Course name:
Growth and Characterization of Nano-electronic Materials (EE728)

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Atomic Layer Deposition

EE669 VLSI Technology

Definition of ALD

- **ALD is a method of applying thin films to various substrates with atomic scale precision.**
- **Similar in chemistry to chemical vapor deposition (CVD), except that the ALD reaction breaks the CVD reaction into two half-reactions, keeping the precursor materials separate during the reaction.**
- **ALD film growth is *self-limited* and based on surface reactions, which makes achieving atomic scale deposition control possible.**
- **By keeping the precursors separate throughout the coating process, atomic layer thickness control of film grown can be obtained as fine as atomic/molecular scale per monolayer.**

CVD vs ALD

Chemical vapor deposition (CVD):

One or more gases or vapors react to form a solid product

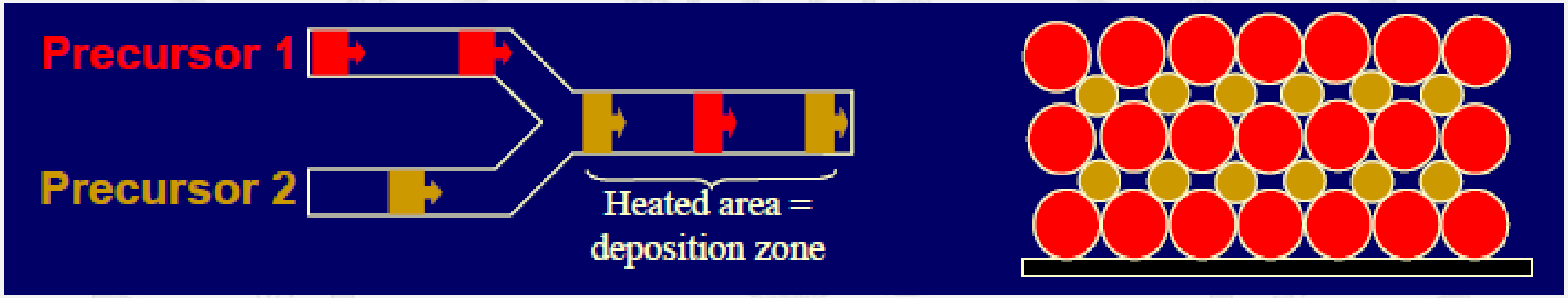
Solid product can be a
- film
- particle
- nanowire
- nanotube

Reaction started by
- heat
- mixing 2 vapors
- plasma

CVD vs ALD

Atomic Layer Deposition (ALD)

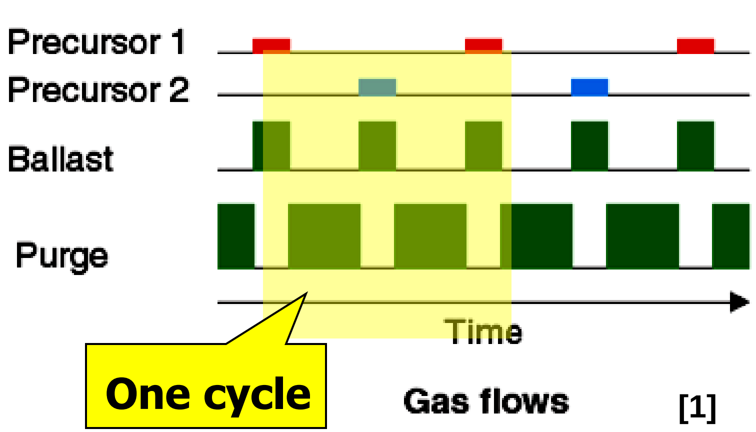
Sequential, self-limiting surface reactions make alternating layers:



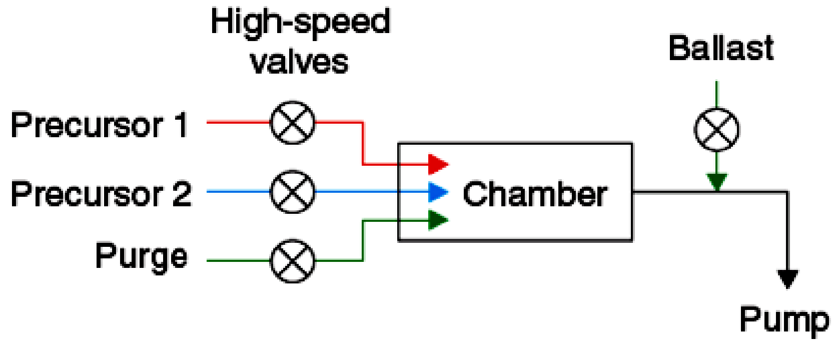
Benefits of ALD:

- Atomic level of control over film composition
  ⇒nanolaminates and multi-component materials
- Uniform thickness over large areas and inside narrow holes
- Very smooth surfaces (for amorphous films)
- High density and few defects or pinholes
- Low deposition temperatures (for very reactive precursors)
- Pure films (for suitably reactive precursors)

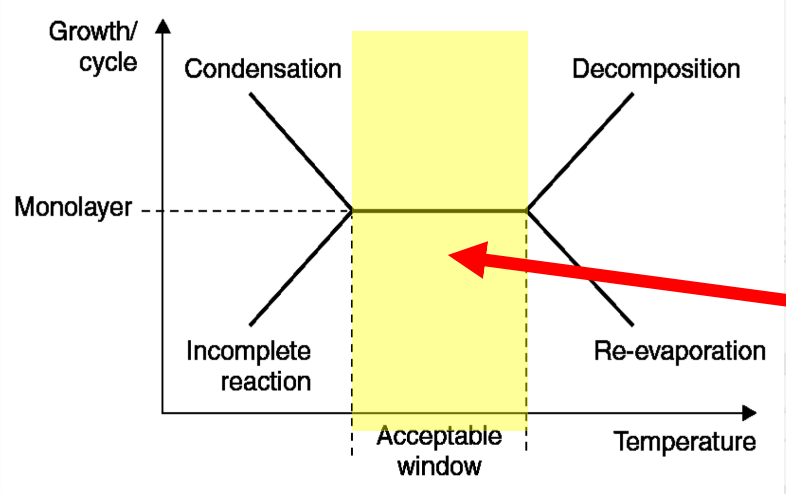
ALD Process and Equipment



Gas flows [1]



System schematic [1]



Process Temperature [1]

Acceptable temperature range for deposition.

The Verano 5500™
A 300-mm ALD system by Aviza Technology, Inc [2].

1 "Technology Backgrounder: Atomic Layer Deposition," IC Knowledge LLC, 24 April 06. <www.icknowledge.com/misc_technology/Atomic%20Layer%20Deposition%20Briefing.pdf>.

Criteria for Both CVD & ALD Precursors

- Sufficient volatility (> 0.1 Torr at T < 200 oC)
- No thermal decomposition during vaporization
- Liquid at vaporization temperature
- Preferably liquid at room temperature
- or soluble in an inert solvent
- Precursors and byproducts don’t etch films

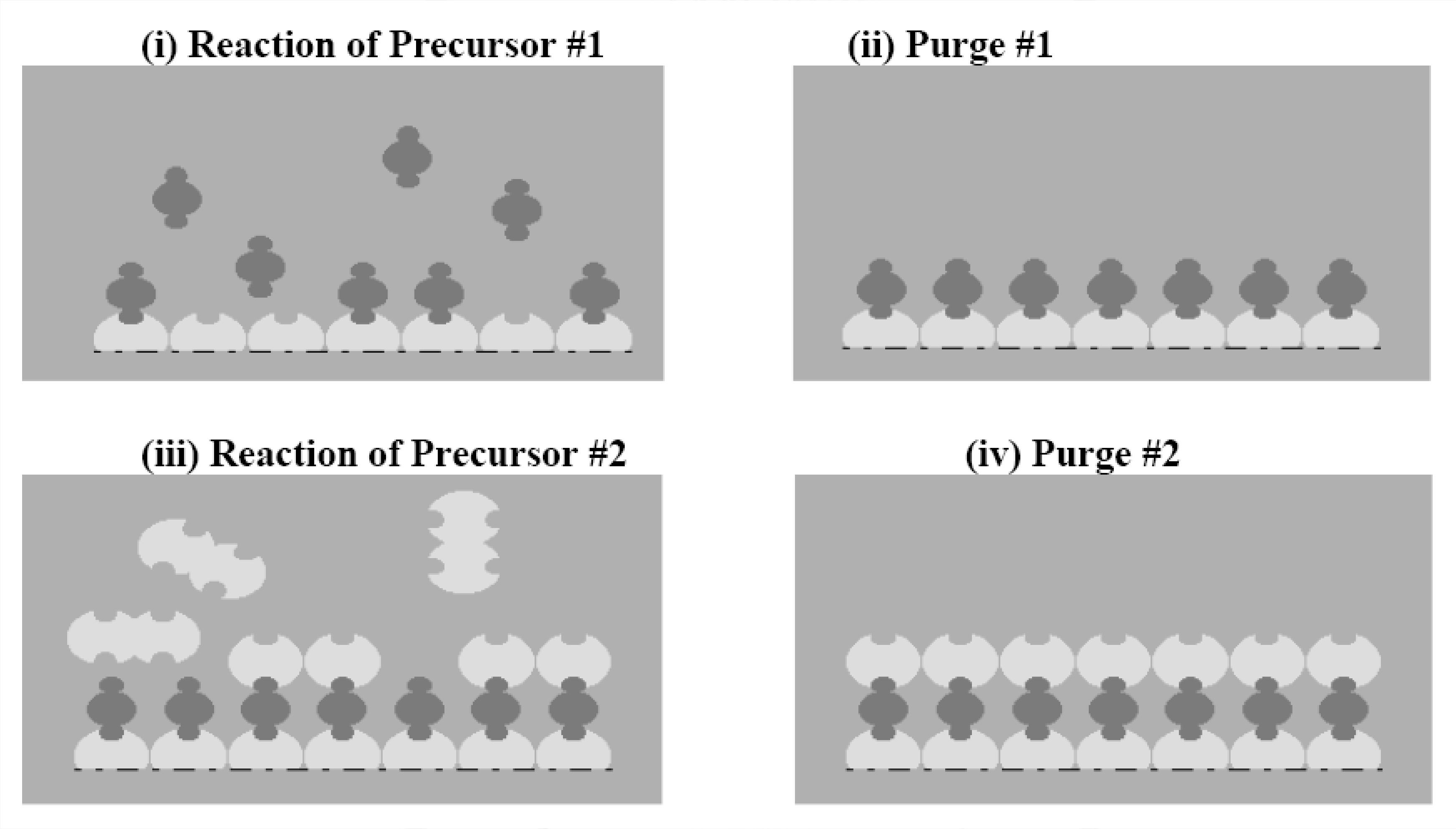
Criteria for CVD Precursors

- Reactivity with substrate
- Reactivity with surface of growing film
- Thermal decomposition allowed or even needed

Criteria for ALD Precursors

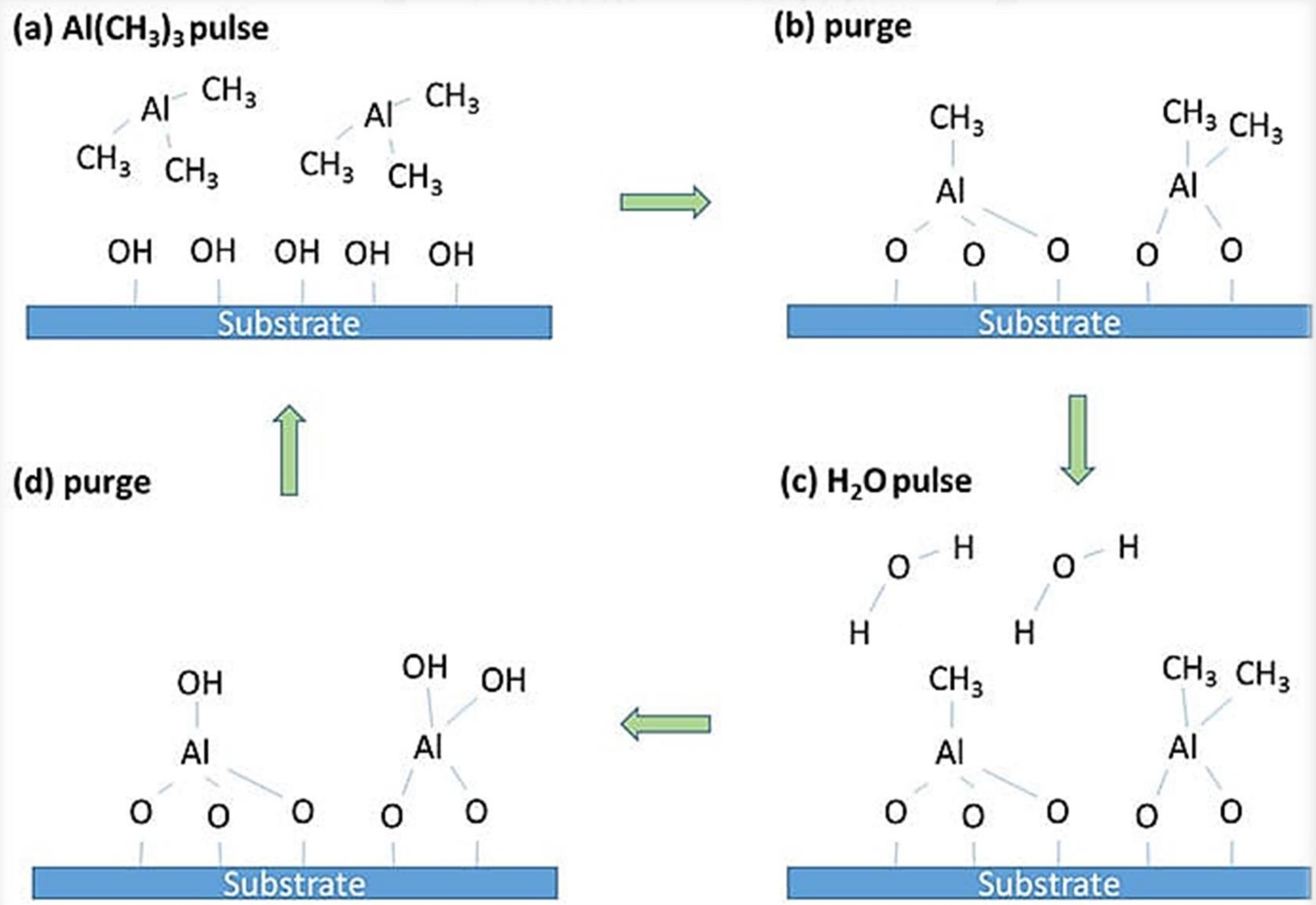
- Self-limited reactivity with substrate
- Self-limited reactivity with the surface made by reaction of the film with the other precursor
- Thermal decomposition not allowed

ALD cycle: ideal scenario



Jill Becker, Ph. D. thesis, MIT, 2002

ALD cycle: Al_2O_3 example

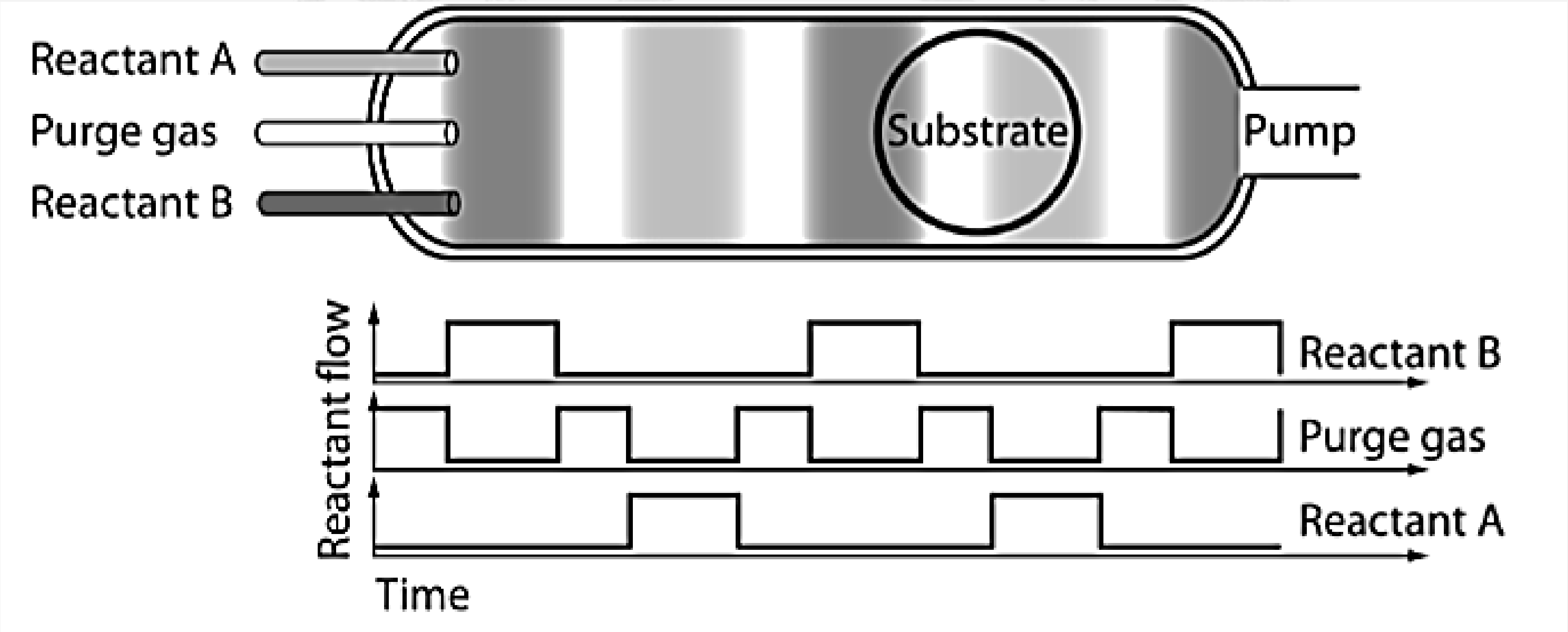


ALD cycle: ideal scenario (2)

- The reactions could be activated thermally (thermal ALD) or by plasma or by both (PE-ALD)
- Reactions A and C are surface limited and saturating, and hence self limiting
  - Excellent control over thickness (monolayer by monolayer)
  - Film uniformity
  - Excellent conformality
  - Sharp interfaces
  - Processing of nanolaminates
  - Easy to scale up

Jill Becker, Ph. D. thesis, MIT, 2002

ALD System: Schematic



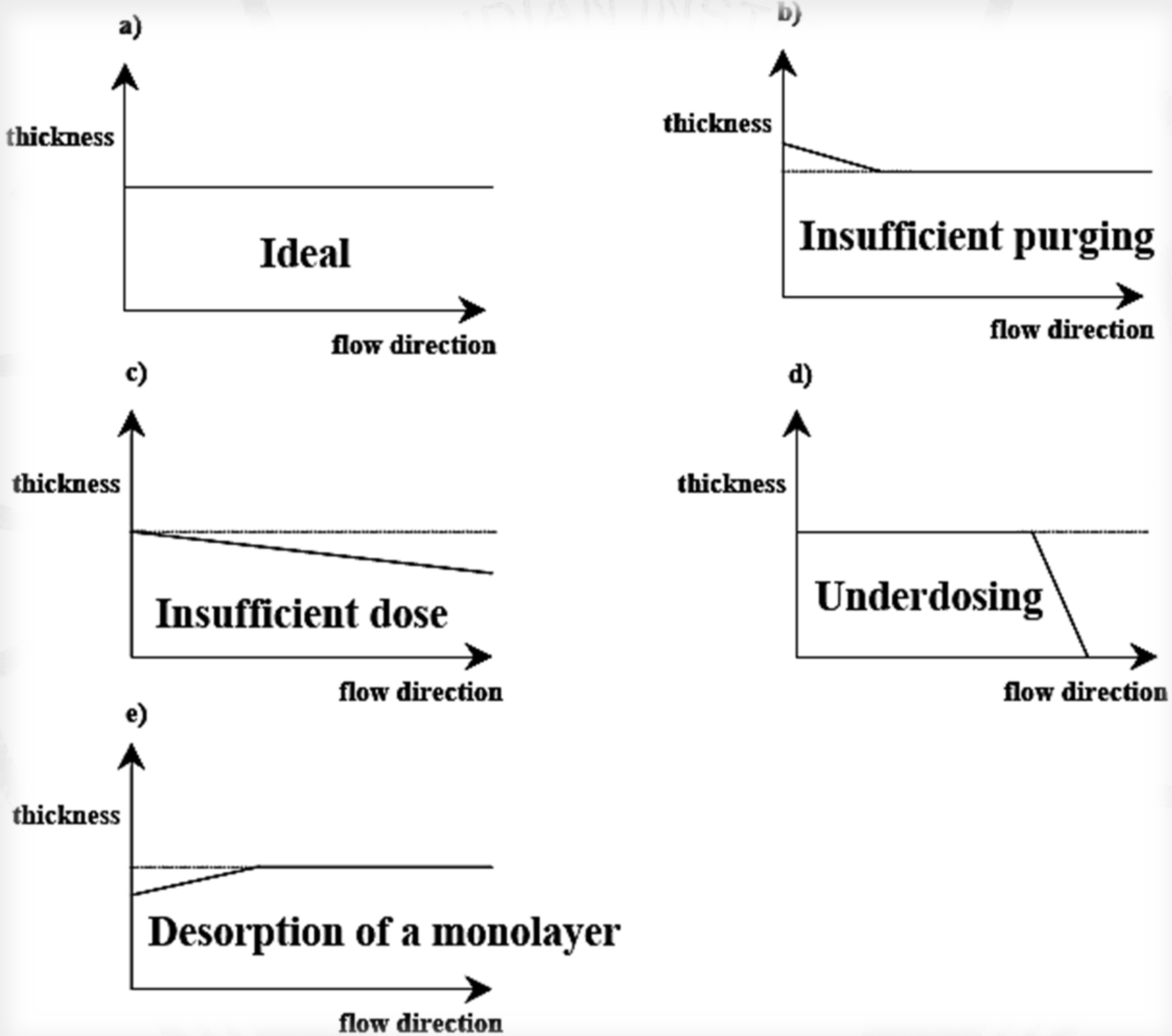
Angus Rockett, "Material Science of Semiconductors", Springer Verlag, 2008

ALD: Non Idealities (1)

- Deposition does not proceed mono layer by mono layer
  - Not enough surface sites are available. For example, some of the surface sites in the Al_2O_3 example could be $Si_3 \equiv Si\text{-}O\text{-}Si \equiv Si_3$
  - Steric hindrance: the precursor molecules could be larger compared to the spacing between adjacent surface sites
  - These could lead to island growth in the initial stages

R. L. Puurunen, JAP 2005; Jill Becker, Ph. D. thesis, MIT, 2002

ALD: Non Idealities (2)

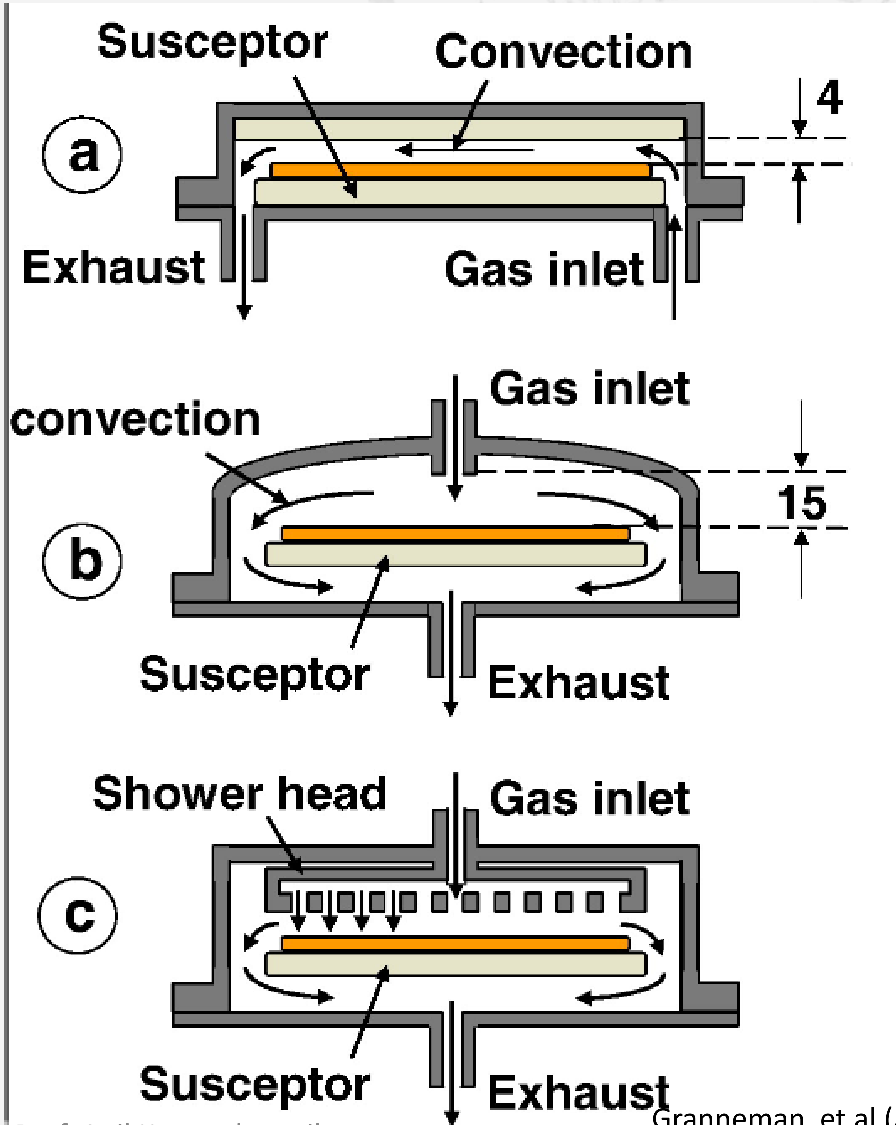


Jill Becker, Ph. D. thesis, MIT, 2002

ALD: Properties of Precursors

- **Should not decompose under the process conditions**
- **The surface obtained after the first reaction should be reactive to the second precursor**
- **Molecule size appropriate for desirable film properties**
  - **Small molecular size for ultra thin closed films**
  - **Large molecular size for discontinuous films**
- **No etching of the substrate and the deposited film**
- **Unreactive volatile products**

Single wafer ALD: Designs



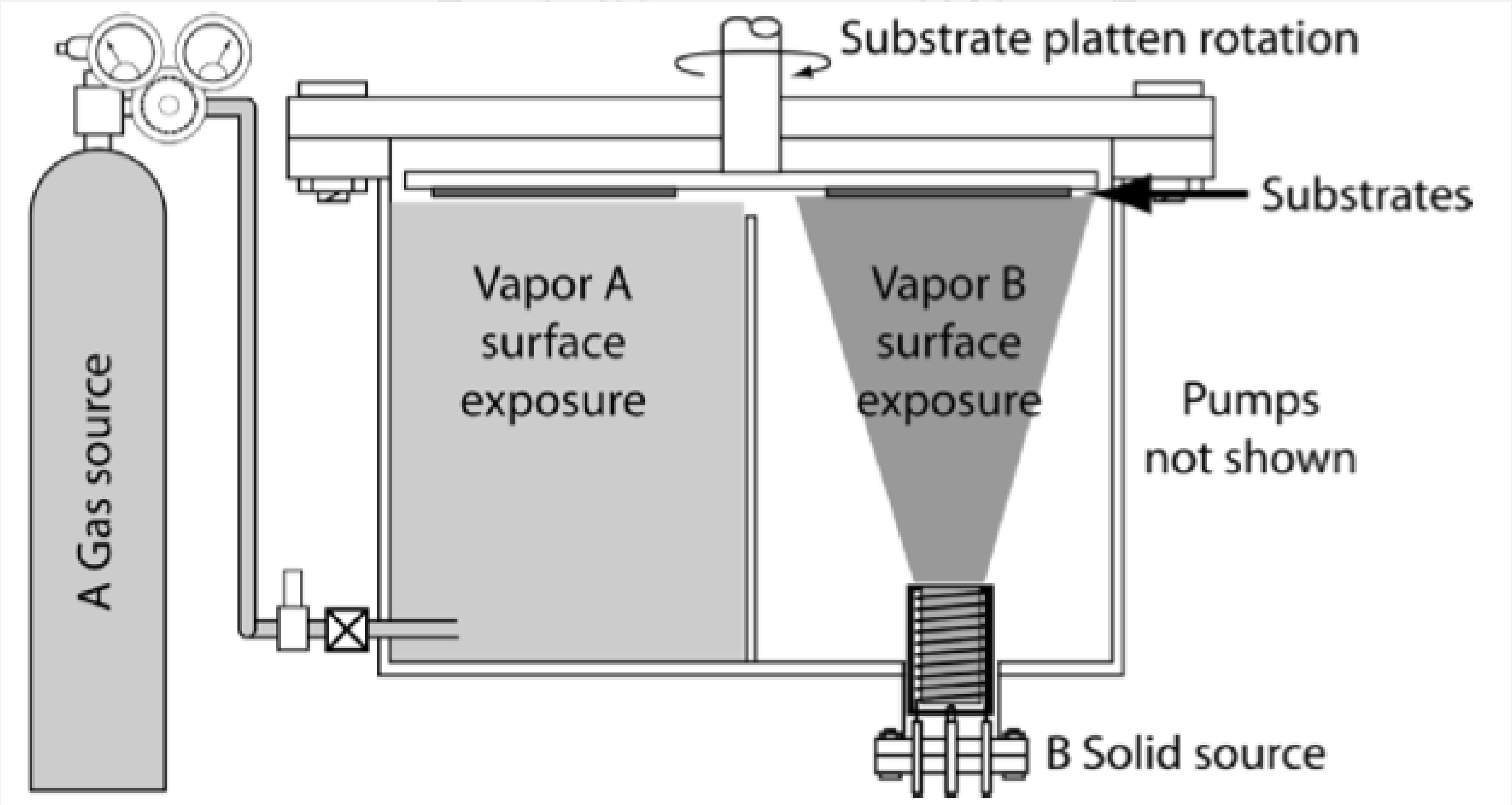
Cross flow

Single hole top injection

Shower head injection

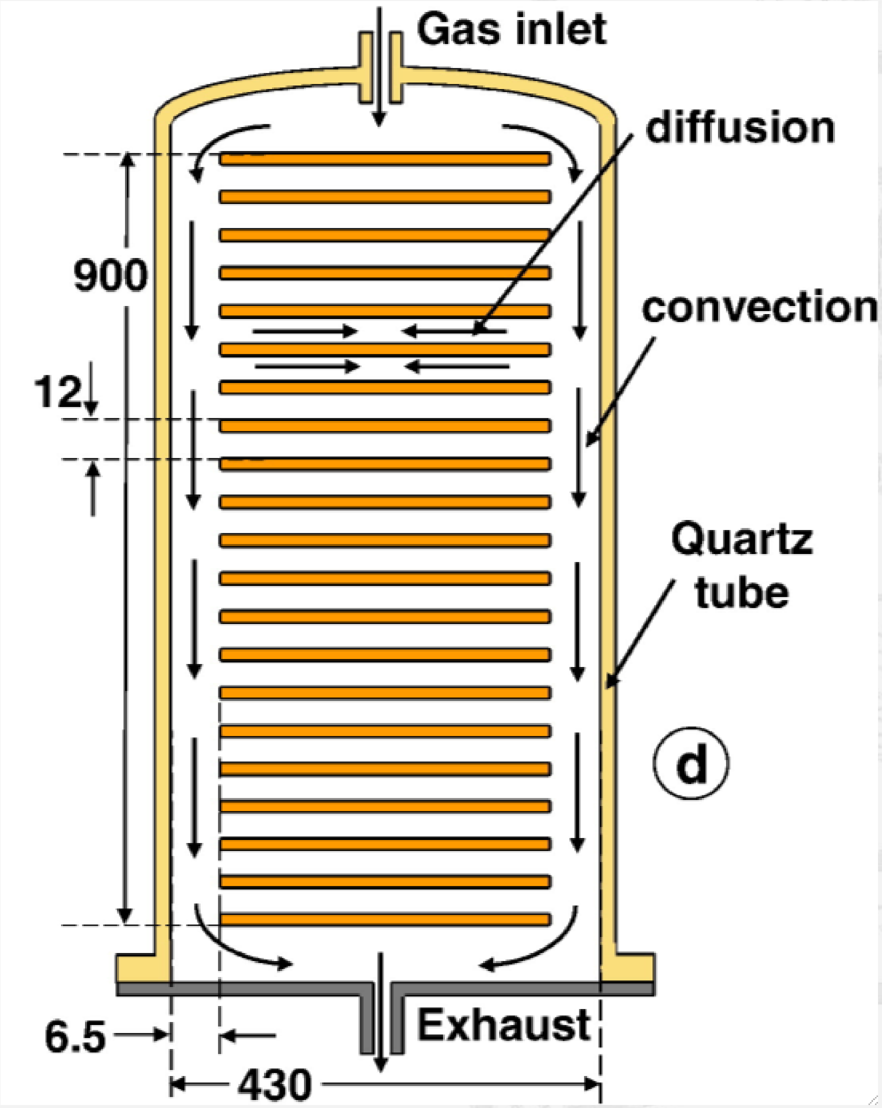
Granneman, et al (ASM); Surface & Coatings Technology 201 (2007)

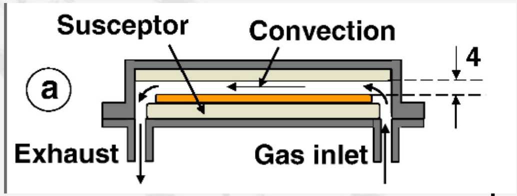
Single wafer ALD: Designs (2)

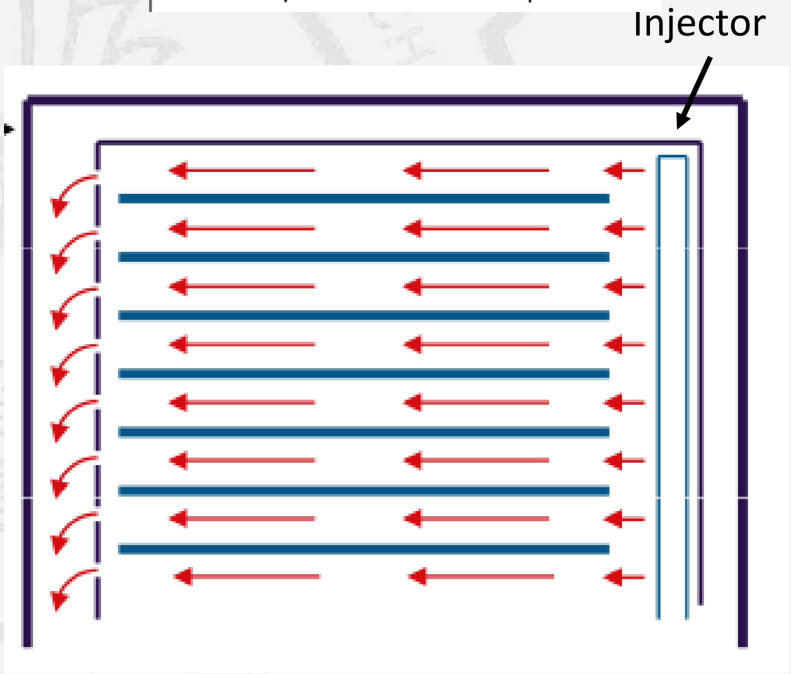


Angus Rockett, “Material Science of Semiconductors”, Springer Verlag, 2008

Batch ALD: Designs



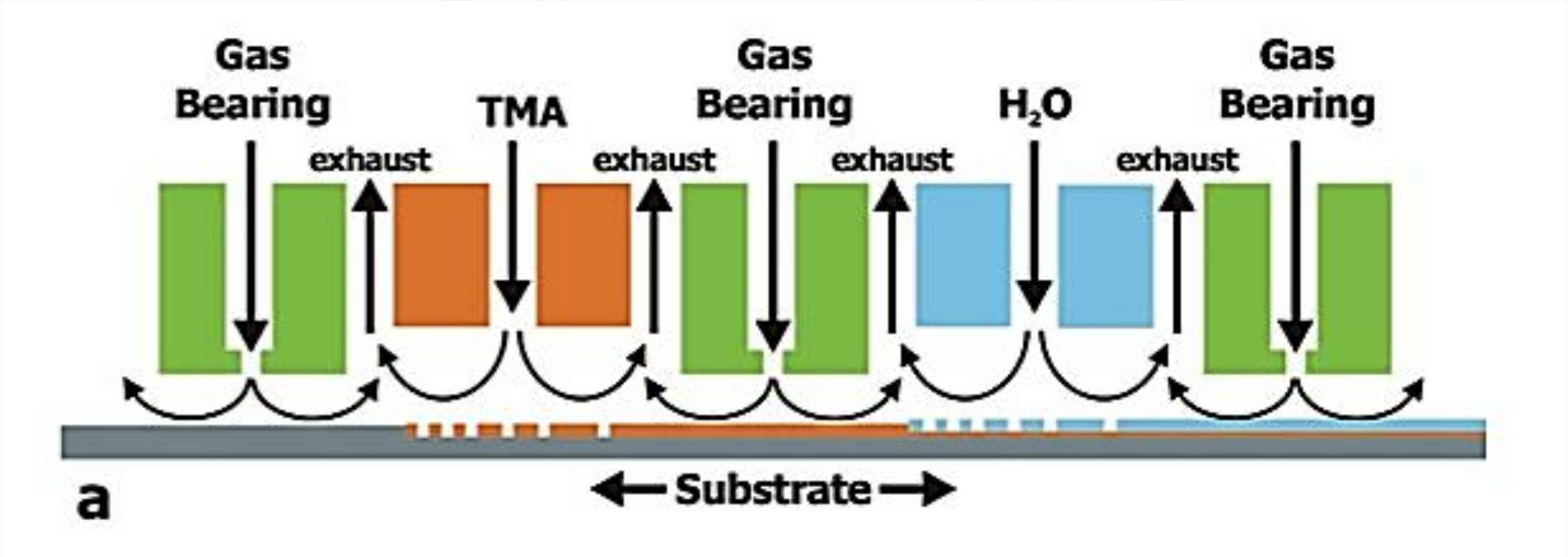




Owyang, Aviza Technology, 2007

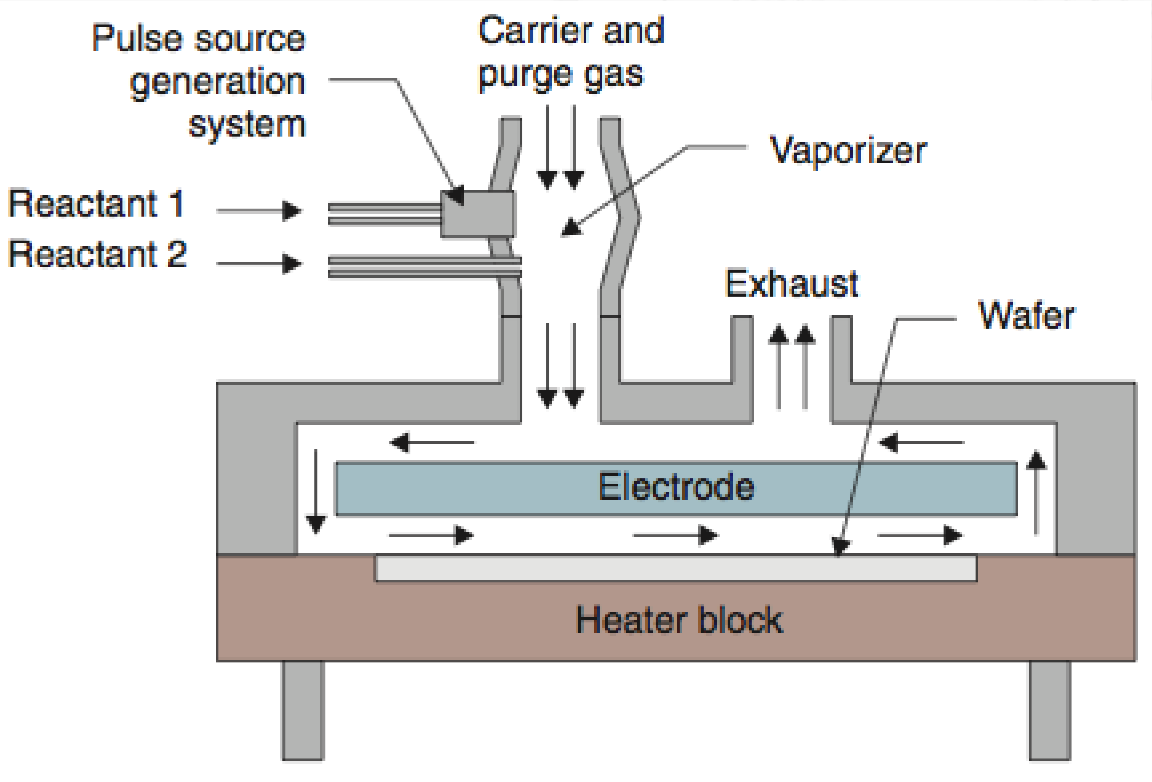
Granneman, et al (ASM); Surface & Coatings Technology 201 (2007)

Batch ALD designs (2)

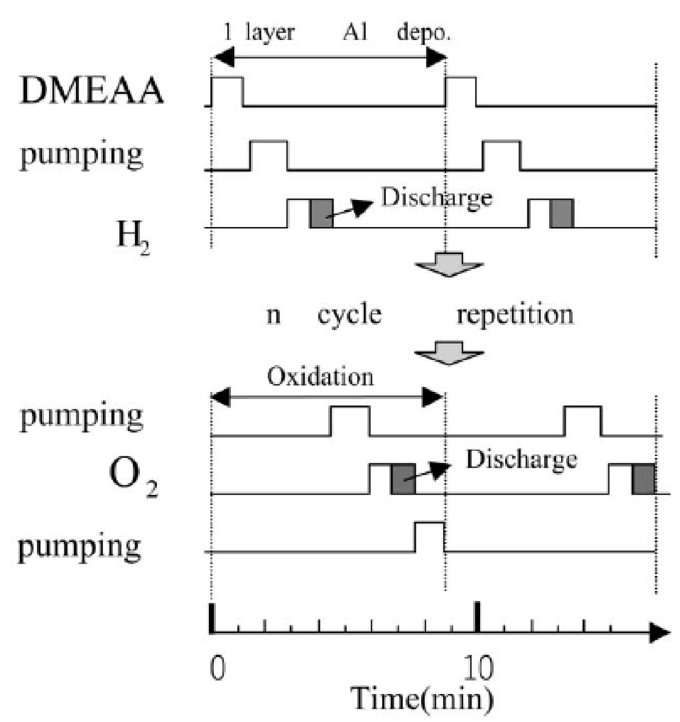


Poodt et al., Advanced Materials, vol. 22, p. 3564, 2010

Plasma Enhanced ALD

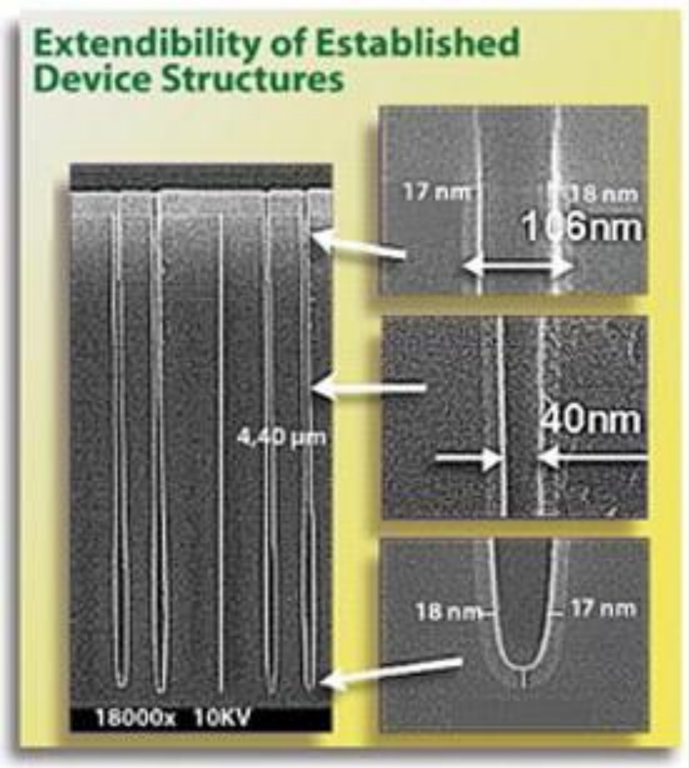


IC Knowledge LLC, 2004



Chang-Wook Jeong, et al;
Materials Science and Engineering © 16(2001)59–64

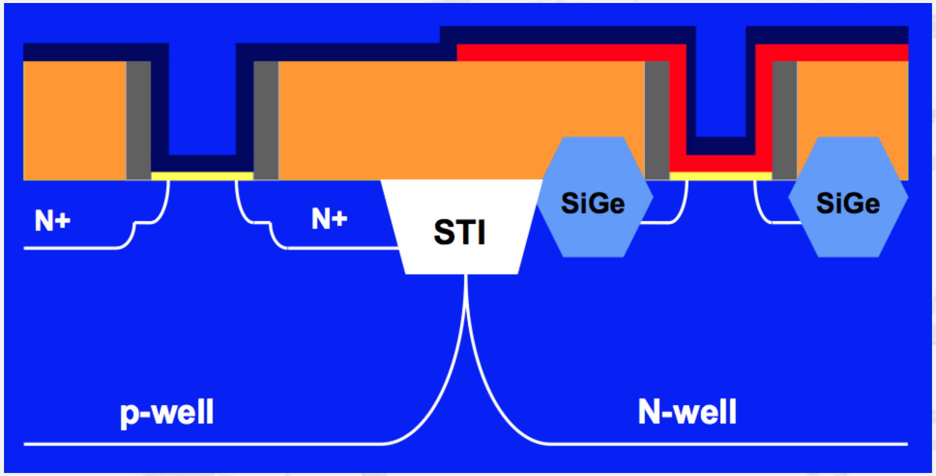
ALD: Applications



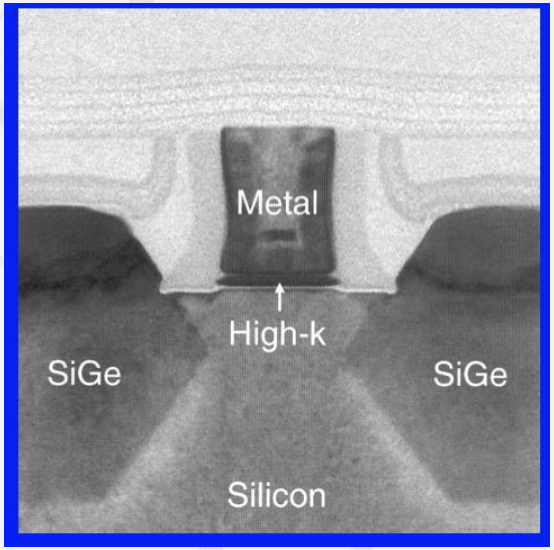
Micromagazine.com, 2007

- **DRAM trench capacitor**
  - **high aspect ratio trenches and hence conformal deposition is critical**
  - **Low temperature process is important for transistor scaling**

ALD: Applications (2)



K. Mistry et al., IEDM 2007

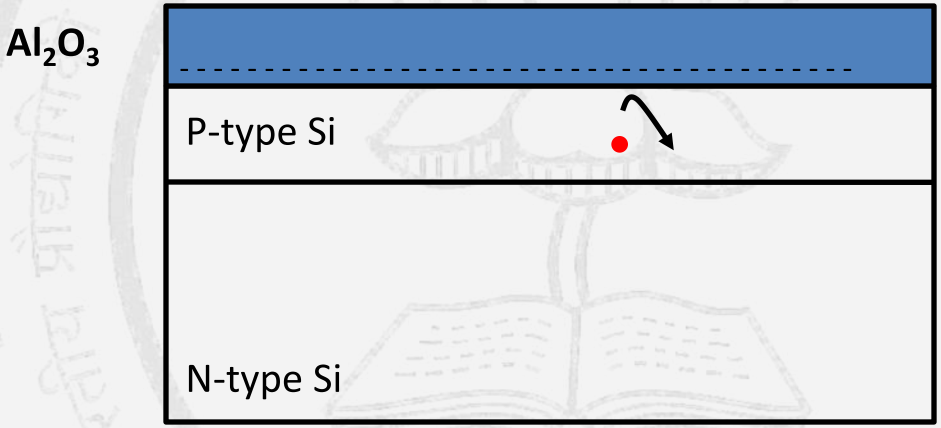


- **High-k/metal gate integration in CMOS Technology**
  - **High-k => low levels of contamination, low temperature process**
  - **Metal gate => conformal deposition, low temperature process**

Courtesy: Prof. Anil Kottantharayil

ALD: Applications (3)

- **Passivation of crystalline Si solar cells fabricated on n-type substrates using Al_2O_3 is an emerging field of application for ALD**



- **Electrons diffusing to the top of the p-type region would be repelled by the negative charges in the Al_2O_3**

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