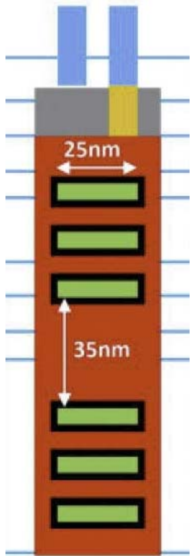
EU - SOUTH KOREA – Joint Researchers Forum
on Semiconductors

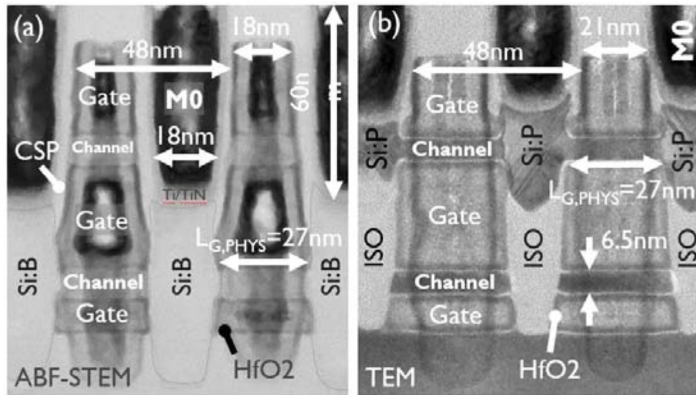
Area-selective deposition and atomic layer etching as enabling technologies for the fabrication of 3-dimensional nanodevices

Adrie Mackus, Associate Professor

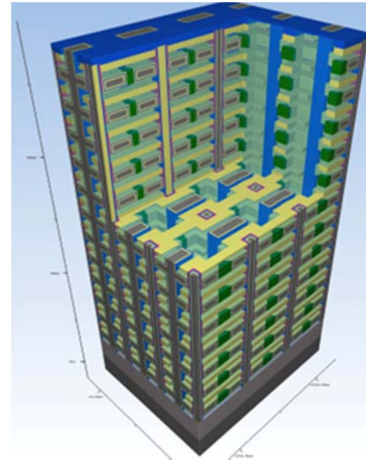
Eindhoven University of Technology,
Department of Applied Physics and Science Education

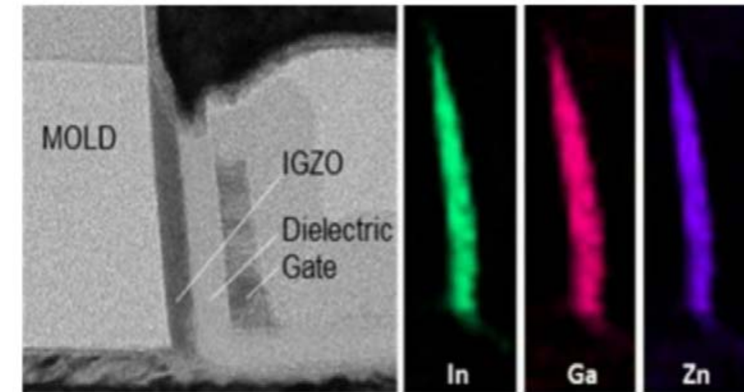
Logic and memory: vertical stacking of devices





Complementary FET





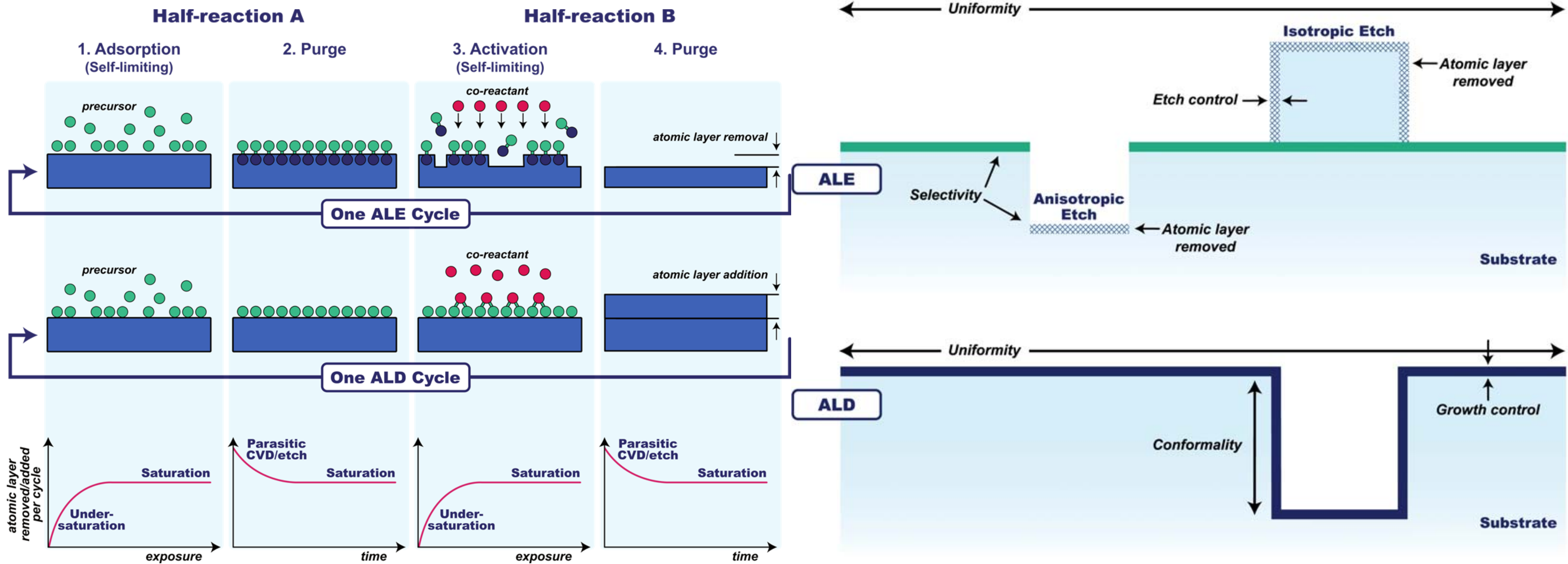
3D DRAM

Scaling of nanoelectronics by vertical stacking of devices requires:

- Techniques for deposition and etching on complex 3-dimensional structures
- Selective processing to enable self-aligned fabrication

https://www.imec-int.com/
Mertens *et al.* (IMEC), VLSI 2023
Ha *et al.* (Samsung), IEDM2023

Atomic layer deposition (ALD) & etching (ALE)



- Processes consisting of **self-limiting** surface reactions
- Deposition and etching with **atomic-level accuracy**

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

ALD & ALE in South Korea and Europe

ALD thesis world map, according to VPHA (July 2019, incomplete)

Puurunen *et al.*, Virtual Project on the History of ALD (VPHA)

South Korea

- Academic research
- Developments triggered by chip manufacturers

Europe

- Academic research
- ALD equipment manufacturers

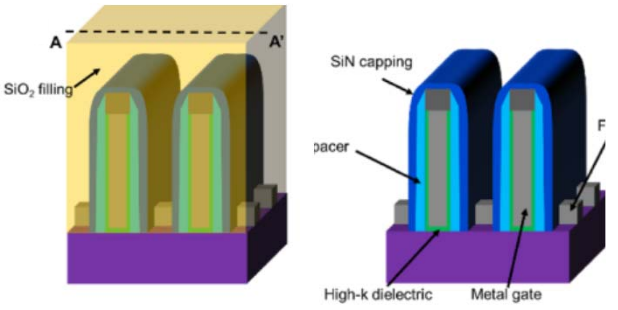
Outline

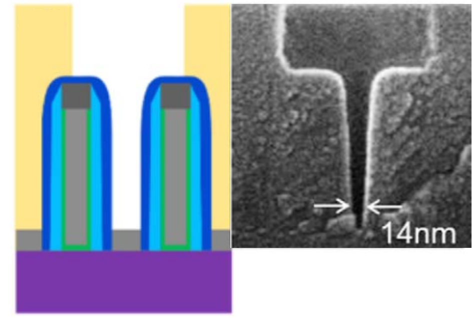
Techniques for selective processing

1. **Atomic layer etching (ALE)**
2. **Area-selective deposition (ASD)**

Anisotropic and isotropic ALE

Self-aligned contact

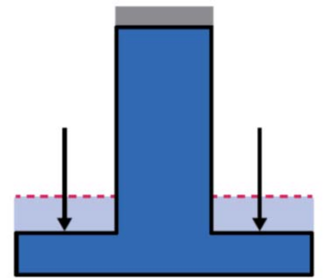




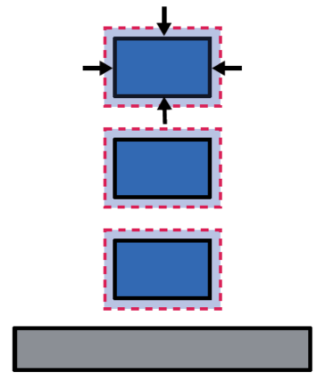
Honda *et al.*, *J. Phys. D: Appl. Phys.* **50**, 234002 (2017)

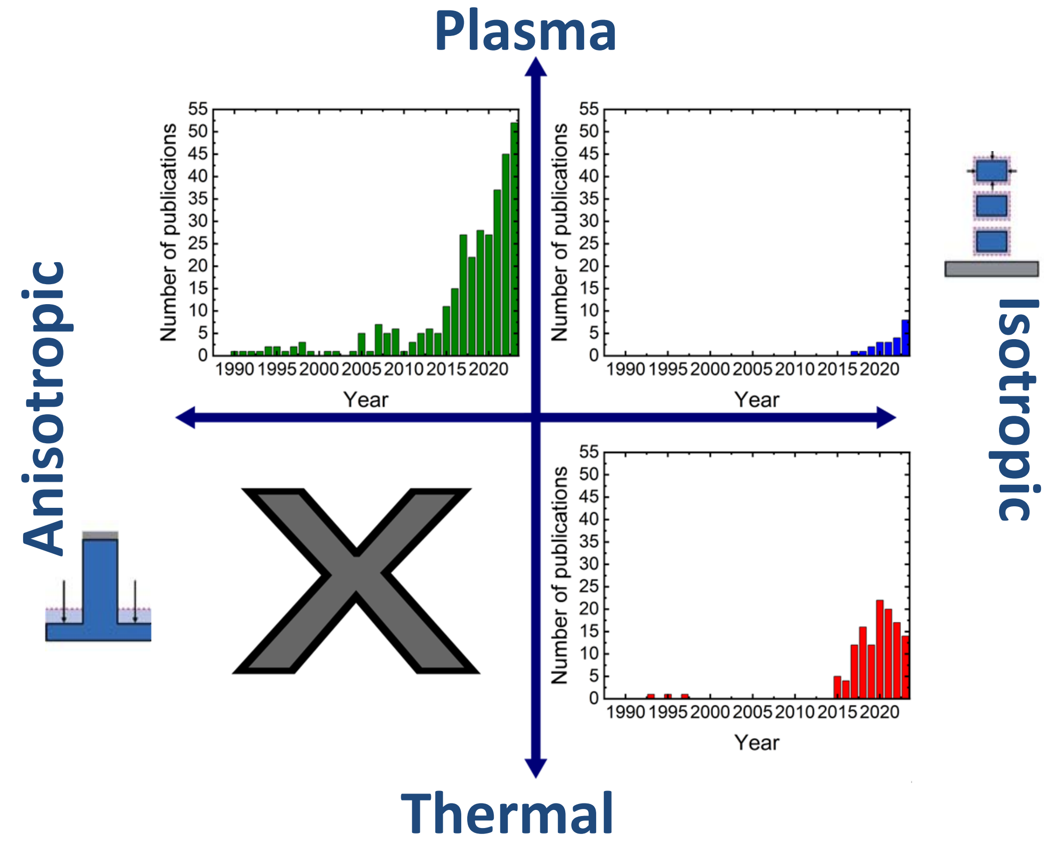
- Selective ALE of SiO_2 w.r.t. SiN_x

Anisotropic ALE

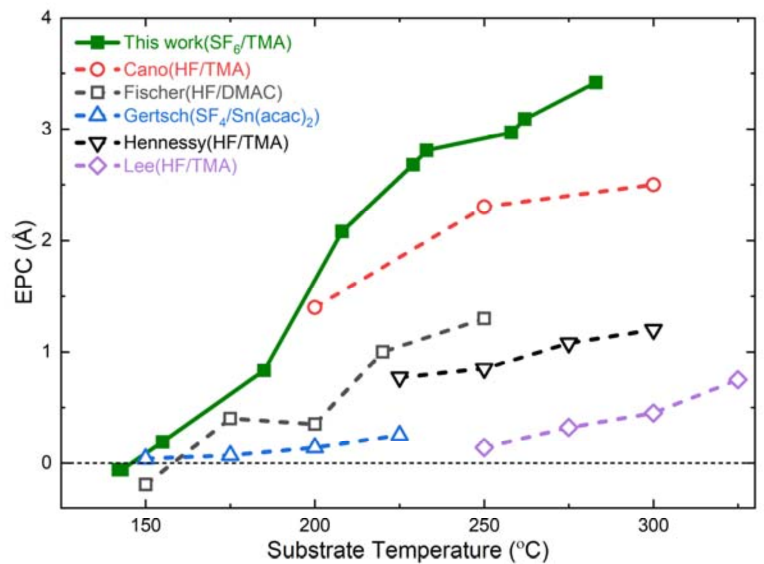


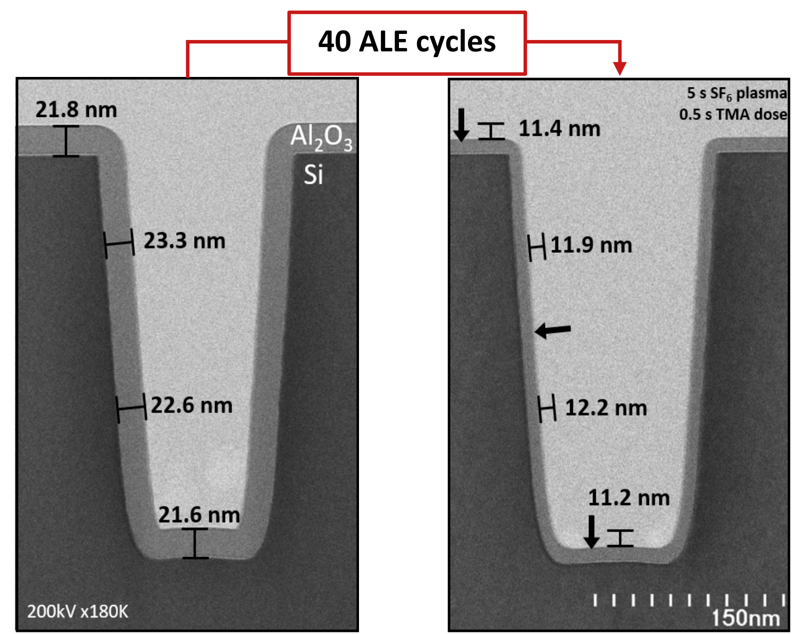
Isotropic ALE

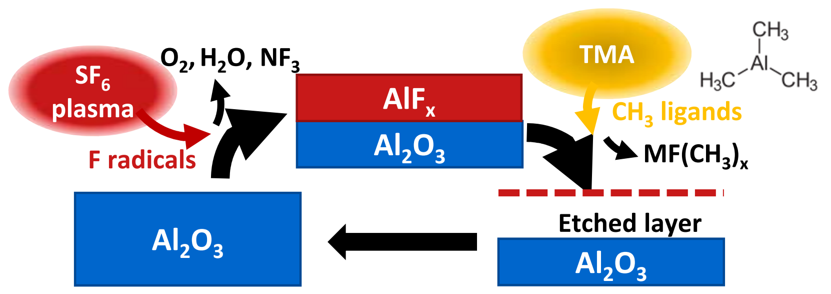




Isotropic plasma ALE



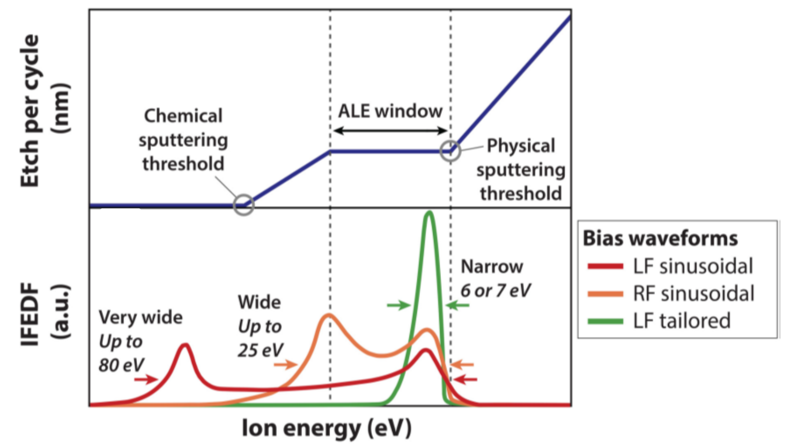


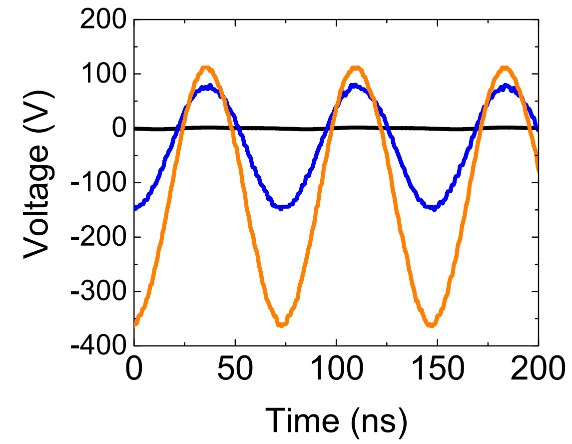


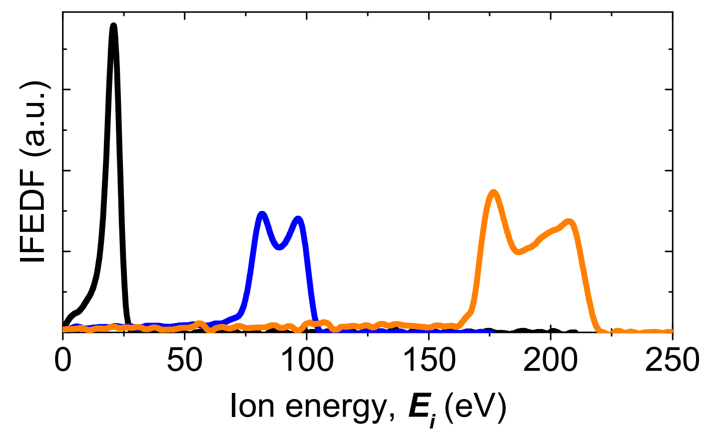
- Isotropic plasma ALE of Al_2O_3
- Higher EPC as compared to thermal ALE
- Etching at low temperatures

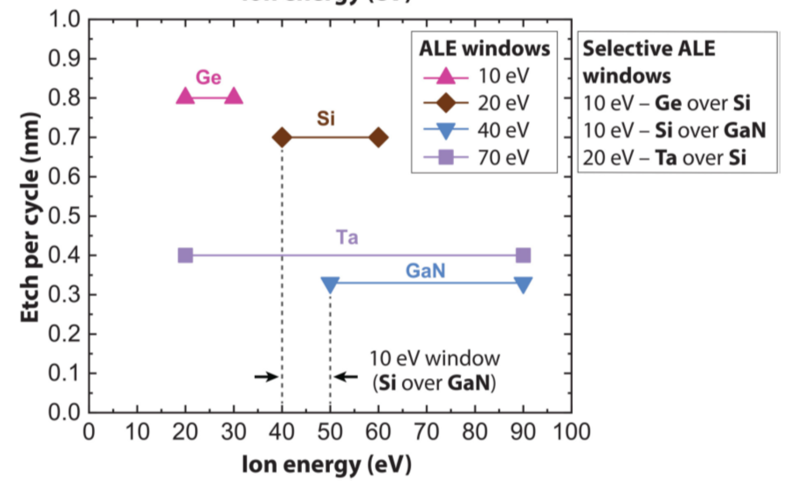
Chittock *et al.*, *Appl. Phys. Lett.* **117**, 162107 (2020)

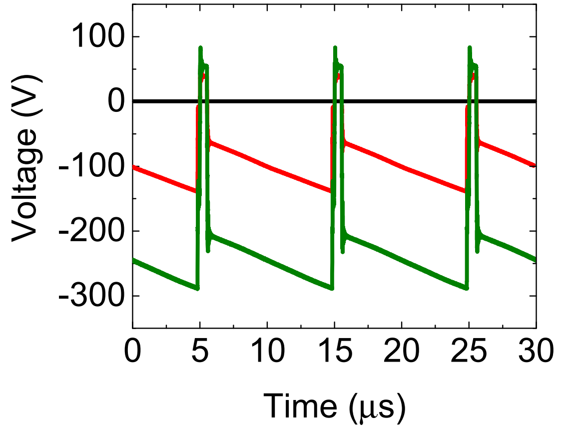
Ion energy control for anisotropic ALE

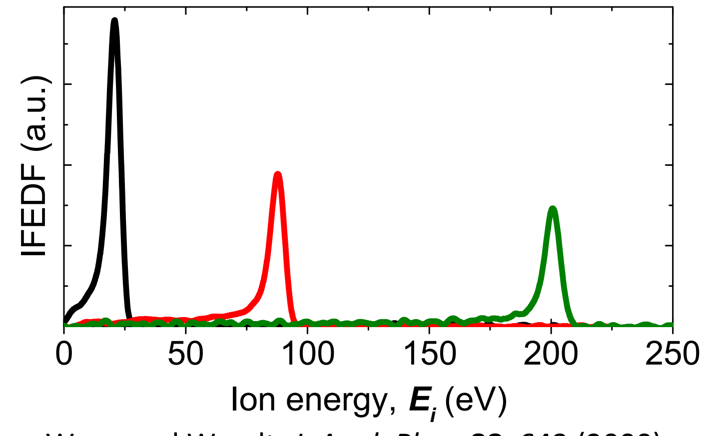












Wang and Wendt, *J. Appl. Phys.* **88**, 643 (2000)
Faraz *et al.*, *J. Appl. Phys.* **128**, 213301 (2020)

Area-selective ALD for self-aligned fabrication

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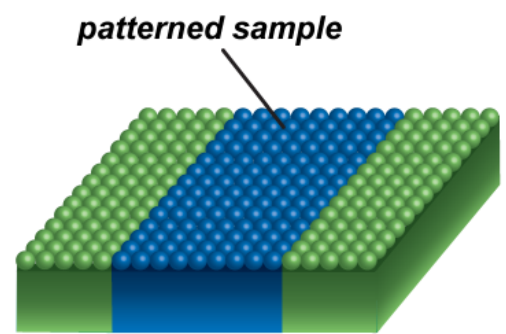
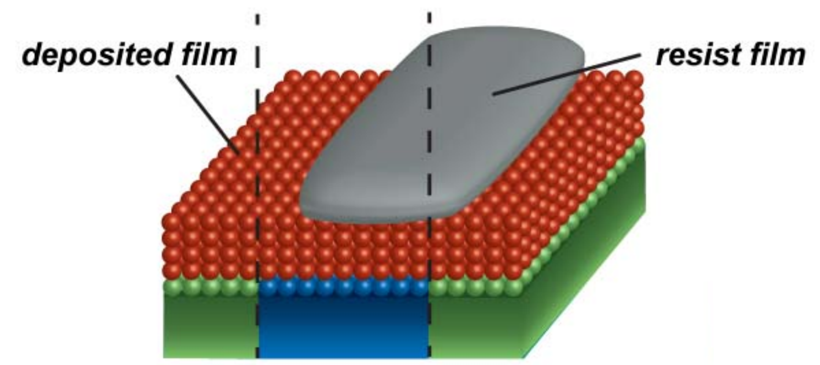
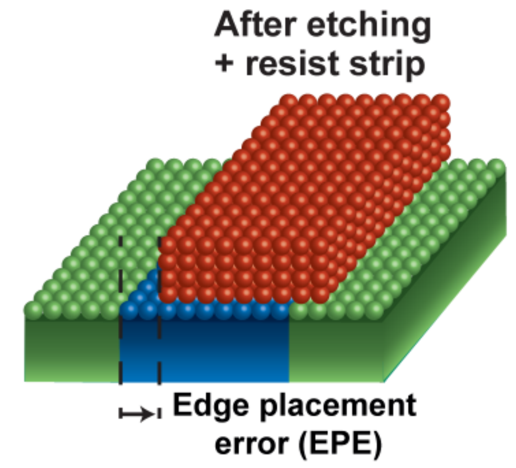
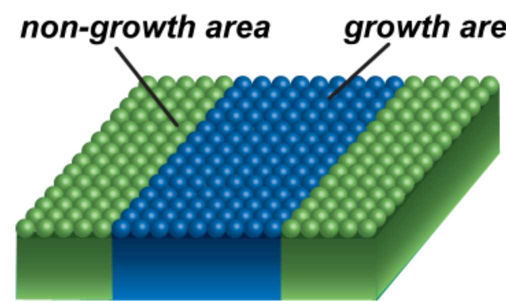
Conventional patterning

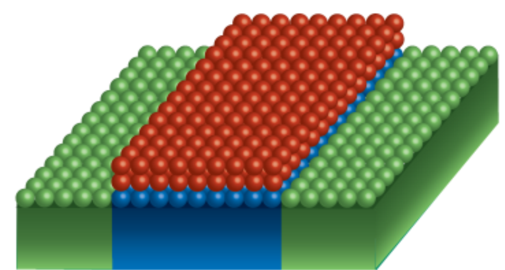


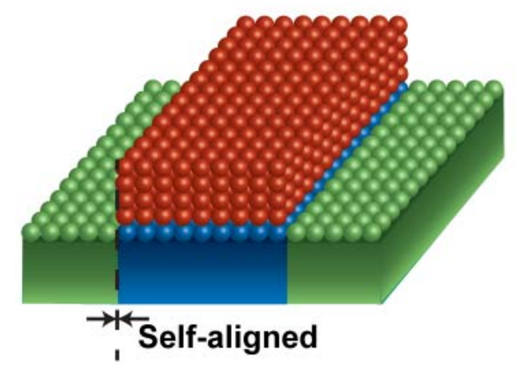




Self-aligned fabrication







Mackus *et al.*, *Chem. Mater.* **31**, 2 (2019)

Area-selective deposition for logic and memory

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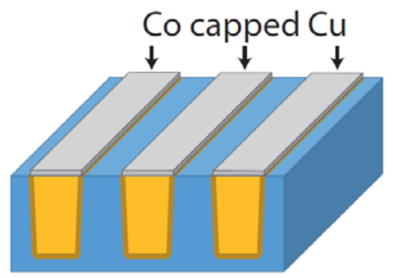
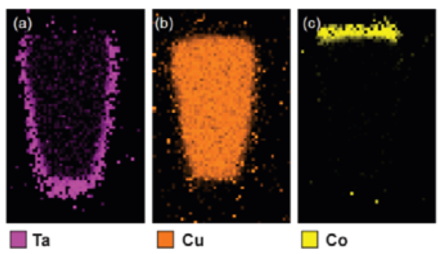
Metal capping

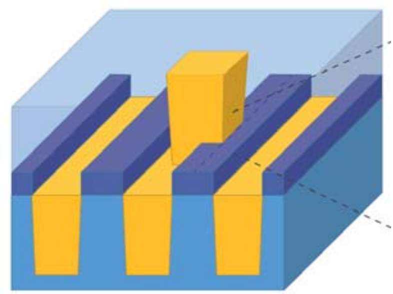


- metal-on-metal
- not on dielectric

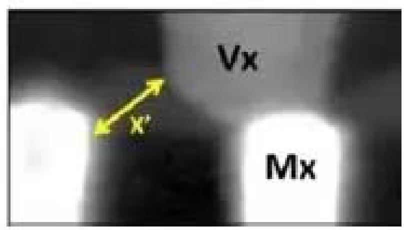


Yang *et al.*, *Microelectron. Eng.* **106**, 214 (2013)

Fully self-aligned via

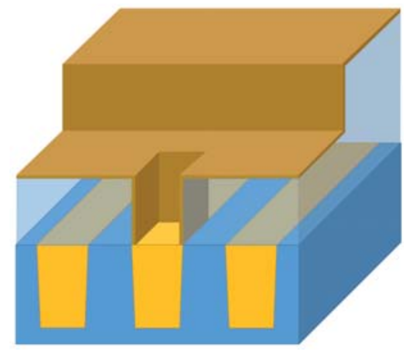


- dielectric-on-dielect
- not on metal

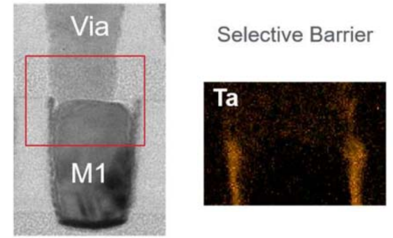


Chen et *al*., IEDM2021

Bottomless barrier

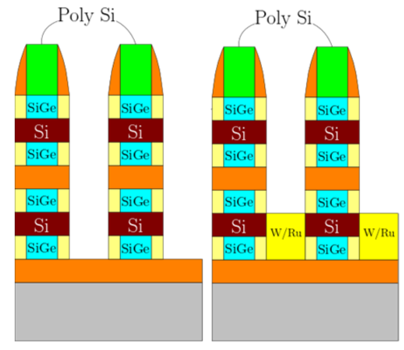


- metal-on-dielectric
- not on metal

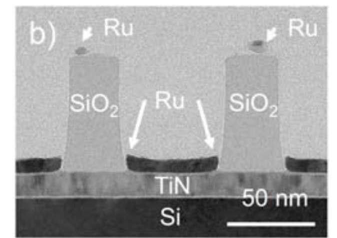


You et *al*, IITC2021.

CFET

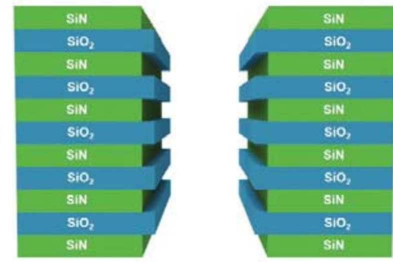


- various ASD steps

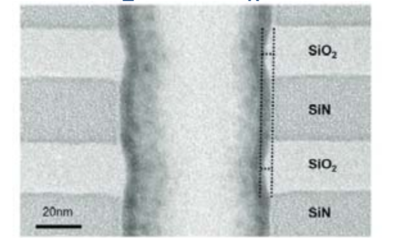


US Patent 10,510,622
Claessens *et al. Sci. Rep.* **12**, 17770 (2022)

Memory



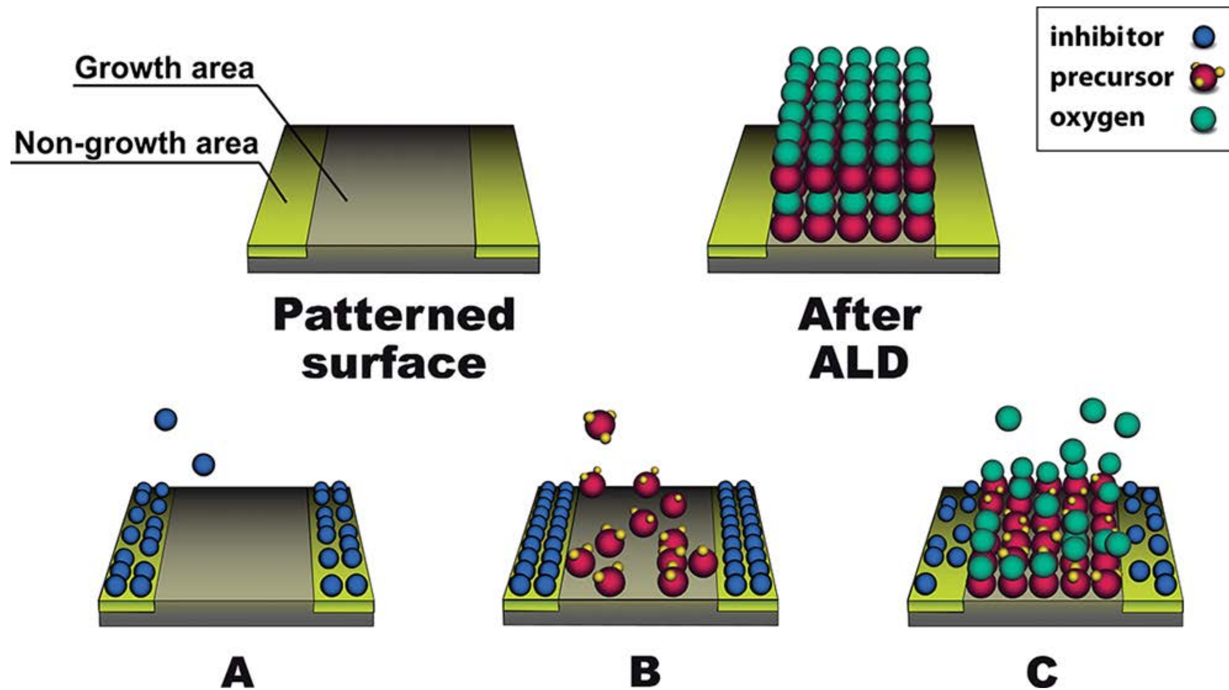
- SiO_2 vs SiN_x
- SiO_2 or SiN_x as NGA



Lee *et al.*, *Adv. Funct. Mater.* **31**, 2102556 (2021)

Blogs on applications: **www.AtomicLimits.com**

Area-selective ALD using small molecule inhibitors



A. Small molecule inhibitor (SMI) selectively adsorbs on the non-growth area

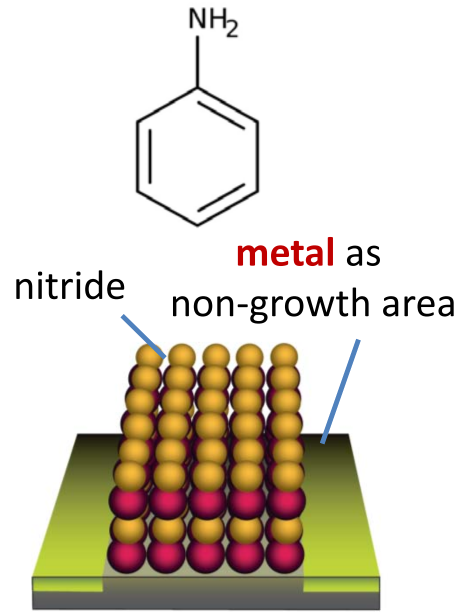
B. Adsorbed SMI blocks the adsorption of the precursor

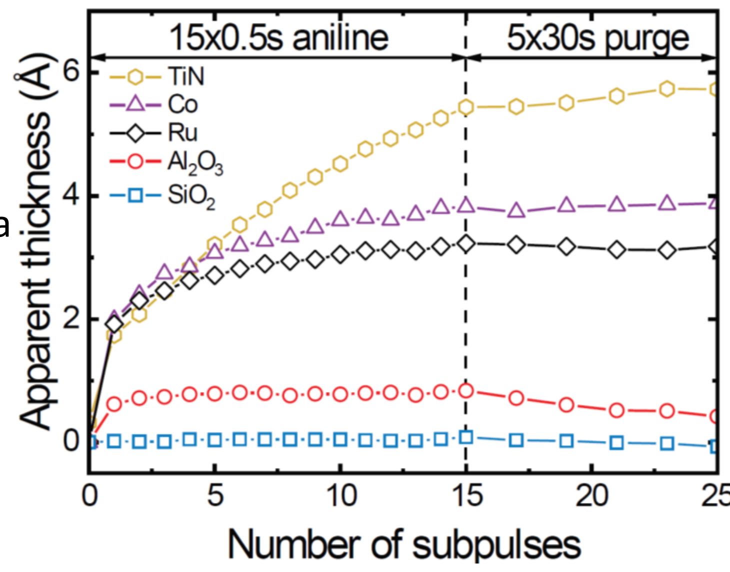
C. SMI and precursor ligands are removed during co-reactant exposure

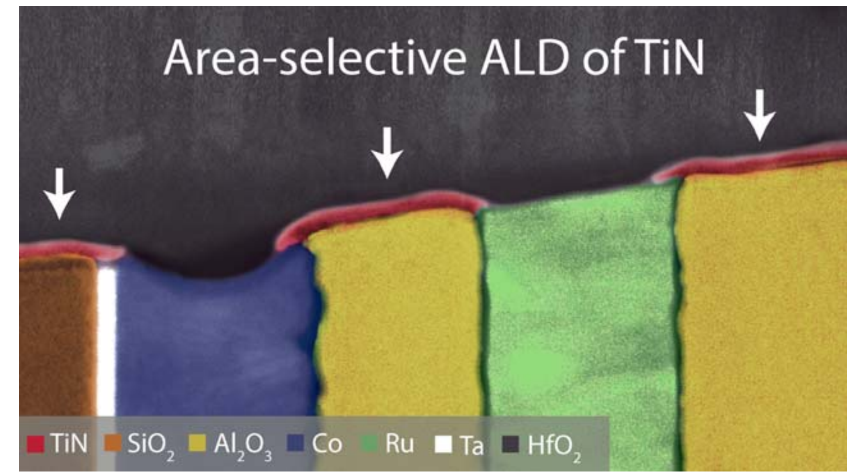
- Vapor-phase dosing of inhibitor molecules → **industry-compatible** approach

Mameli *et al.*, *ACS Nano* **11**, 9303 (2017)

Area-selective ALD of TiN







- Demonstrator for area-selective ALD of TiN
- Aniline inhibitor selectively adsorbs on metal surfaces
- 6 nm of selective TiN ALD achieved on oxide surfaces

Merkx *et al.*, Chem. Mater. **32**, 7788 (2020)

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Conclusions

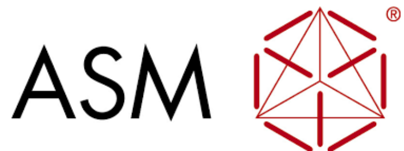
- Area-selective ALD and ALE enable **self-aligned fabrication** for future technology nodes
- **Plasmas isotropic ALE** results in etching at lower substrate temperatures and with higher etch rates as compared to thermal ALE
- Tailored waveform biasing allows for better **control of the ion energy** towards anisotropic ALE
- **Small molecule inhibitors** (SMI) enable industrial-compatible ASD

Perspective article: Mackus *et al.*, *Chem. Mater.* **31**, 2 (2019)

Acknowledgements

ERC Starting grant - BottomUp3D

From the bottom-up: a physico-chemical approach towards 3D nanostructures with atomic-scale control



This project has received funding from the European Union's Horizon Europe research and innovation programme under GA Nº 101092562

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www.icos-semiconductors.eu