Thin film deposition for next generation DRAM structures

ISPR 2017
13.09.2017

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NTNU Trondheim/ Stanford University

NTNU

40000 students
50 faculties
Nobel prize winner 2014

NTNU

NTNU Team

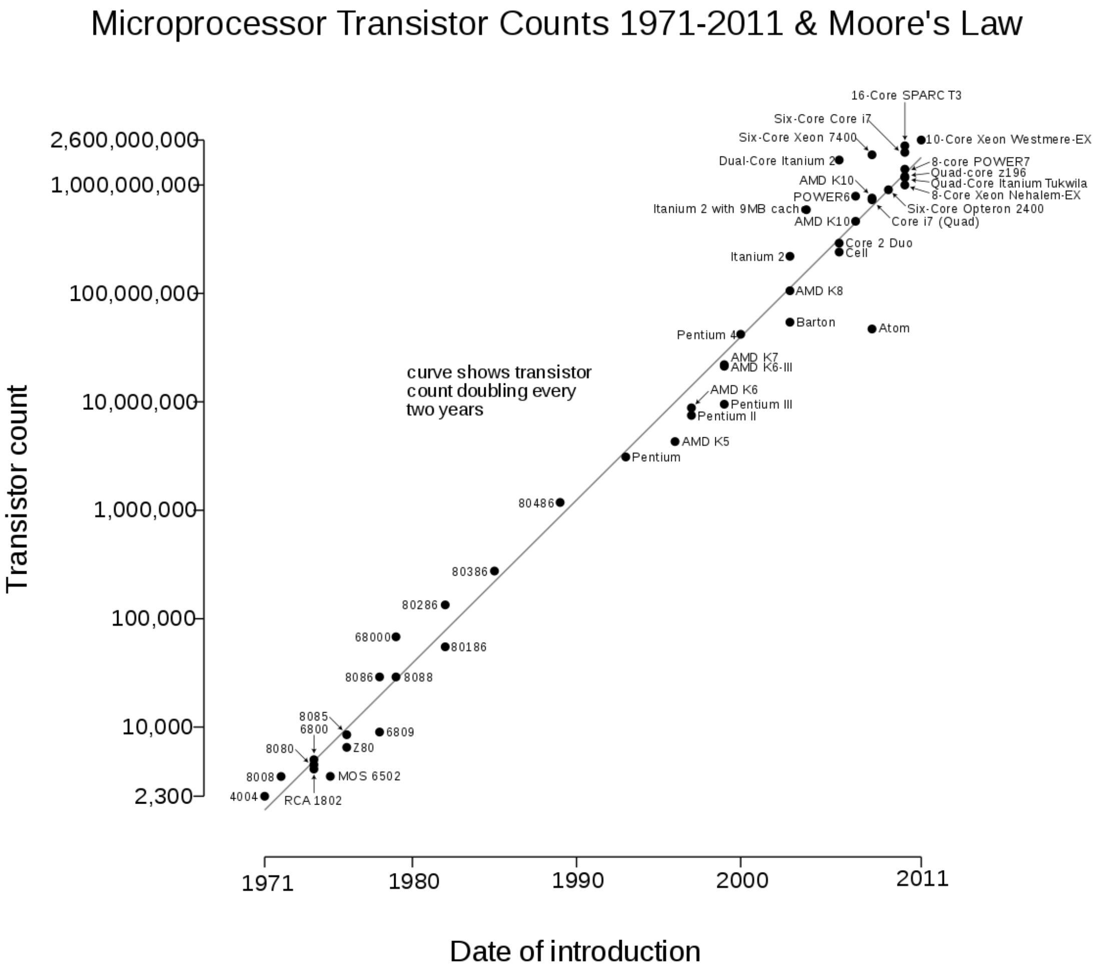
Our group:
3 Faculty
10 PhD students
15 Master Students/ year
Addlab, Fatigue and Nanolab
~ Supported by workshop and admin staff

Research Directions:
Material Design
Material Property Prediction
Surface and Interface Science
Biocompatible Implants
Light weight components
Protective Coatings

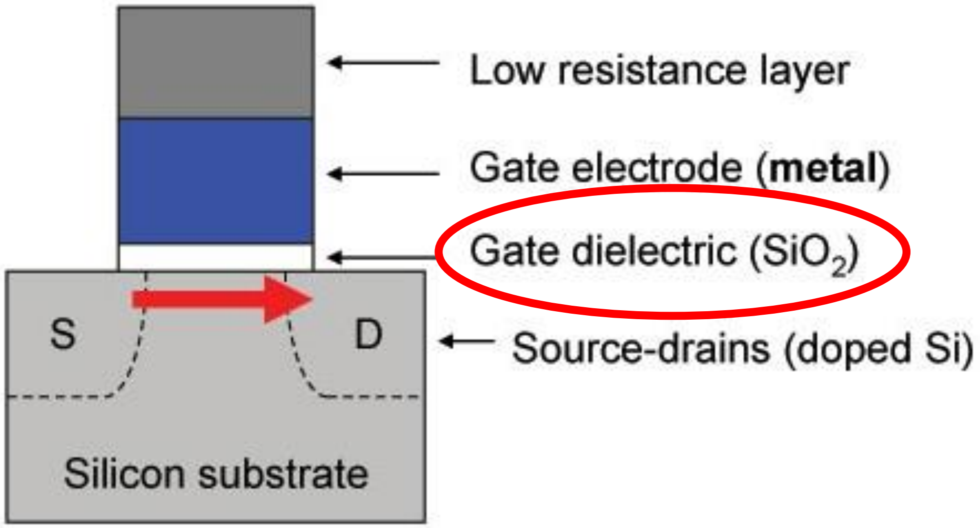
Atomic Layer Deposition- Motivation

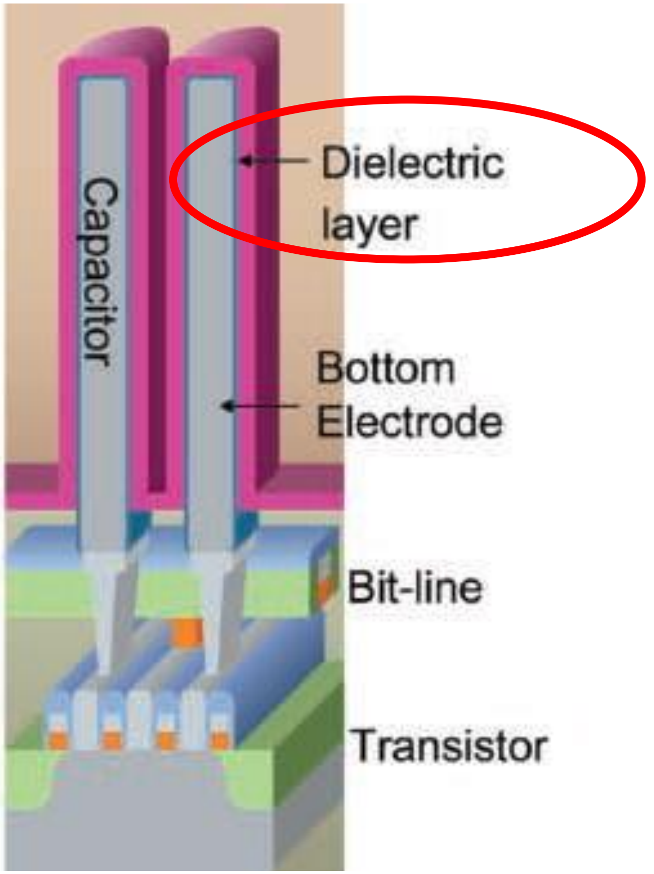
Moore's law

- One of humanity's greatest achievements
- Over 40 years of exponential improvement
- What is the limit?



Atomic Layer Deposition- Motivation

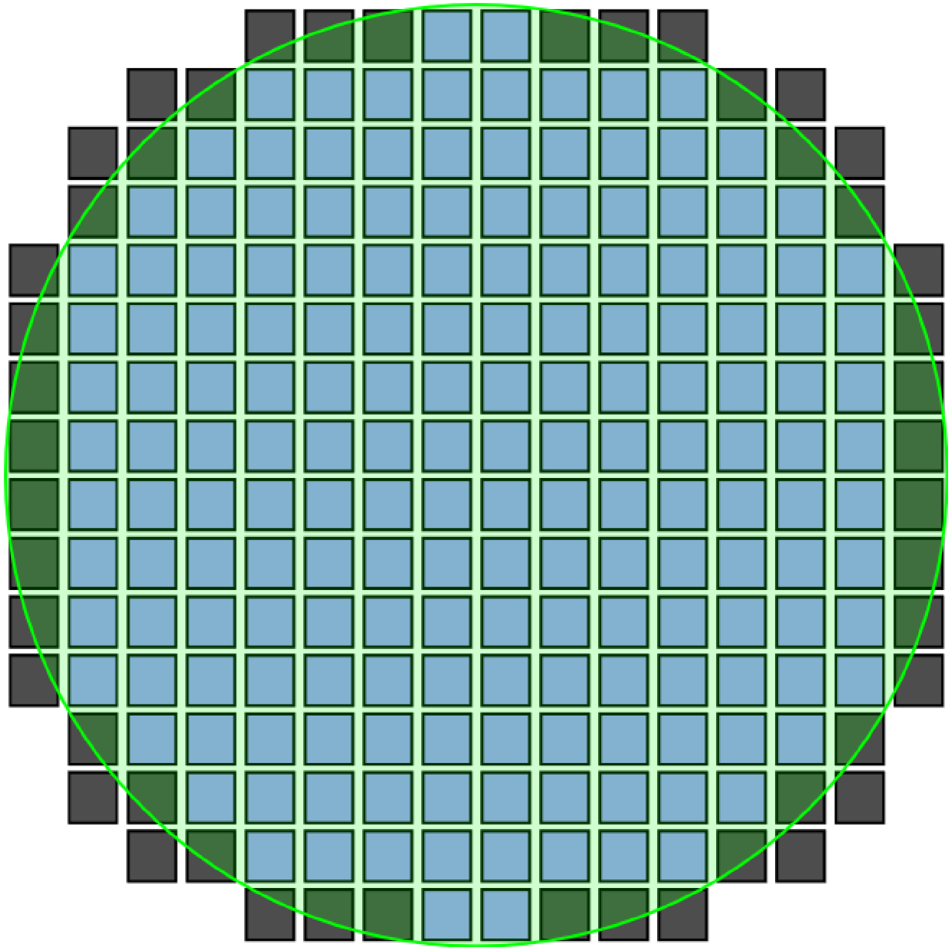




How to Increase the Capacitance?

$$U = \frac{1}{2} C V^2 \qquad C = e_0 e_r \frac{A}{d}$$

Atomic Layer Deposition- Motivation



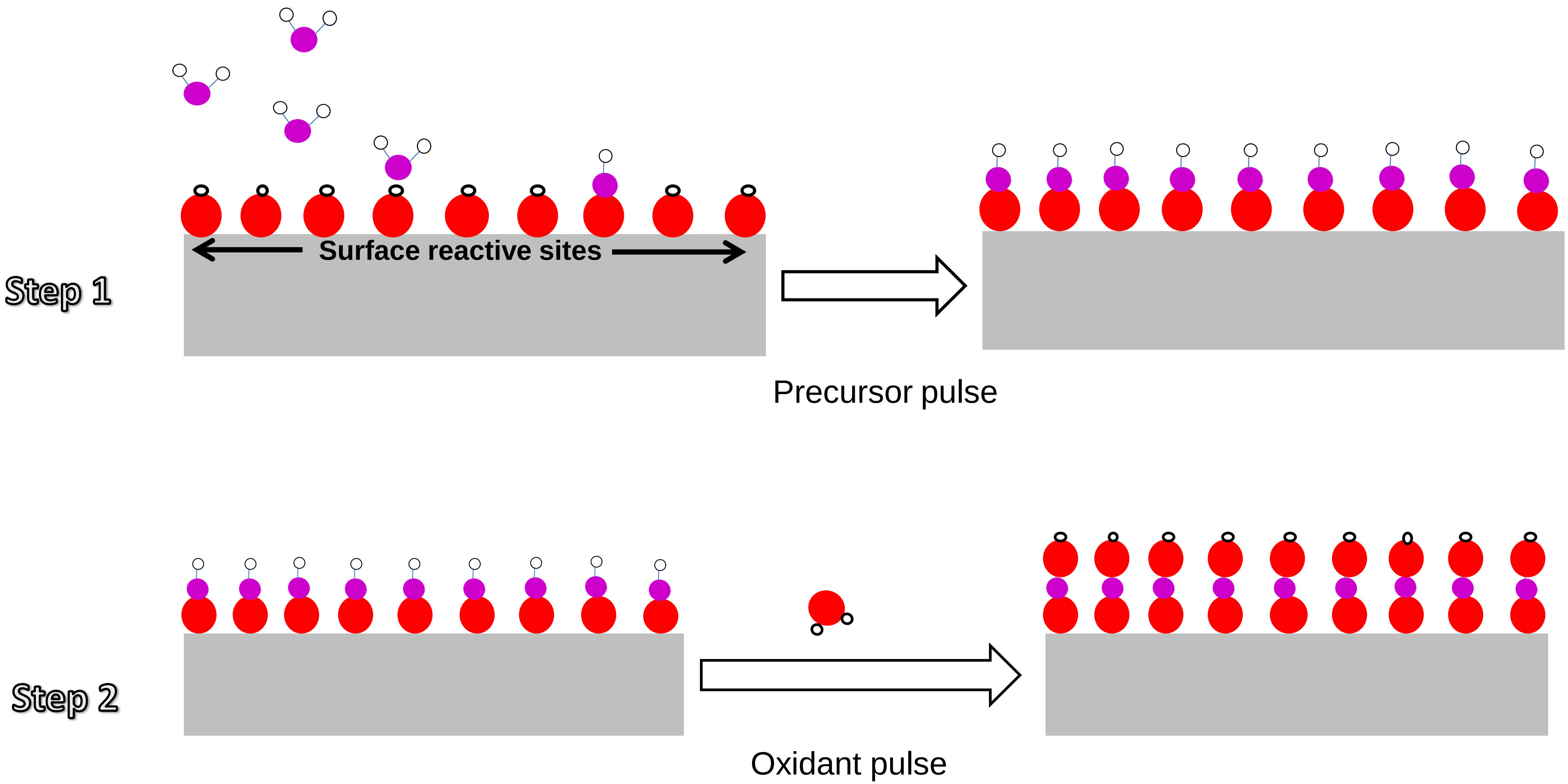
Smallest die size:
0.683 mm × 0.683 mm at the 90 nm
151.527 dies

Average die size
2.130 mm × 2.130 mm at the 65 nm
1434 dies

Biggest die size:
20.253 mm × 20.253 mm at the 65 nm
127 dies

Core i3-2310E
Transistors: 624 million
Die size: Average (149 mm^2)

Atomic Layer Deposition- The principle

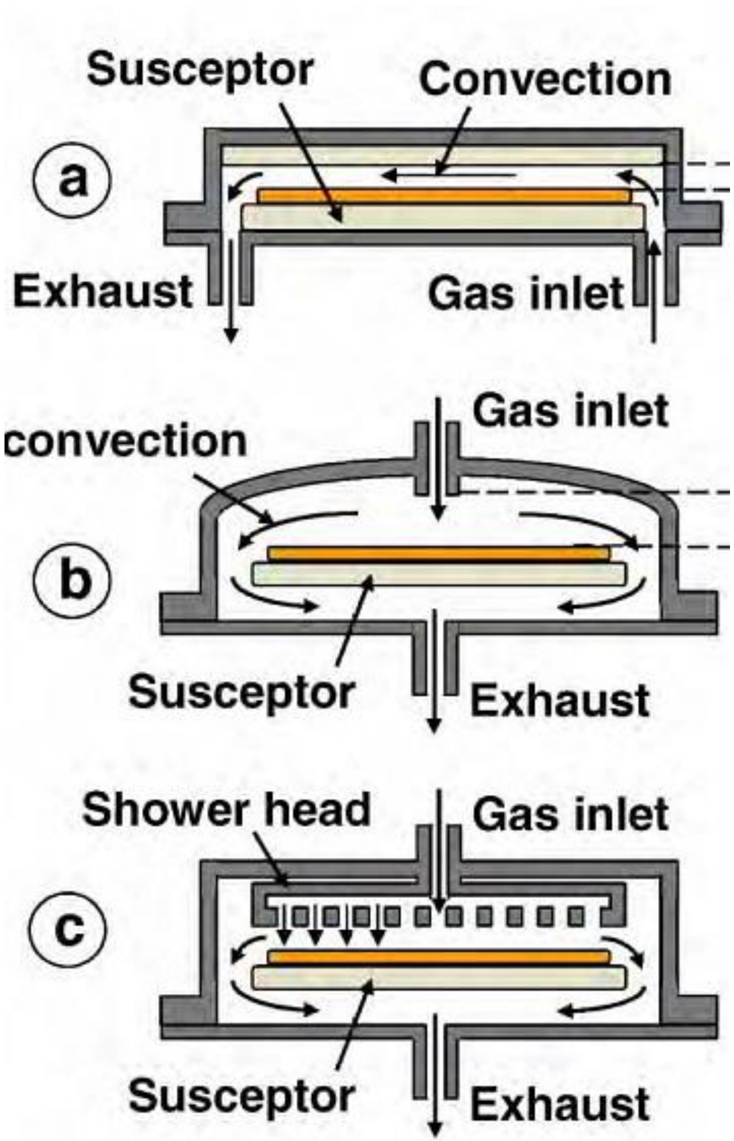


Atomic Layer Deposition- Scale Up

Crossflow

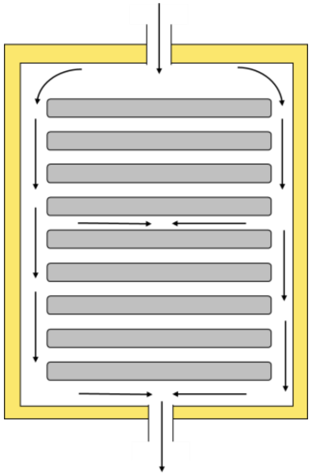
Single Injector

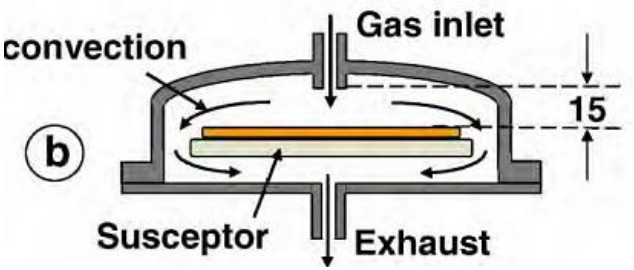
Showerhead



Self-limiting nature enables easy scale up

Atomic Layer Deposition- Scale Up



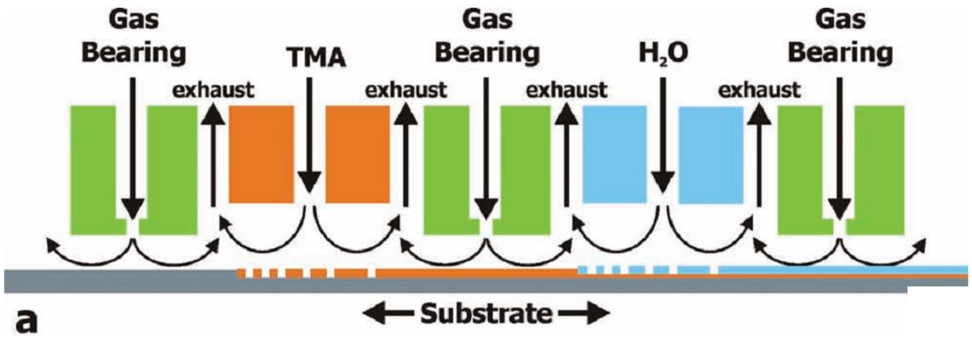


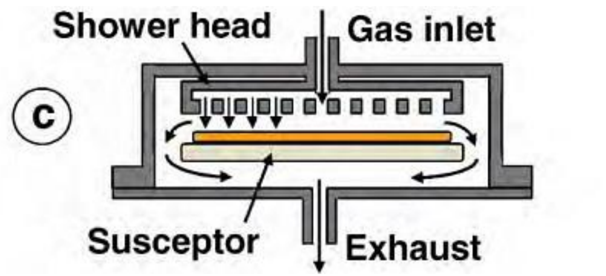
<u>ASM A400C</u>

- Batch size of 125 8-inch wafers
- Dual tube for material stacks
- Process line integration
- Different wafer sizes processable
- Major applications for silicon nitride, amorphous silicon, doped polysilicon
- Wide range of metals and dielectrics processable

http://www.asm.com/PublishingImages/solutions/products/low-pressure-chemical-vapor-deposition-and-diffusion-products/advance-vertical-furnace/a412-plus.png

Atomic Layer Deposition- Scale Up





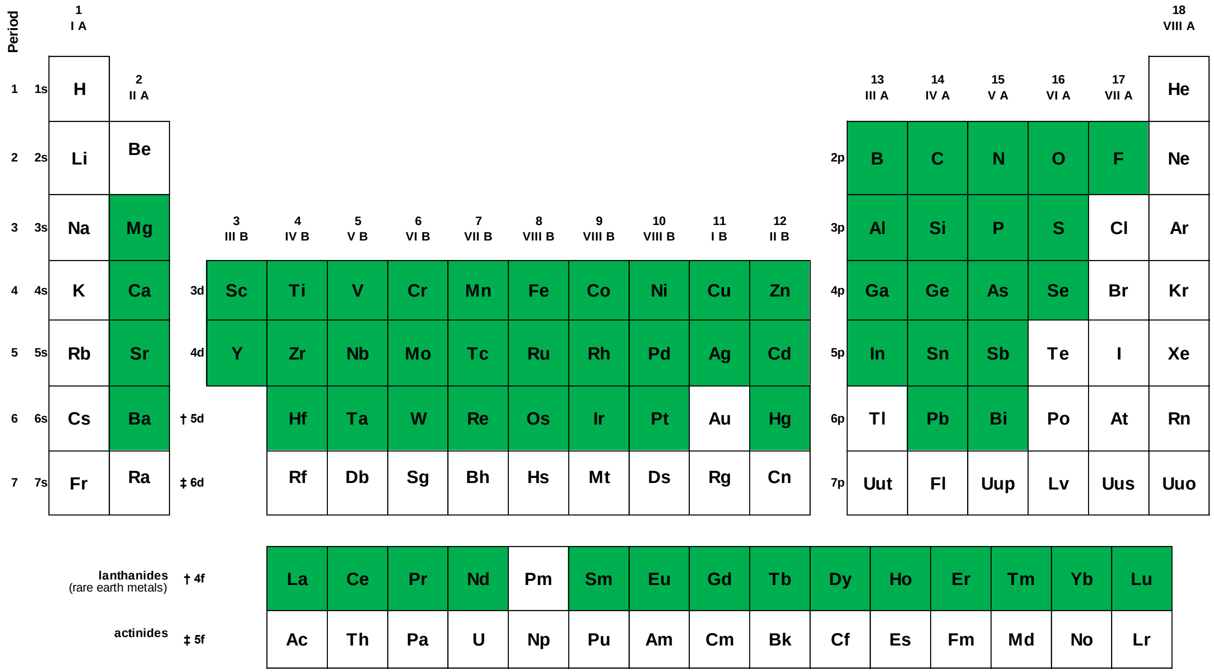
<ins>Solaytec</ins>

- Wafer moves back and forth performing 4 cycles at a time
- 8 depositions/s with one head
- 5000 wafers/h
- Atmospheric pressure, no pump required
- Deposition rate 1nm/s per module
- Only TMA and H_2O so far

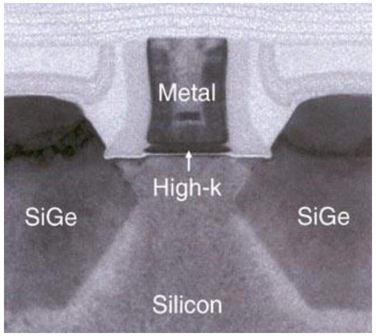
http://www.solaytec.com/images/stories/flexicontent/l_solaytec-2919-v1.jpg

Atomic Layer Deposition- The materials

Depositing elements all across the periodic table

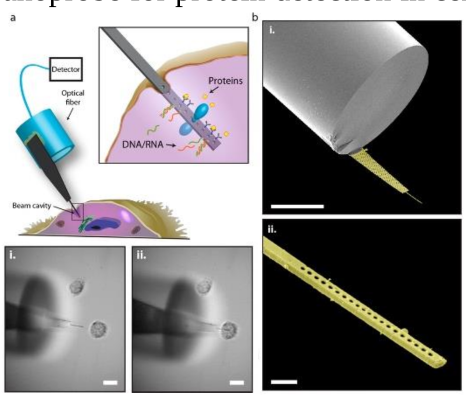


Intel's 45-nm high-k transistor



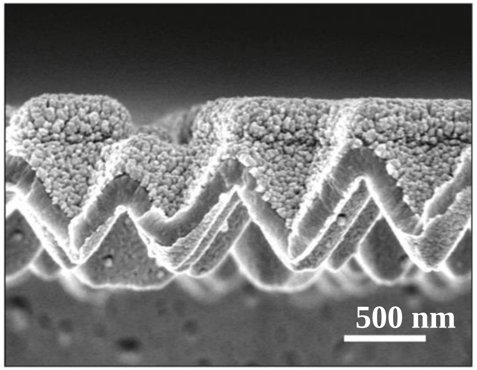
Mistry, K. et al, *Electron Devices Meeting, 2007. IEDM 2007. IEEE International* , pp.247-250 (2007)

Nanoprobe for protein detection in cells



Shambat et al.; Nano Lett. 2013, 13, 4999-5005.

Thin film solid oxide fuel cell

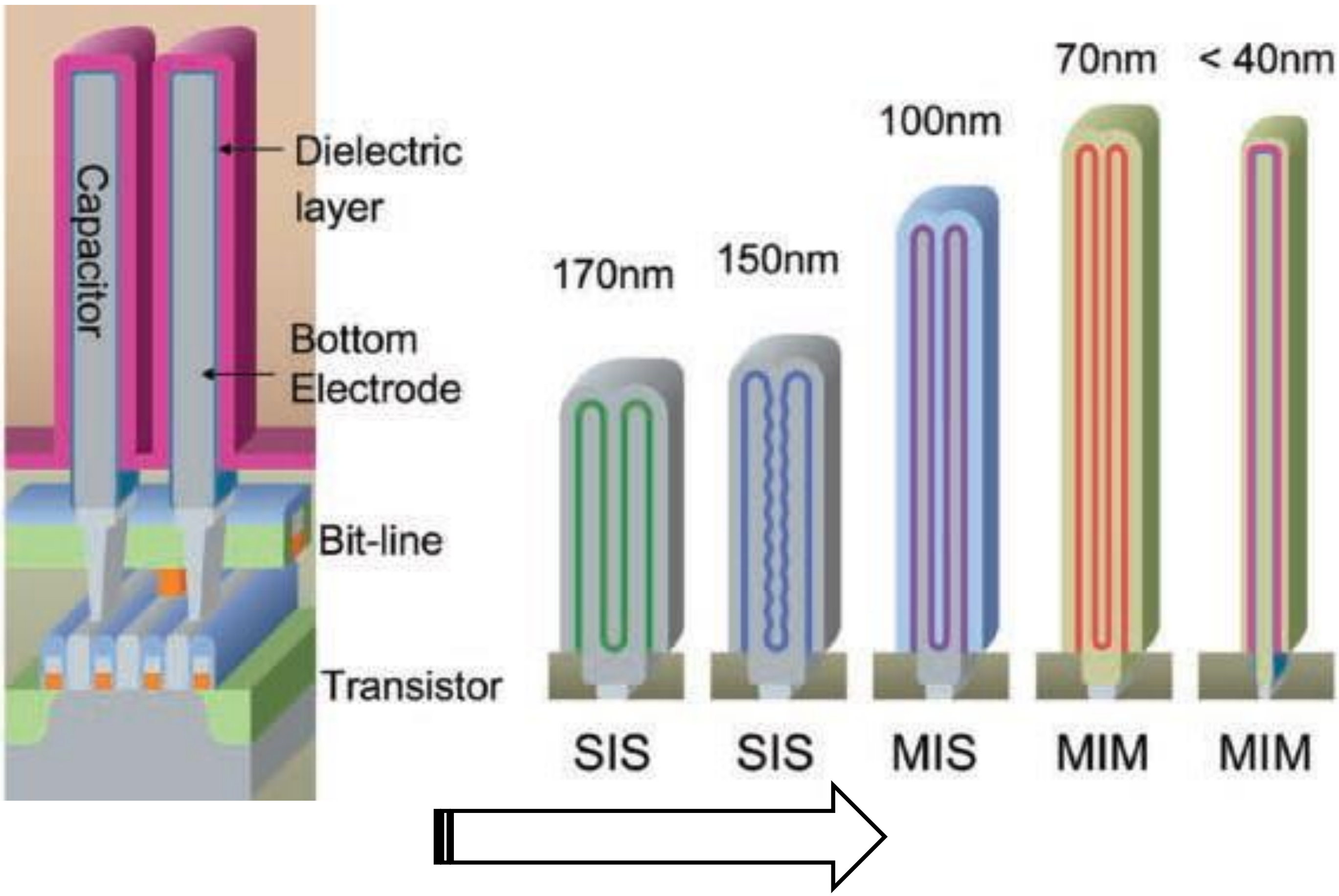


Chao, C. C., Hsu, C. M., Cui, Y., Prinz, F. P. , ACS Nano, 5, 5692-5696 (2011).

High-k thin films for DRAMs

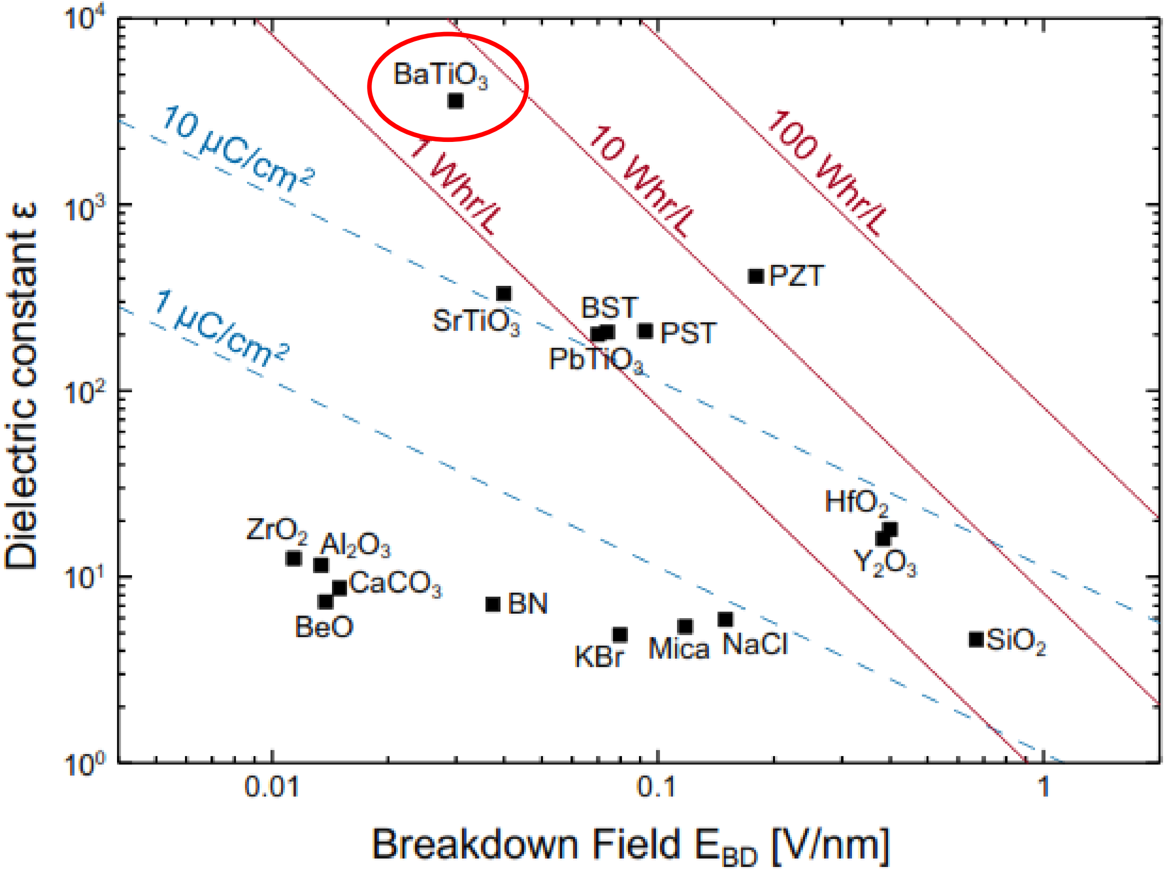
How to Increase the Capacitance?

$$U = \frac{1}{2} C V^2 \qquad C = e_0 e_r \frac{A}{d}$$

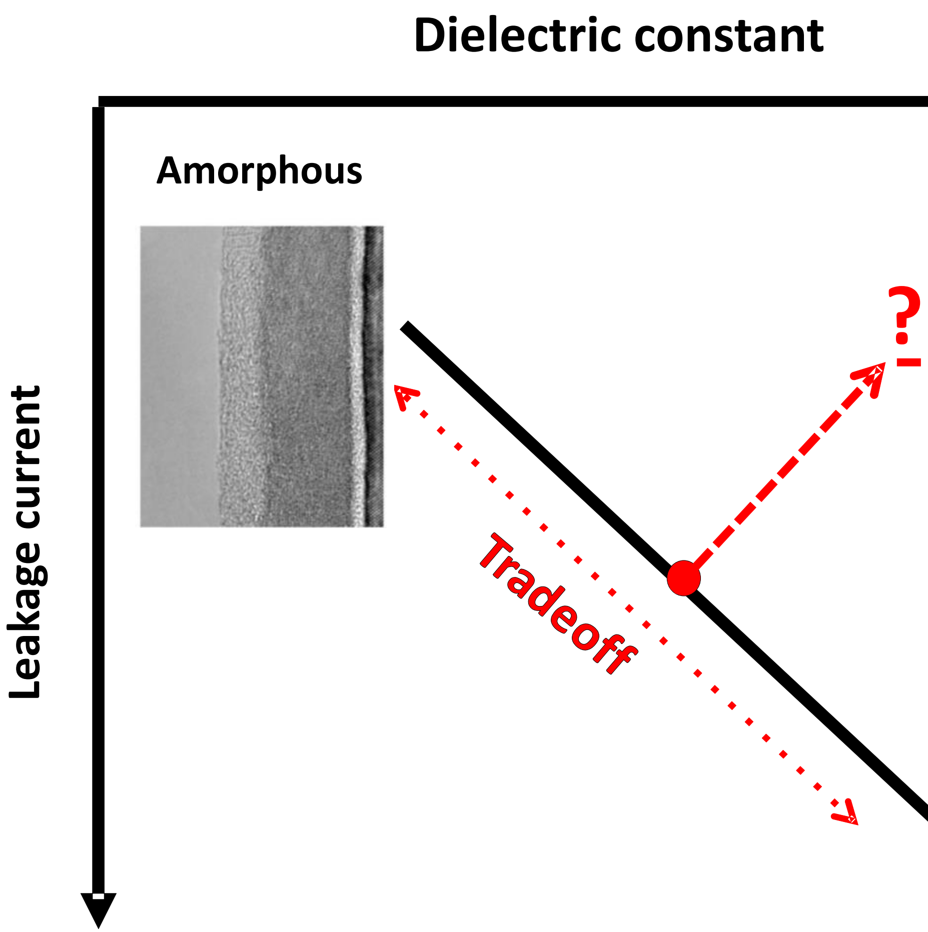


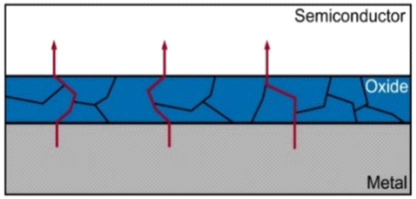
High-k materials

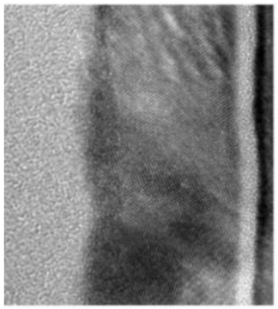
$$C = e_0 e_r \frac{A}{d}$$

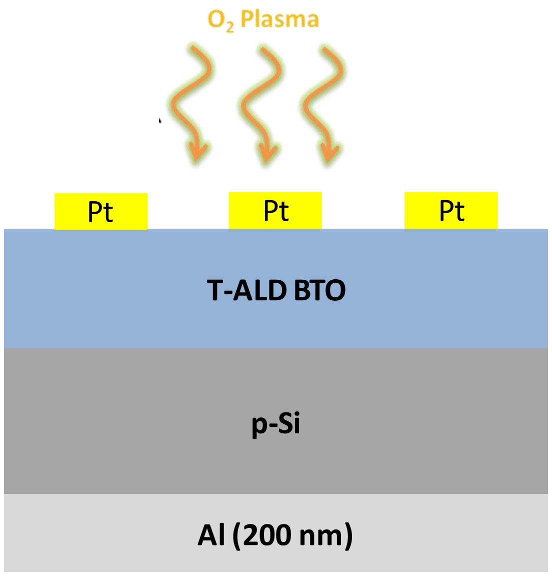


High-k thin films for DRAMs



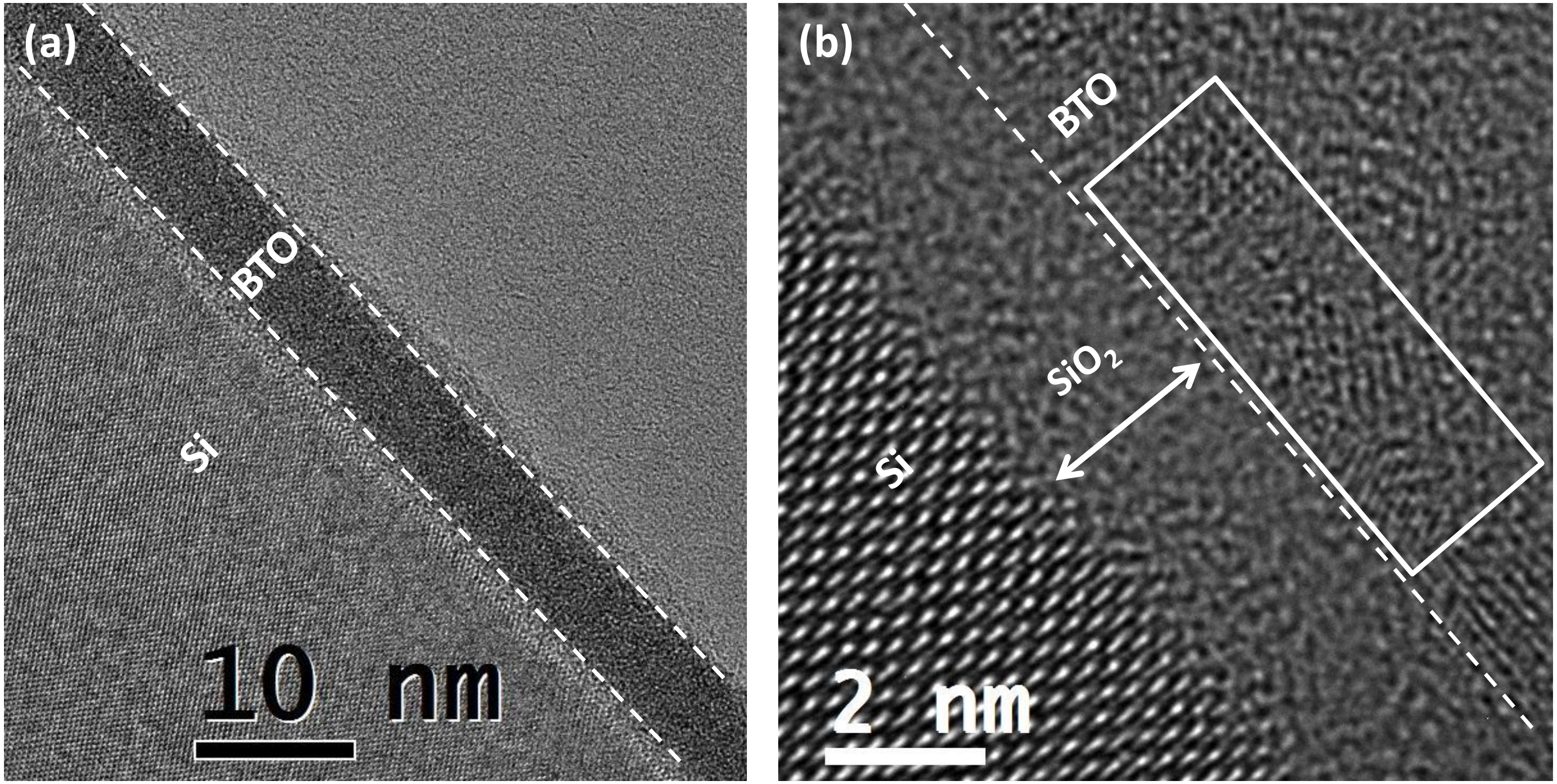






P. Schindler et al., Scripta Mater. (2015)

High-k thin films for DRAMs

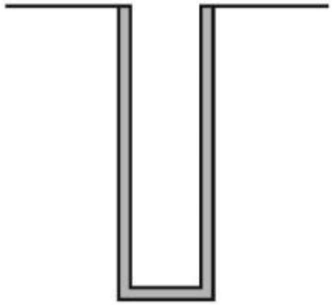


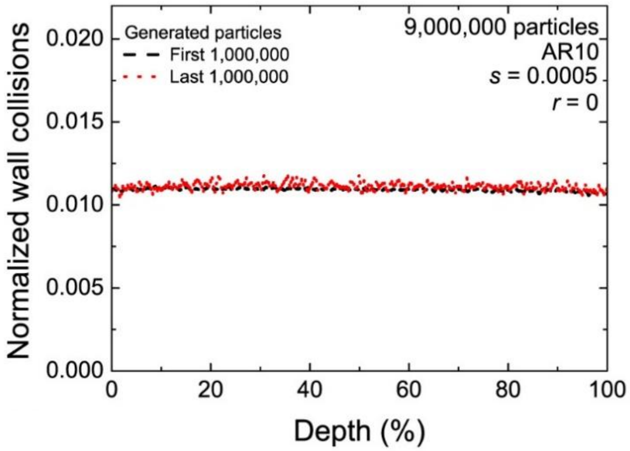
Crystallites buried in amorphous matrix of 7 nm thick $BaTiO_3$

P. Schindler et al., Scripta Mater. (2015)

High-k thin films for DRAMs

Reaction limited



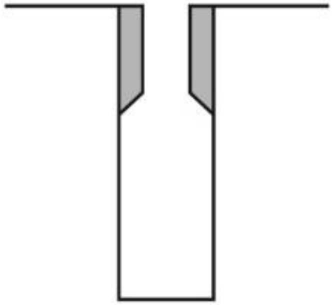


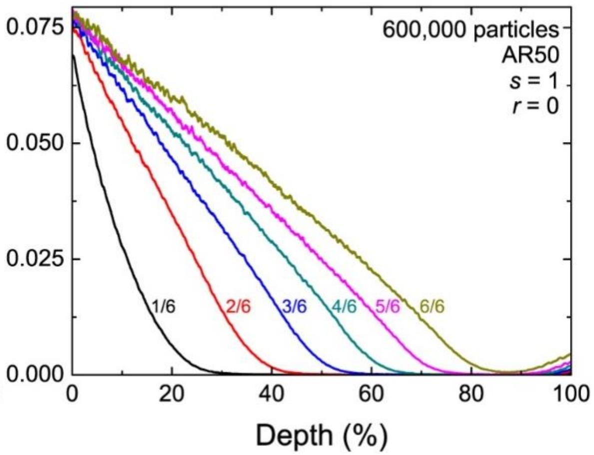
s << 1

r = 0

AR independent

Diffusion limited



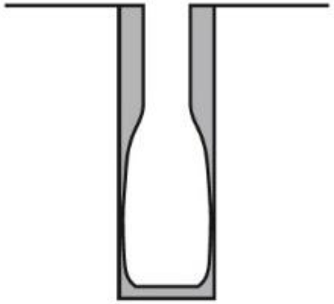


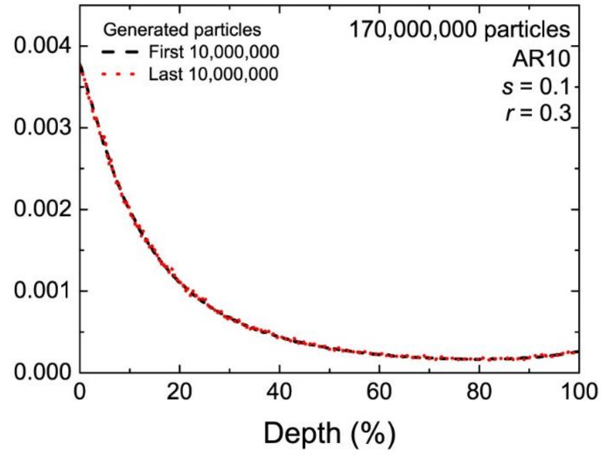
s = 1

r = 0

AR dependent

Recombination limited





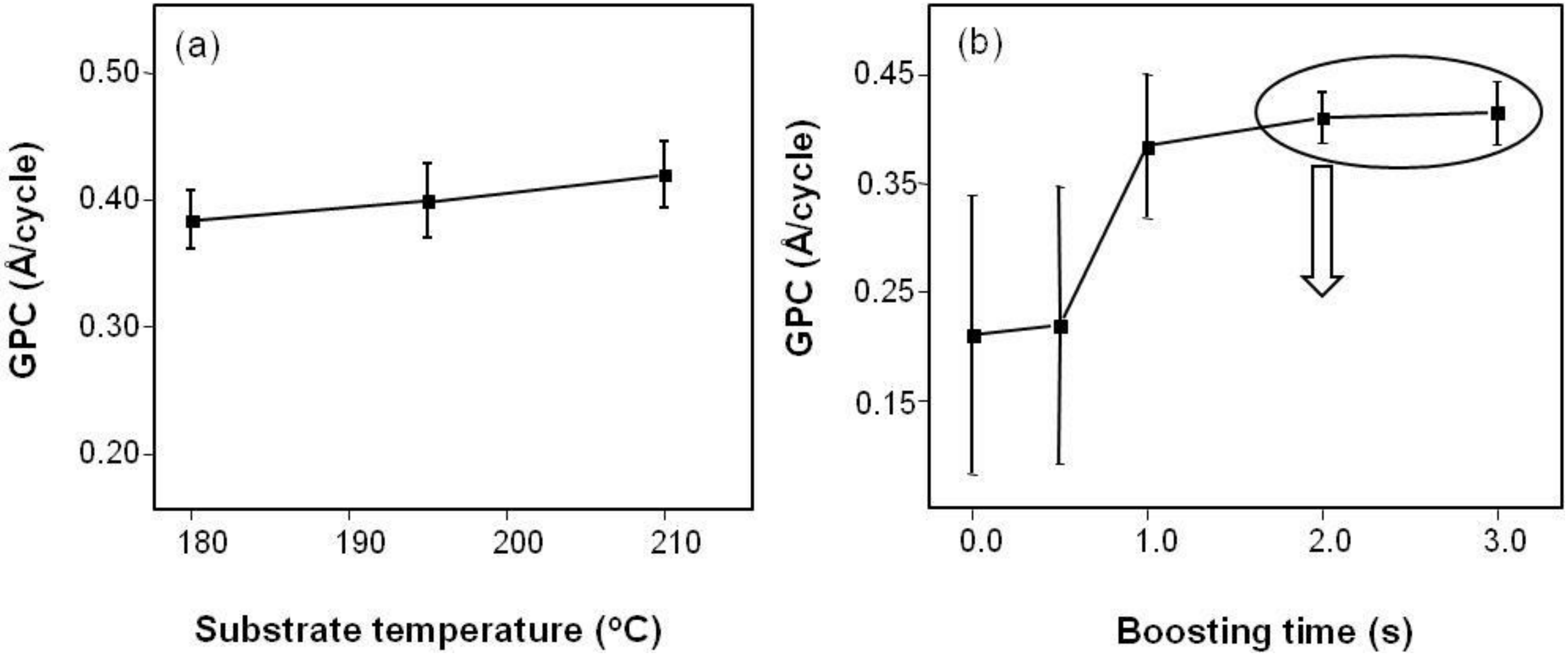
s independent

r > 0

AR dependent

Knoops et al. J. El. Chem. Soc. 2010

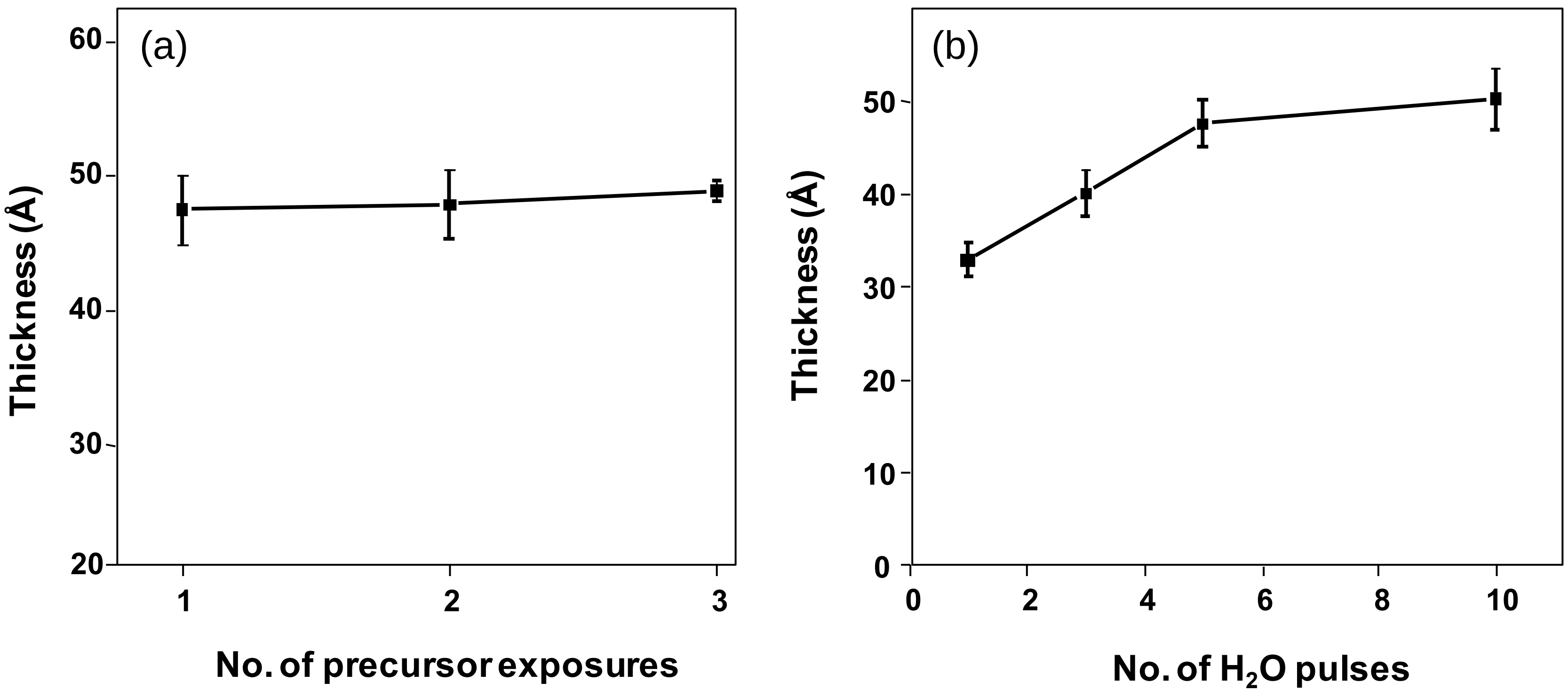
High-k thin films for DRAMs



GPC ~ 0.45 Å/cycle

Acharya, Torgersen et al 2016 J. o. Material Chemistry C

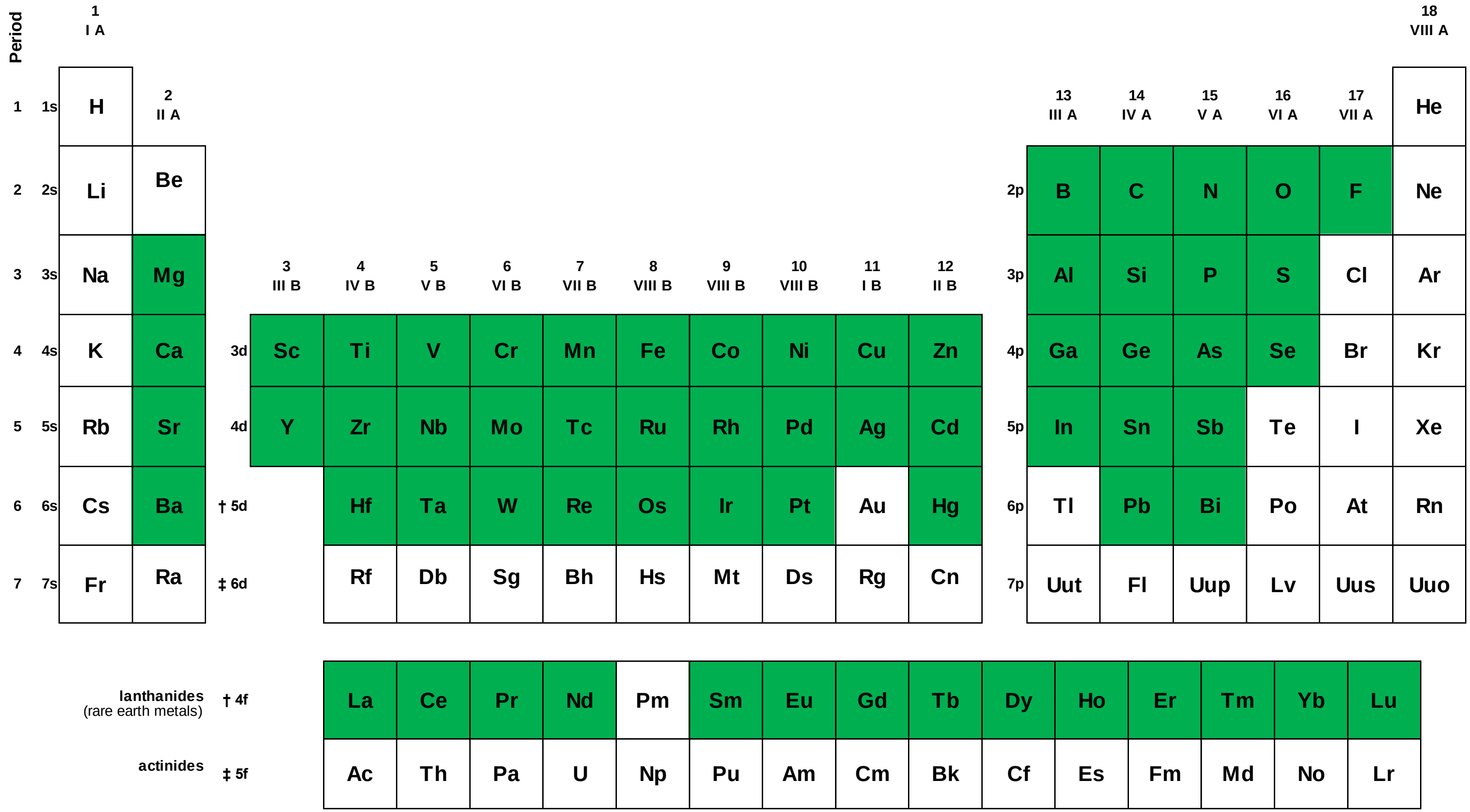
High-k thin films for DRAMs

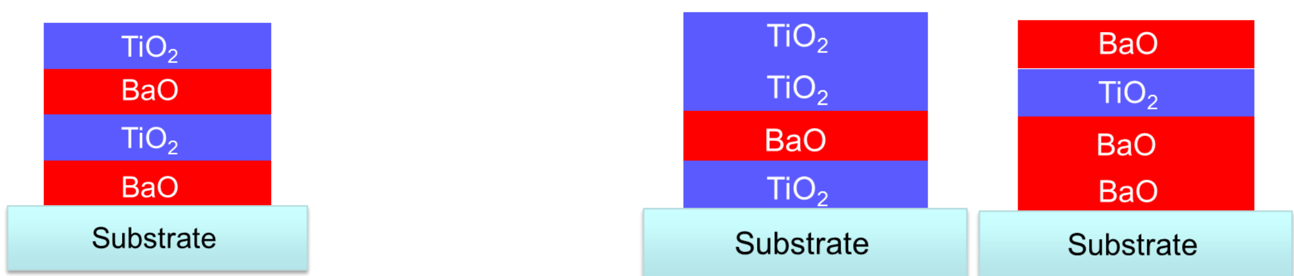


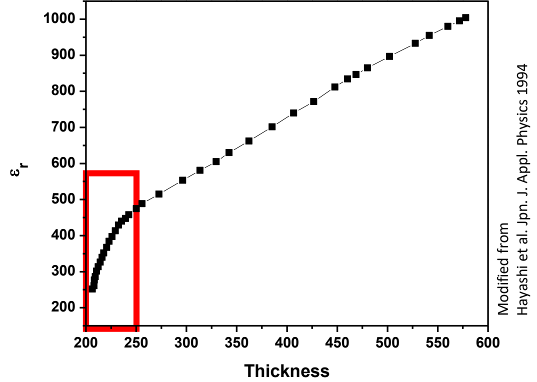
Self-limiting mode of growth in both half cycles of reaction

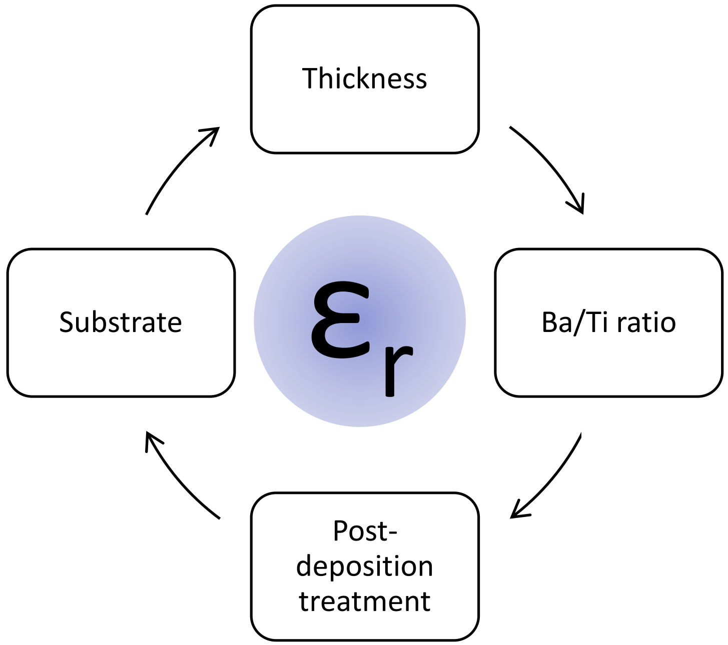
Acharya, Torgersen et al 2016 J. o. Material Chemistry C

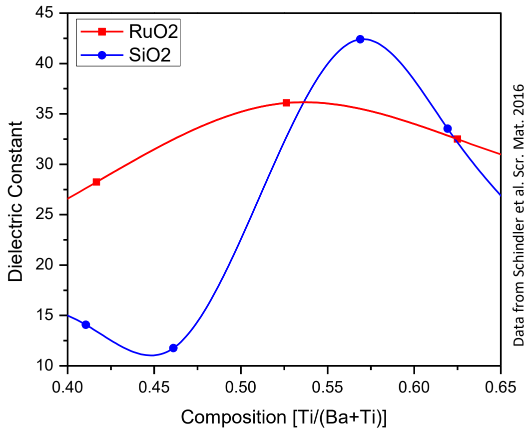
High-k thin films for DRAMs

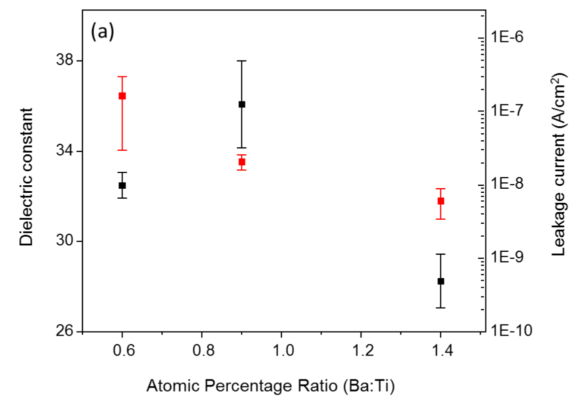


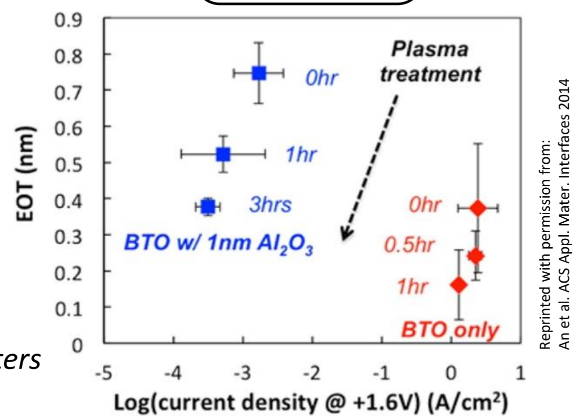








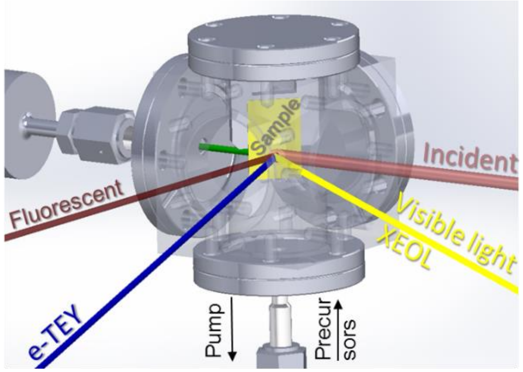




Torgersen et *al* 2016 *J.o. Physical Chemistry Letters*

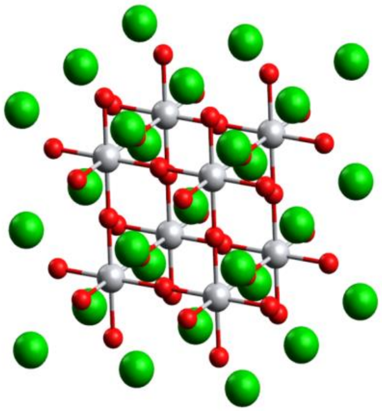
ALD characterization in the SSRL

What is the chemical and structural nature for thin film performance modifications?



XANES

+



Quantum Simulations

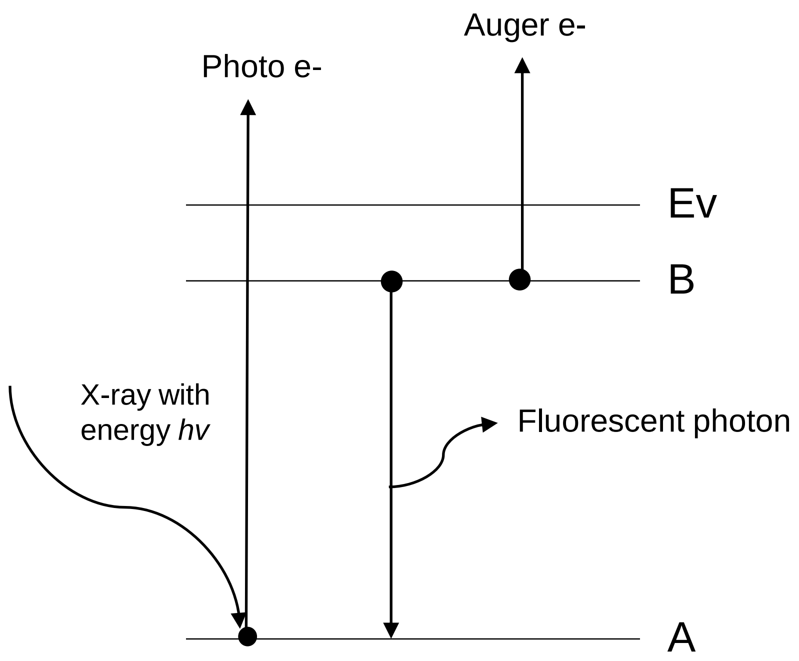
Provides
Chemical Identity
Oxidation State
Coordination
Local geometric Structure
Local Density of unoccupied States

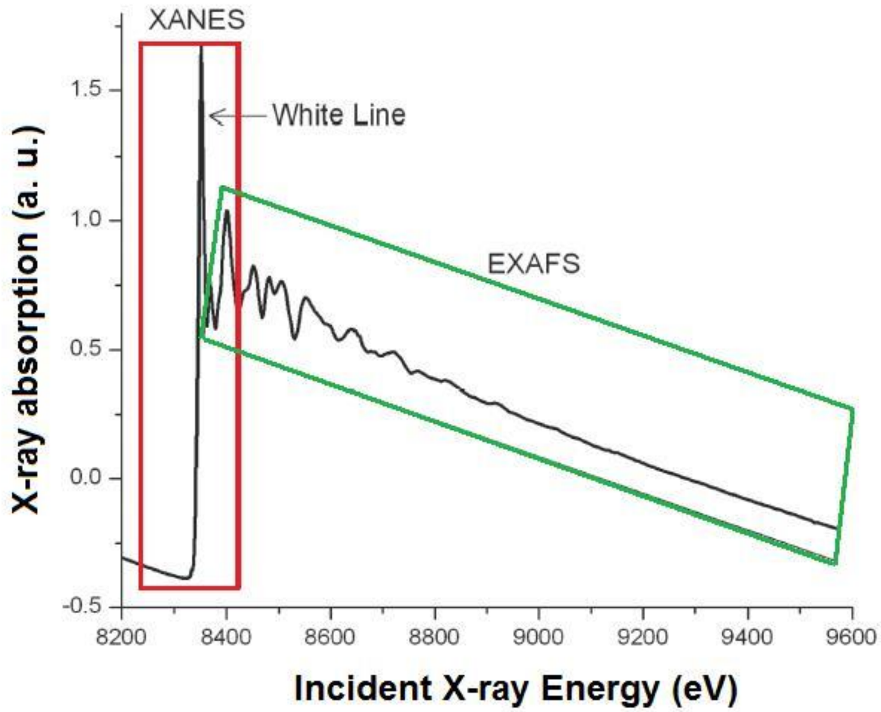
Allows studying
Interfaces
Structural distortions
Dopant atoms
Nucleation process

Torgersen et *al* 2016 *J.o. Physical Chemistry Letters*

ALD characterization in the SSRL

Photoelectron
E= *hv* - binding energy
Ejected to unoccupied state





Beer's law: Absorbance= $\log(I_0/I_t)$ or $\log(I_0/I_f)$

X-ray absorption near edge structure (XANES)

Pre-edge:

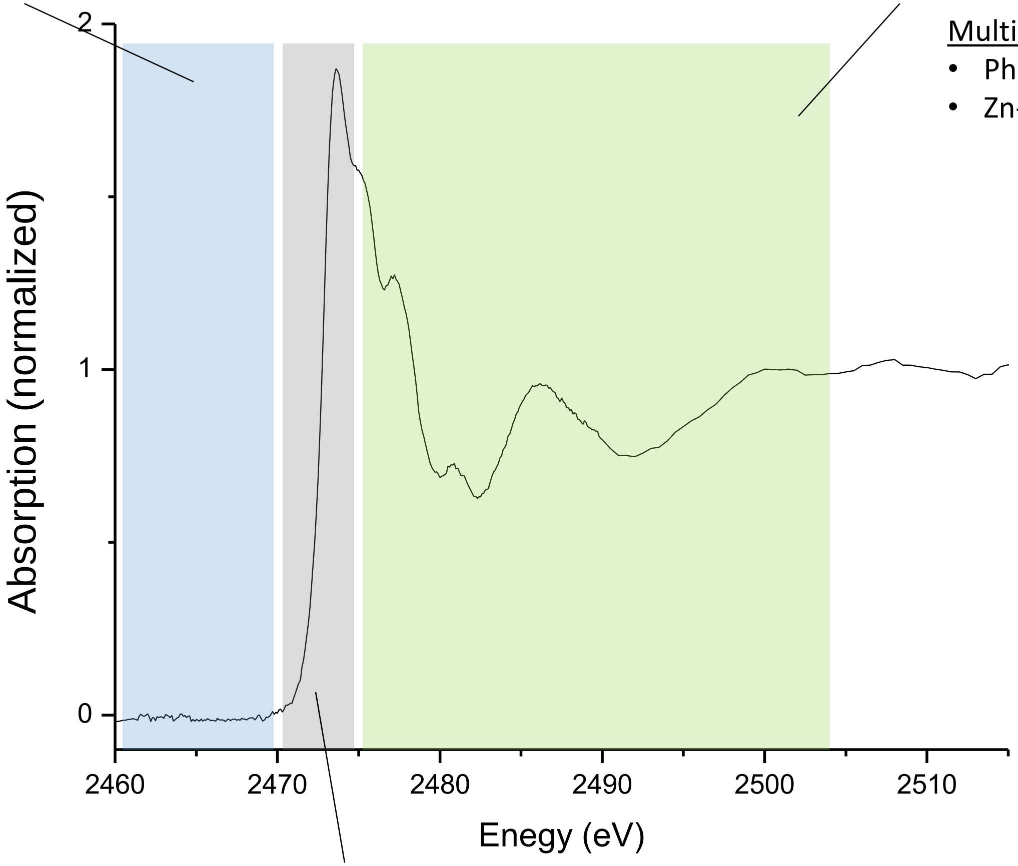
<u>Molecular symmetry</u>

- Forbidden transitions
- Weak intensity
- Featureless

Post-edge:

<u>Multiple scattering paths</u>

- Photo e- longer than Zn-S bond
- Zn-S-Zn



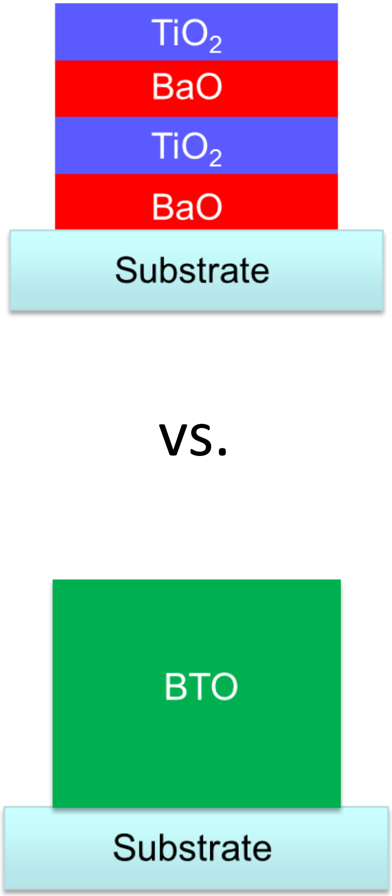
Edge-jump:

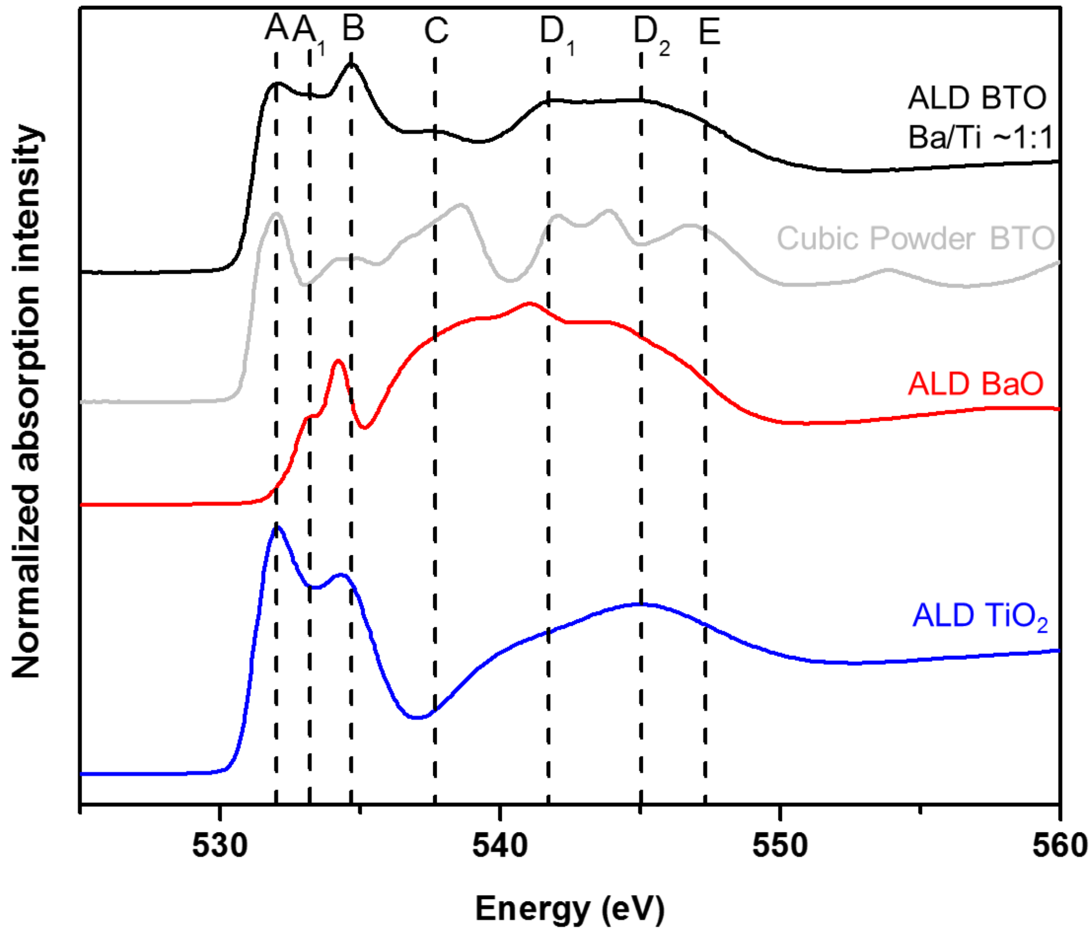
<u>Oxidation state</u>

- Unoccupied state in valence orbitals
- Empty S 3p and Zn 4 sp orbitals

XANES of ALD BTO

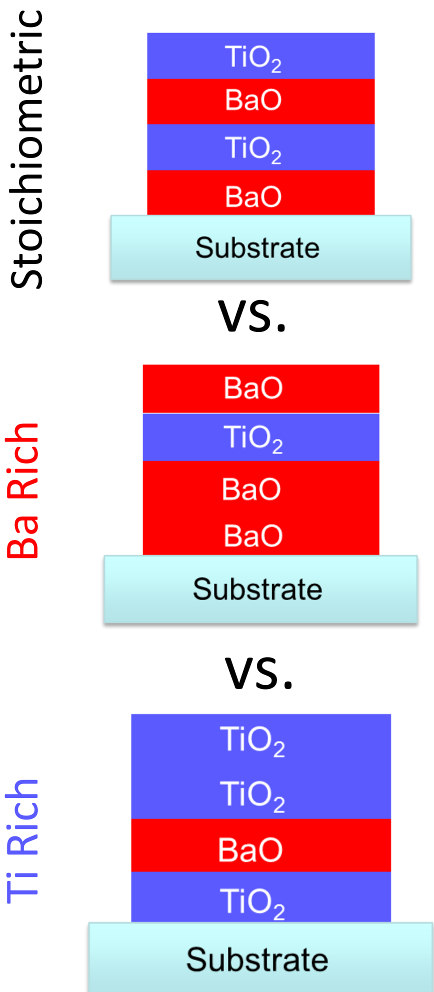
Mixing of BaO and TiO_2 to form $BaTiO_3$

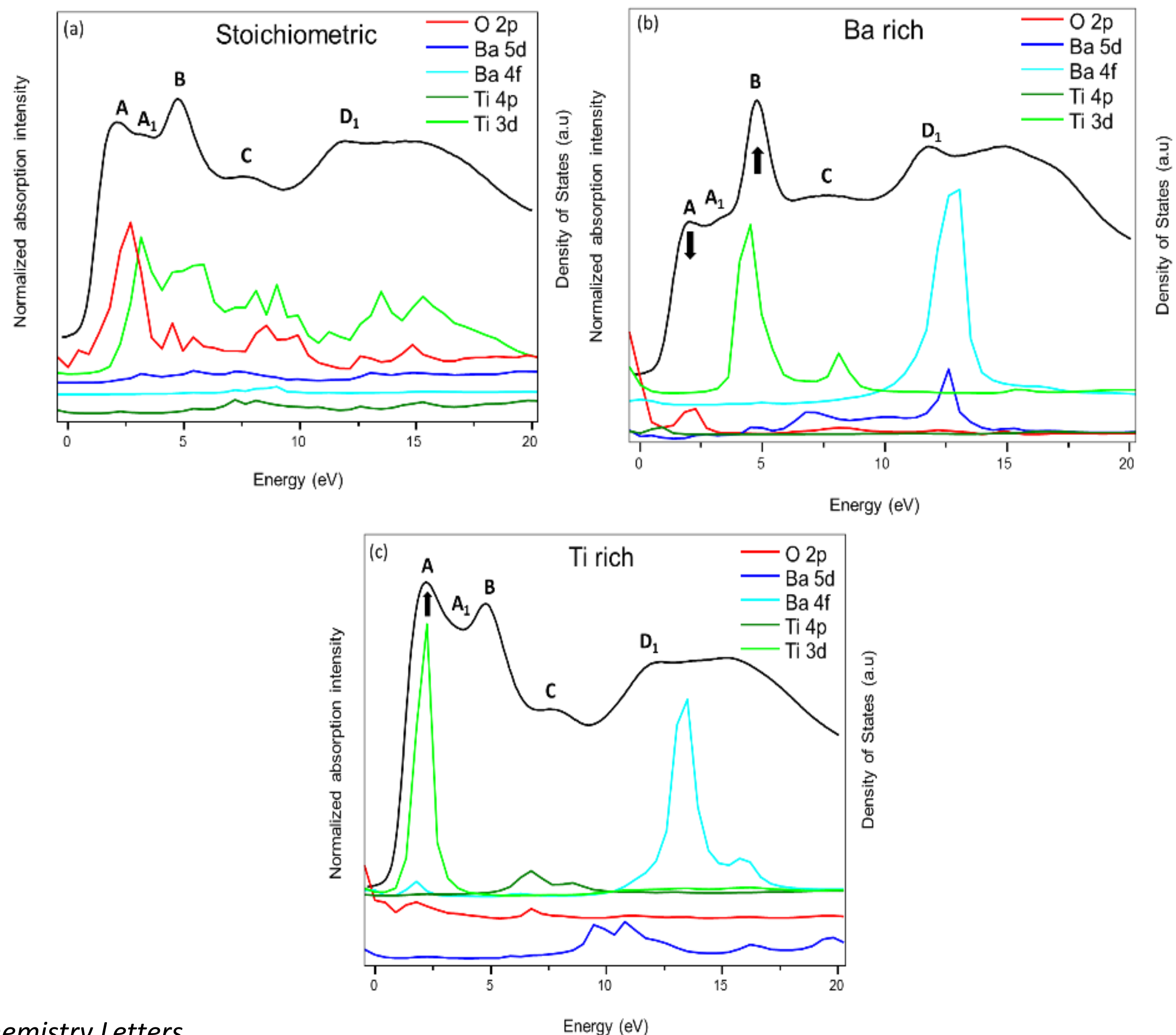




XANES of ALD BTO

Changing Ba/Ti composition





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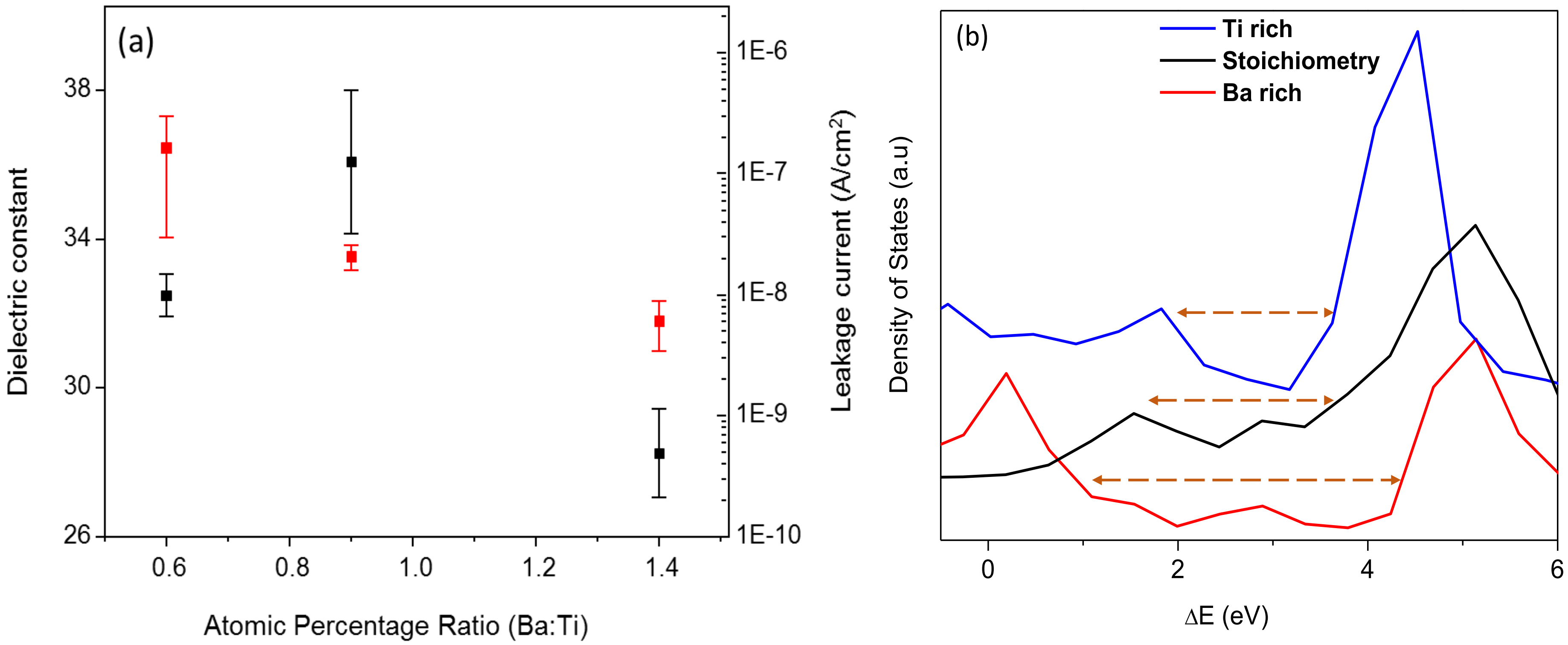
XANES of ALD BTO

Leakage current and band gap



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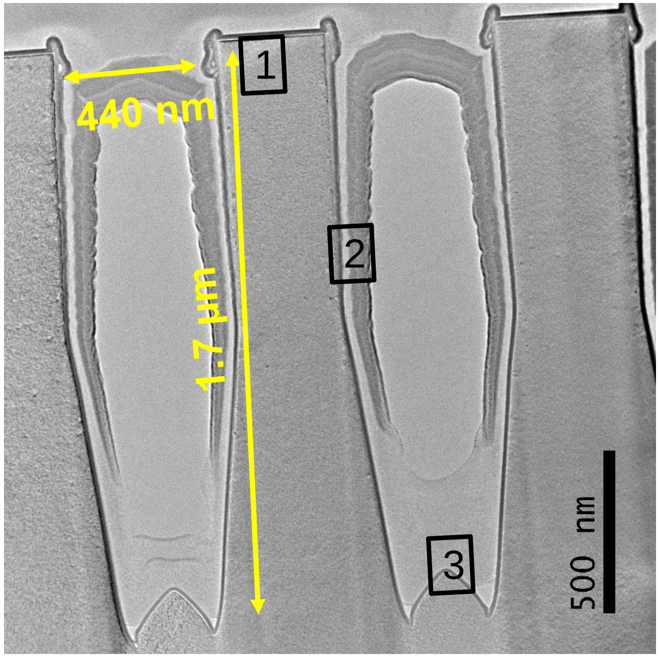
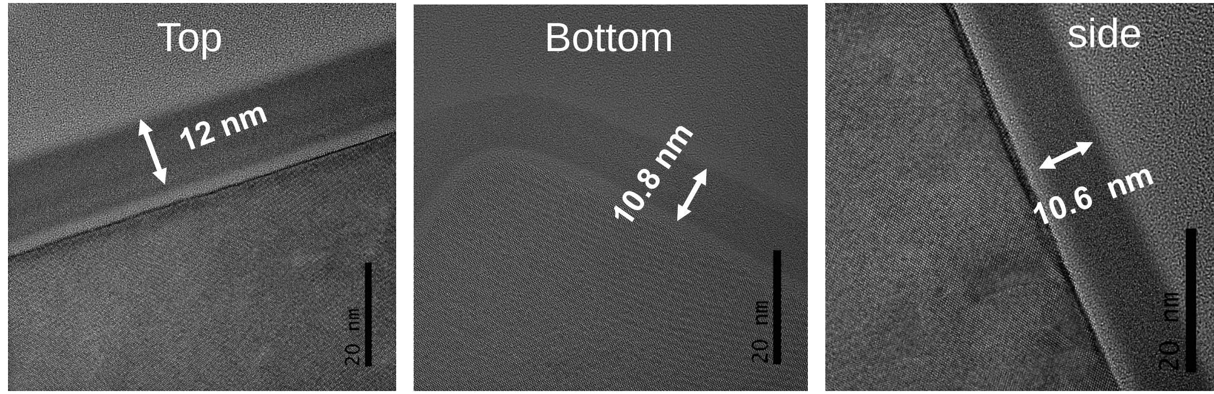
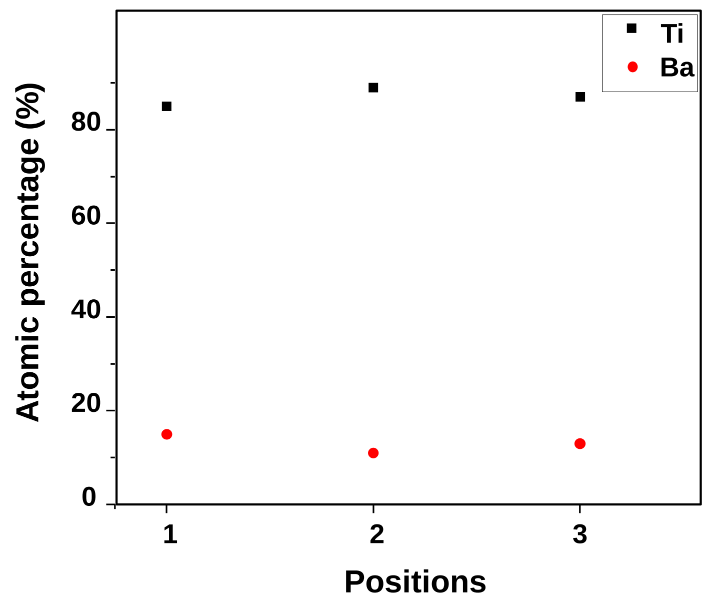
High-k thin films for DRAMs





- ➢ Aspect ratio of the trench ~ 1:3.9
- ➢ Step coverage (d_{bottom}/d_{top}) ~ 90%
- ➢ Uniform composition distribution.



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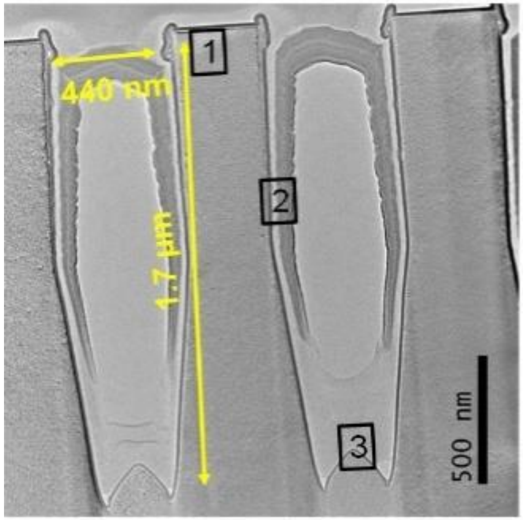
Summary

- **ALD for reaching the ultimate limit in downascaling**
- **ALD high-k Barium Titanate for next generation DRAM structures**
- **Novel chemistry for self limiting growth of BTO**
- **Explanation of dielectric properties with electronic structure revealed by synchroton based X-ray absorption**




Shinjita


Yongmin


Ioannis


Anup

Ongoing activity with TU Wien

Additive Manufacturing Technical Commitee

ESIS Technical committee 15 (Chief)

ESFRI HORIZON 2020 PROPOSAL (180 ME, 13 PARTNERS)