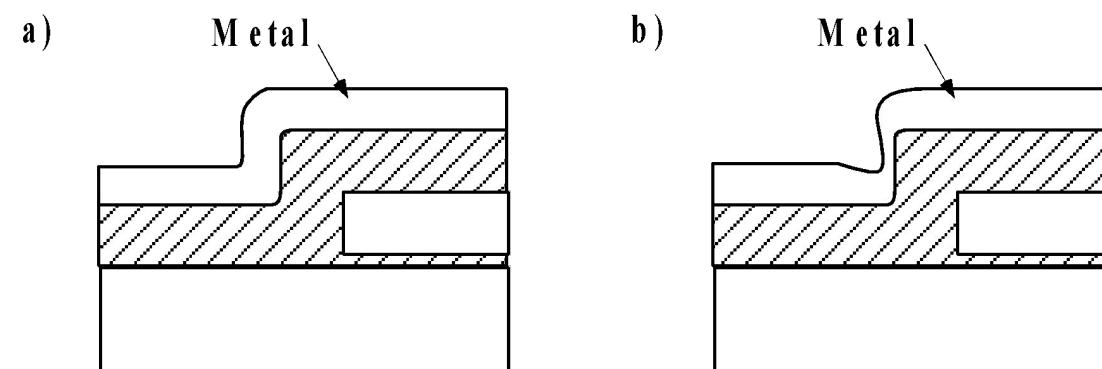
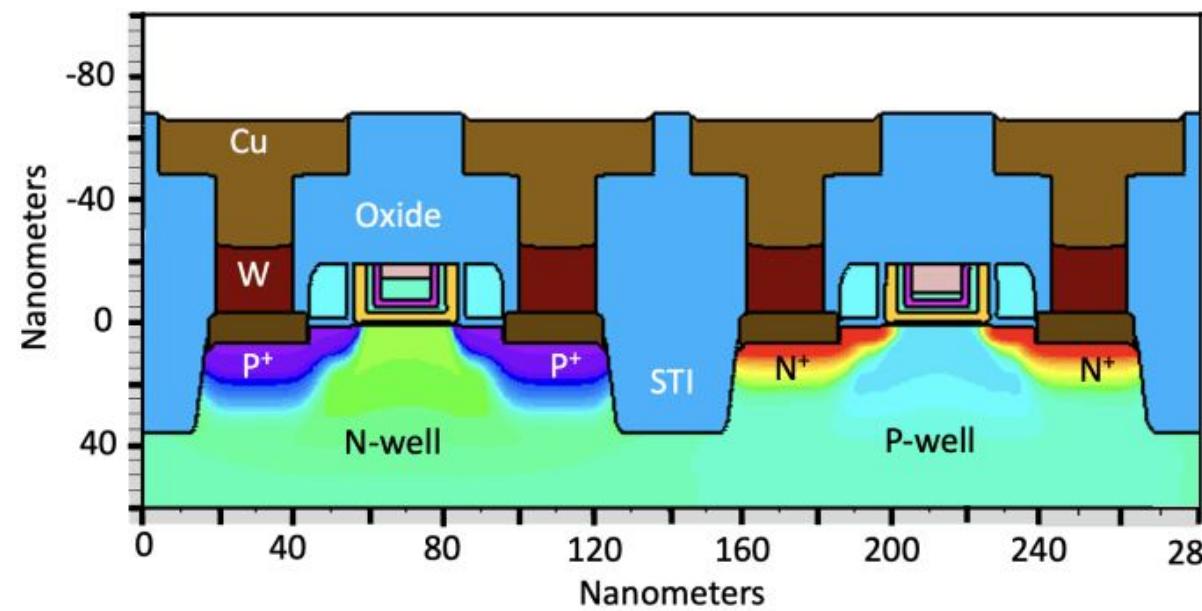


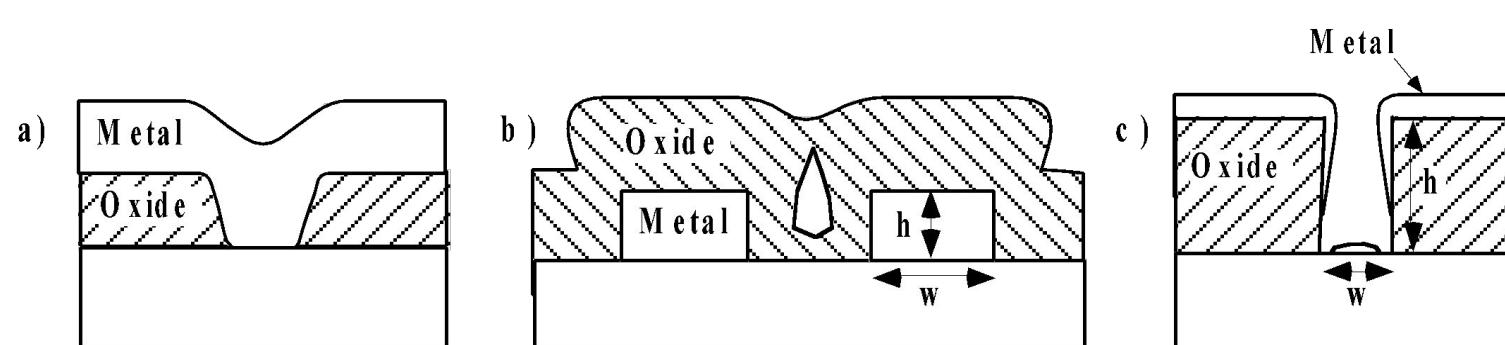
Deposition Techniques

KEY CONCLUSIONS

Deposition Systems - Classification



Step Coverage



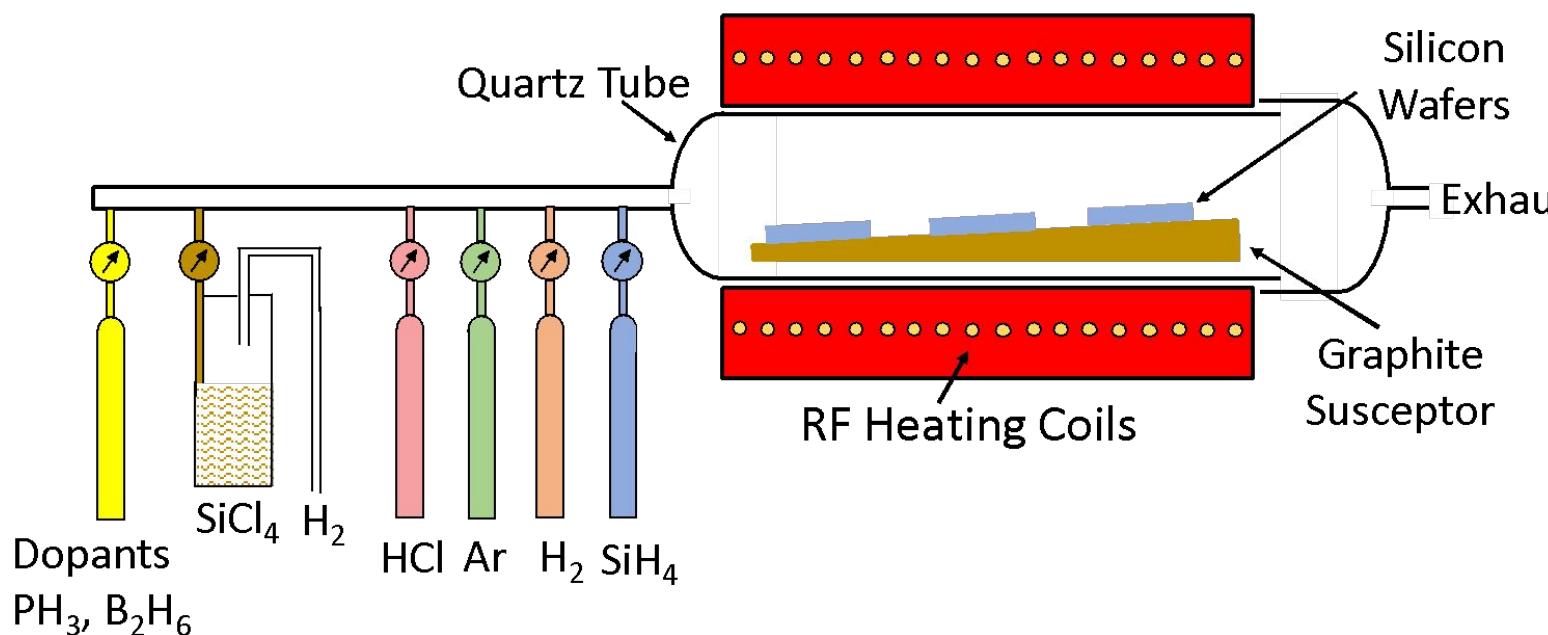
Aspect Ratio: H/W

Formation of Voids

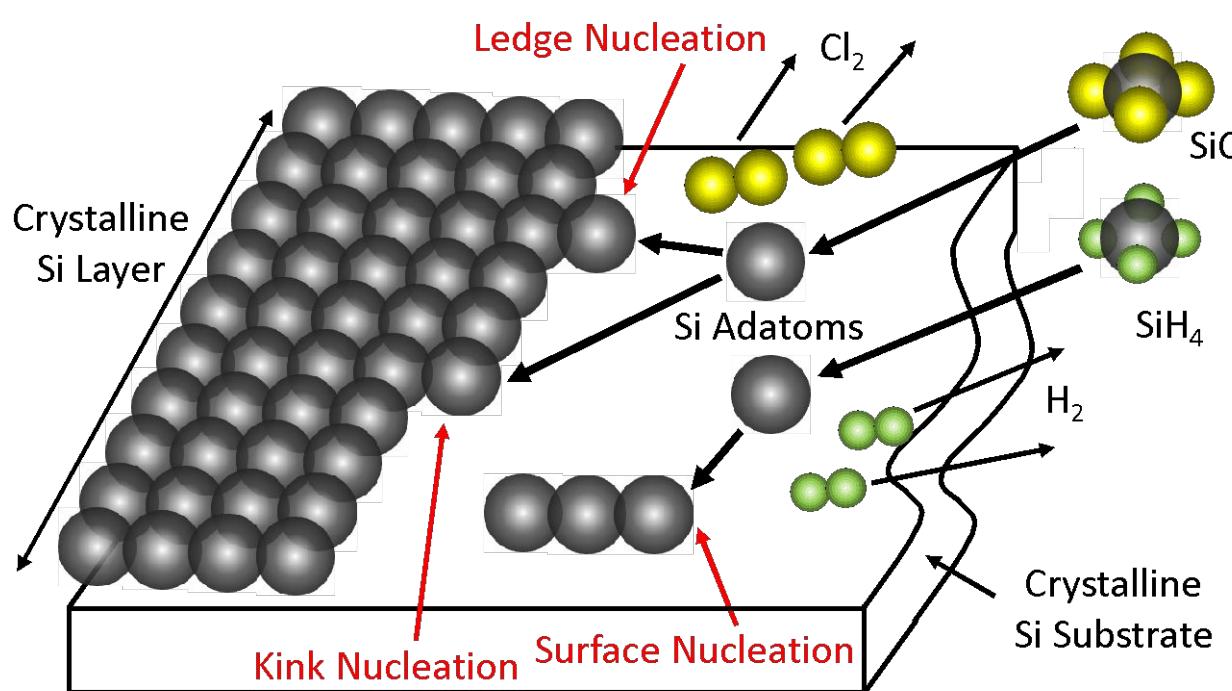
- Desirable traits for deposition:
 - Desired composition, low contaminates, good electrical and mechanical properties.
 - Uniform thickness across wafer, and wafer-to-wafer.
 - Good step coverage (“conformal coverage”)
 - Good filling of spaces.
 - Planarized films .
- Challenge: Filling higher aspect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

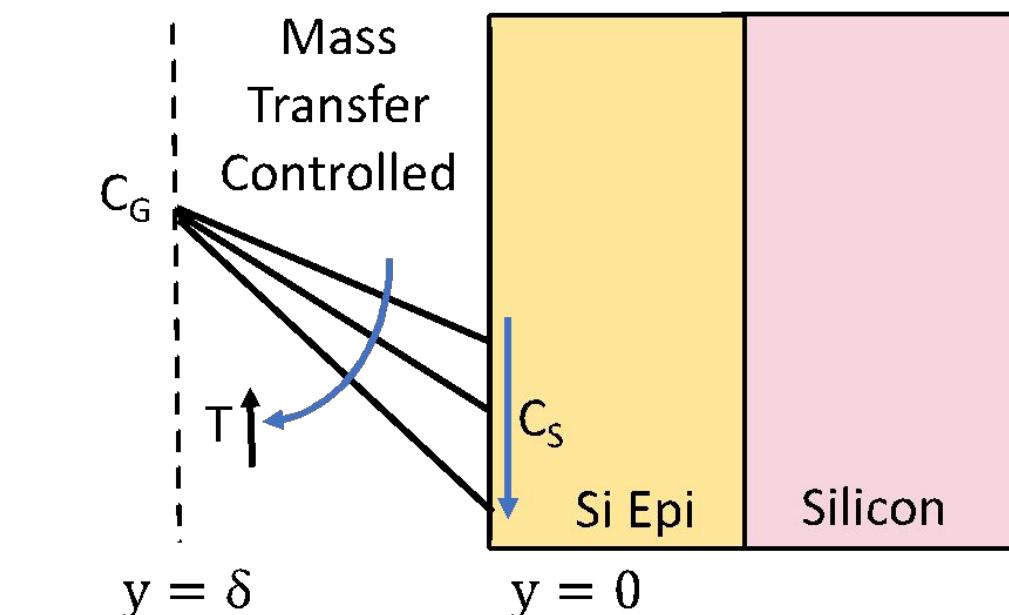
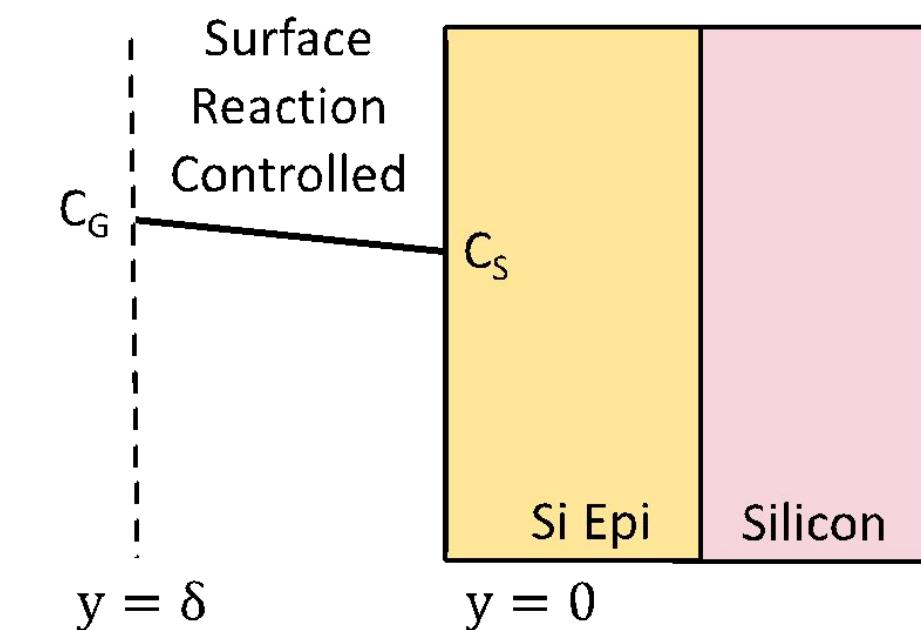
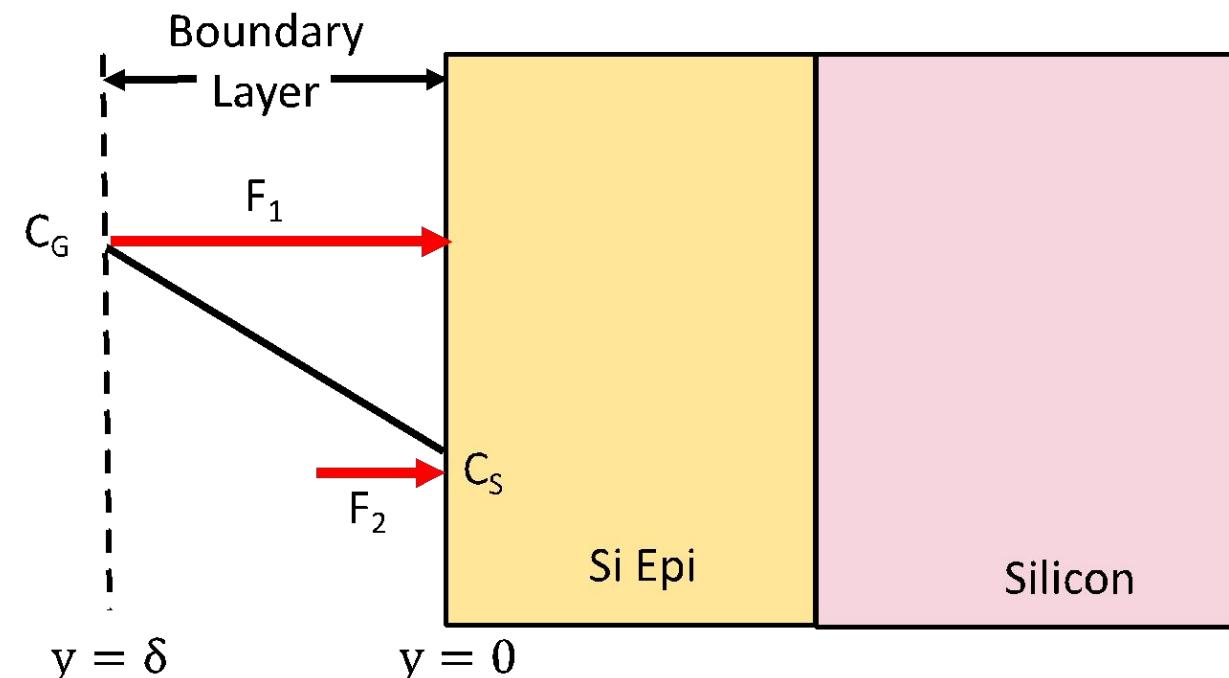
Chemical Vapor Deposition



- Atmospheric Pressure
- Gas Phase Reactions
- Typically high T ($500 - 1100^\circ\text{C}$)
- Most common application is epitaxial growth.
- High T provides surface mobility so single crystal films can grow.



CVD Growth rate



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

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

$F = F_1 = F_2$

In steady state:

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

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

Kinetic Limited Regime

Mass Transport Limited Regime

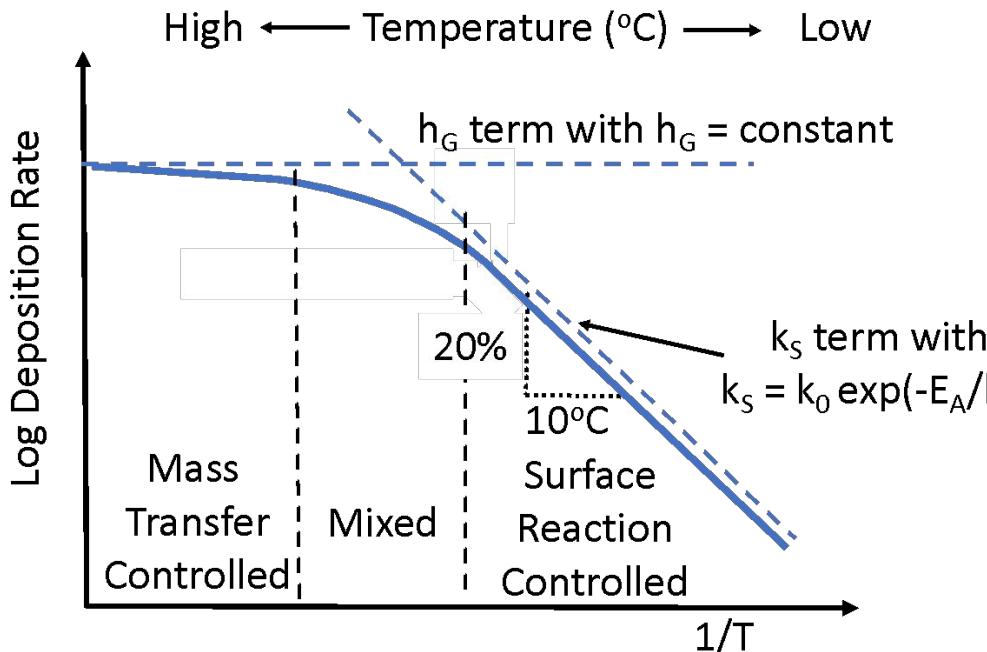
Growth Rate

$$v = \frac{F}{N} = \frac{k_S h_G}{k_S + h_G} \frac{C_G}{N} = \frac{k_S h_G}{k_S + h_G} \frac{C_T}{N} Y$$

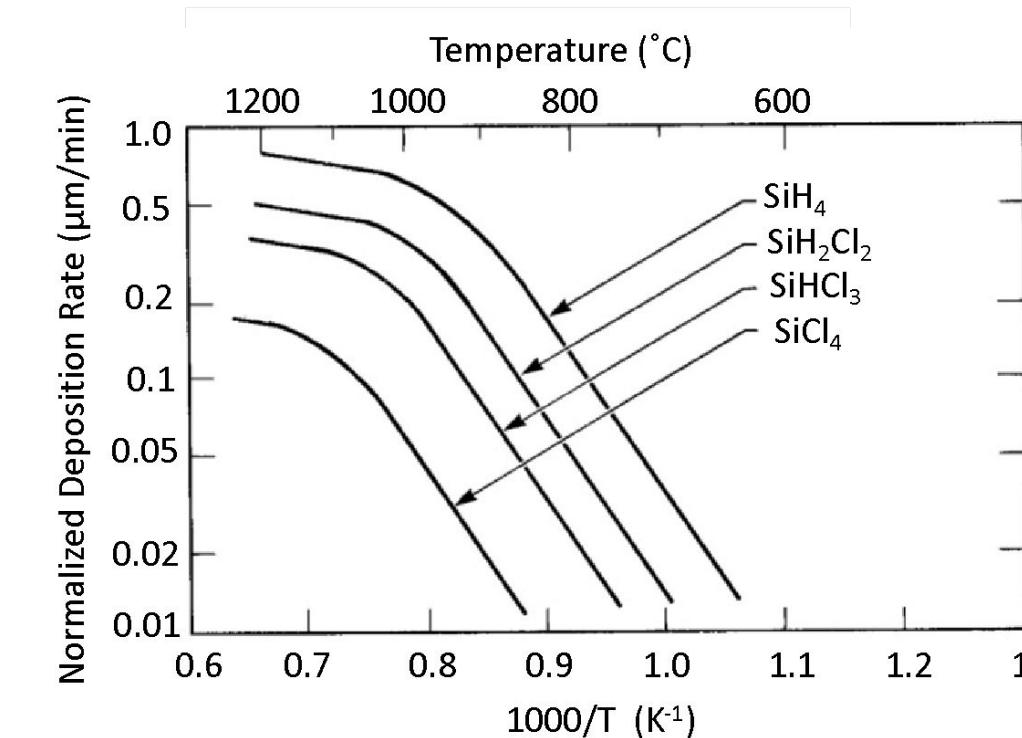
N - number of atoms per unit volume in the film ($5 \times 10^{22} \text{ cm}^{-3}$ for the case of epitaxial Si deposition)

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

The two limited Regimes

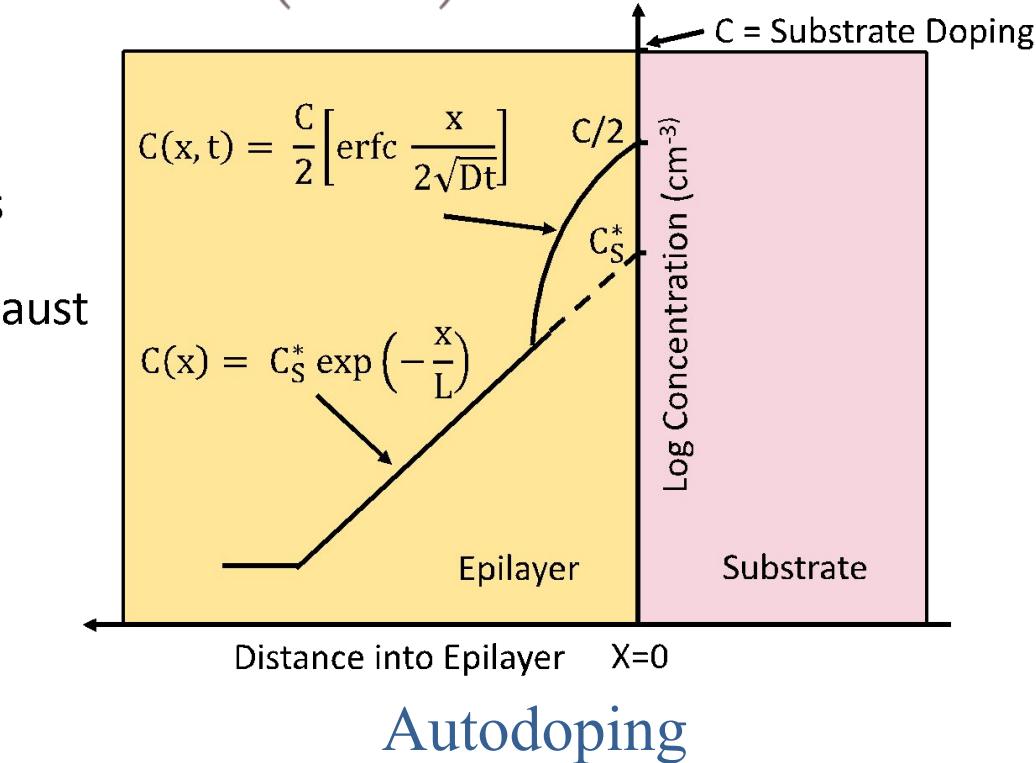
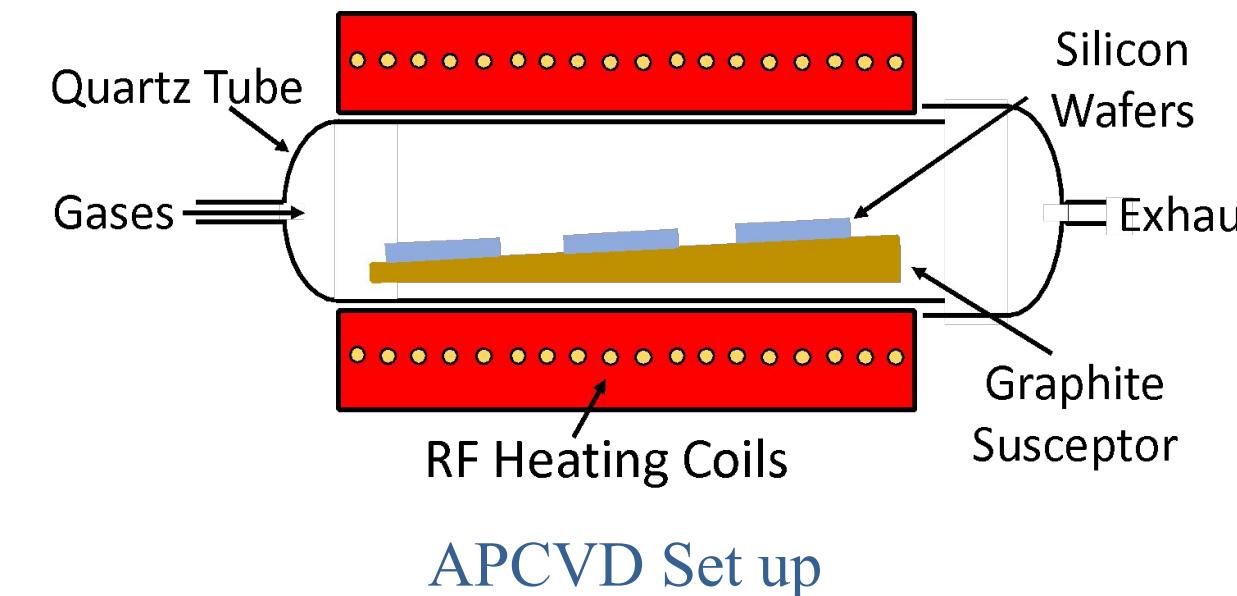


Temperature	SiH_4 900-1050°C	SiH_2Cl_2 950-1100°C
Reaction		
Reversible HCl byproduct	No	Yes
Gas Phase	No	Yes
Nucleation	Yes	No
Flow Control	Easy	Moderate
Cost	High	Moderate
Danger	High	Moderate
Deposition Rate	Thin layers	Many layers
Uses		



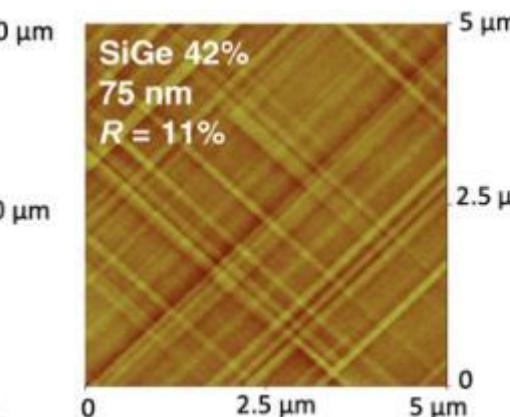
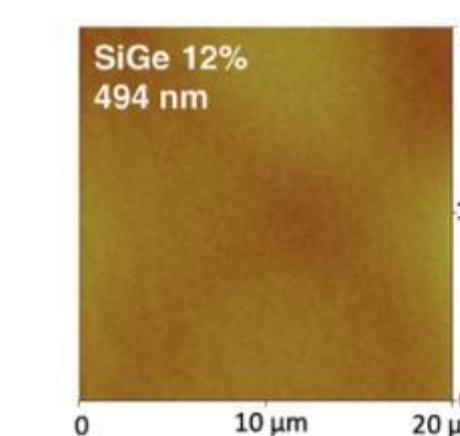
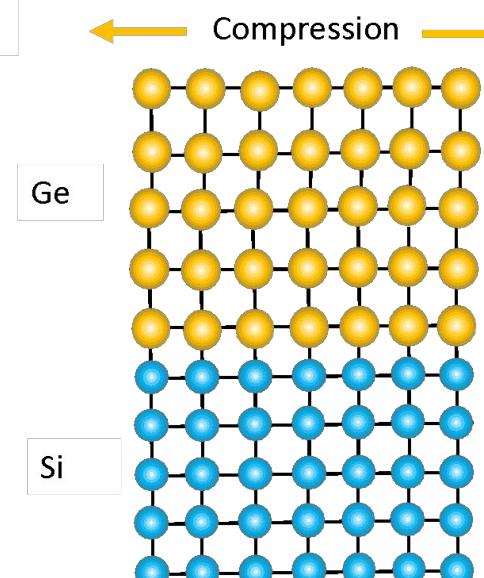
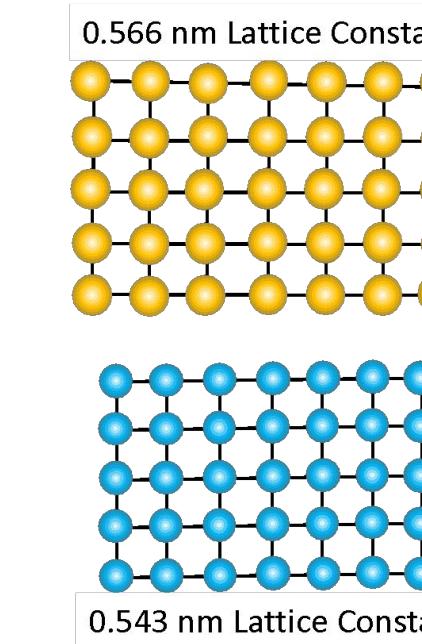
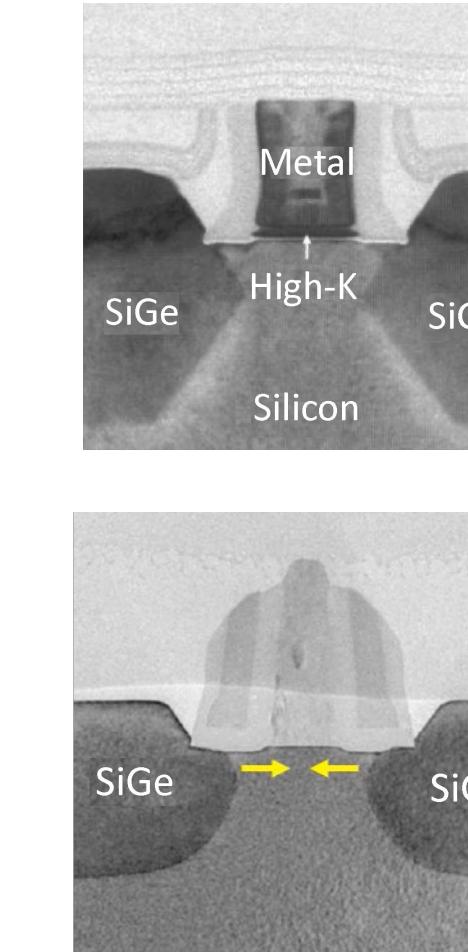
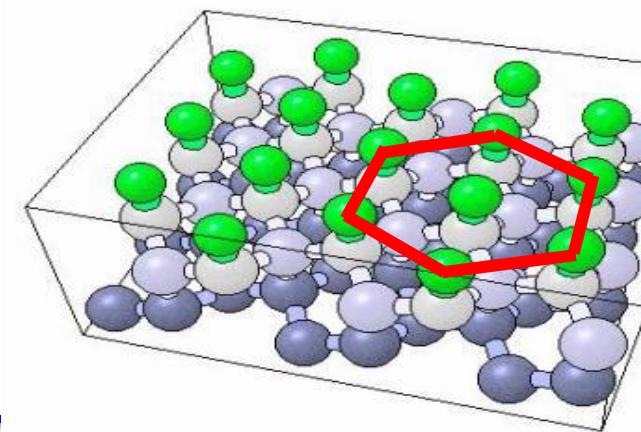
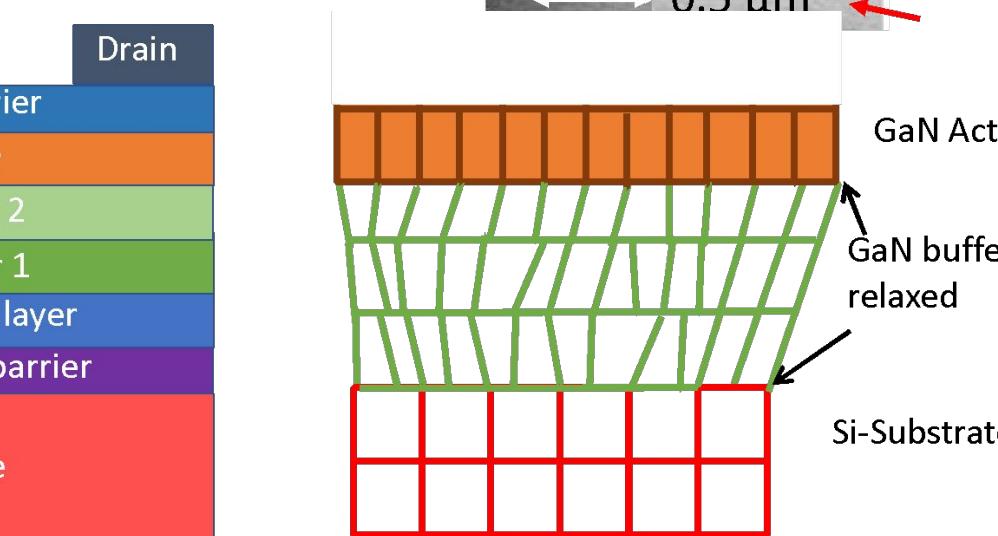
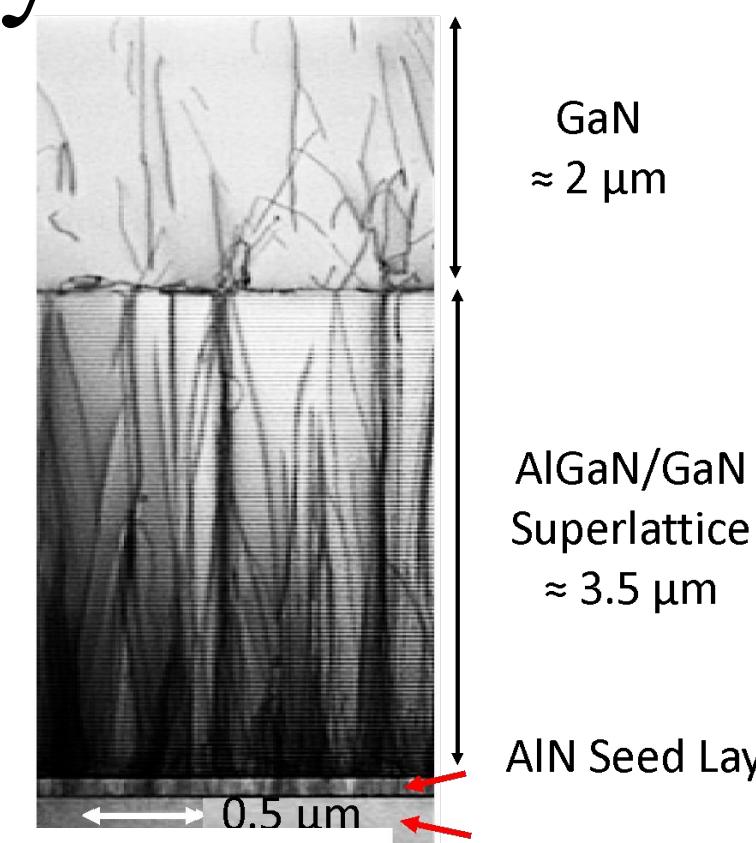
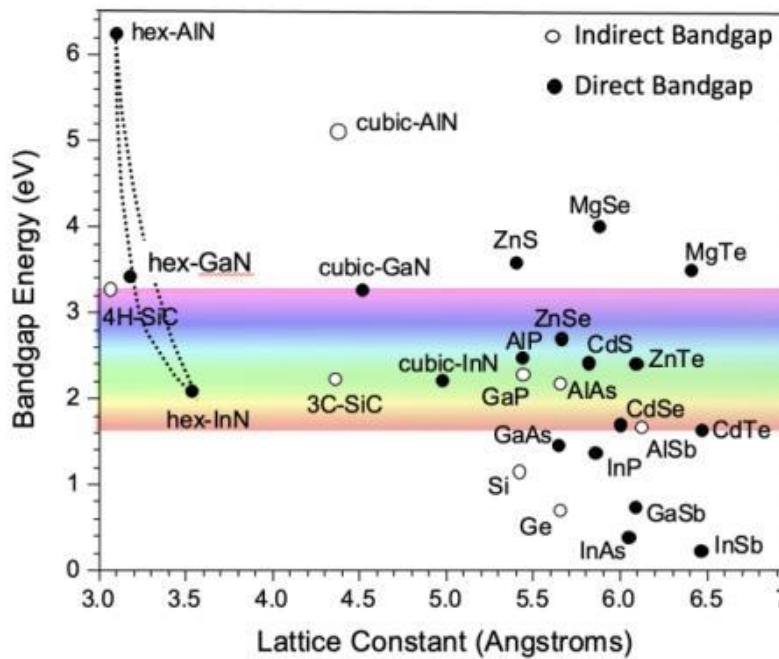
- Mass transport is more or less independent of T
- Rate Kinetics is exponentially dependent on T
- In both regimes the growth rate is constant with time

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



- 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

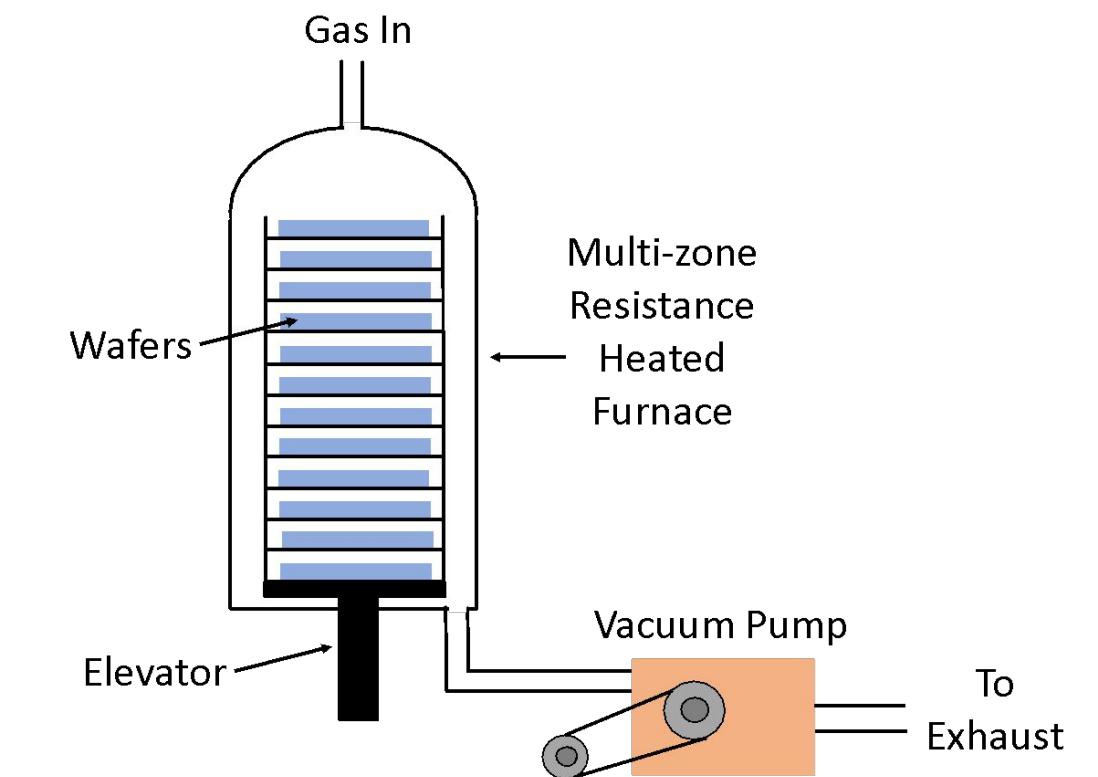
Heteroepitaxy



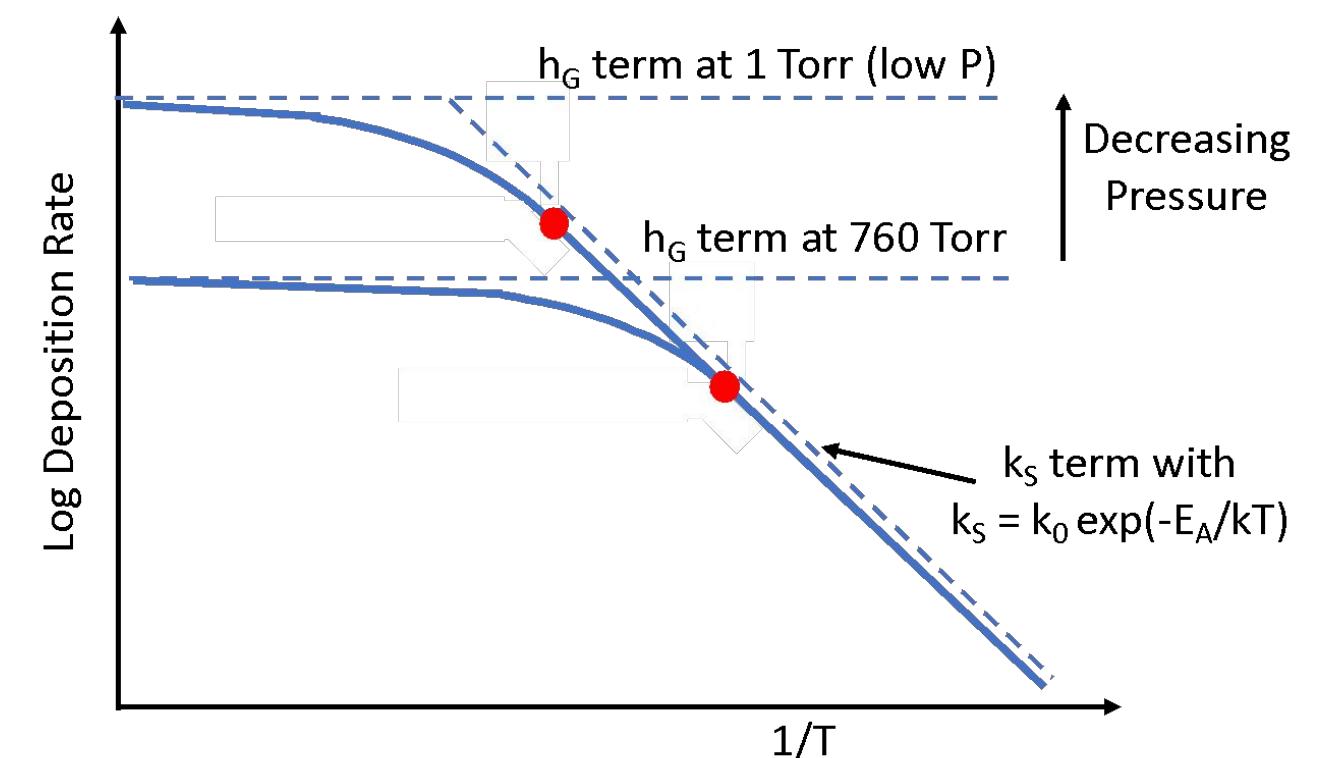
- Growing of dissimilar material on a substrate
- Lattice mismatch introduces Strain
- Large strain introduces defects
- Optimal Strain is used in enhancing mobility
- Used for growing III-V semiconductors
- Wide Band gap tuning applications
- Buffer layer growth for minimize lattice mismatch
- Si(111)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

LPCVD

- Atmospheric pressure CVD is horizontal configuration
- Only a few wafers at a time
- At low T deposition rate is slow

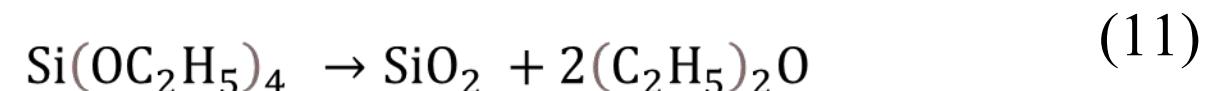


- Decreasing pressure increases mass transfer coefficient
- Mass transport is no longer time limited
- Process depends on temperature
- Temperature can be controlled precisely using modern control systems



CVD of Compound Materials - MOCVD

- For Si CMOS applications, we mostly deposit epitaxial Si films, or we deposit dielectrics like SiO_2 , Si_3N_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.

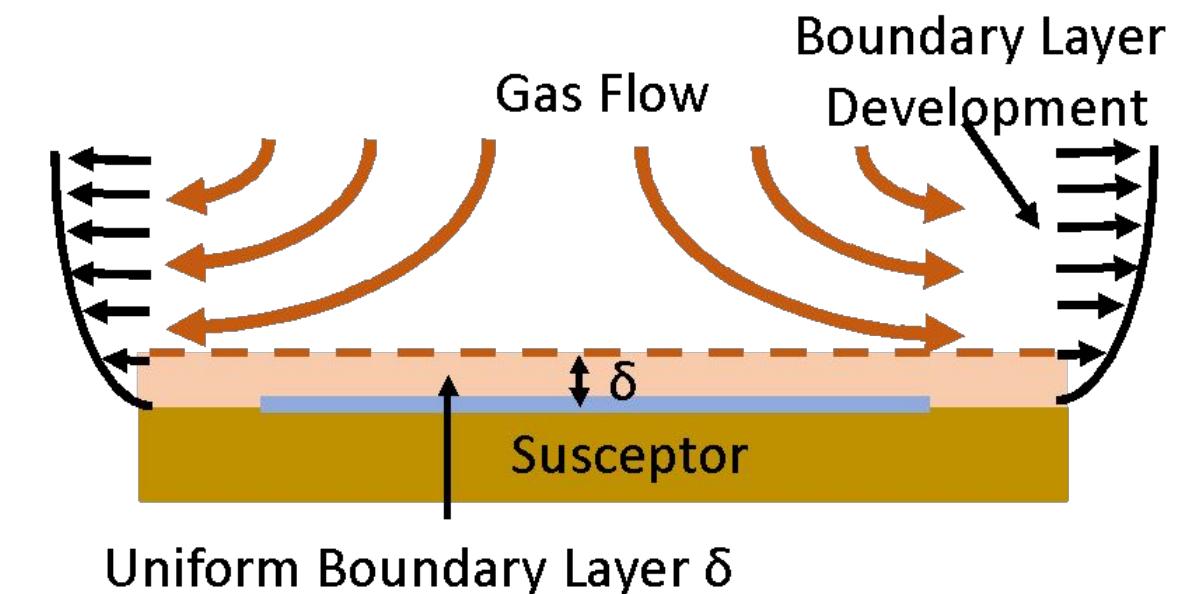
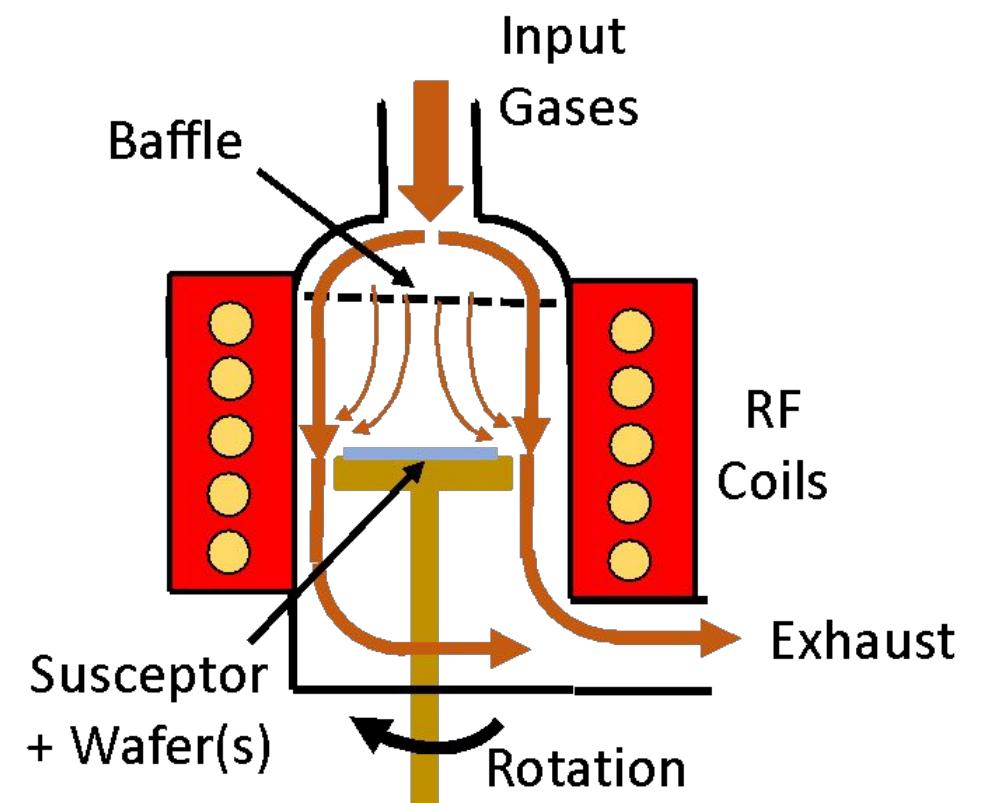
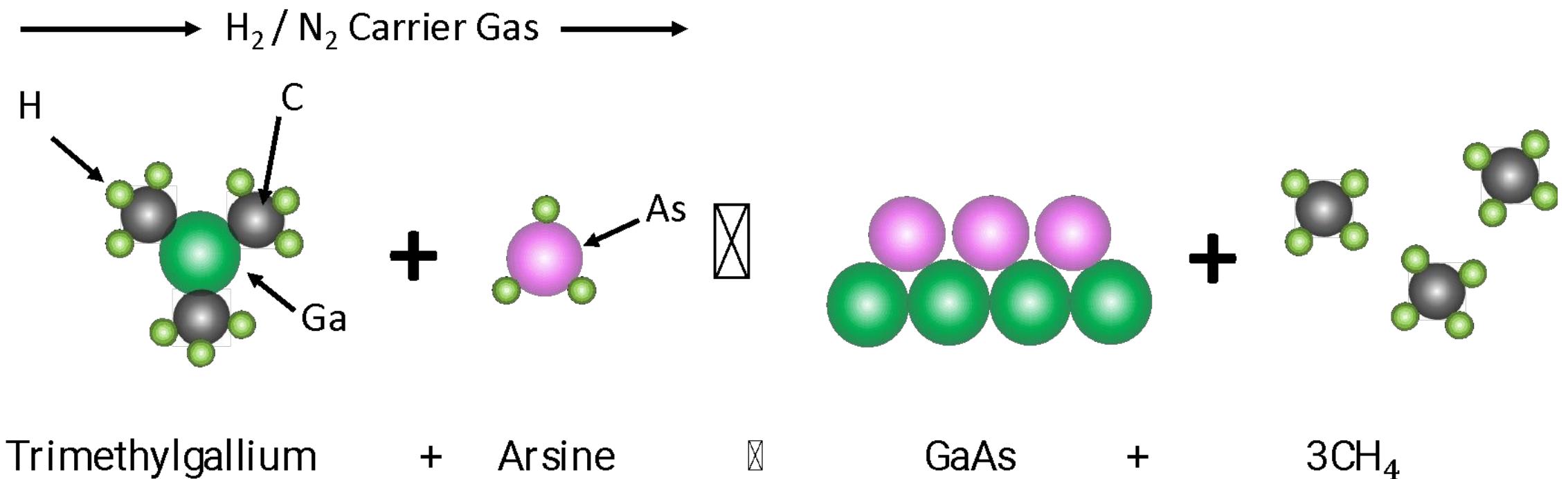


- Many such precursors have been developed for compound semiconductor materials.
- These are metal-organic precursors, hence MOCVD.
- Example:



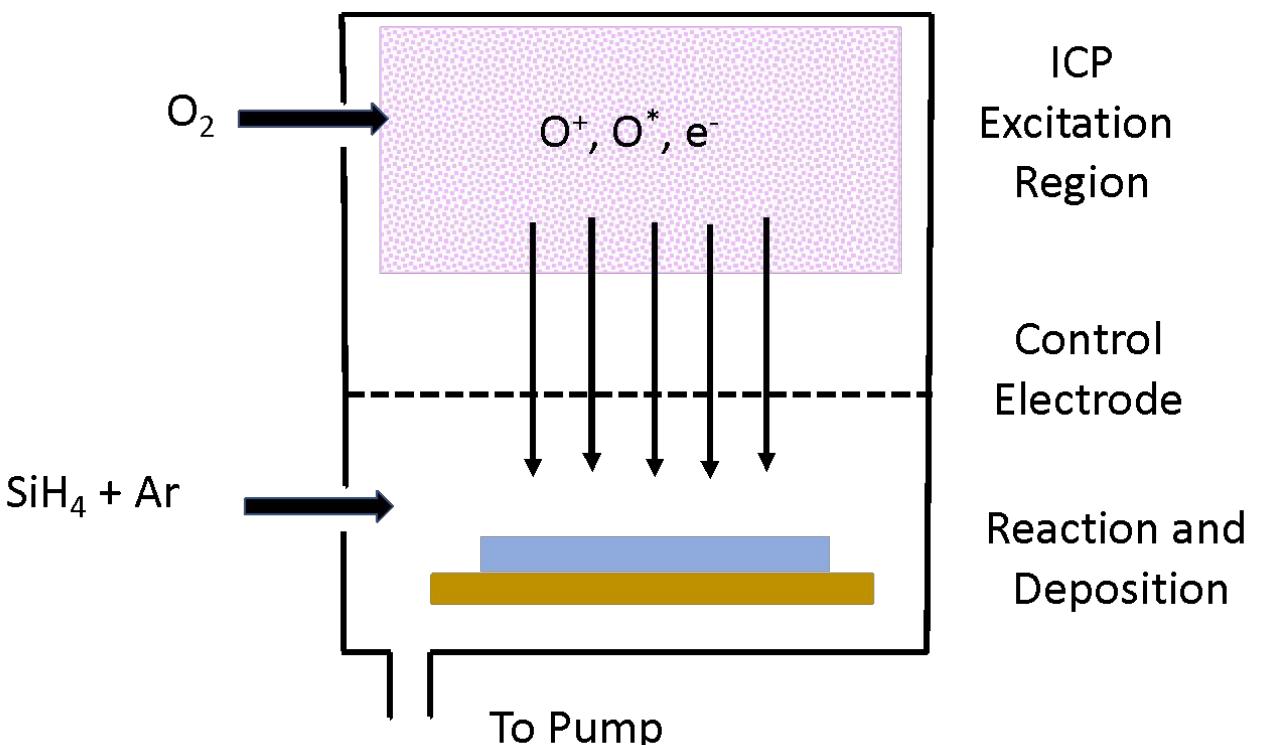
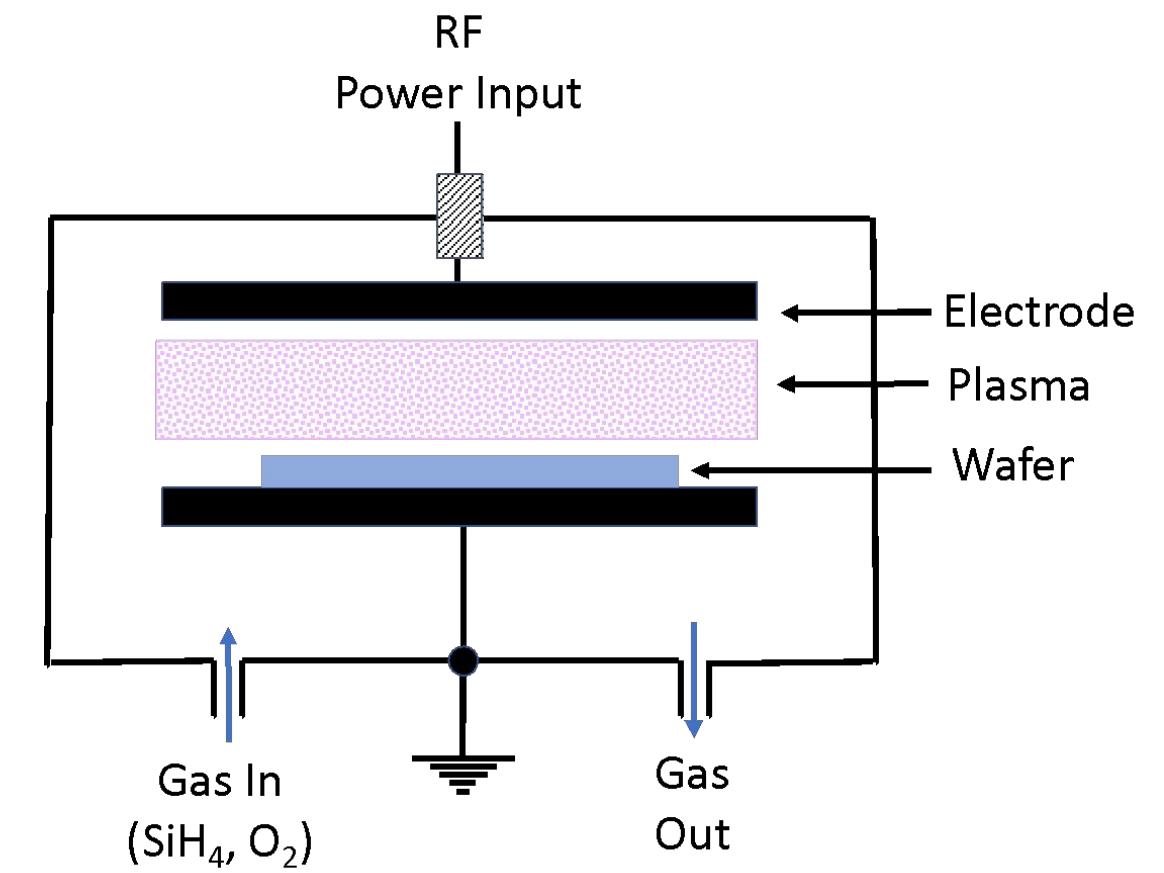
Common Metals	Common Organics	Common Precursors	MOCVD
Gallium	Methyl	Tri or Tetra methyl = TM	
Aluminum		Triethyl= TE	
Indium		Triisopropyl = TiP	
Arsenic		Dimethyl = DM	
Antimony		Diethyl = DE	
Zinc	Ethyl	Trimethylgallium (TMGa)	
Cadium		Triethylgallium (TEGa)	
Telluride		Triisopropylgallium (TiPGa)	
Germanium		Trimethylaluminum (TMAI)	
		Trimethylindium (TMIn)	
		Triethylindium (TEIn)	
		Trimethylarsenic (TMA ₃)	
		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 δ .
- Normally operate at $500 - 800 \text{ }^\circ\text{C}$ and moderate pressures ($0.1 - 1 \text{ atm}$).



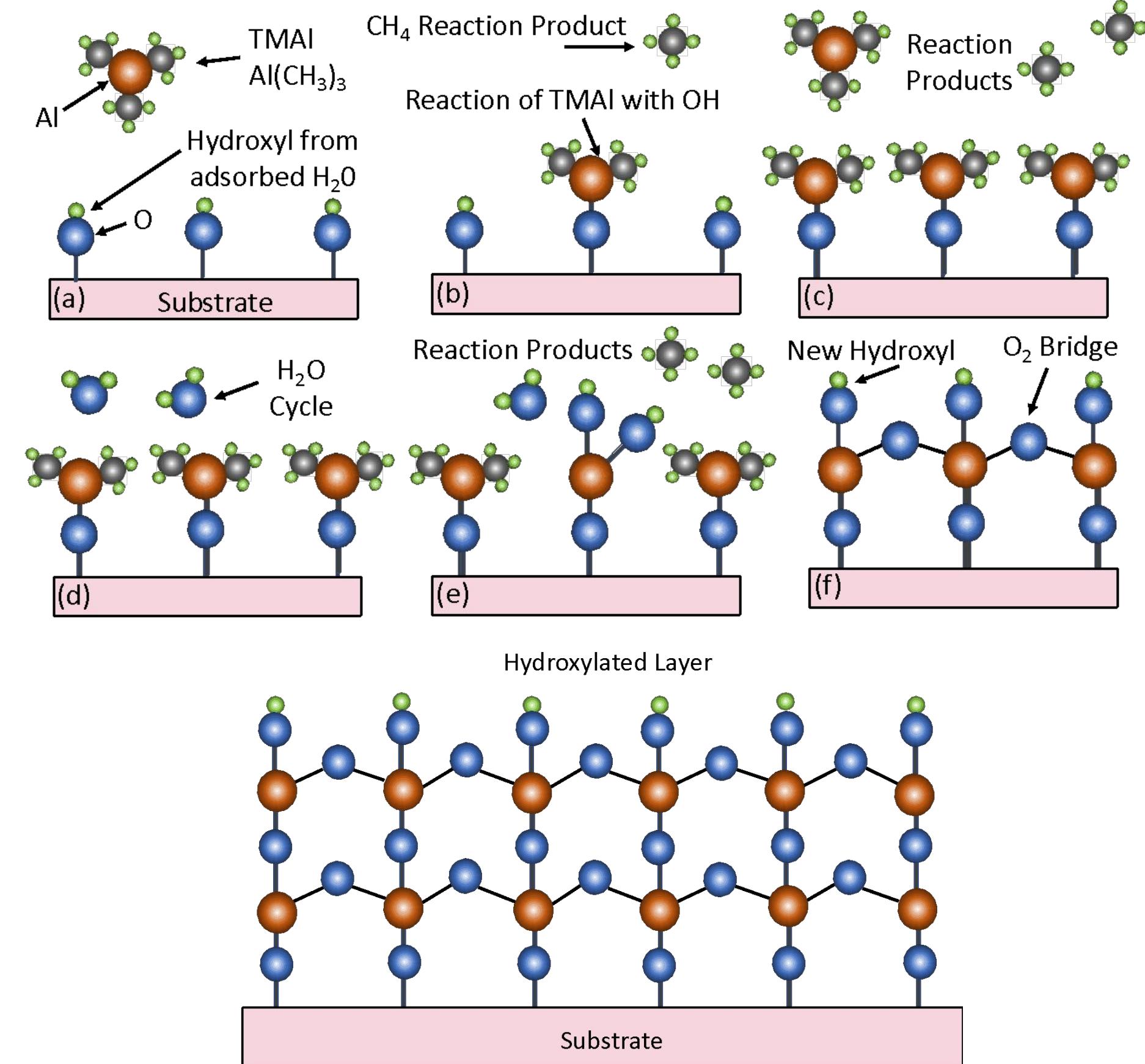
Plasma Enhanced CVD (PECVD) and HDPCVD Systems

- 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. SiO , SiH_3 , F).
- High density plasma (HDPCVD) systems add a “third knob” to produce higher densities of reactive species. SiO_2 deposition shown where O_2 is less reactive.
- Deposition is mass transport limited so relatively T independent. Ion bombardment can help to densify films.



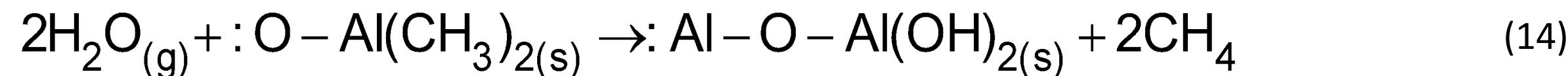
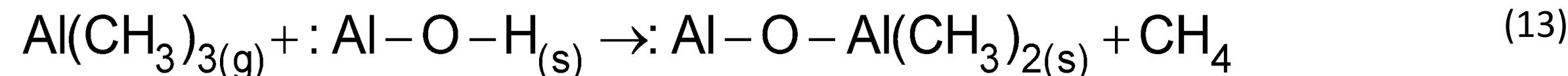
Atomic Layer Deposition (ALD)

- 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. Al_2O_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)

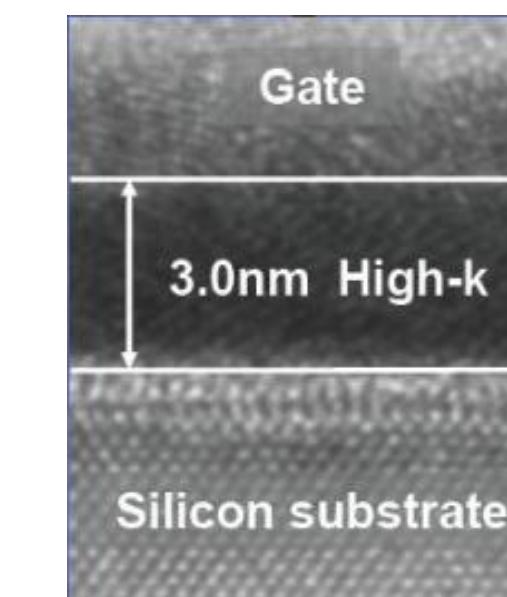
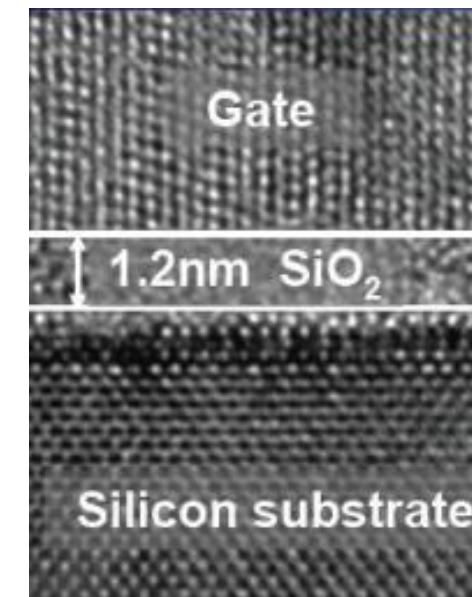
- One TMA and one H₂O vapor pulse form one cycle. Here two cycles are shown, with approximately 1 Angstrom per cycle.
Each cycle includes pulsing and pumping takes about 3 seconds.
- Two half reaction steps in each cycle



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

ALD Applications

- High-K dielectrics for CMOS

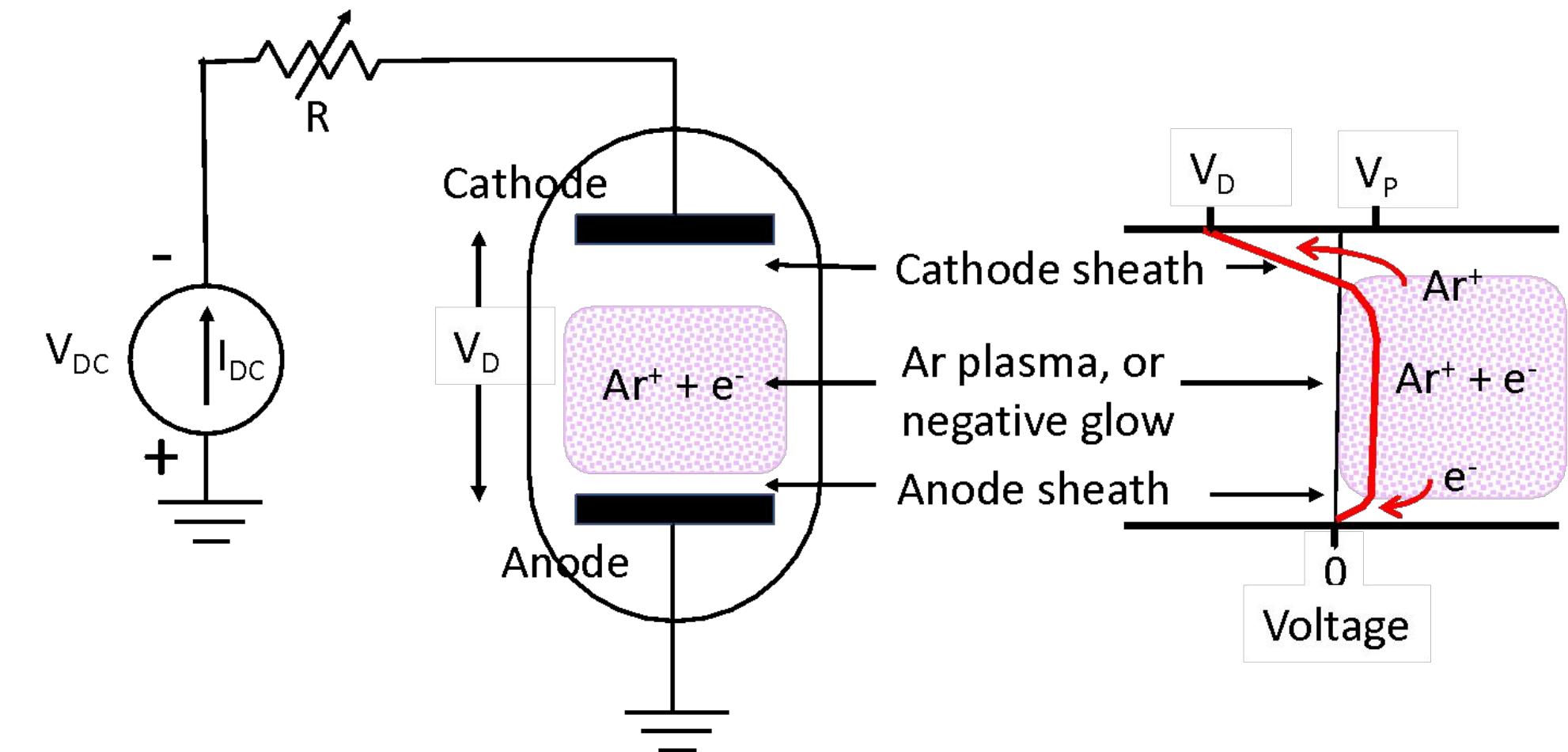


Candidates for High-K dielectrics

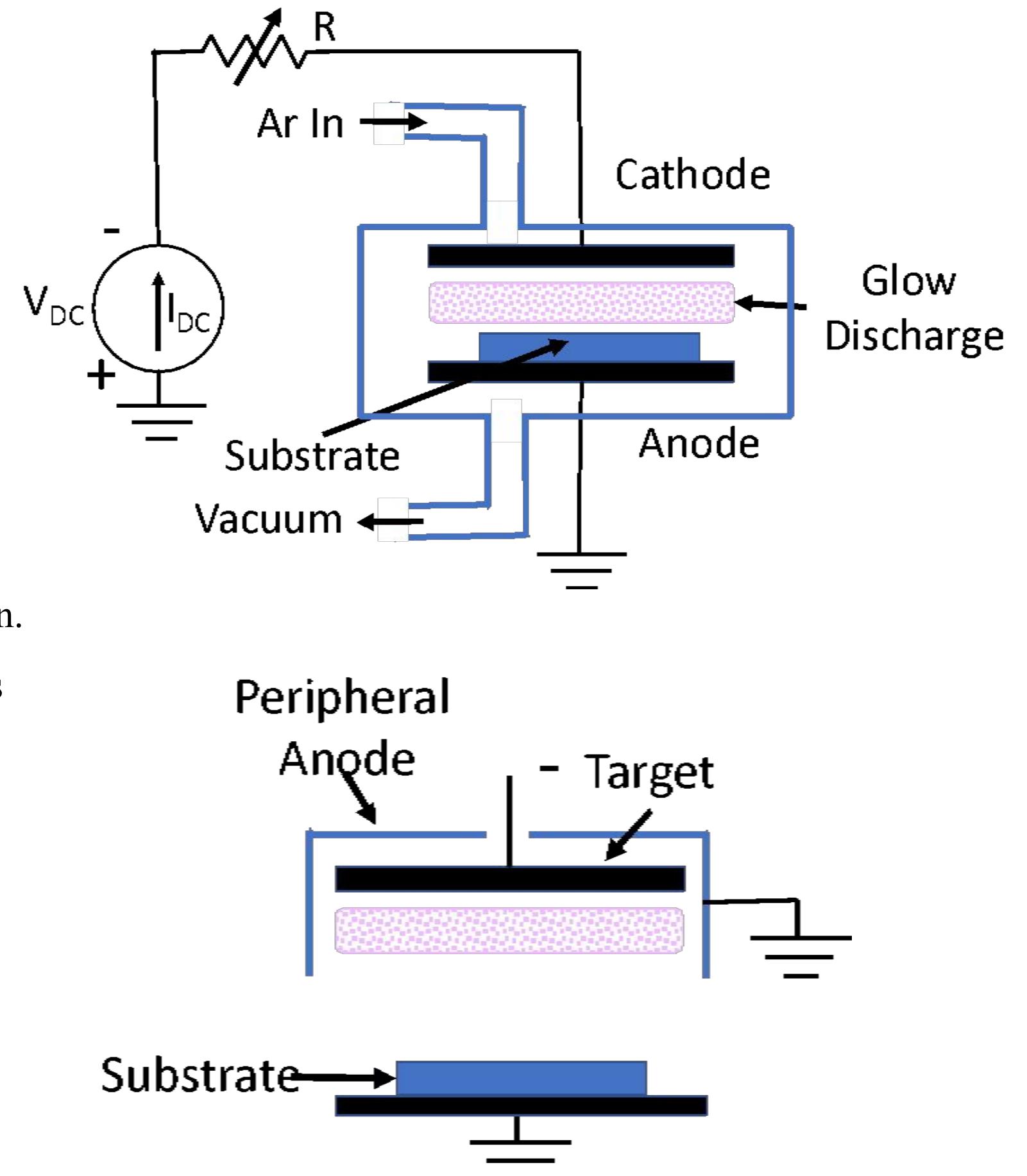
Film	Precursors
Al ₂ O ₃	Al(CH) ₃ , H ₂ O or O ₃
HfO ₂	HfCl ₄ or TEMAH, H ₂ O
ZrO ₂	ZrCl ₄ , H ₂ O

Physical Deposition Systems - DC Sputter Deposition

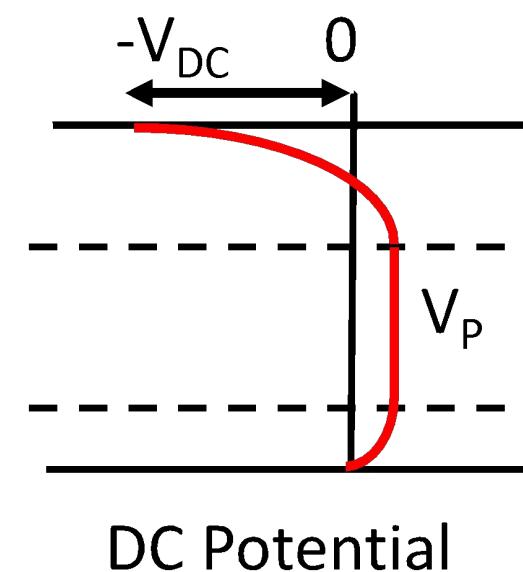
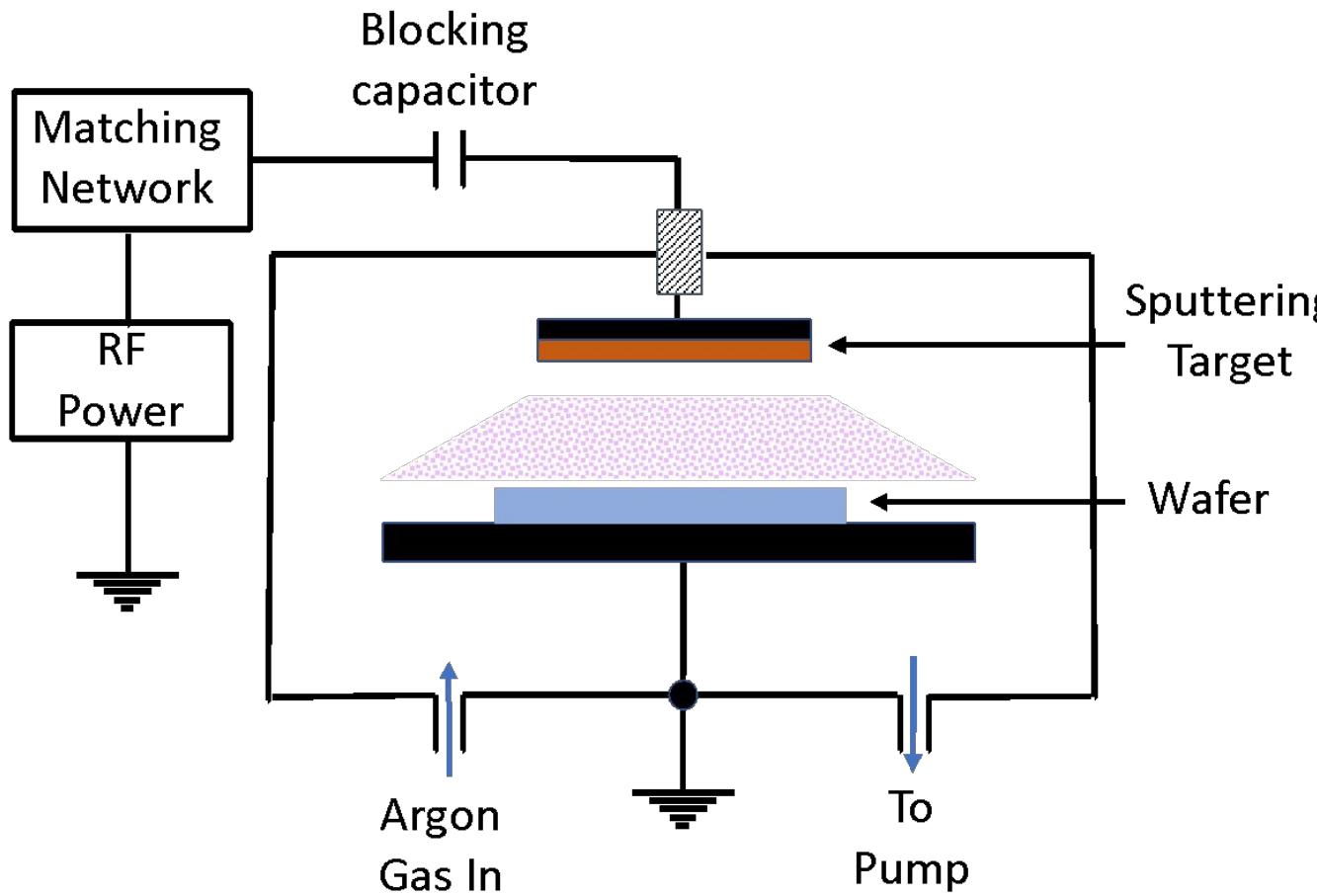
- DC plasma systems were not discussed in Chapter 9.
They have almost no use in etching.
- For sputtering conductive materials this is a simple and effective approach.
- Dc voltage high enough to ionize gas is applied (500 – 1000 volts) depending on geometry.
- Cathode and anode voltage are fixed externally. The plasma takes on a small positive potential.
- DC current must be continuous. Cathode current is largely ions, anode current is largely electrons.
- $J = q\mu n \varepsilon$ Because μ 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, 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. N_2) can be added to the plasma. Ti sputtering TiN (see text).



RF Sputter Deposition



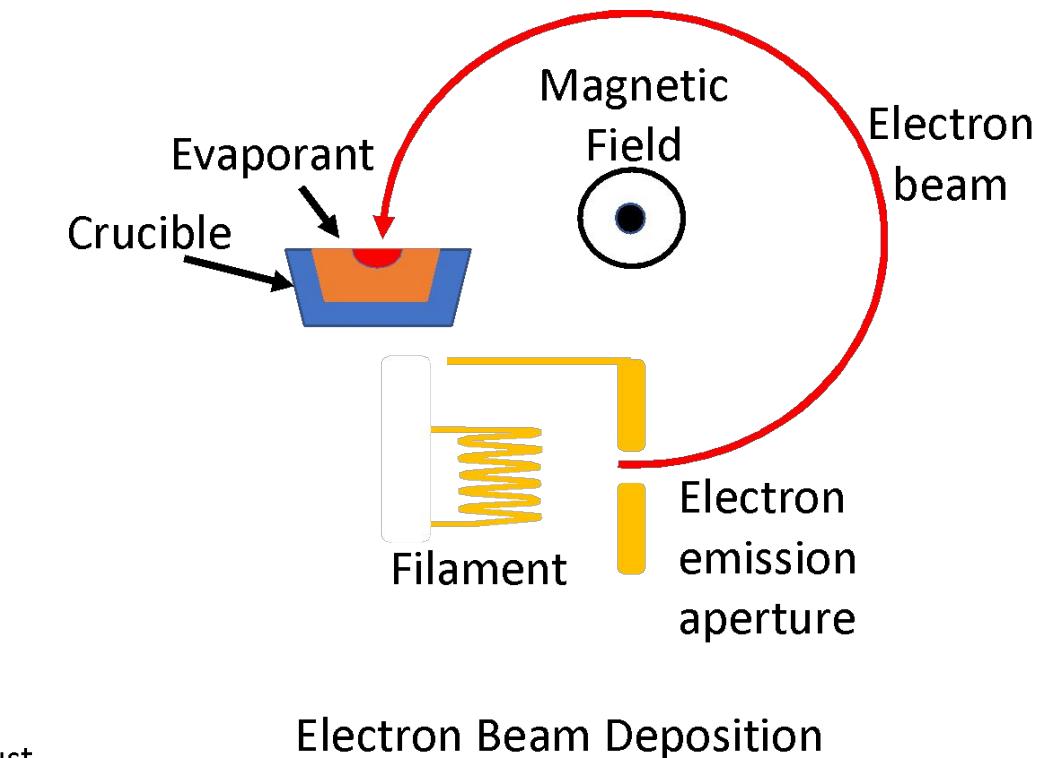
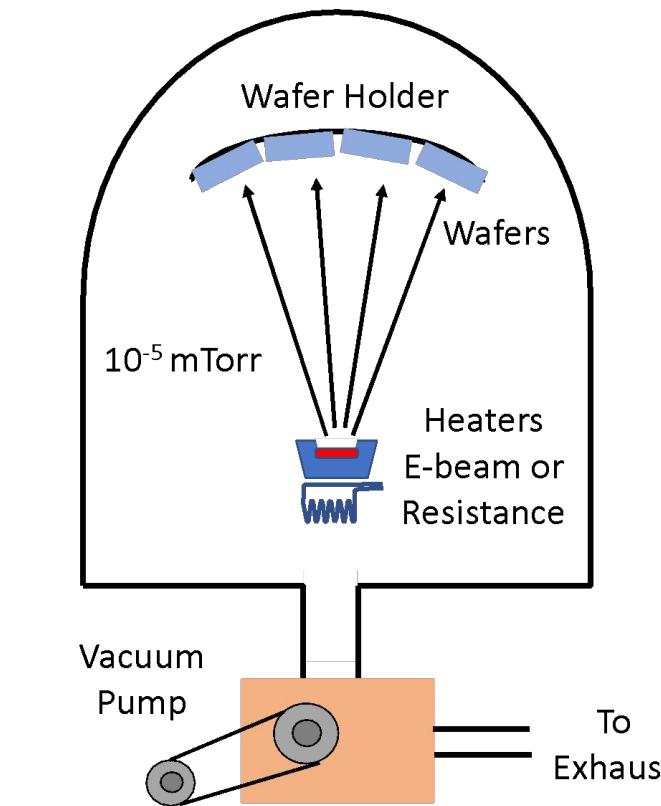
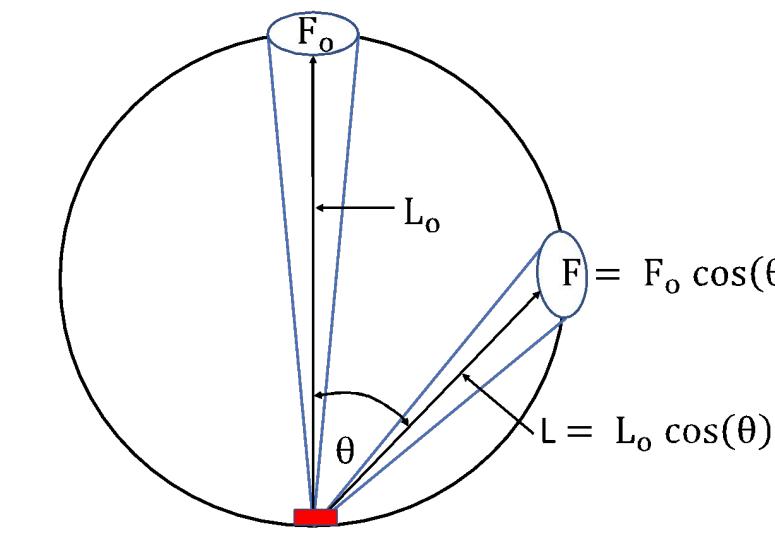
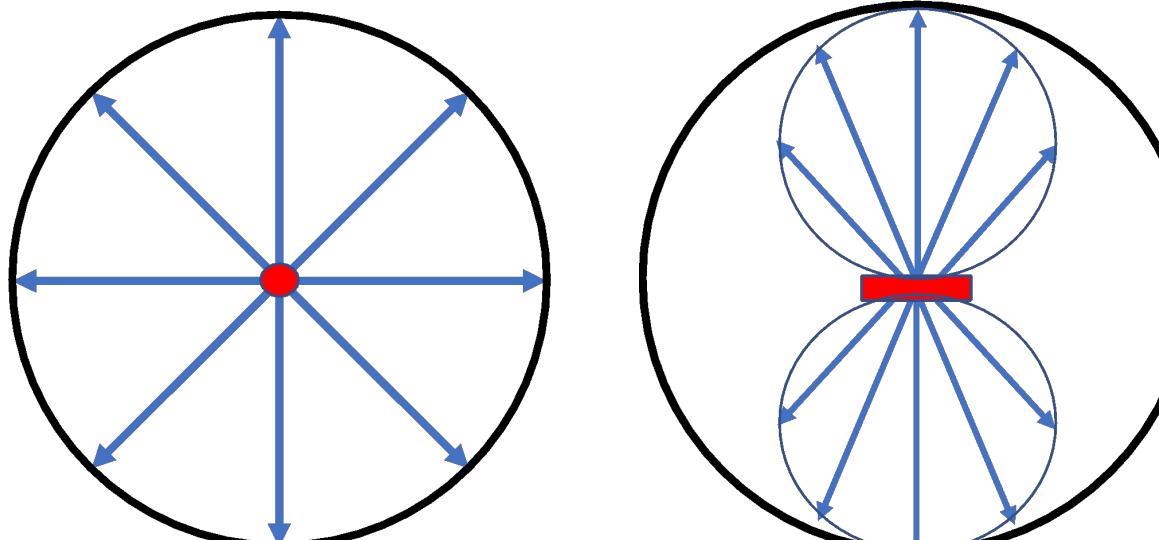
- For DC sputtering, target electrode must be conducting. To sputter dielectric materials use RF power source.
- As we saw in Chapter 9 (Fig. 9.9), if the electrode areas are not equal, the field is higher at the smaller electrode (higher current density), to maintain AC current continuity.
- V_{DC} 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

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

- 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^2 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 (≈ 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.

