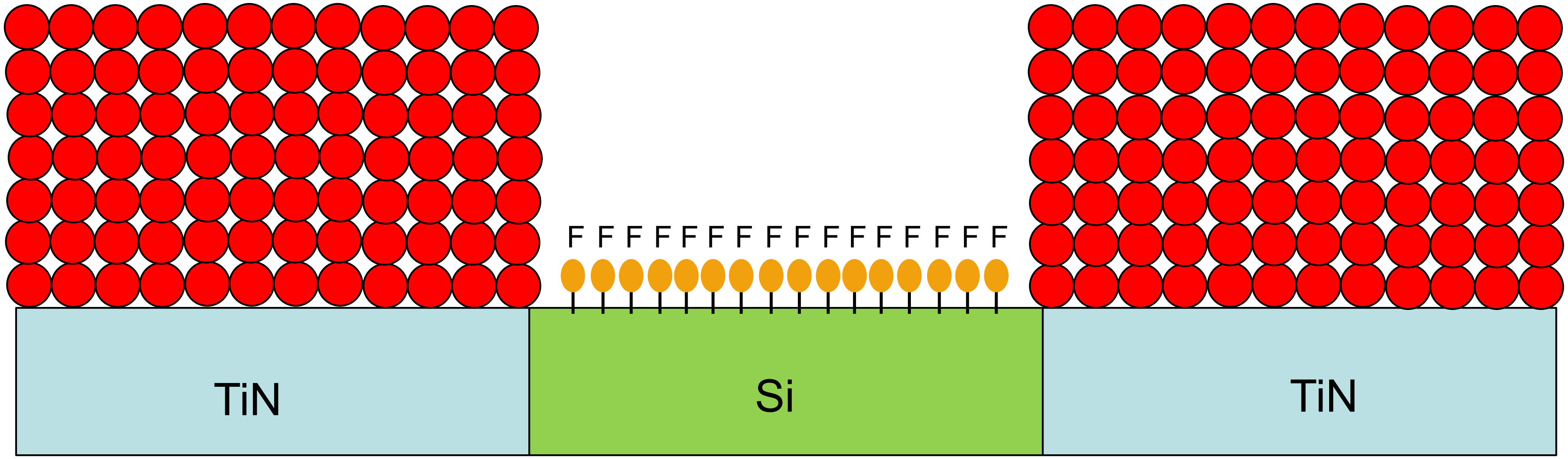


Need to optimize the PEALD / etching cycles ratio !



Selective deposition of TiO_2 and Ta_2O_5 on TiN versus Si substrate

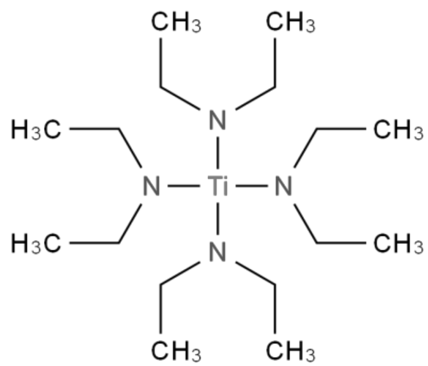
PEALD (x cycles) + plasma etching (1 cycle) = 1 super cycle

Selective deposition = x super cycles

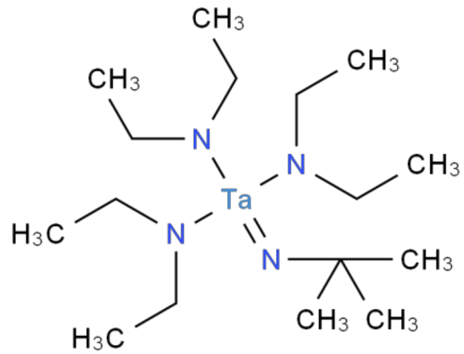
Presentation today: selective deposition of Ta_2O_5 and TiO_2

PEALD of Ta_2O_5 (TiO_2) with TBTDET (TDEAT) and O_2 plasma

Etching cycle by adding fluorine-based plasma



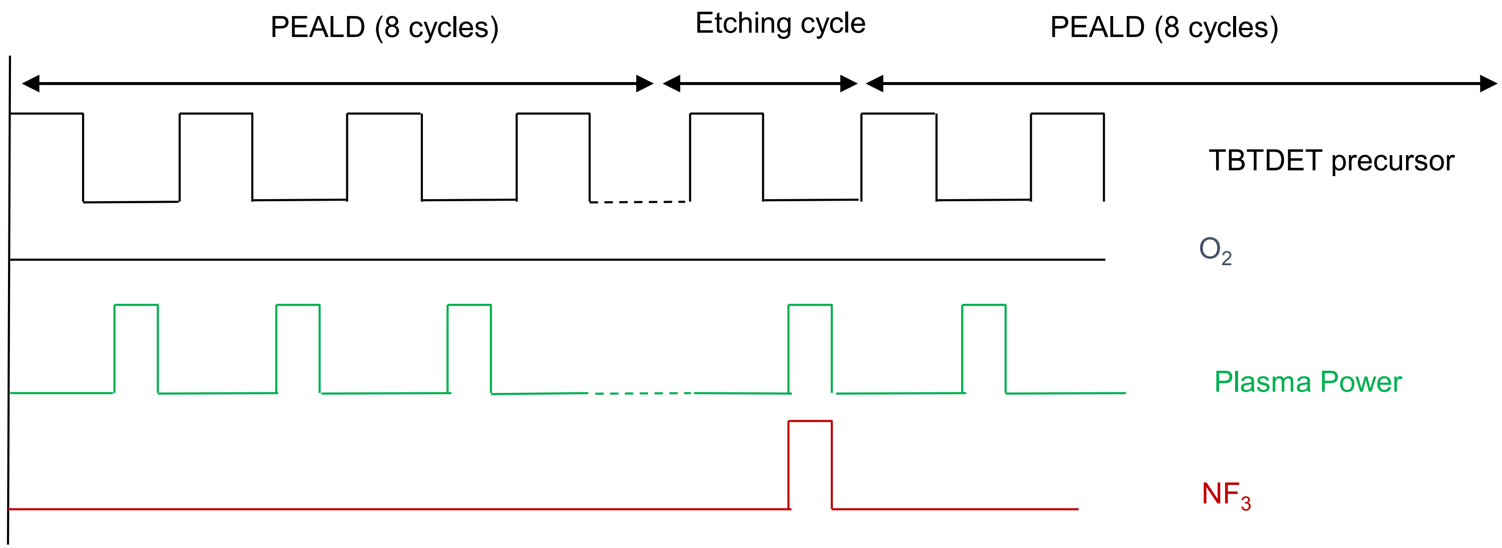
Tetrakis(diethylamido)titanium (TDEATi)



tert-Butylimido)tris(diethylamido)tantalum (TBTDET)

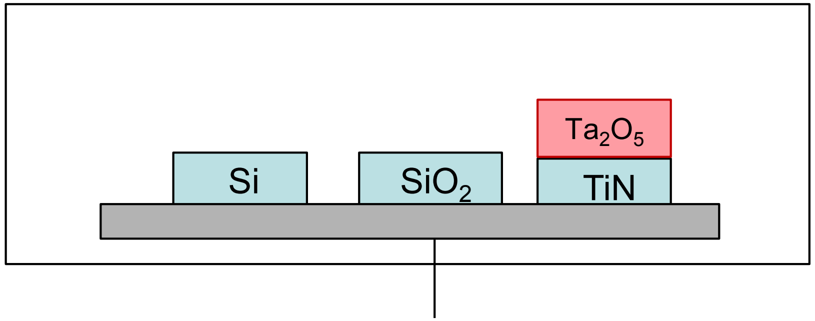
All requirements are ok!   Let's go for selective deposition

- In the selective deposition process for Ta_2O_5 we only slightly modified the PEALD process by adding a NF_3 pulse in O_2 pulse every 8 cycles* (O_2/Ar (250 / 2500 scm - 75W plasma – 2 Torr)



- For TiO_2 the number of PEALD cycles before plasma etching exposure has been fixed to 20

*More details in: R. Vallat, R. Gassilloud, B. Eychenne, and C. Vallée J. Vac. Sci Technol. A 35(1) 01B104 (2017)



Number of super cycles	Ta_2O_5 thickness on Si / SiO_2 (nm)	Ta_2O_5 thickness on TiN (nm)	Ta_2O_5 density ($g.cm^{-3}$)
11	0 / 0	3.6	6.4
22	0 / 0	7.1	6.1

R. Vallat, R. Gassilloud, B. Eychenne, and C. Vallée
J. Vac. Sci Technol. A 35(1) 01B104 (2017)

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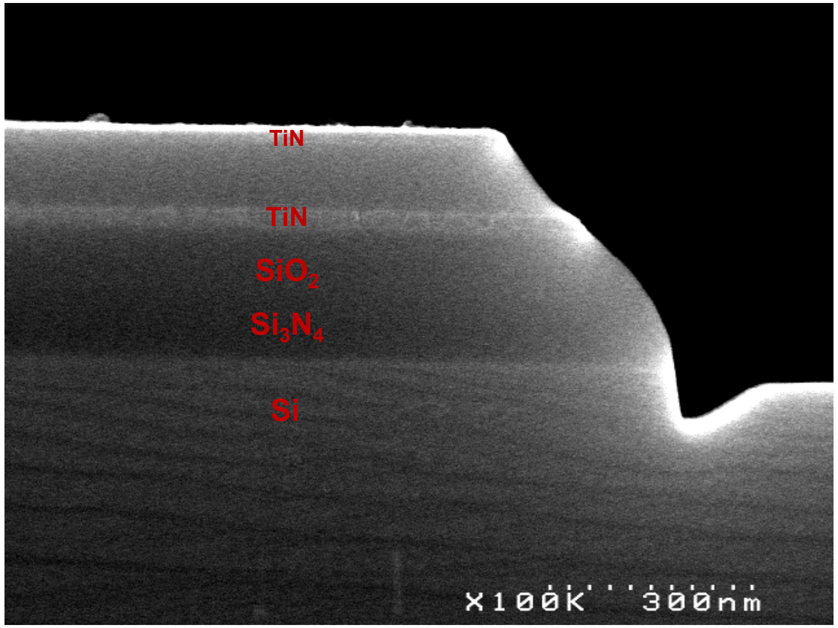
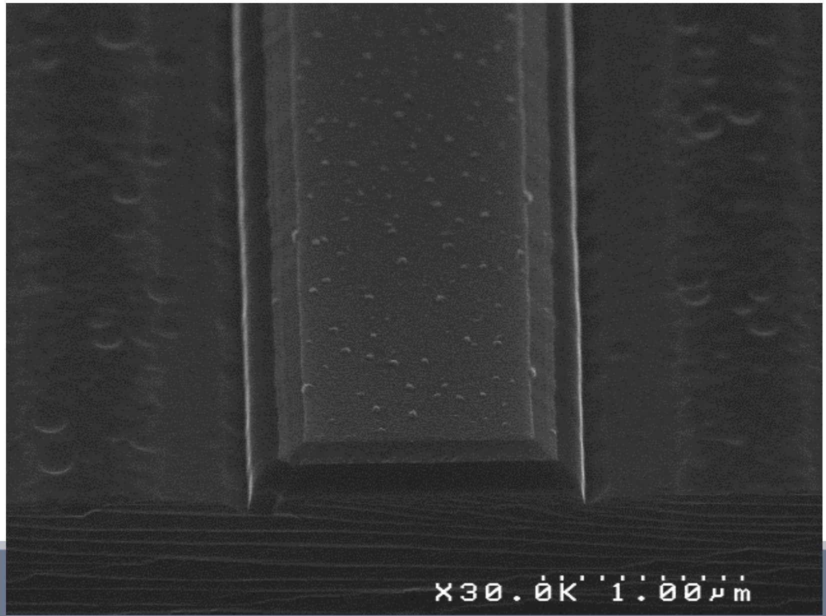
11	0 / 0	3.6	6.4
22	0 / 0	7.1	6.1

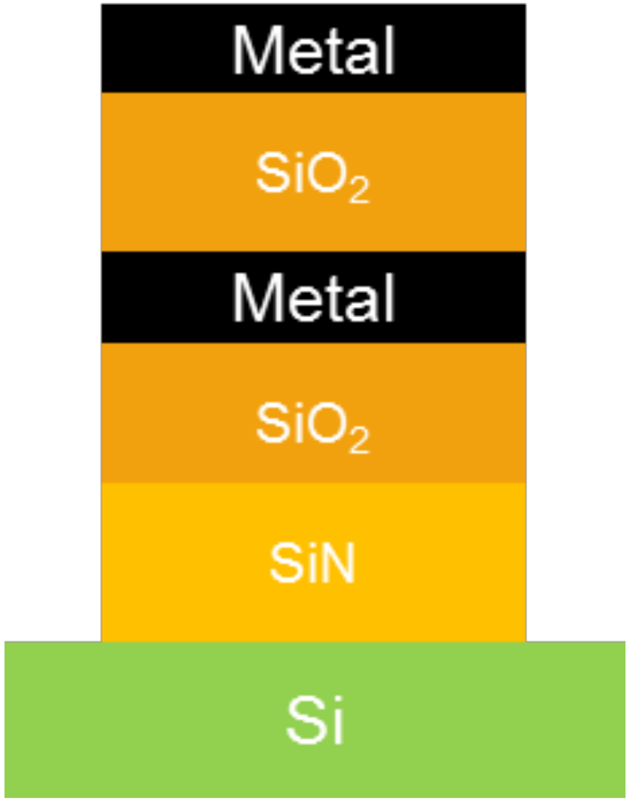
Number of super cycles	TiO_2 thickness on Si (nm)	TiO_2 thickness on TiN (nm)	TiO_2density ($g.cm^{-3}$)
6	0	4.3	4.1
12	0	6.4	3.9

Density is slightly reduced when increasing the number of super cycles: Origin? Voids? Contamination by F atoms? Impact on electrical properties?

ASD on 3D patterned substrate (SEM image by M. Fraccaroli)



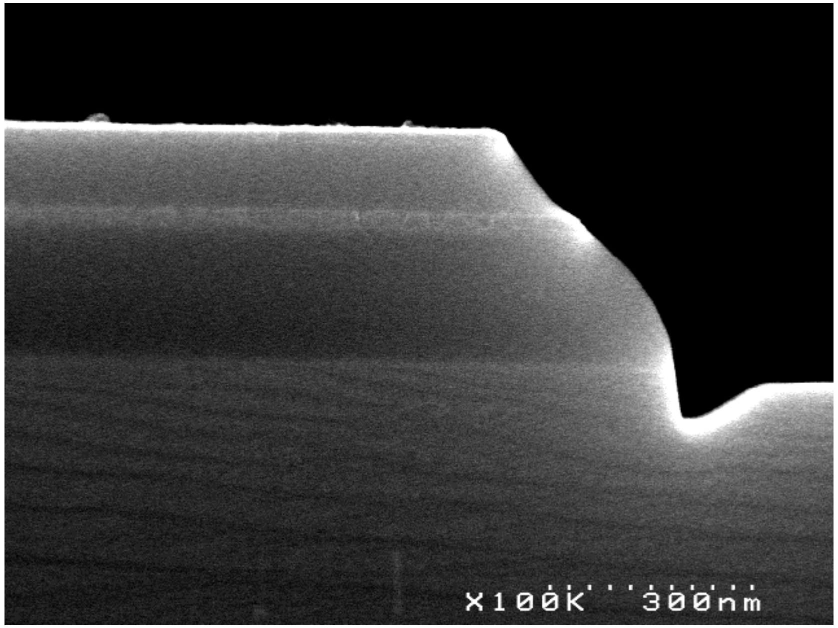


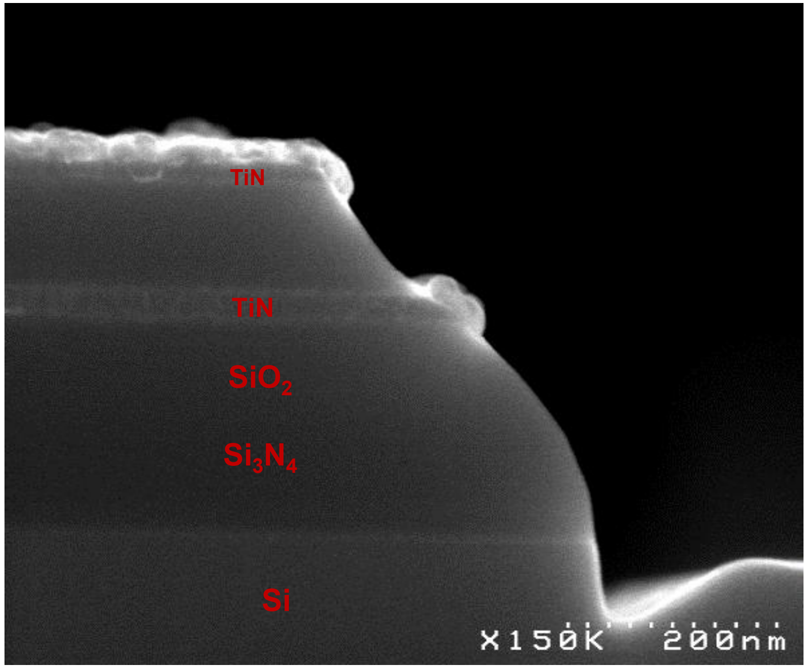


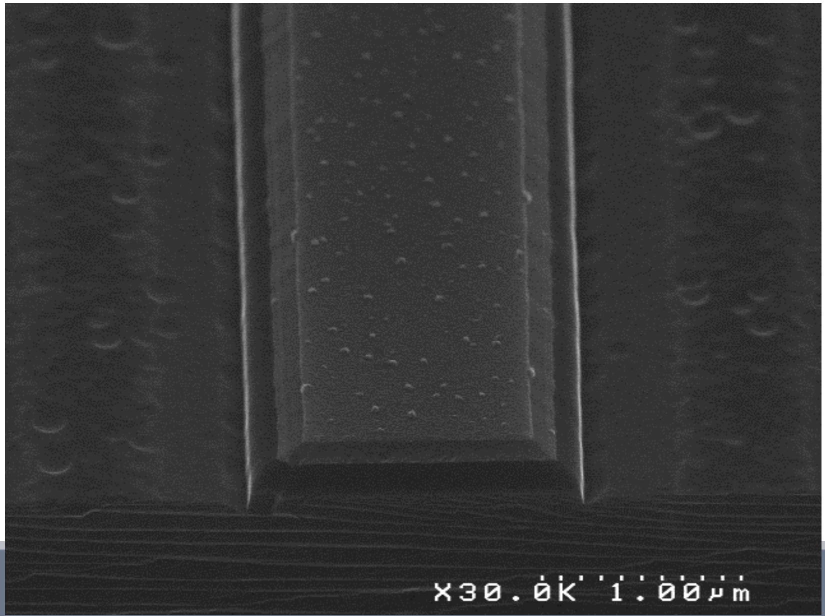
R. Vallat *et al.* submitted to JVSTA

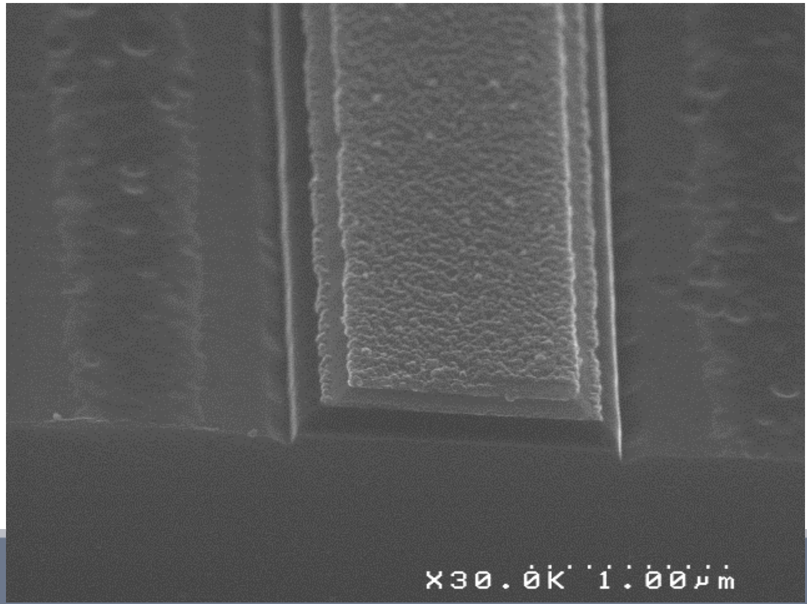
ASD on 3D patterned substrate (SEM image by M. Fraccaroli)

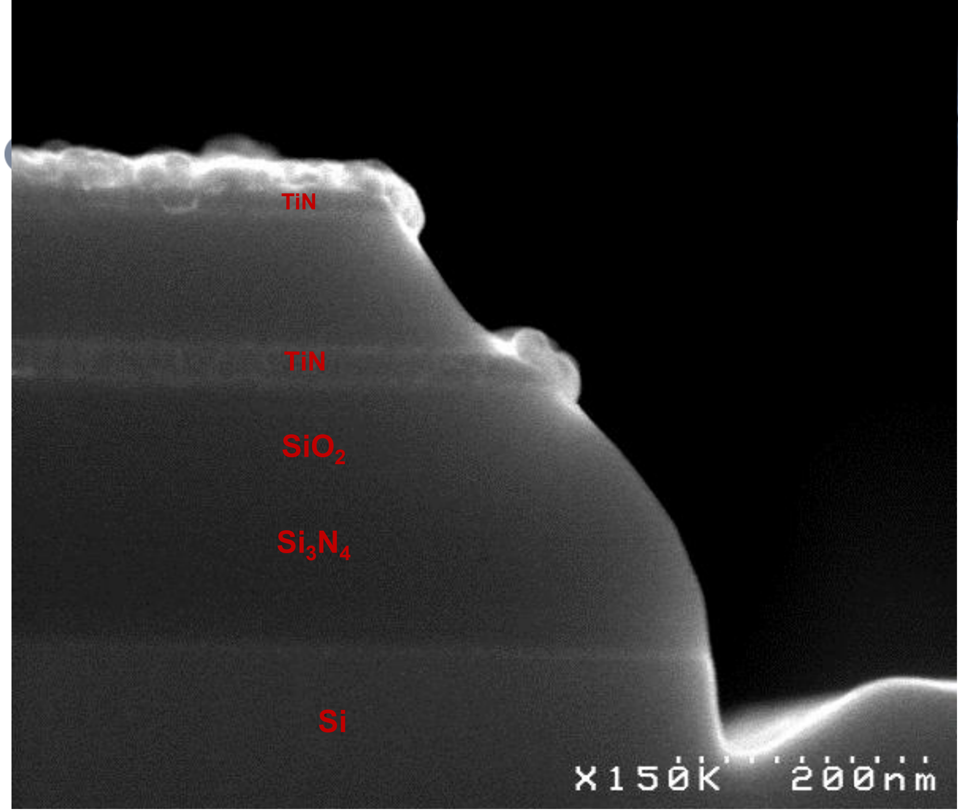
R. Vallat *et al*. submitted to JVSTA

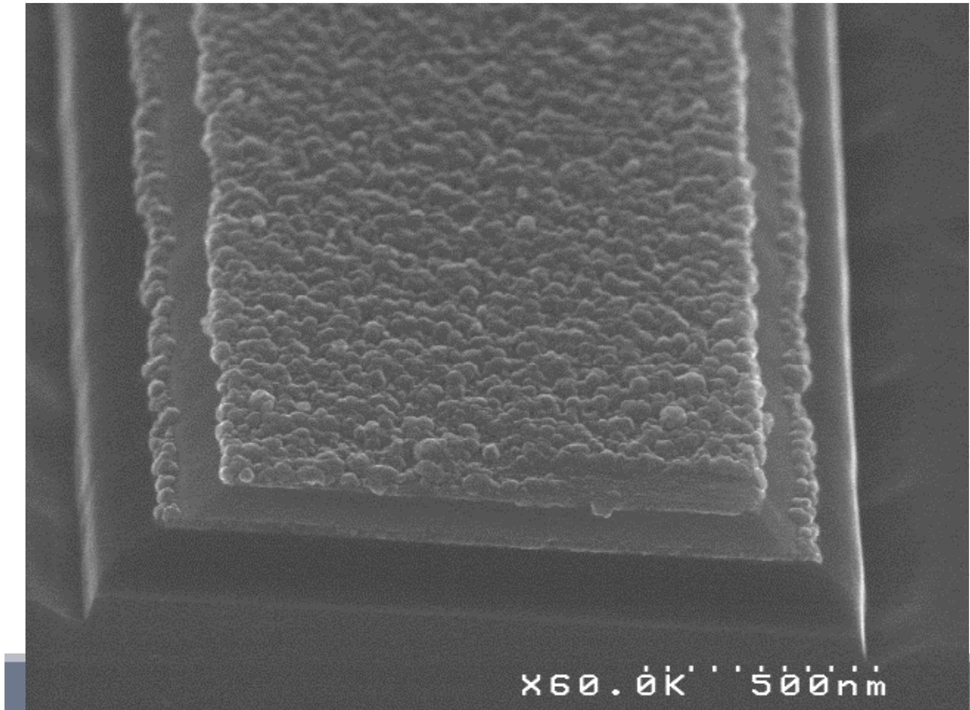


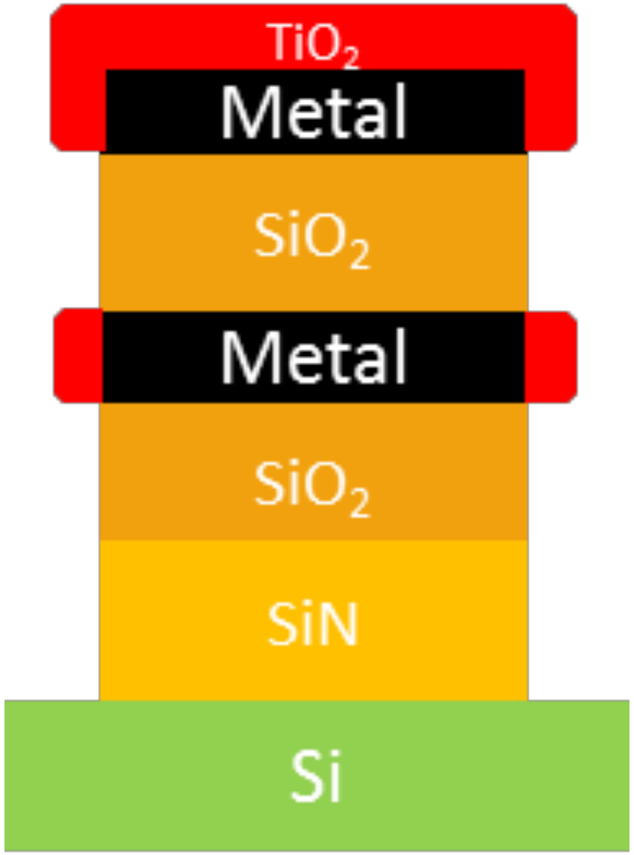












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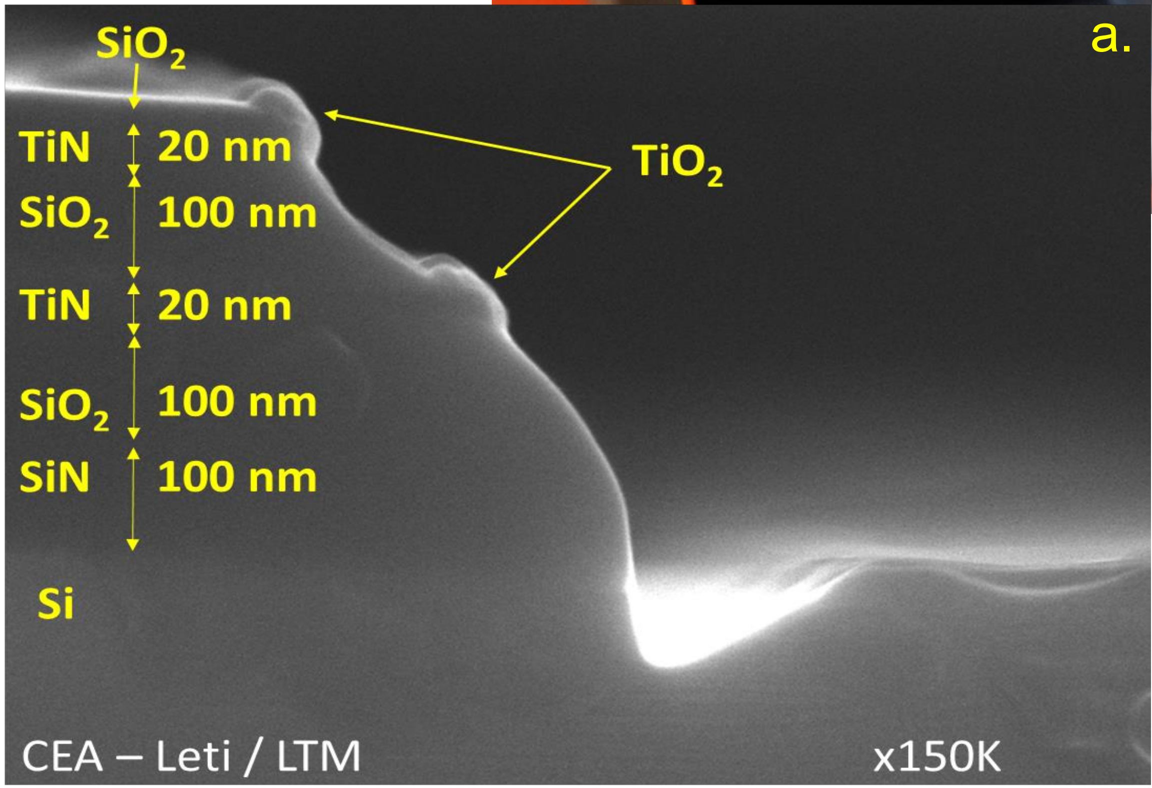
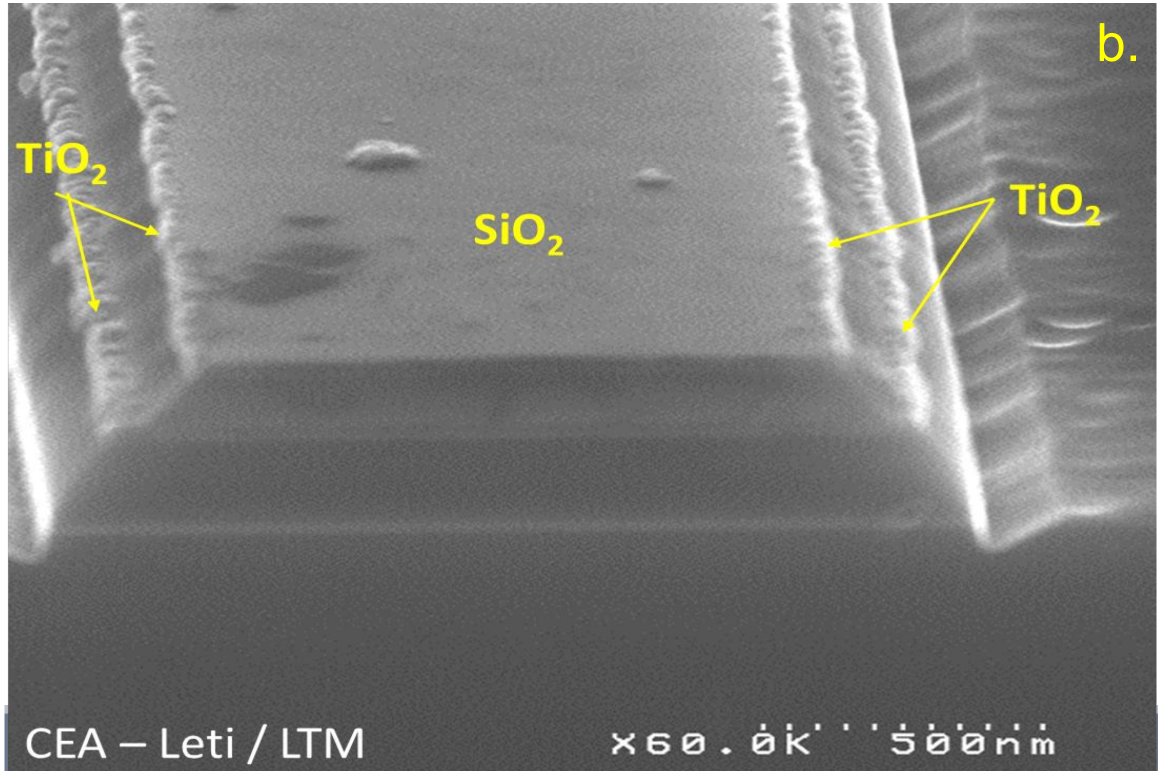
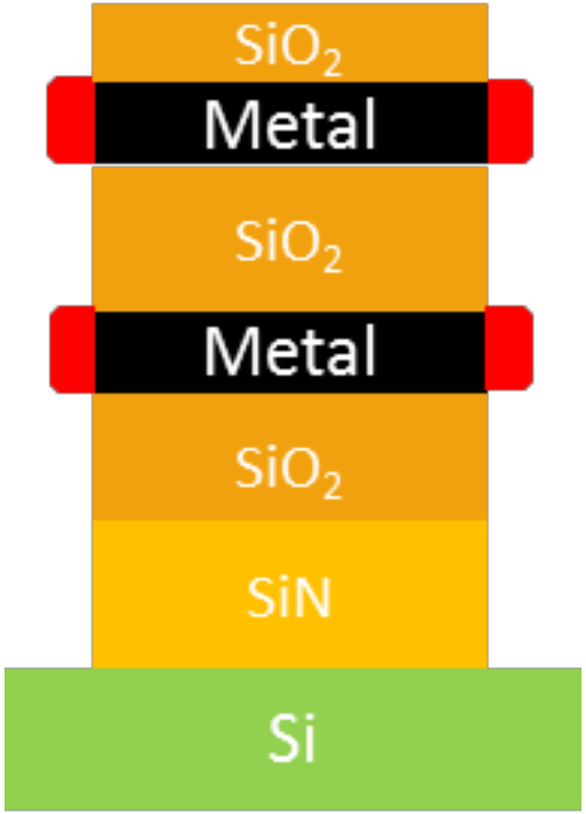




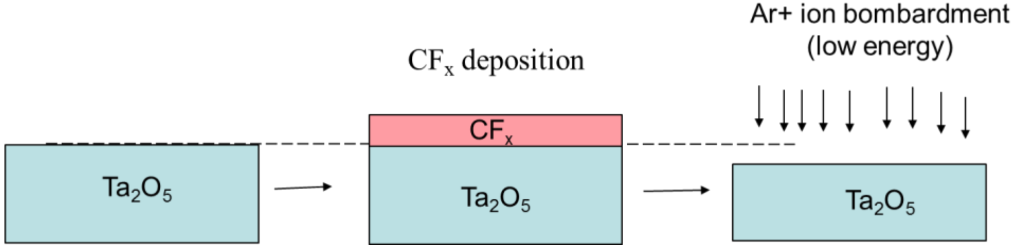


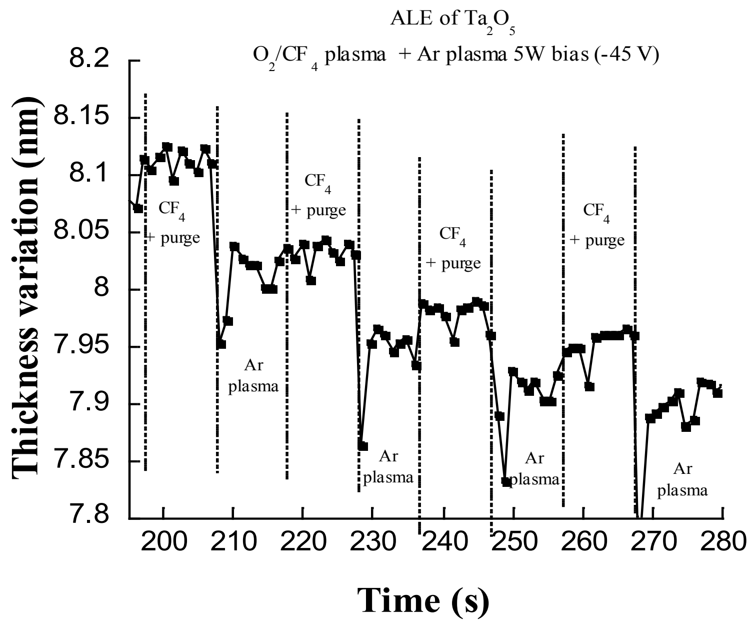
R. Vallat et al. submitted to JVSTA

Conclusion

- Not radicals only can be useful for PEALD processes
- Depending on the materials, ions can increase/decrease the GPC, modify the density, roughness, crystalline phase. Ions can also be used for area selective deposition on 3D patterned substrates
- What about the others? UV photons, O_3….
- Whatever the ASD process (SAM,,...), etching is needed to improve selectivity
- Optimum goal: ALD + ALE

ALE in the PEALD FLEXAL tool is now optimized





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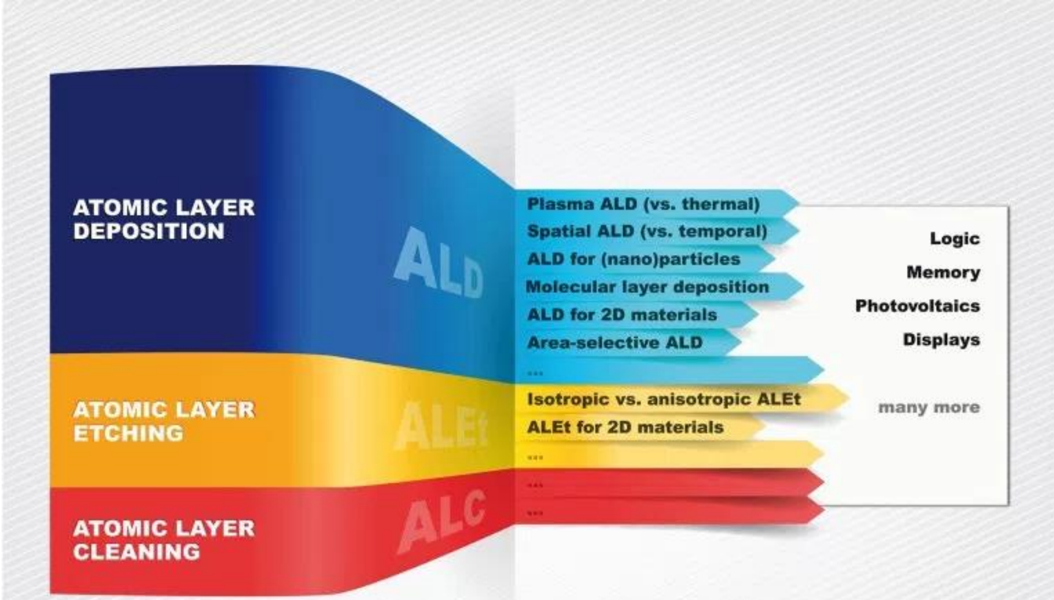
LABORATOIRE DES TECHNOLOGIES DE LA MICROÉLECTRONIQUE

Futur trends: All is Atomic Layer Processing

- Atomic layer deposition
- Atomic layer etch
- Atomic level planarization
- Atomic level contamination control
- Atomically pure materials
- Atomic level characterization
- Atomic level measurement



http://www.atomiclimits.com/2017/07/03/the-dawn-of-atomic-scale-processing-the-growing-importance-of-atomic-layer-deposition-and-etching/

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http://rafald.org