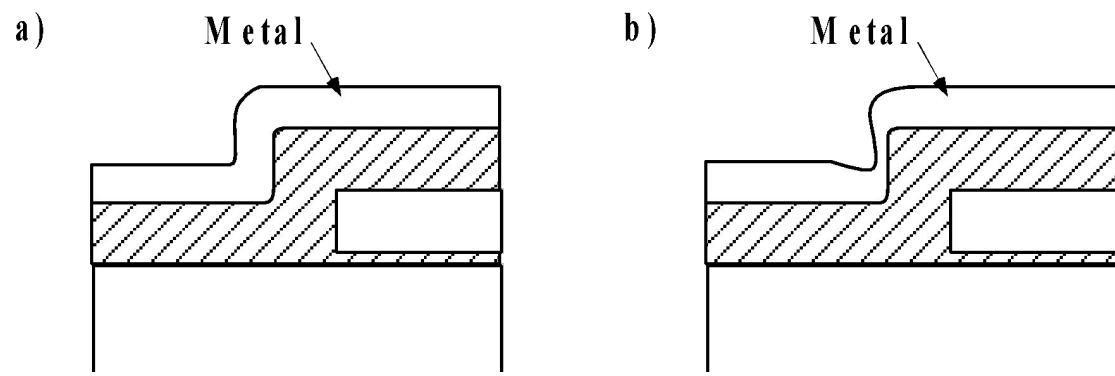
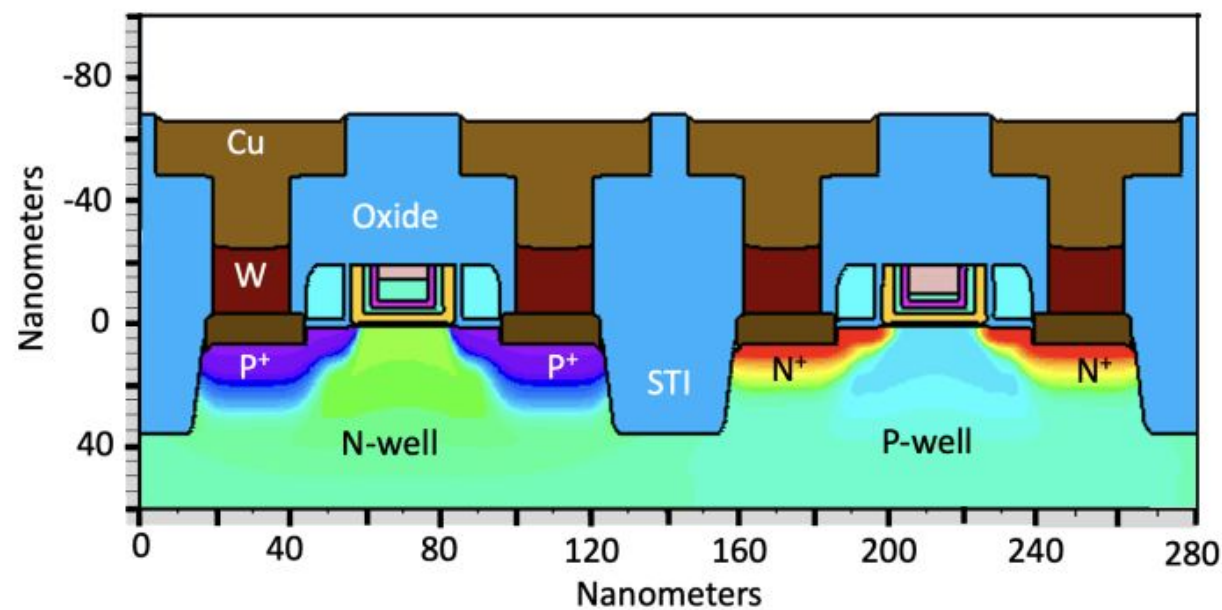


# Deposition Techniques

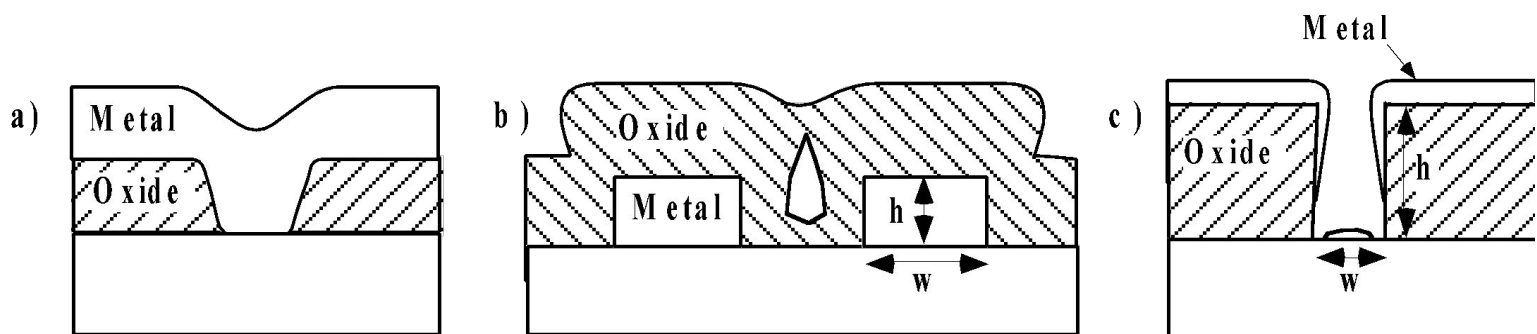


# KEY CONCLUSIONS

# Deposition Systems - Classification



Step Coverage



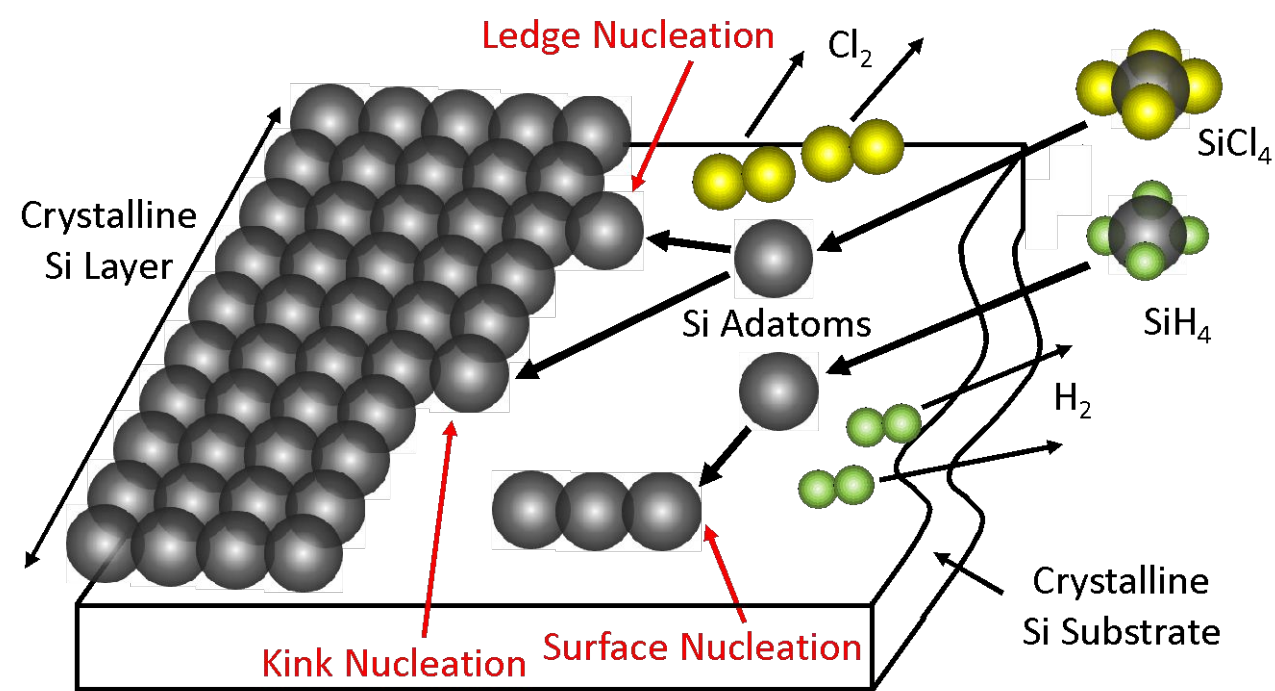
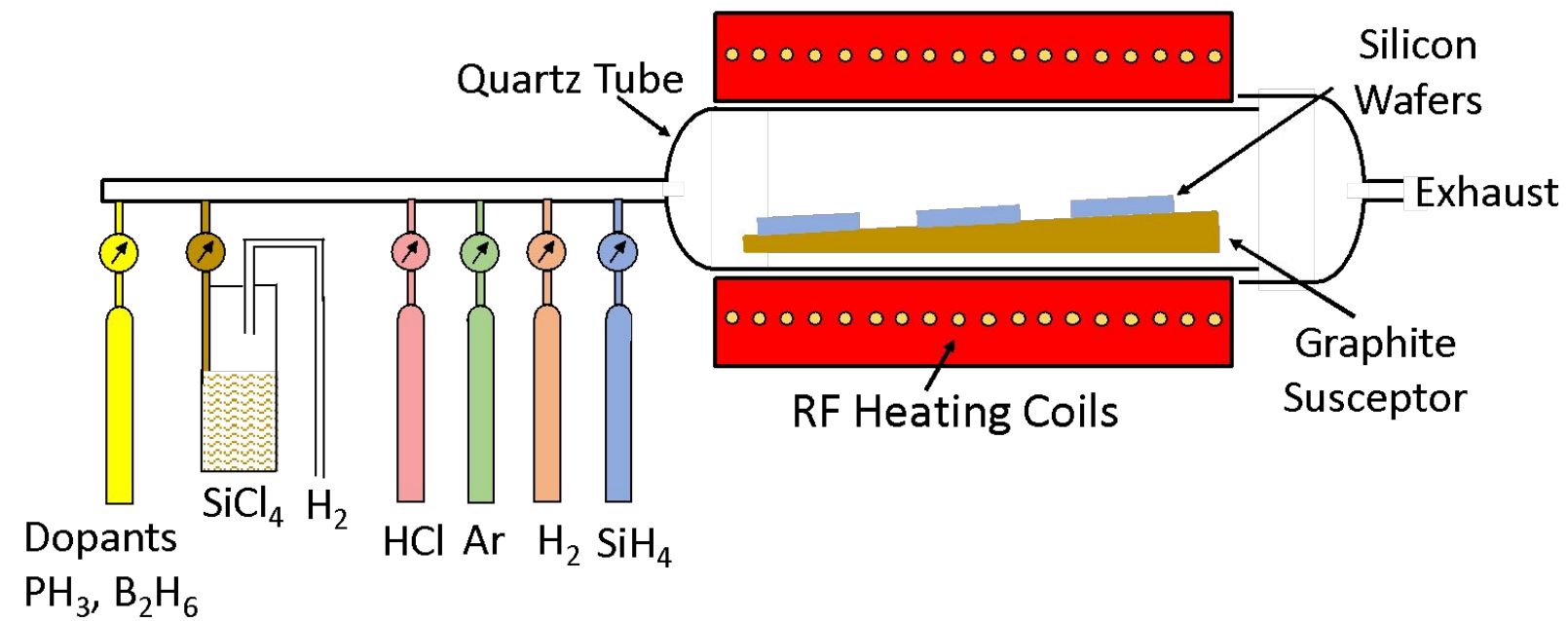
Aspect Ratio:  $H/W$

Formation of Voids

- Desirable traits for deposition:
  - Desired composition, low contaminants, good electrical and mechanical properties.
  - Uniform thickness across wafer, and wafer-to-wafer.
  - Good step coverage (“conformal coverage”)
  - Good filling of spaces.
  - Planarized films .
- Challenge: Filling higher aspect ratio

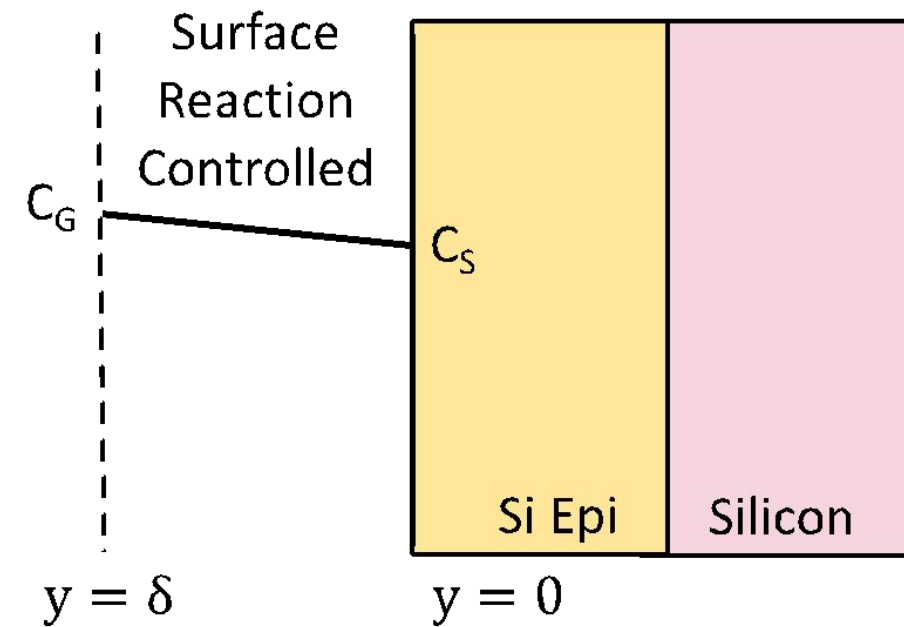
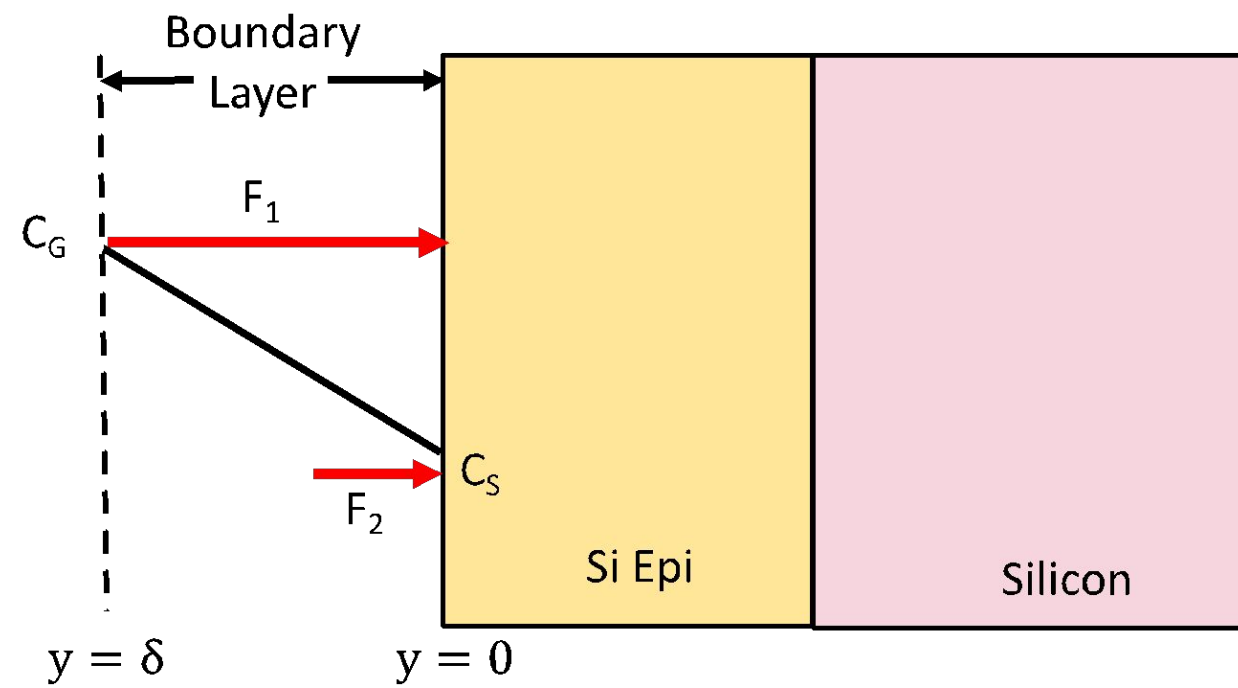
Process	Abbreviation	Temperature Range	Method
Chemical Vapor Deposition	CVD	500 - 1100°C	Gas phase, chemical
Low Pressure Chemical Vapor Deposition	LPCVD	500 - 800°C	Gas phase, low pressure chemistry
Metal-Organic Chemical Vapor Deposition	MOCVD	600 - 1200°C	Gas phase chemistry
Plasma Enhanced Chemical Vapor Deposition	PECVD	300 - 450°C	Plasma chemistry
Atomic Layer Deposition	ALD	100 - 400°C	Chemistry
Plasma Sputtering	Sputtering	100 - 300°C	Physical deposition
Evaporation	Evaporation	100 - 500°C	Physical deposition
Molecular Beam Evaporation	MBE	100 - 400°C	Physical deposition

# Chemical Vapor Deposition



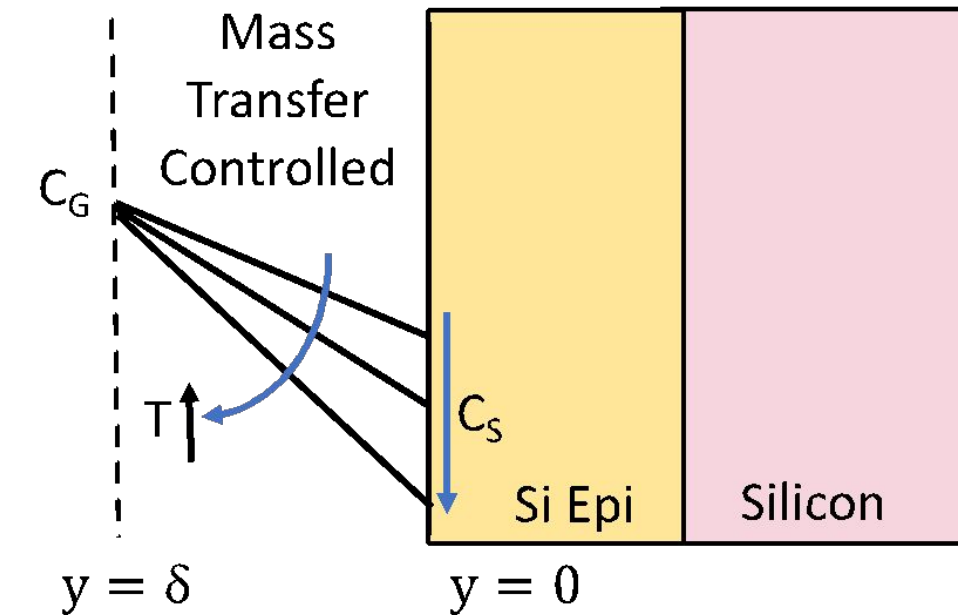
- Atmospheric Pressure
- Gas Phase Reactions
- Typically high T (500 – 1100 °C)
- Most common application is epitaxial growth.
- High T provides surface mobility so single crystal films can grow.

# CVD Growth rate



$$v \cong \frac{C_T}{N} k_S Y$$

Kinetic Limited Regime



$$v \cong \frac{C_T}{N} h_G Y$$

Mass Transport Limited Regime

$$F_1 = h_G (C_G - C_S) \quad h_G - \text{mass transfer coefficient (in cm/sec).}$$

$$F_2 = k_S C_S \quad k_S - \text{the surface reaction rate (in cm/sec).}$$

$$F = F_1 = F_2 \quad \text{In steady state:}$$

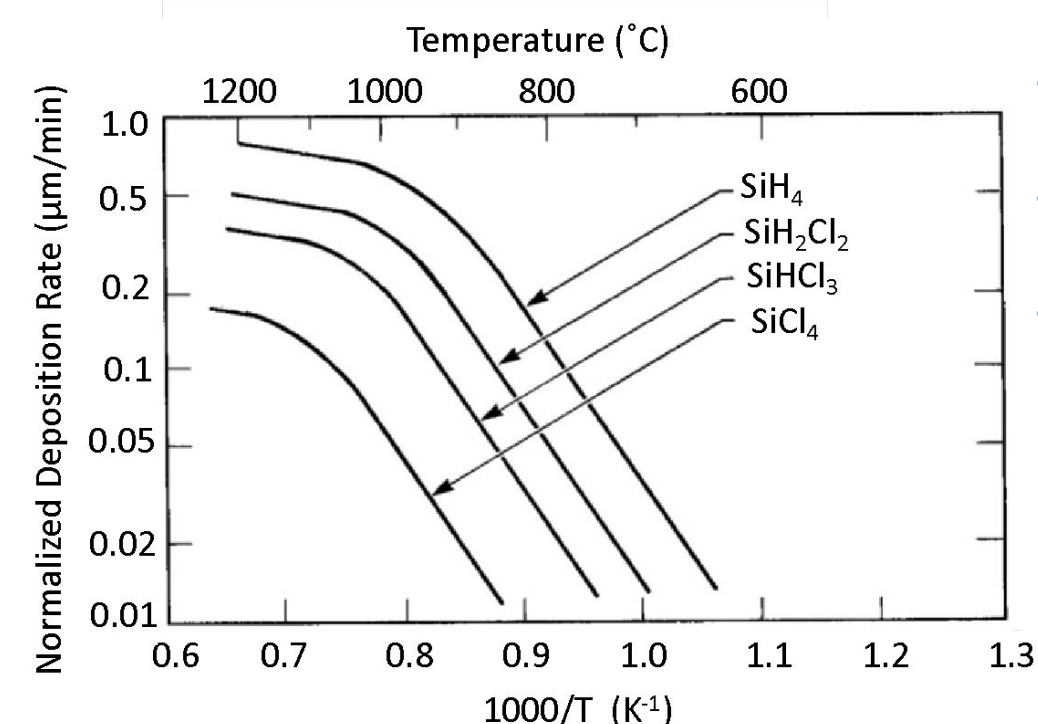
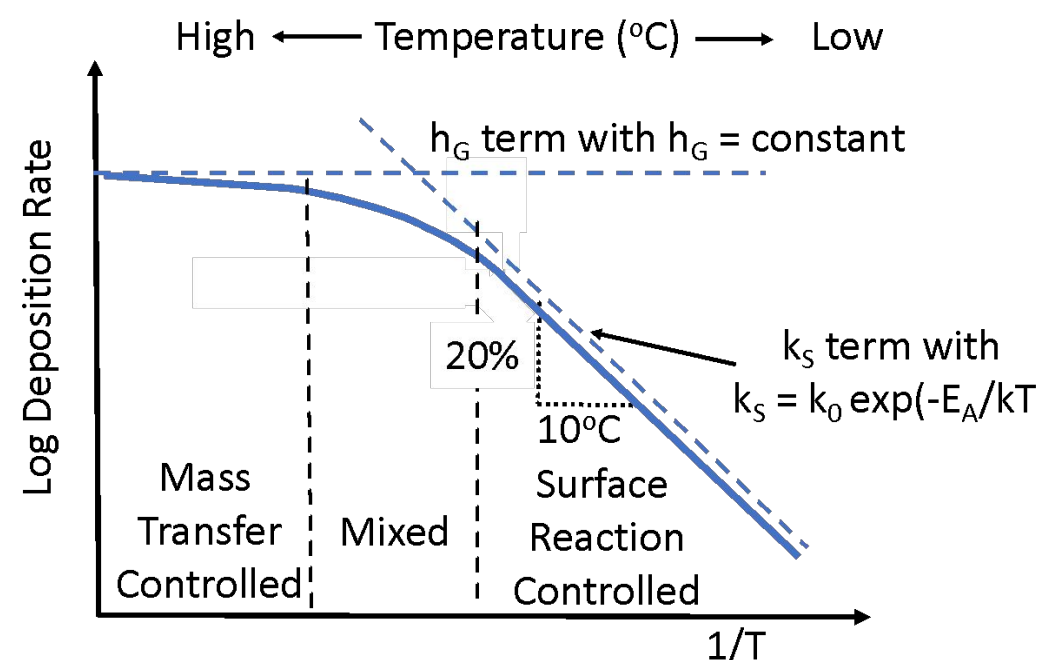
$$C_S = C_G \left( 1 + \frac{k_S}{h_G} \right)^{-1}$$

$$\text{Growth Rate} \quad v = \frac{F}{N} = \frac{k_S h_G}{k_S + h_G} \frac{C_G}{N} = \frac{k_S h_G}{k_S + h_G} \frac{C_T}{N} Y$$

$N$  - number of atoms per unit volume in the film ( $5 \times 10^{22} \text{ cm}^{-3}$  for the case of epitaxial Si deposition)

$Y$  - the mole fraction (partial pressure/total pressure) of the incorporating species.

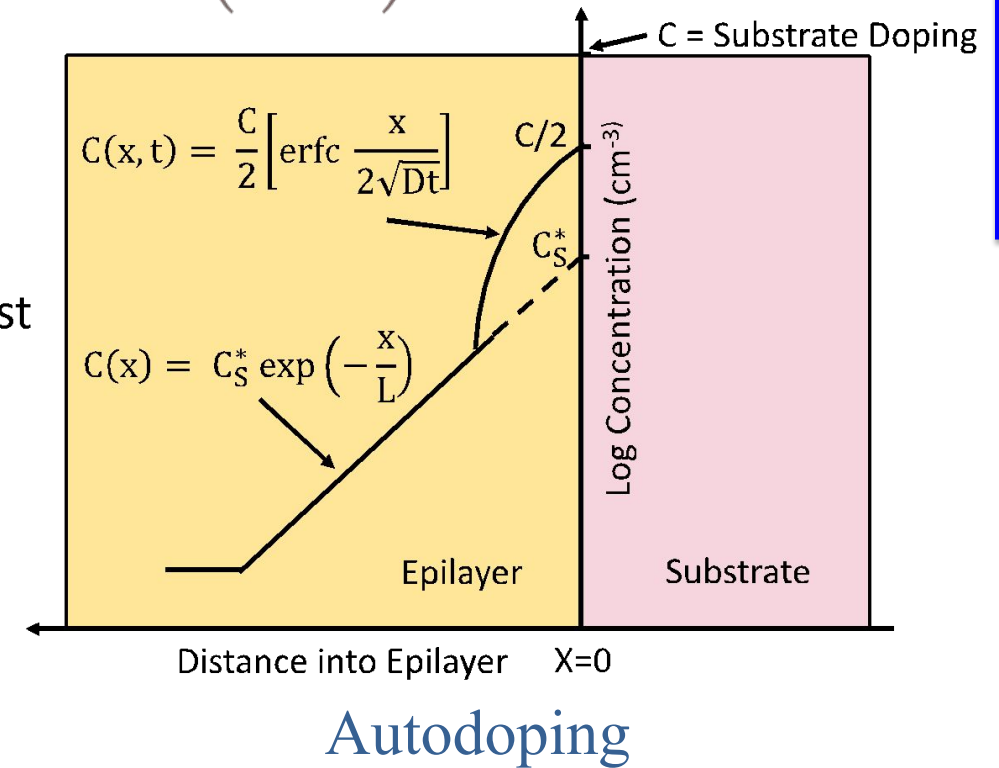
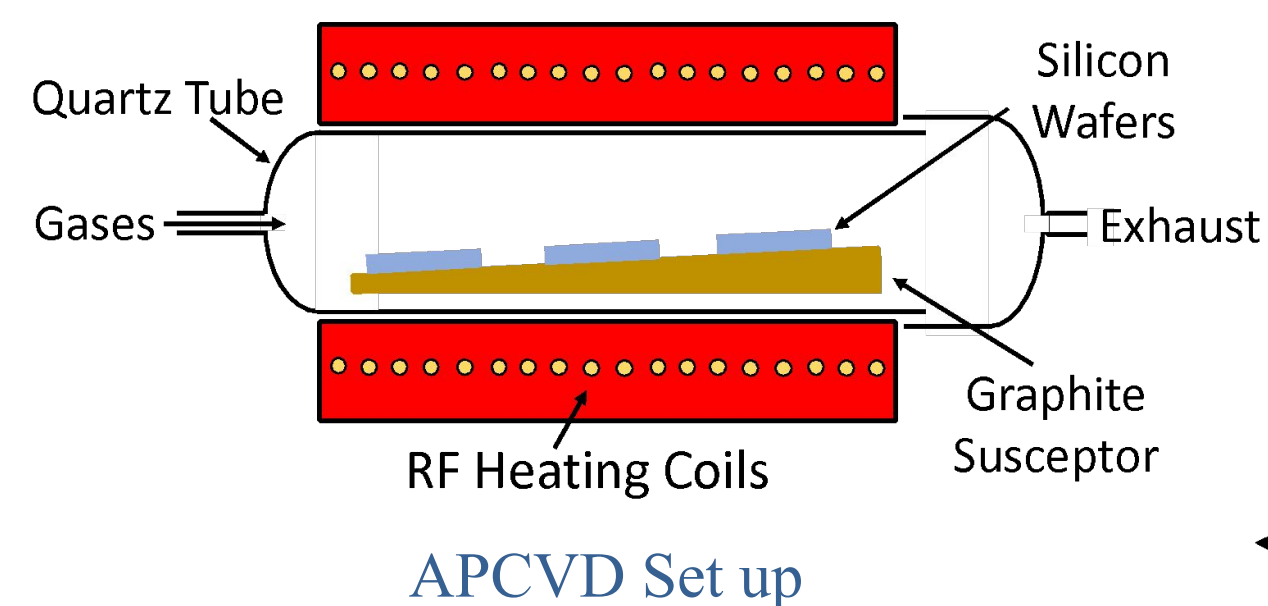
# The two limited Regimes



- Mass transport is more or less independent of T
- Rate Kinetics is exponentially dependent on T
- In both regimes the growth rate is constant with time

$$k_s = k_0 \exp\left(-\frac{E_A}{kT}\right)$$

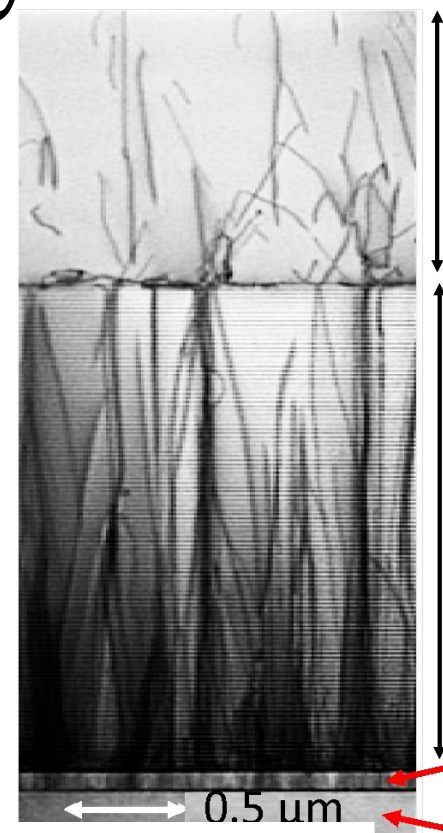
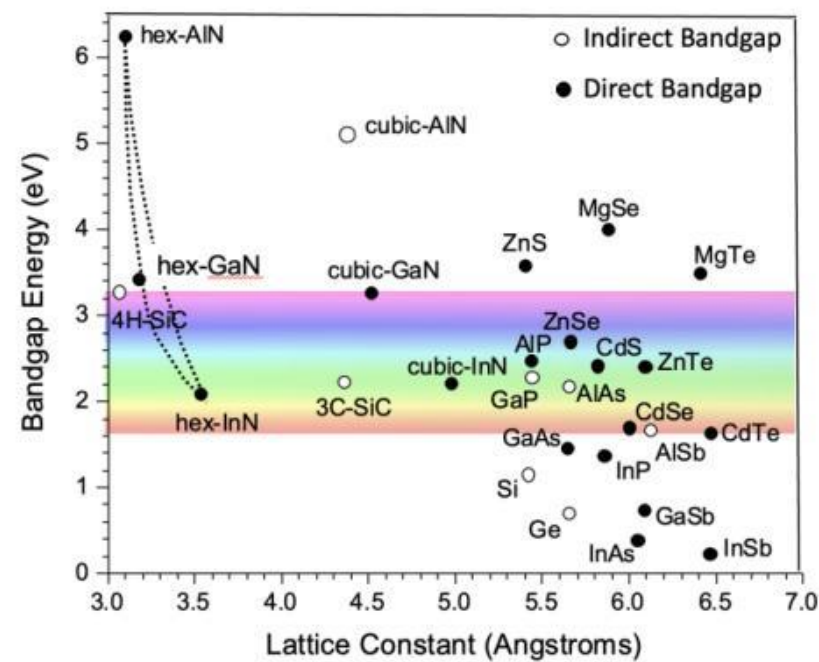
	SiH <sub>4</sub>	SiH <sub>2</sub> Cl <sub>2</sub>	SiCl <sub>4</sub>
Temperature	900-1050°C	950-1100°C	1100-1200°C
Reaction			
Reversible	No	Yes	Yes
HCl byproduct	No	Yes	Yes
Gas Phase	Yes	No	No
Nucleation			
Flow Control	Easy	Moderate	Moderate
Cost	High	Moderate	Low
Danger	High	Moderate	Moderate
Deposition Rate			
Uses	Thin layers	Many layers	Thick layers



- Epitaxy is usually done at high T in the  $h_G$  dominated regime.
- Gas flow dynamics are very important.
- During growth dopants can be incorporated both by upward diffusion and autodoping



# Heteroepitaxy

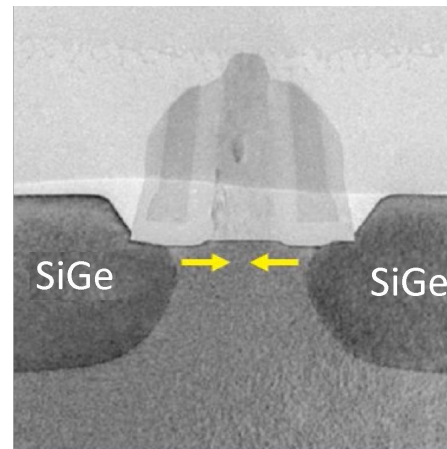
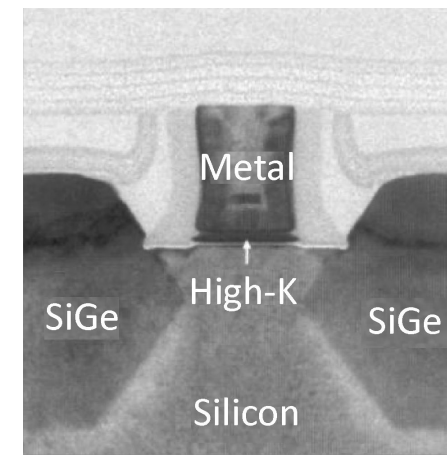
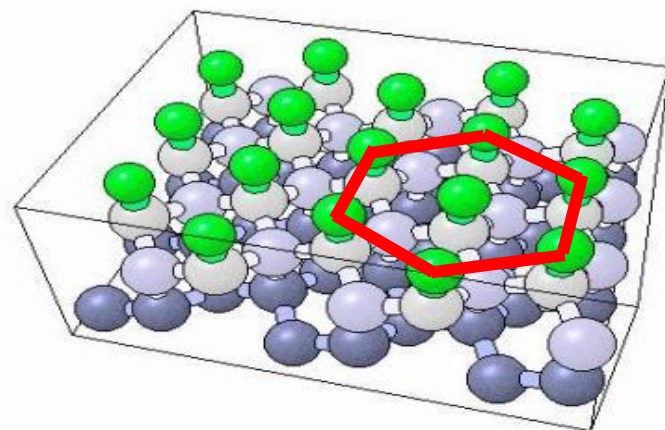
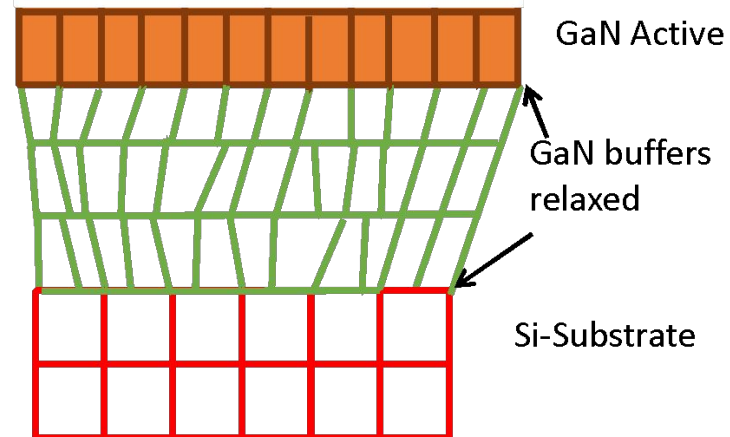
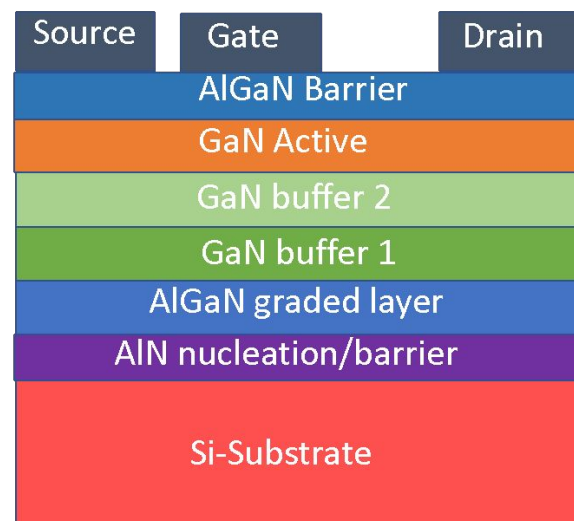


GaN  
≈ 2 μm

AlGaN/GaN  
Superlattice  
≈ 3.5 μm

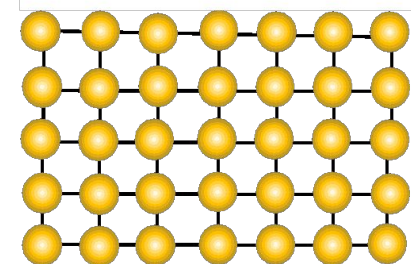
AlN Seed Layer

0.5 μm

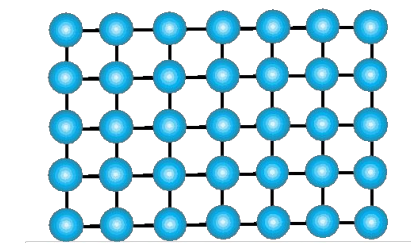


- Growing of dissimilar material on a substrate
- Lattice mismatch introduces Strain
- Large strain introduces defects
- Optimal Strain is used in enhancing mobility
- Used for growing III-V semiconductors
- Wide Band gap tuning applications
- Buffer layer growth for minimize lattice mismatch
- Si(111) is preferable due to hexagonal structure

0.566 nm Lattice Constant



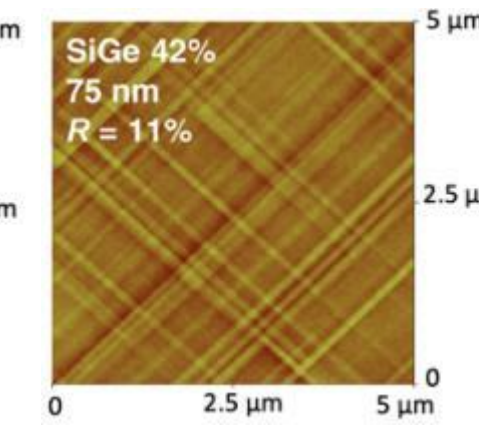
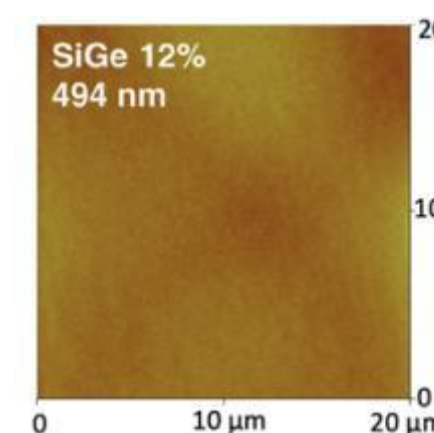
Ge



0.543 nm Lattice Constant

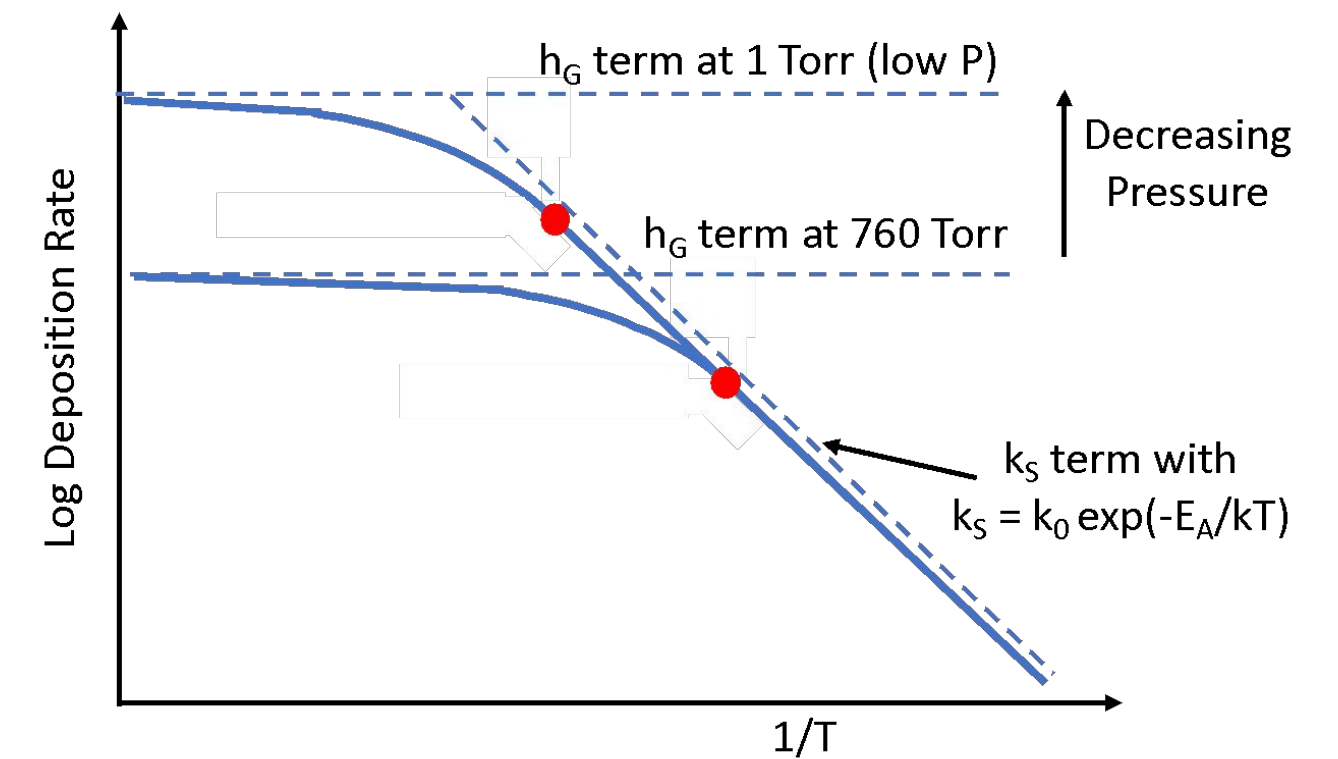
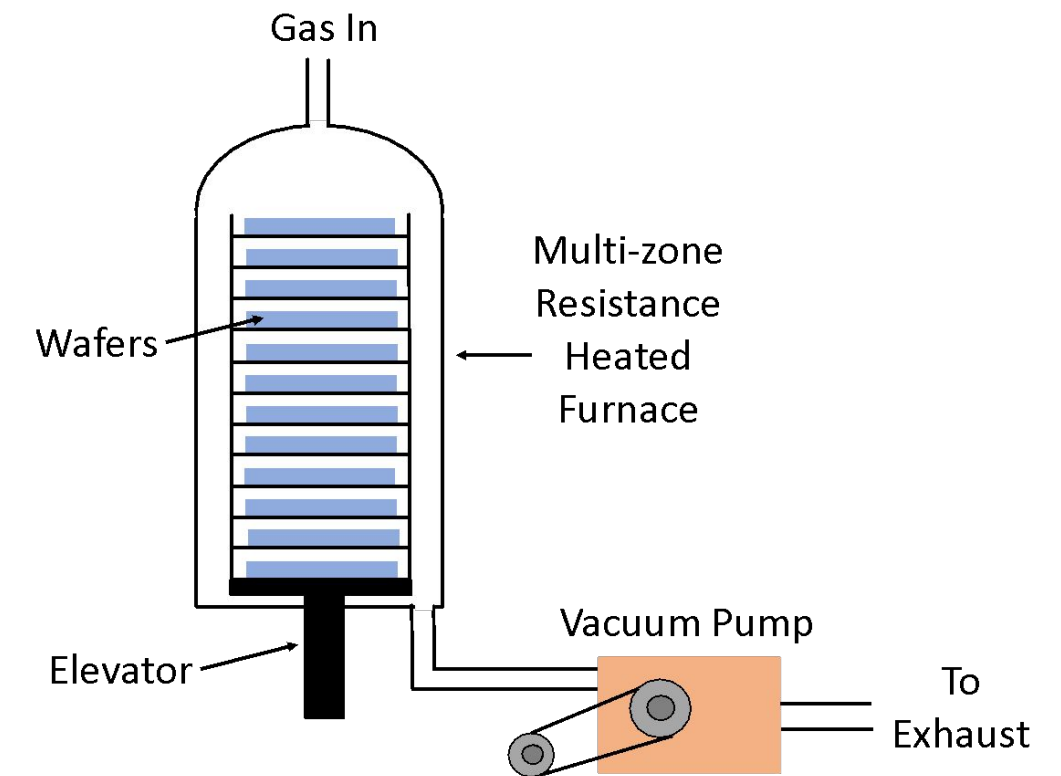
Si

← Compression →



# LPCVD

- Atmospheric pressure CVD is horizontal configuration
  - Only a few wafers at a time
  - At low T deposition rate is slow
- 
- Decreasing pressure increases mass transfer coefficient
  - Mass transport is no longer time limited
  - Process depends on temperature
  - Temperature can be controlled precisely using modern control systems

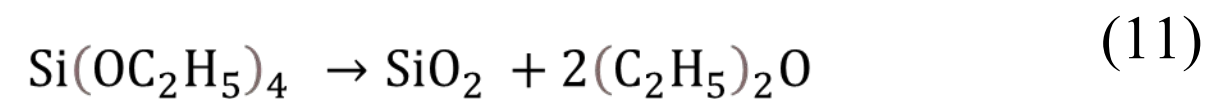




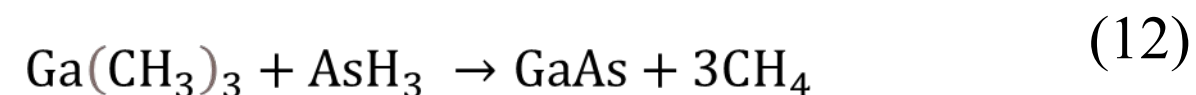
# CVD of Compound Materials - MOCVD

- For Si CMOS applications, we mostly deposit epitaxial Si films, or we deposit dielectrics like  $\text{SiO}_2$ ,  $\text{Si}_3\text{N}_4$ .
- Many compound semiconductor applications require epitaxial growth of III-V materials. MOCVD is used..

- More “unstable” precursors like TEOS allow deposition of silicon materials at lower T.



- Many such precursors have been developed for compound semiconductor materials.
- These are metal-organic precursors, hence MOCVD.
- Example:



Common Metals  
Gallium  
Aluminum  
Indium  
Arsenic  
Antimony  
Zinc  
Cadmium  
Telluride  
Germanium

Common Organics

Methyl

Ethyl

Isopropyl

Common Precursors

Tri or Tetra methyl = TM

Triethyl= TE

Triisopropyl = TiP

Dimethyl = DM

Diethyl = DE

Trimethylgallium (TMGa)

Triethylgallium (TEGa)

Triisopropylgallium (TiPGa)

Trimethylaluminum (TMAI)

Trimethylindium (TMIn)

Triethylindium (TEIn)

Trimethylarsenic (TMAs)

Trimethylantimony (TMSb)

Dimethylzinc (DMZn)

Diethylzinc (DEZn)

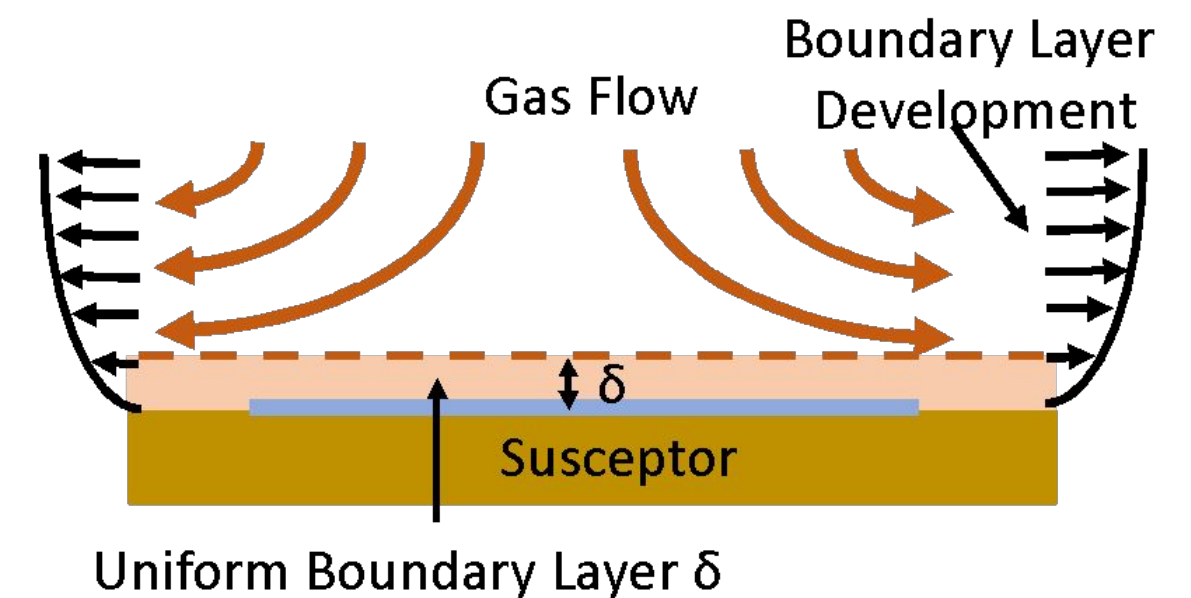
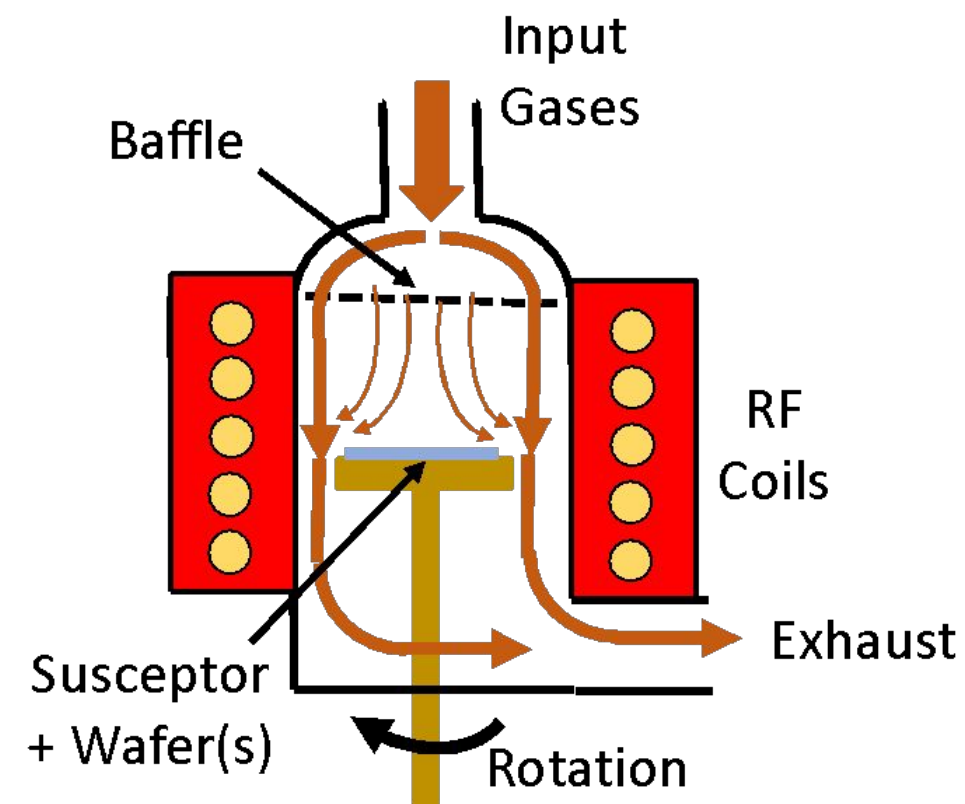
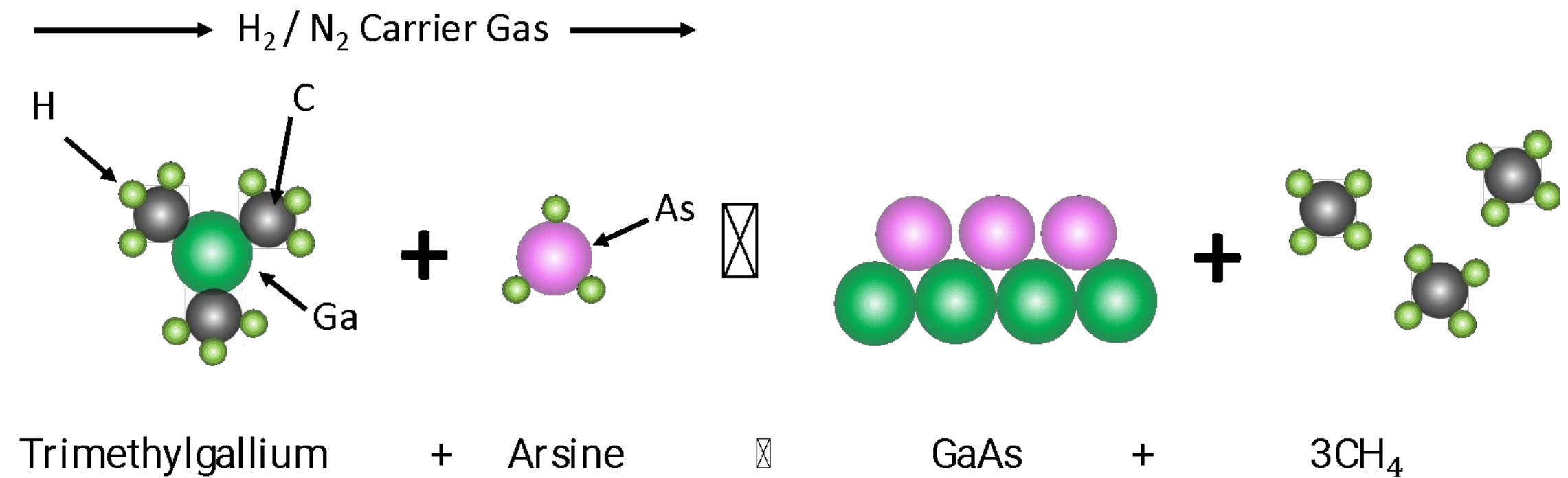
Dimethylcadmium (DMCd)

Dimethyltellurium (DMTe)

Diethyltellurium (DETe)

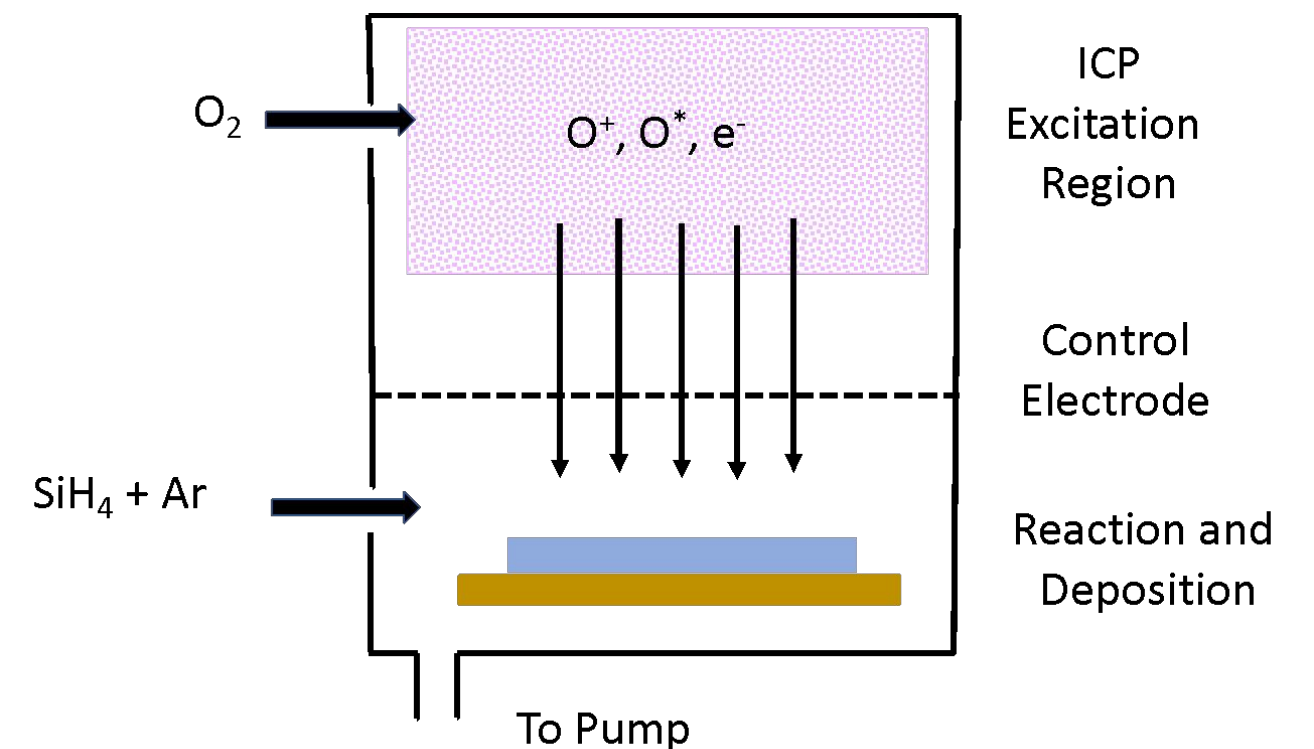
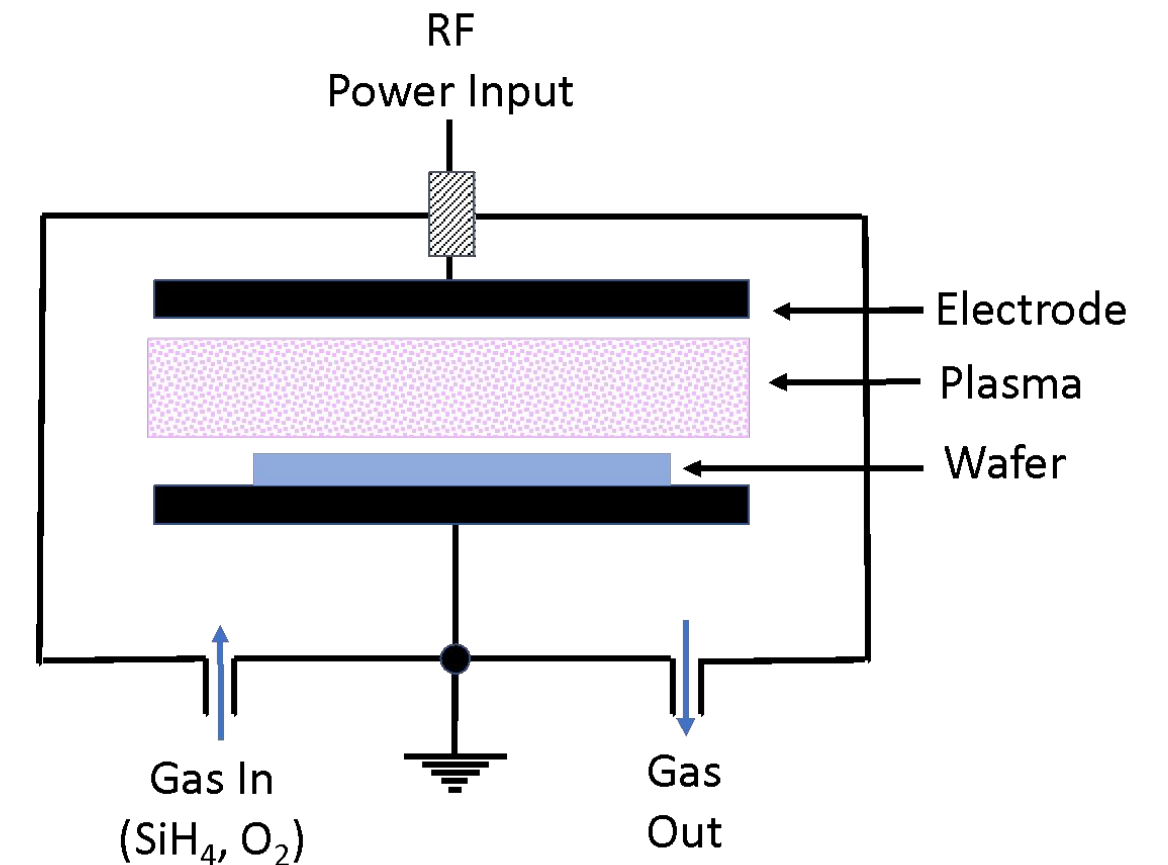
Tetramethylgermanium (TMGe)

- Typically these systems operate in the “ $h_G$ ” dominated regime so boundary layer transport is critical.
- Uniform growth means optimizing the gas flow pattern.
- Typically vertical flow reactors and rotating substrates are used to achieve a uniform  $\delta$ .
- Normally operate at 500 – 800 °C and moderate pressures (0.1 – 1 atm).



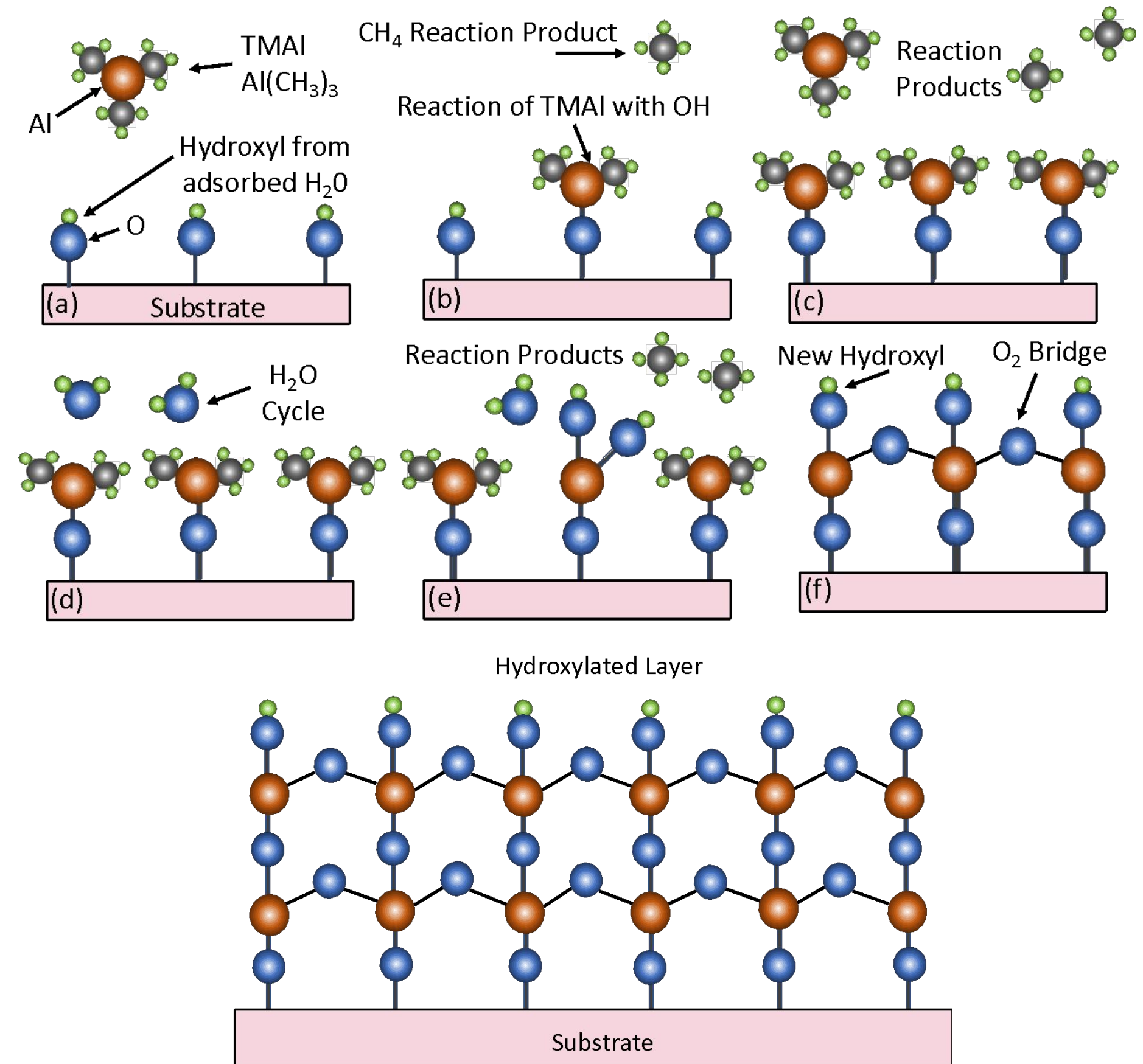
# Plasma Enhanced CVD (PECVD) and HDPCVD Systems

- Non-thermal energy to enhance processes at lower temperatures.
- Plasma consists of electrons, ionized and neutral molecules, neutral and ionized fragments of broken-up molecules, excited molecules, free radicals.
- Free radicals are electrically neutral species with incomplete bonding, extremely reactive. (e.g.  $\text{SiO}$ ,  $\text{SiH}_3$ ,  $\text{F}$ ).
- High density plasma (HDPCVD) systems add a “third knob” to produce higher densities of reactive species.  $\text{SiO}_2$  deposition shown where  $\text{O}_2$  is less reactive.
- Deposition is mass transport limited so relatively  $T$  independent. Ion bombardment can help to densify films.



# Atomic Layer Deposition (ALD)

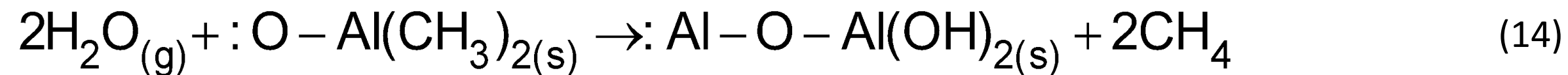
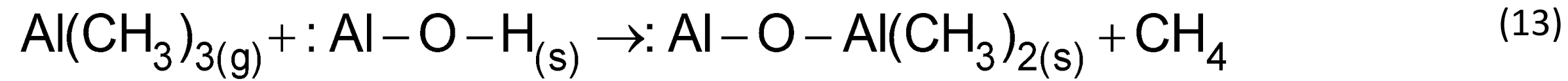
- Similar in chemistry to CVD, except that in ALD the reaction is broken down into two half-reactions, keeping the precursor materials separate during the reactions.  $\text{Al}_2\text{O}_3$  example below.
- ALD film growth is self-limited and based on surface reactions, which makes achieving atomic scale deposition control possible.





# Atomic Layer Deposition (ALD)

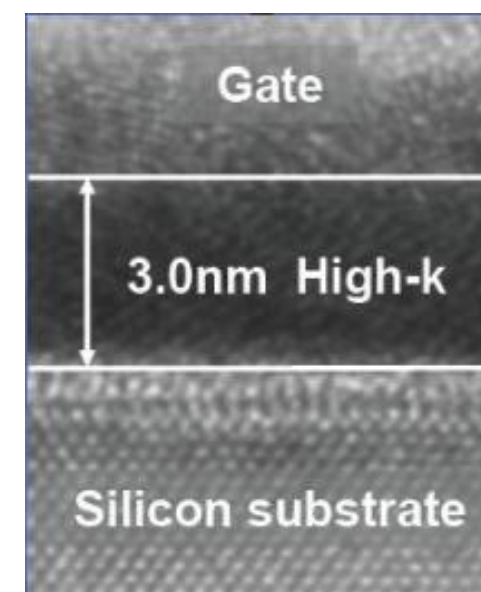
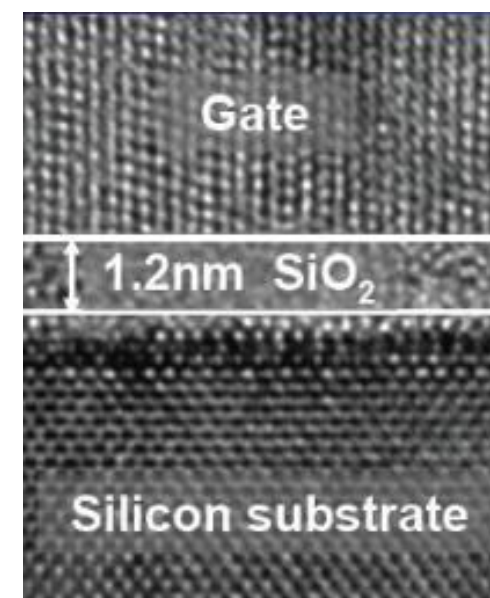
- One TMA and one H<sub>2</sub>O vapor pulse form one cycle. Here two cycles are shown, with approximately 1 Angstrom per cycle. Each cycle includes pulsing and pumping takes about 3 seconds.
- Two half reaction steps in each cycle



- The net result is that atomically controlled layers can be deposited.

## ALD Applications

- High-K dielectrics for CMOS

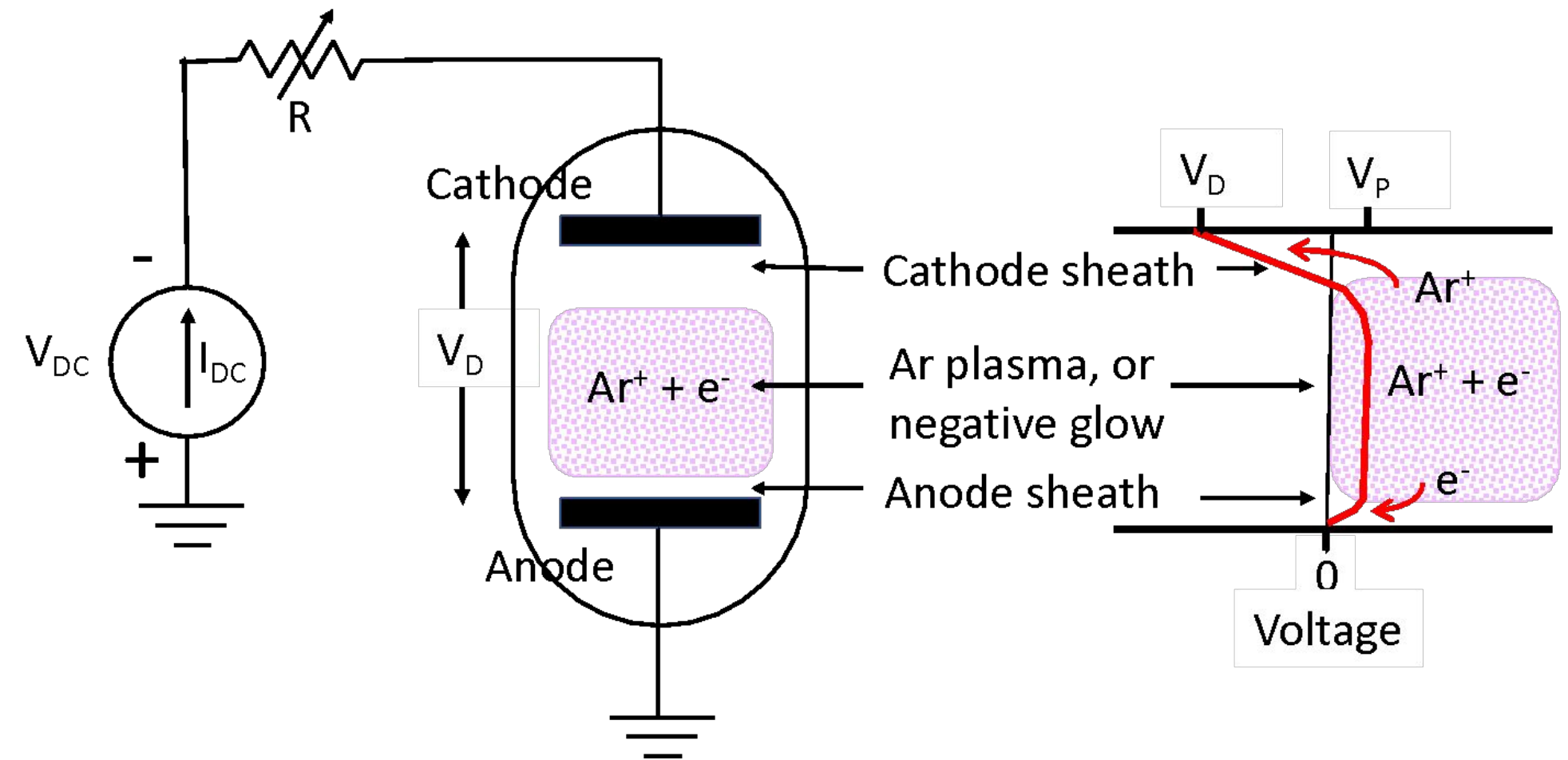


## Candidates for High-K dielectrics

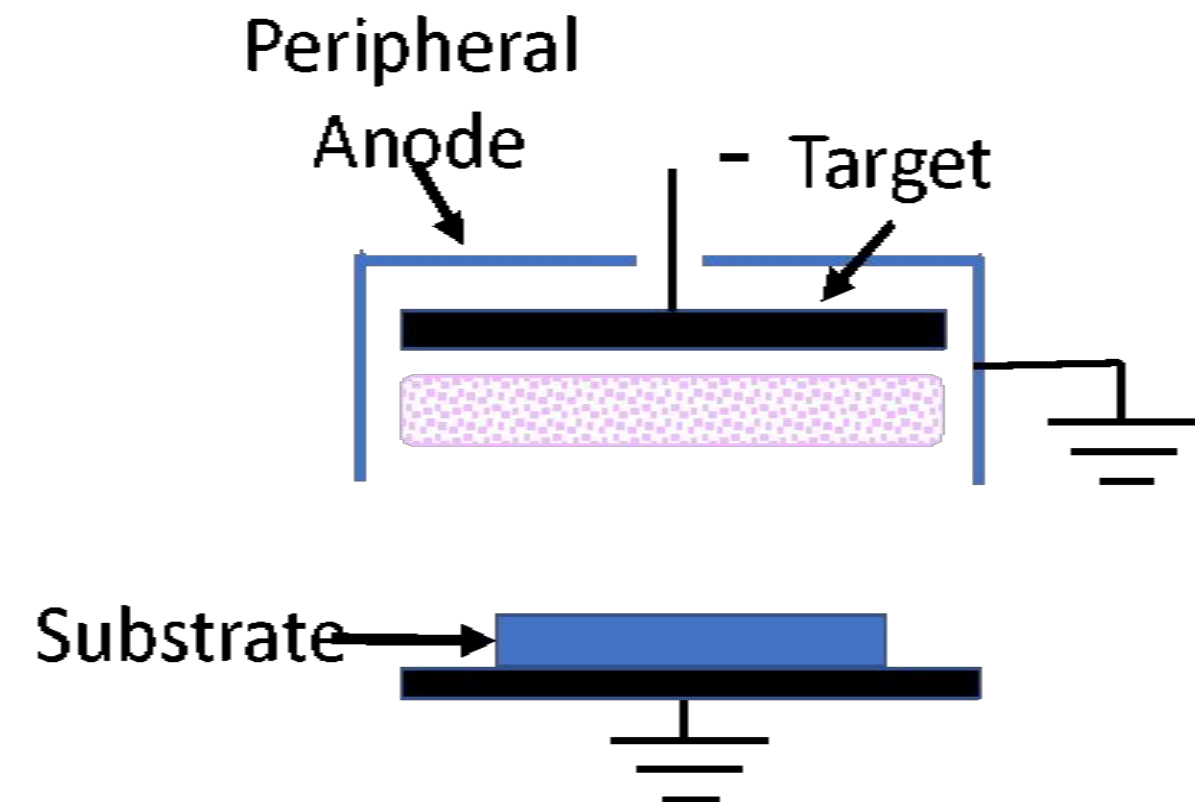
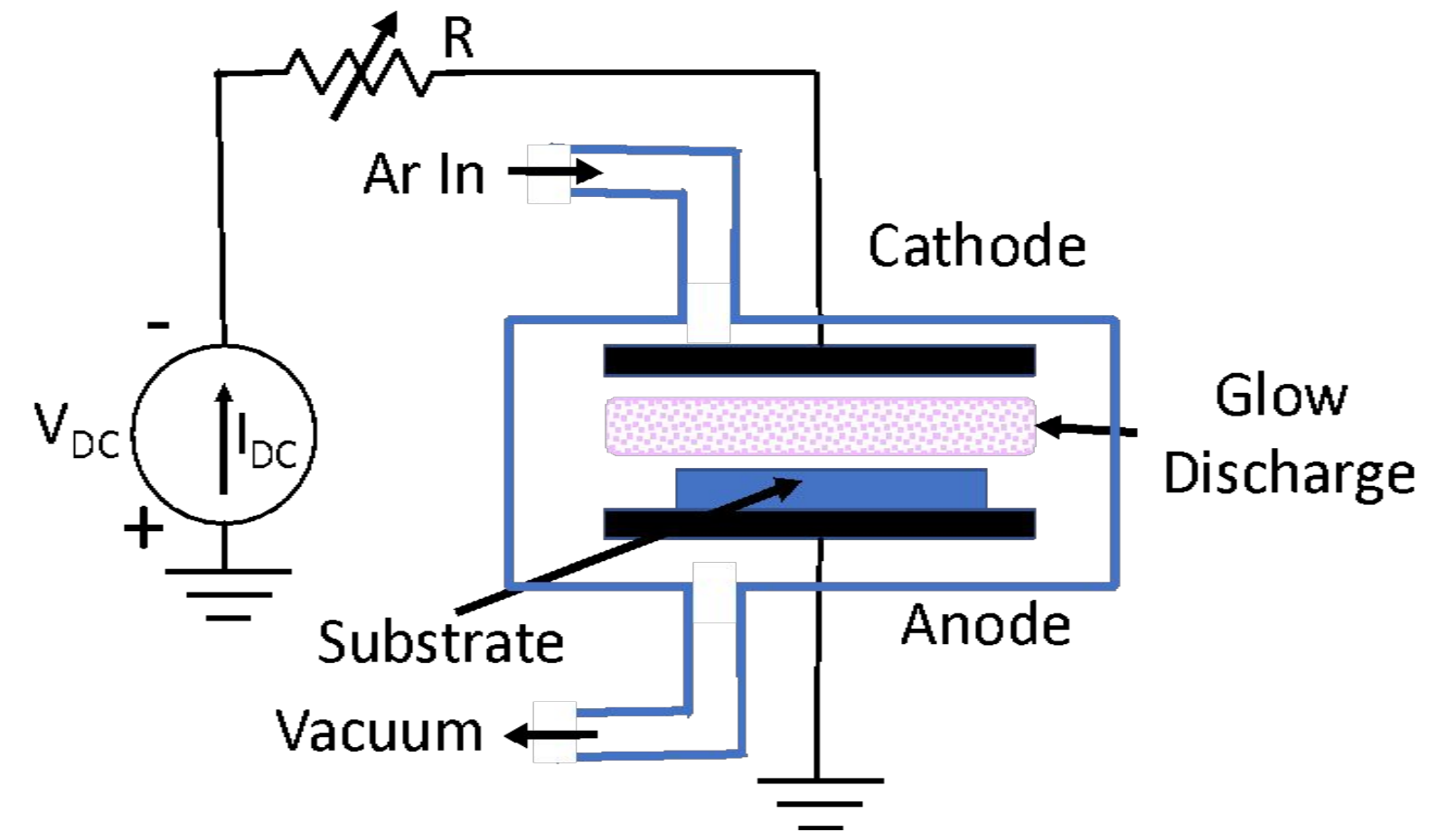
<u>Film</u>	<u>Precursors</u>
Al <sub>2</sub> O <sub>3</sub>	Al(CH <sub>3</sub> ) <sub>3</sub> , H <sub>2</sub> O or O <sub>3</sub>
HfO <sub>2</sub>	HfCl <sub>4</sub> or TEMAH, H <sub>2</sub> O
ZrO <sub>2</sub>	ZrCl <sub>4</sub> , H <sub>2</sub> O

# Physical Deposition Systems - DC Sputter Deposition

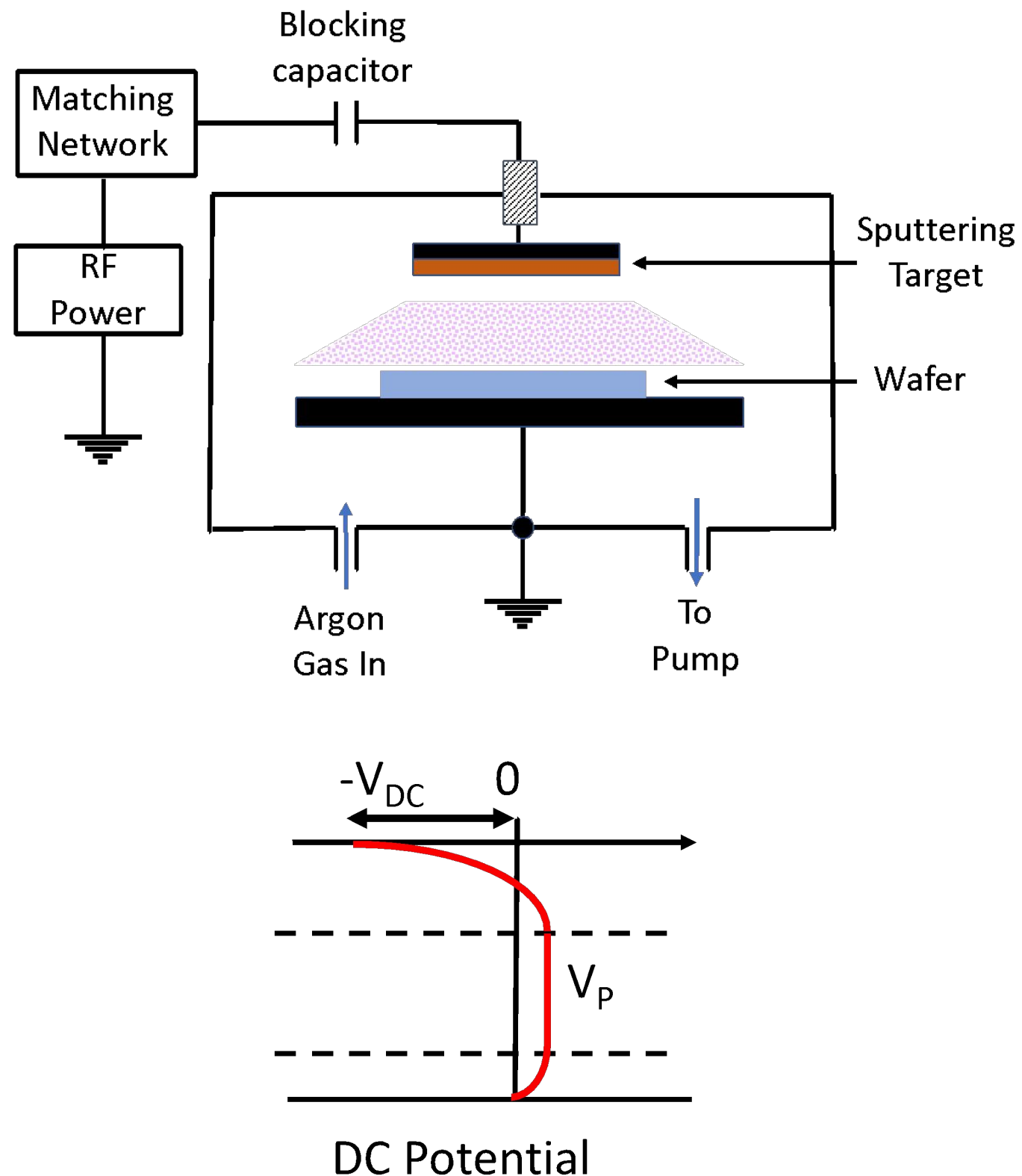
- DC plasma systems were not discussed in Chapter 9. They have almost no use in etching.
- For sputtering conductive materials this is a simple and effective approach.
- Dc voltage high enough to ionize gas is applied (500 – 1000 volts) depending on geometry.
- Cathode and anode voltage are fixed externally. The plasma takes on a small positive potential.
- DC current must be continuous. Cathode current is largely ions, anode current is largely electrons.
- $J = q\mu nE$  Because  $\mu$  is so different for ions and electrons,  $+V_p$  is set up to balance the two currents.



- If Ar gas is used in the plasma,  $\text{Ar}^+$  ions hit the target at high energy, sputtering material which can then diffuse and deposit on the substrate (wafer).
- This works well for conductive materials (metals, silicides . .) including alloys and compounds.
- The system on the right is a practical implementation, minimizing DC current through the substrate.
- Magnetron sputtering adds magnets on the cathode to trap  $e^-$  so they are not free to bombard the target. This improves the efficiency of deposition.
- DC sputtering works typically between 5 – 50 mT. Thus many collisions occur between ions and neutrals resulting in a wide angular distribution of the incoming depositing material atom.
- Reactive gases (e.g.  $\text{N}_2$ ) can be added to the plasma. Ti sputtering TiN (see text).



# RF Sputter Deposition



- For DC sputtering, target electrode must be conducting. To sputter dielectric materials use RF power source.
- As we saw in Chapter 9 (Fig. 9.9), if the electrode areas are not equal, the field is higher at the smaller electrode (higher current density), to maintain AC current continuity.
- $V_{DC}$  is set up automatically by the plasma. It must be large enough (10 – 20 eV) to cause sputtering.
- The voltages across the two sheaths are

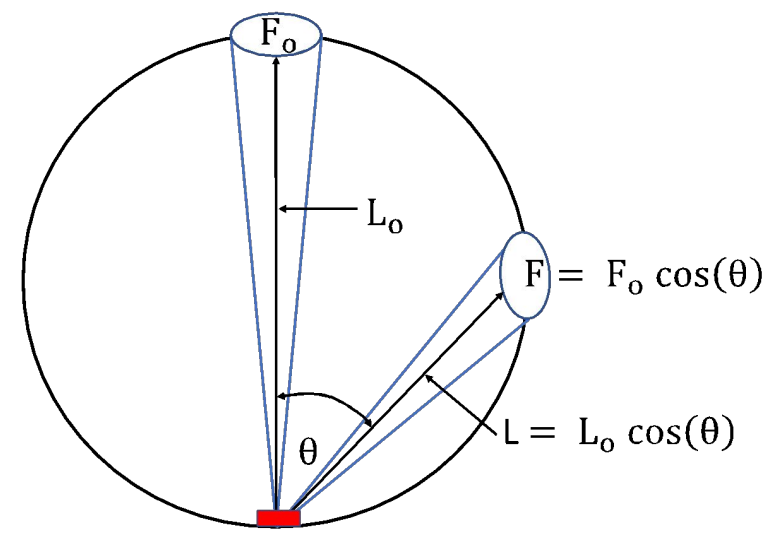
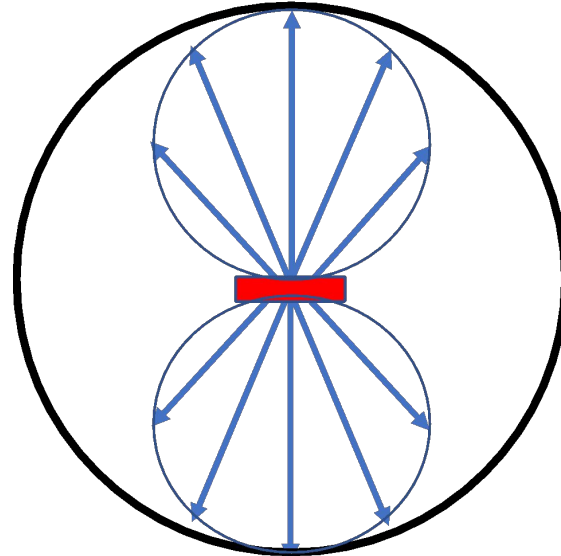
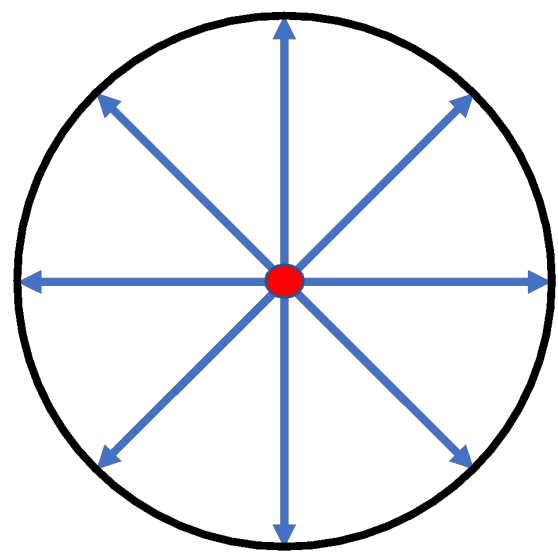
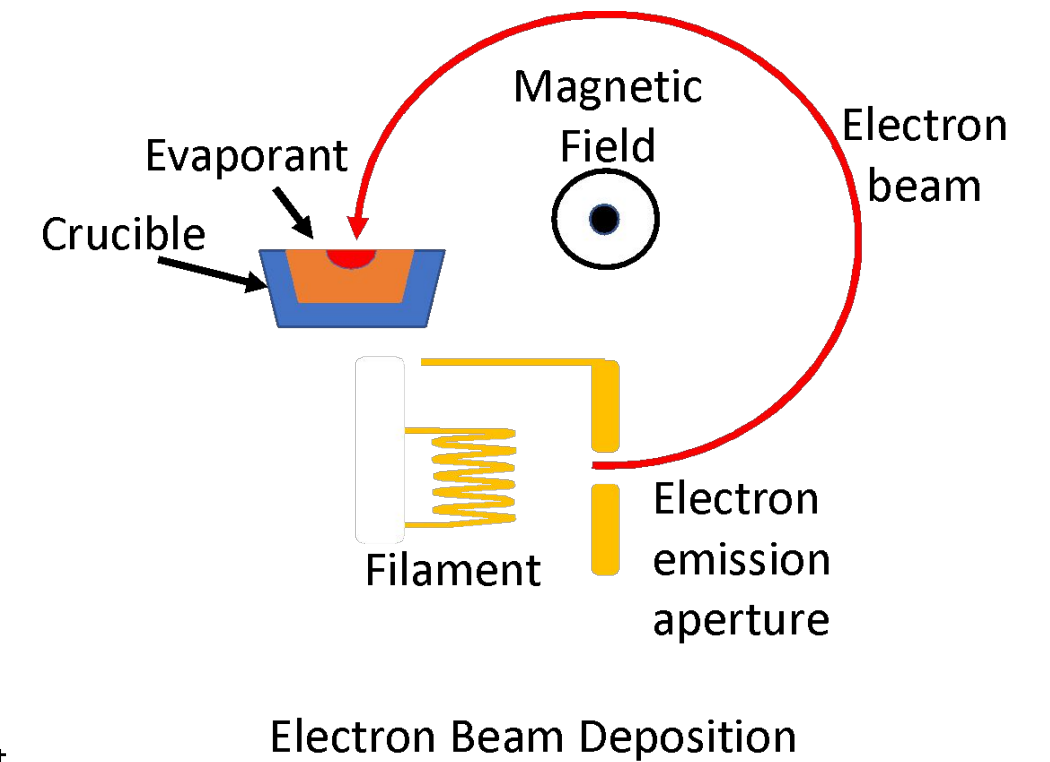
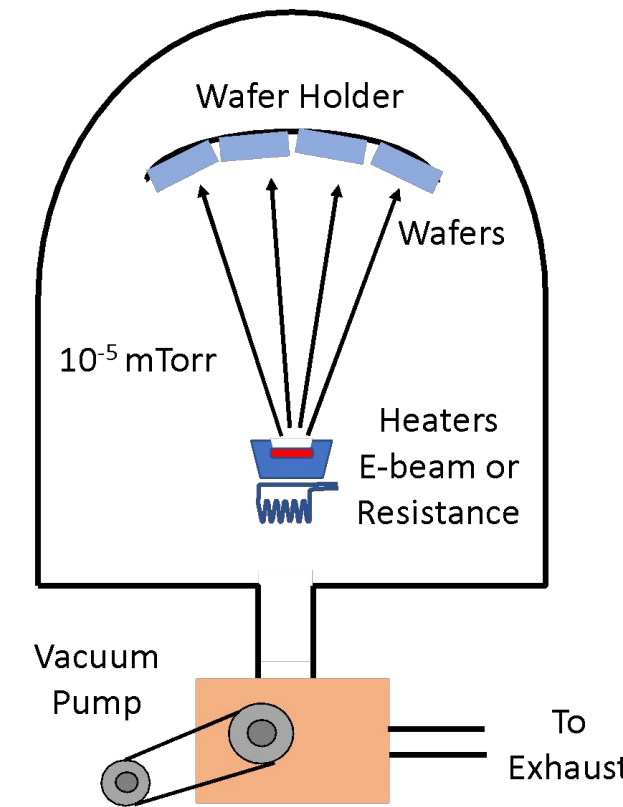
$$\frac{V_1}{V_2} \approx \left( \frac{A_2}{A_1} \right)^m \quad (m = 4 \text{ in theory and } 1-2 \text{ experimentally}) \quad (19)$$

- Wafer electrode can be connected to chamber walls further increasing the voltage ration.



# Physical Deposition Systems - Evaporation

- In evaporation, source material is heated or E-beam is used in a vacuum chamber.
- Mostly line-of-sight deposition since pressure is low.
- Deposition rate is determined by emitted flux and by geometry of the target and wafer holder.



- Ideal point sources emit isotropically.
- Realistic planar sources emit with a  $\cos\theta$  distribution.
- Placing a small planar source at the base of a sphere results in more uniform deposition.
- The angular drop-off in emitted flux is compensated by the shorter distance.

# Molecular Beam Epitaxy - MBE

- Operates under high vacuum, line of sight deposition, epitaxial layers can be deposited if substrate is heated to provide thermal energy.
- Deposition rate usually slow so epitaxial growth can occur ( $\approx 1$  atomic layer/sec).
- “Effusion” sources used to evaporate elements needed for thin films to be deposited. T of effusion cells controls relative evaporation rates.
- Widely used in university and industry research, generally too slow for manufacturing.

