Chemical Vapour Deposition: CVD
Reference: Jaeger Chapter 6 & Ruska: Chapter 8

- CVD - Chemical Vapour Deposition
- React chemicals to create a thin film layer at the surface
- Typically gas phase reactions
- Liquid phase reactions used but seldom in Si microfab (most common for III-V semiconductors)

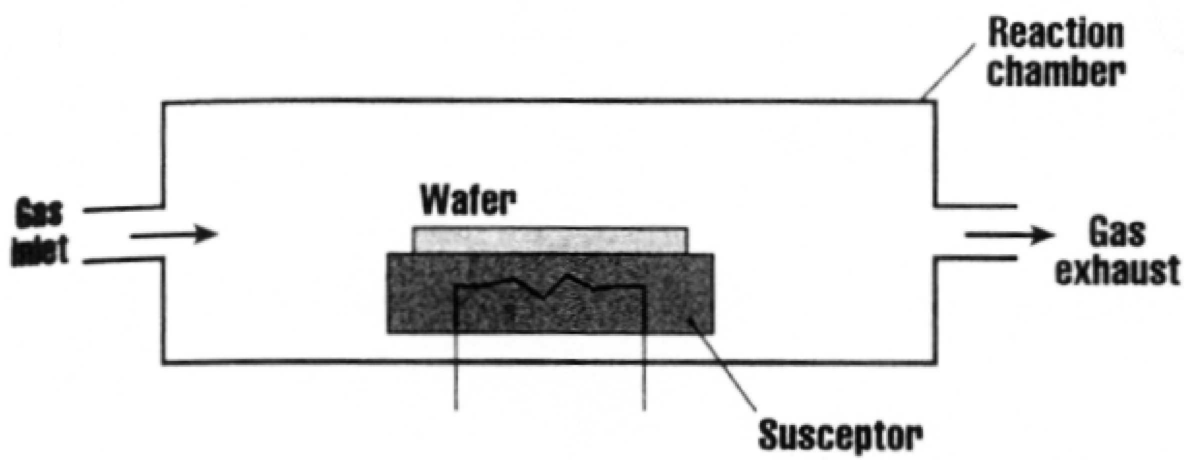
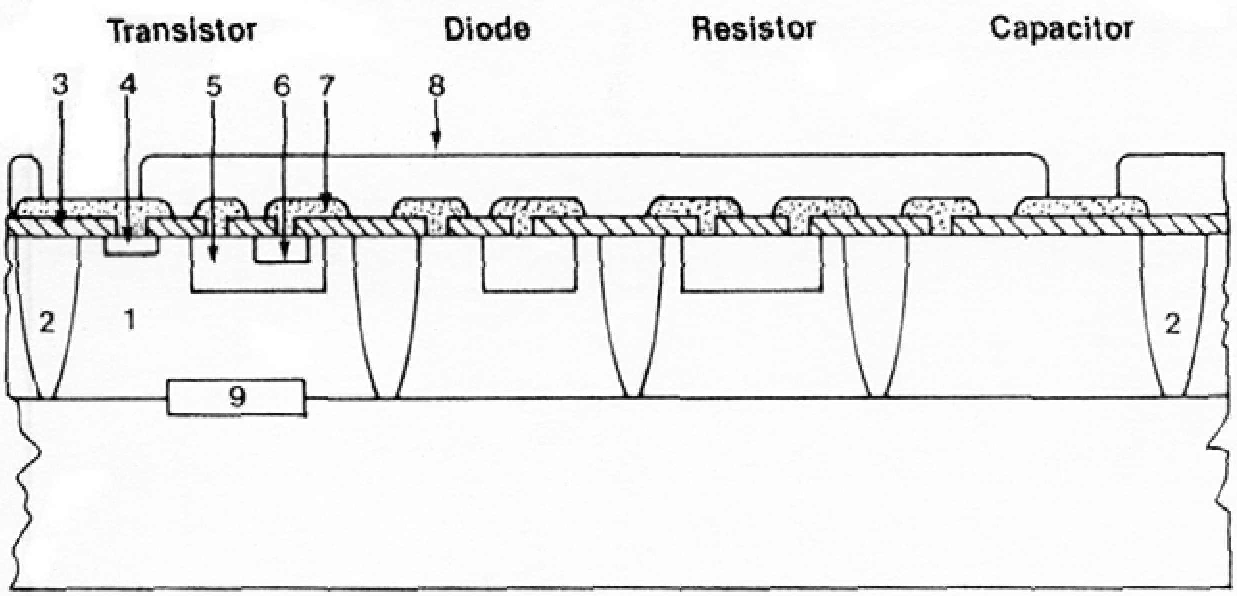


Figure 13-1 A simple prototype thermal CVD reactor.

CVD Applications

- Depositing thin insulating films
  Intermetal glass, Silicon Nitride
- Polysilicon (gates/conductors)
- Epitaxial silicon (single crystal on wafer)
- Silicide materials
- III-V compounds



1. *EPI and Collector*
2. Isolation
3. Surface Oxide
4. *Collector Contact*
5. Base
6. Emitter
7. Metalization
8. Passivation Layer
9. Buried Layer

Figure 12.1 Cross section of bipolar circuit showing epitaxial layer and isolation.

CVD and Evolution of MOS technology

- Initially used metal gates in FETS
- Now double poly processes, double metal as minium
- Poly Si layers form gate and first/second level conductors

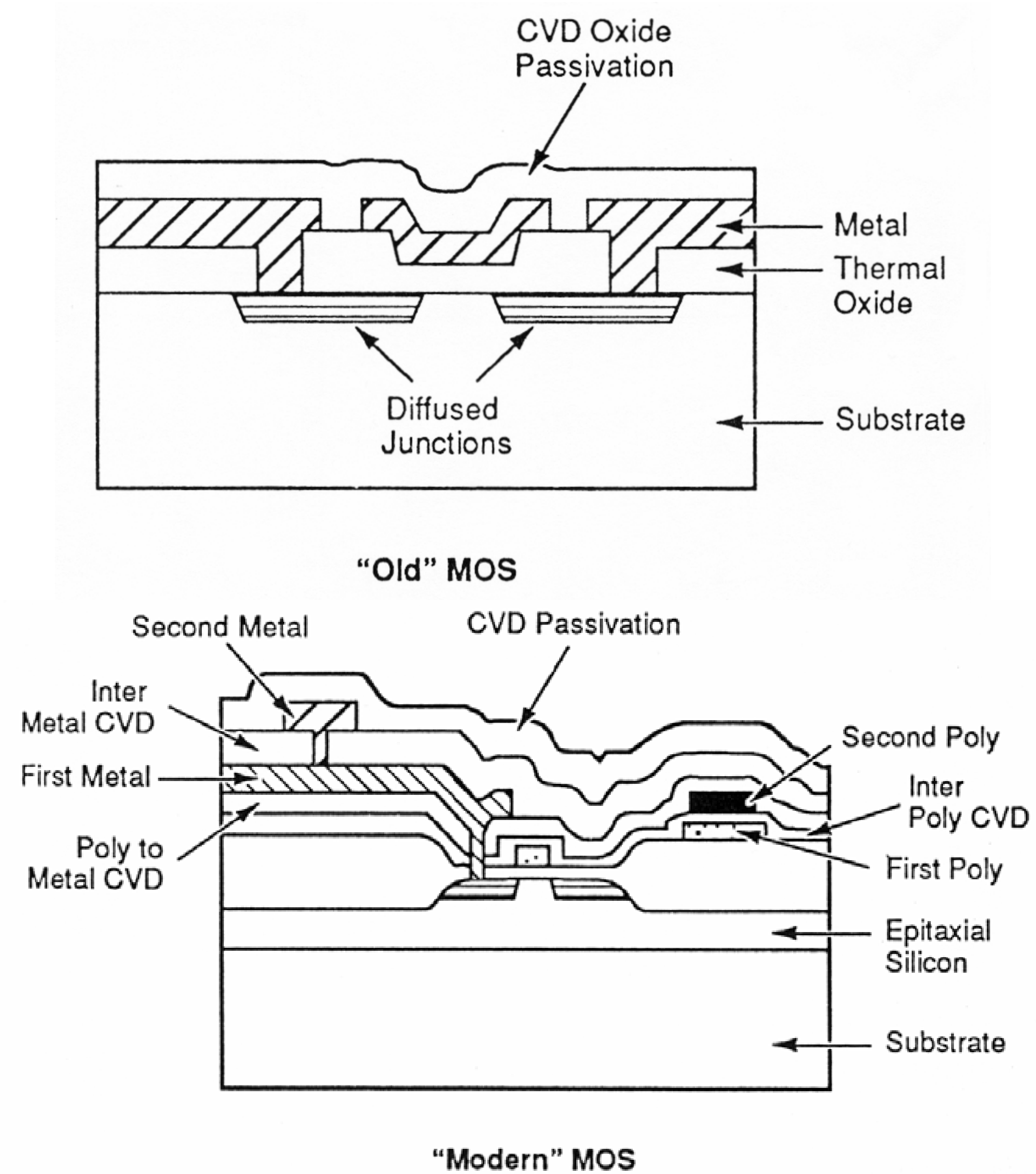


Figure 12.2 Evolution of MOS layers.

Four main CVD Reactions

- Pyrolysis: heat driven break down
- Reduction: usually react with Hydrogen
- Oxidation: react with oxygen to form oxides
- Nitradation: create nitrides with nitrogen compounds

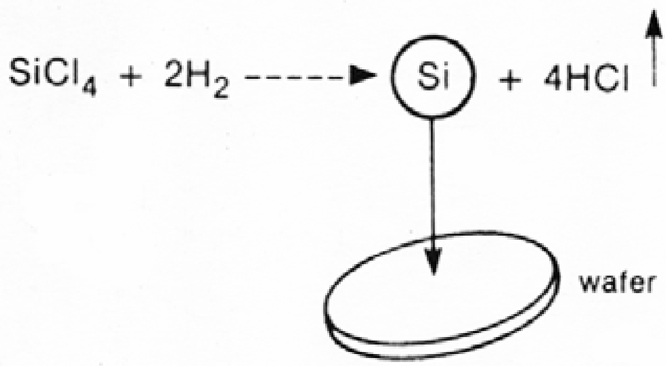


Figure 12.4 Chemical vapor deposition of silicon from silicon tetrachloride.

Pyrolysis	$SiH_4 = Si + 2H_2$
Reduction	$SiCl_4 + 2H_2 = SI + 4HCL$
Oxidation	$SiH_4 + O_2 = SiO_2 + 2H_2$
Nitridation	$3SiH_2Cl_2 + 4NH_3 = Si_3N_4 + pH + 6H_2$

Figure 12.5 Examples of CVD reactions.

Major CVD Processes

- Reactants diffuse to surface
- Film reaction at surface
- Film reformed at surface
- Products Desorbed and diffuse from surface
- Reaction rate may be limited by any of these steps just as in wet etching

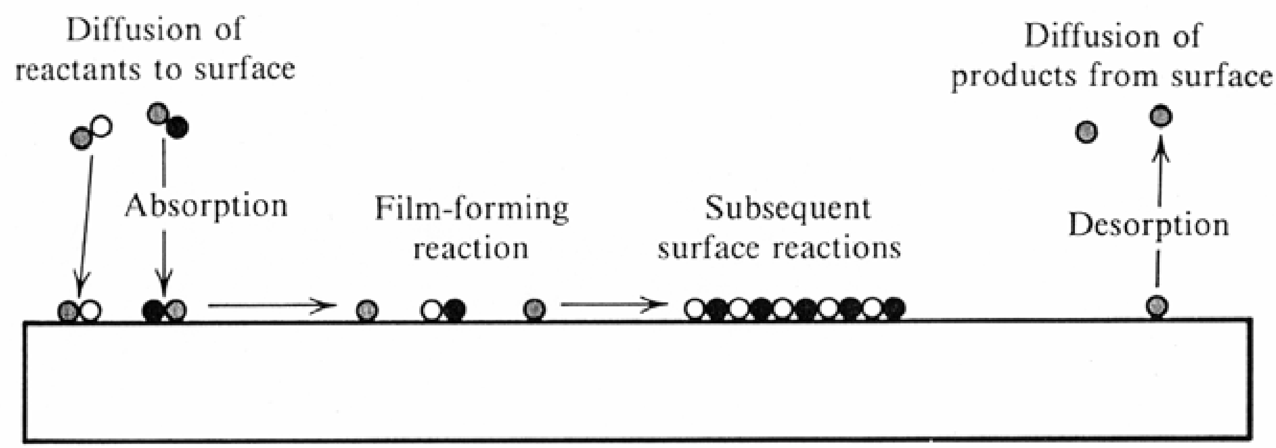


Figure 8-1 The sequence of reaction steps in a CVD reaction.

Fluid Flow

- As gas or liquid process these follow Fluid Flow equations
- Assume "laminar flow" ie smooth flow with no turbulence
- Near surface fluid velocity decreases due to drag of surface
- Force on Fluid:

$$F = \mu \frac{dv}{dz}$$

Where: v = velocity of fluid
z = distance from the surface
μ= viscosity of fluid

- Fluid flow is often measured by Reynolds number

$$\mathrm{Re} = \frac{dv\rho}{\mu}$$

Where: d = length of system (diameter of pipe)
ρ = density of fluid
v = velocity

- Reynolds number for CVD system ~ 100
- When Re >2000 tend to get turbulent flow
- Boundary Layer: slow moving layer near surface
- Thickness δ goes from full fluid velocity point to the surface
- Laminar Boundary thickness varies as distance from flow start

$$\delta = \frac{l}{\sqrt{\mathrm{Re}}}$$

l = distance from the front edge of object flowed around

- Equation varies with object shape

Fluid Flow - Transport of Reactants to Surface

- Transport flux of reactant through the boundary layer

$$j = \frac{D}{\delta}\left(N_g - N_0\right)$$

where D = the diffusion coefficient
N_0 = concentration at top of boundary layer
N_g = concentration at surface

- Gas phase diffusion coefficients D vary less with temperature
- Common formula Hammond's

$$D \propto T^{3/2} \frac{P_s}{P}$$

where T = Temperature (K)
P_s = partial pressure of diffusing species
P = total pressure

- Diffusion of reactant to the surface must be determined

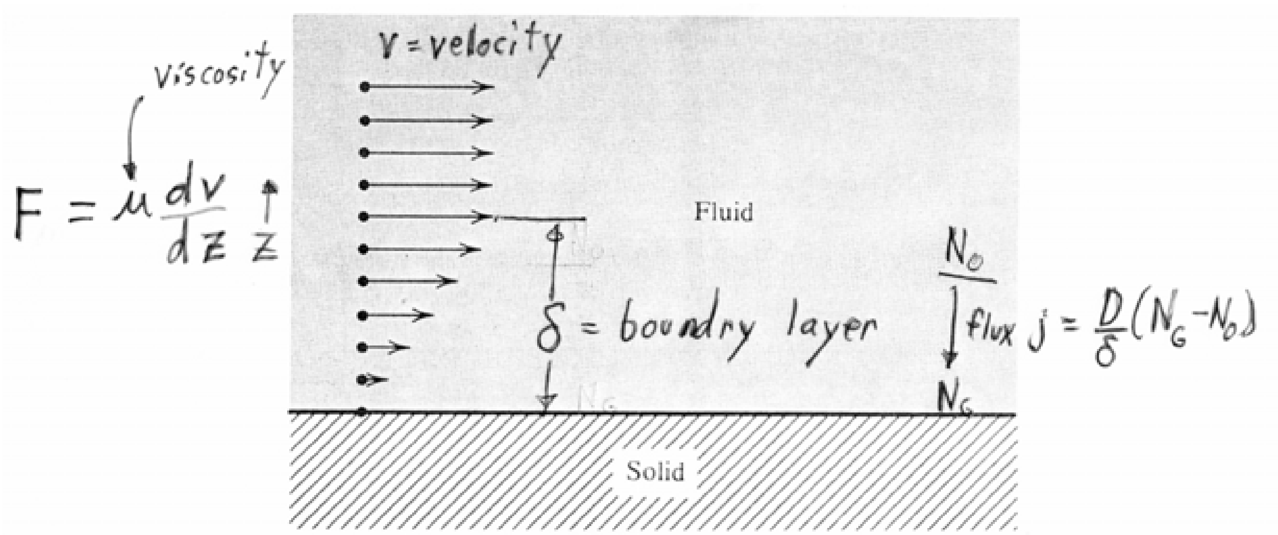


Figure 8-2 Movement of a fluid past a solid surface, illustrating the formation of a boundary layer.

Reaction at Substrate Surface

- Flux at surface controlled by reaction

$$j = k_s N_g$$

where k_s = surface reaction rate

- Reaction rate flows an Arrhenius law

$$k_s = k' \exp\left(\frac{-E_A}{KT}\right)$$

where k' = reaction constant

E_A = Activation energy of the reaction

KT = thermal energy

- Thus the Reaction Flux at the surface

$$j = \frac{D N_g k_s}{D + \delta k_s}$$

Reaction at Substrate Surface

- Thus the reaction rate r:

$$r = \frac{j}{\gamma} = \frac{DN_g k_s}{\gamma\left(D + \delta k_s\right)}$$

where γ = the number of atoms per unite volume of reactant

- At high temperatures: **Mass transport limited**:

$$r \approx \frac{DN_g}{\gamma\delta} \qquad \delta k_s >> D$$

- Surface reaction >> than diffusion
- At low temperatures: **Reaction rate limited**:

$$r \approx \frac{N_g k_s}{\gamma} \qquad D >> \delta k_s$$

- Surface reaction << than diffusion

CVD Film Growth - Reaction Rate Plot

Mass transport limited

- At high temperatures:
- little change with temperature
- Affect by transport effects (eg flow rate)

Reaction Rate Limited

- At low temperatures:
- Changes rapidly with temperature
- at Room Temp: 20% change every 10°C

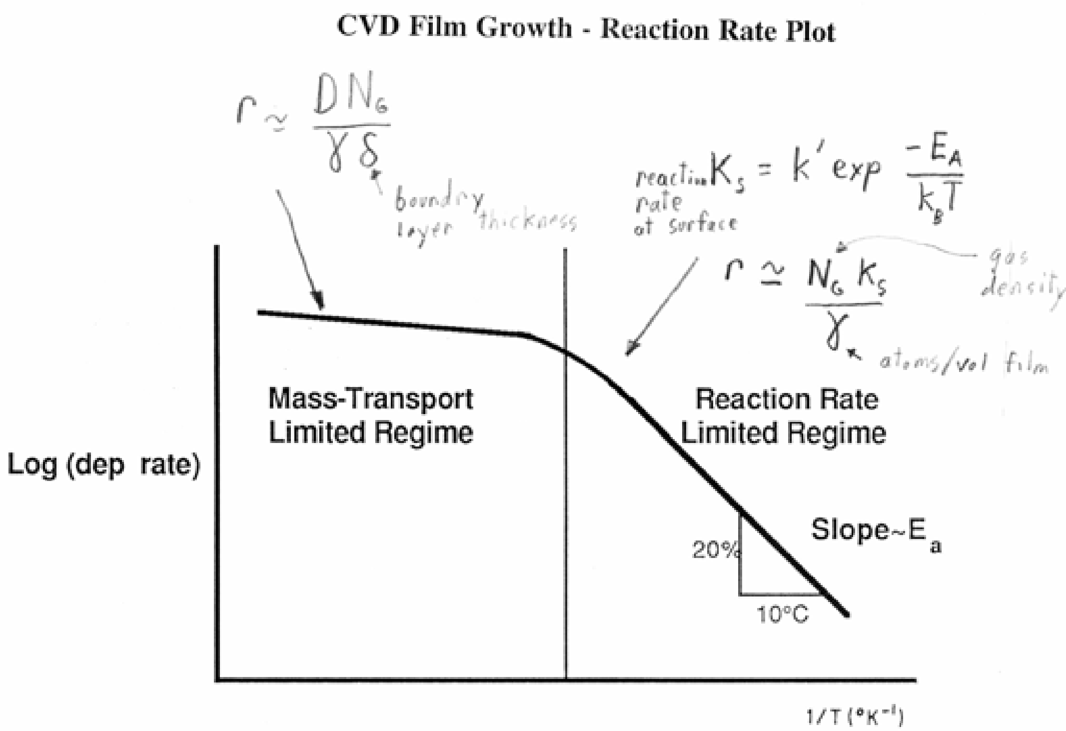


Fig. 1 Temperature dependence of growth rate for CVD films.

CVD Important film parameters

- Stoichiometery: exact composition of film
- Physical parameters: hardness, optical density
- Electrical parameters:
  dielectric constant, breakdown voltage
- Purity of film: lack of contamination
- Thickness and uniformity
- Conformality and step coverage
- Pin hole (very small holes) and particle free
- Adhesion (how well does film stick to surface)

Summary of CVD systems

- Gas Phase: Atmospheric & Low Pressure
- VPE: Vapour Phase Epitaxy (Si single crystal)
- MOCVD: Metal-Organic CVD (metal films)
  used in III-V compounds

Figure 12.2 Evolution of MOS layers.

Atmospheric Pressure	Low Pressure
Cold wall	Hot wall
• Horizontal	Plasma enhanced
• Vertical	Vertical isothermal
• Pancake	
Hot wall	
Photochemical	
VPE	
MOCVD	

Figure 12.3 Overview of CVD systems.

Basic CVD System

- Chemical source (typically gas)
- Flow control for setting film parameters
- Reaction chamber: with energy input

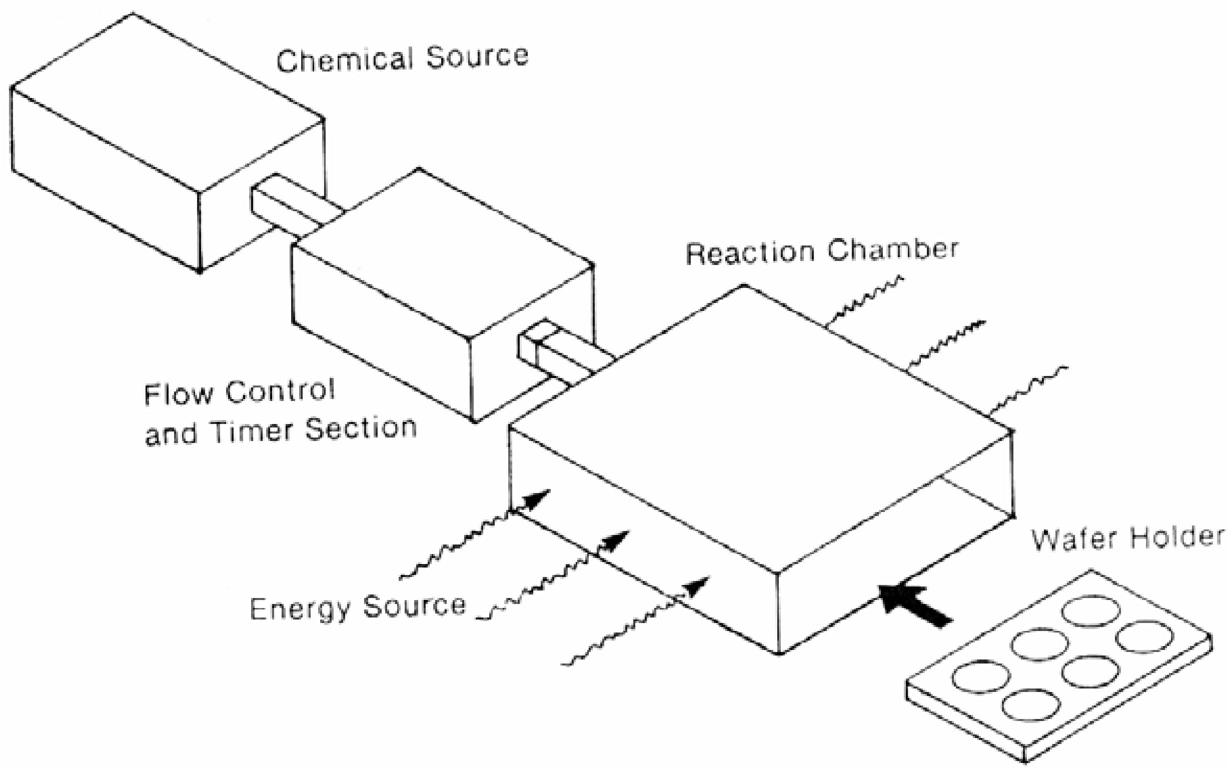


Figure 12.8 Basic CVD subsystems.

Energy sources for CVD Reactions

- Conductive/convective heating
- Inductive RF (Radio Frequency)
- Radiant heat (heater strips or lamps)
- RF plasma
- Light (ultraviolet)

Level	Temperature Range	Methods
High Temp.:	600–1250°C	R.F. Induction (Cold Wall) Radiant Heat (Cold Wall) Resistance Coils (Hot Wall)
Mid Temp.:	200–600°C	Hot Plates Plasma Enhanced LPCVD
Low Range:	22–200°C	Hot Plates P.E. CVD Photochemical

CVD Film Growth appearance

- Deposition starts at nucleation sites
  isolated points on surface
- Film grows around nuclei (grains)
- Crystallites collide, forming film
  grain boundaries
- Grain size set by deposition parameters

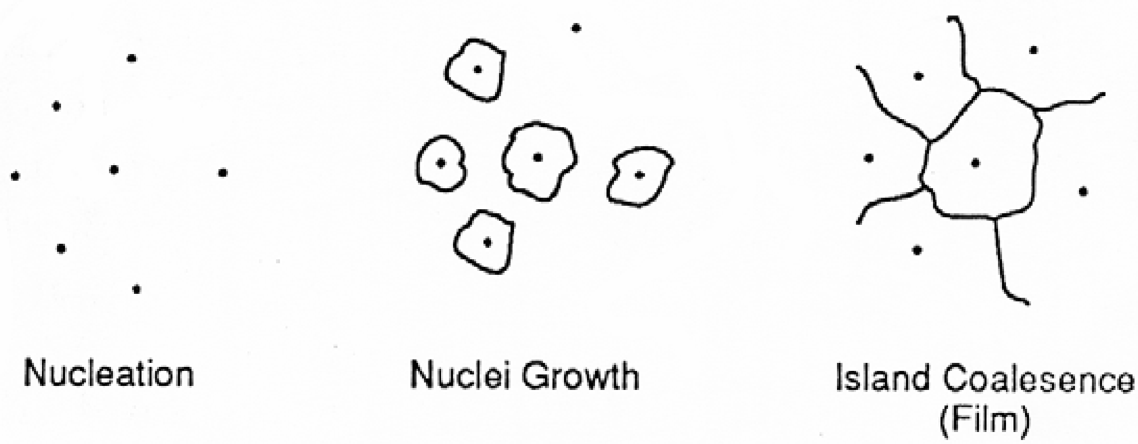


Figure 12.6 CVD film growth steps.

CVD Steps

- Pre clean wafer
- Deposition
- Post deposition evaluation

Two main Gas CVD types

- APCVD: Atmospheric Pressure CVD
- LPCVD: Low Pressure CVD

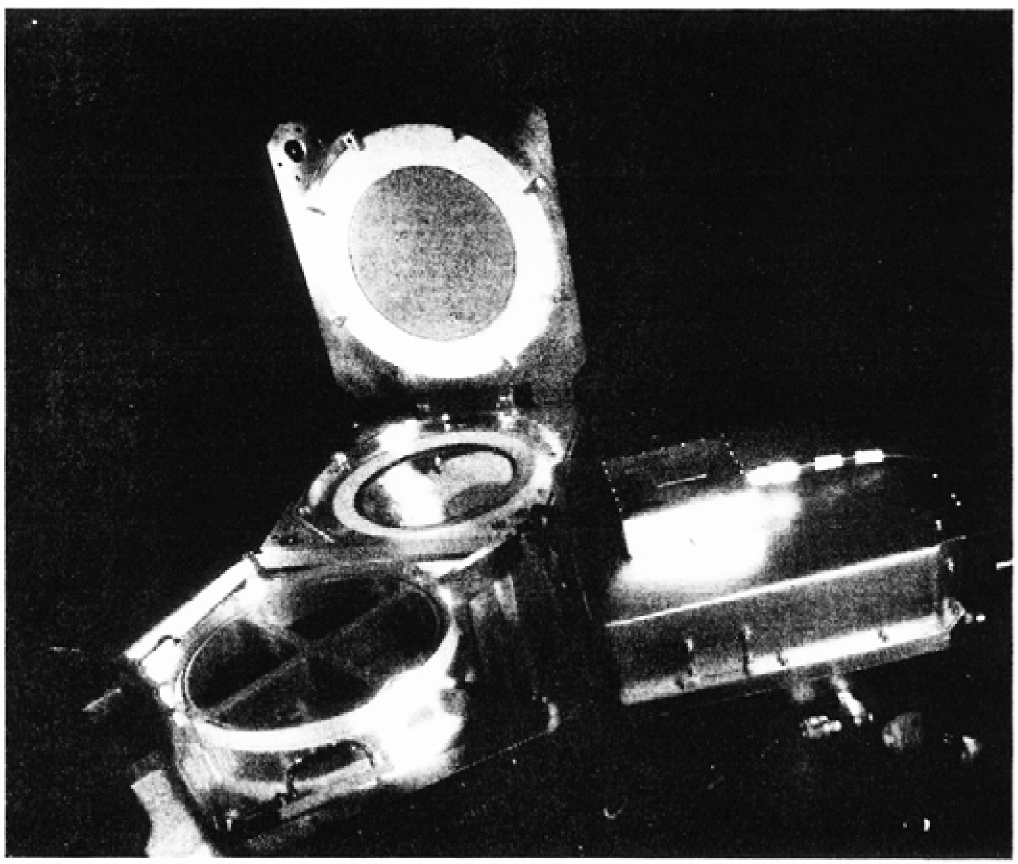


Figure 13-15 A CVD cluster tool showing the central robot and one of the single wafer processing stations *(photo courtesy Applied Materials)*.

CVD Reactor types

- Grouped by pressure: AP & LP
- Then by energy source and chamber
  Hot walls have energy coming from temperature of walls
  Cold wall have other energy sources (eg RF heating)
- Gas distribution method other division

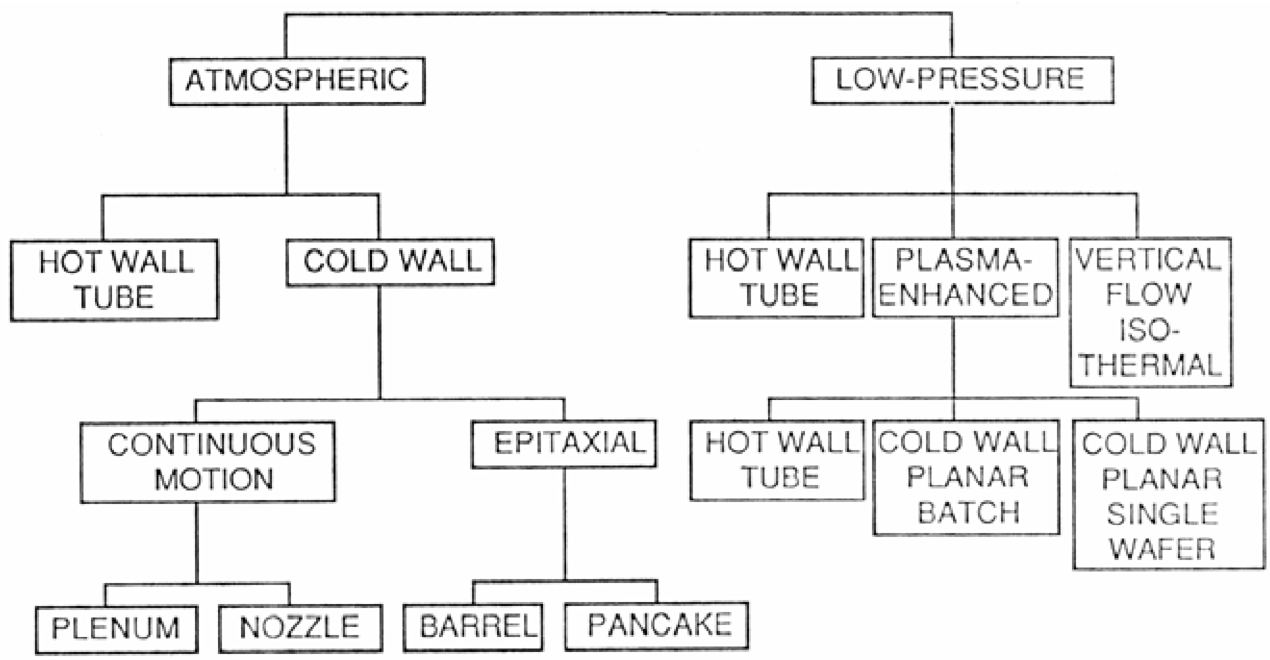


Fig. 4 CVD reactor types.

Typical CVD Gases

- All with important toxic properties

Gas	Formula	Hazard	Flammable limits in air (vol%)	Exposure limit (ppm)
Ammonia	NH_3	toxic, corrosive	16–25	25
Argon	Ar	inert	—	—
Arsine	AsH_3	toxic	—	0.05
Diborane	B_2H_6	toxic, flammable	1–98	0.1
Dichlorosilane	SiH_2Cl_2	flammable, toxic	4–99	5
Hydrogen	H_2	flammable	4–74	—
Hydrogen chloride	HCl	corrosive, toxic	—	5
Nitrogen	N_2	inert	—	—
Nitrogen oxide	N_2O	oxidizer	—	—
Oxygen	O_2	oxidizer	—	—
Phosphine	PH_3	toxic, flammable	pyrophoric	0.3
Silane	SiH_4	flammable, toxic	pyrophoric	0.5

Cold Wall CVD

- Induction (RF) heating of graphite plate

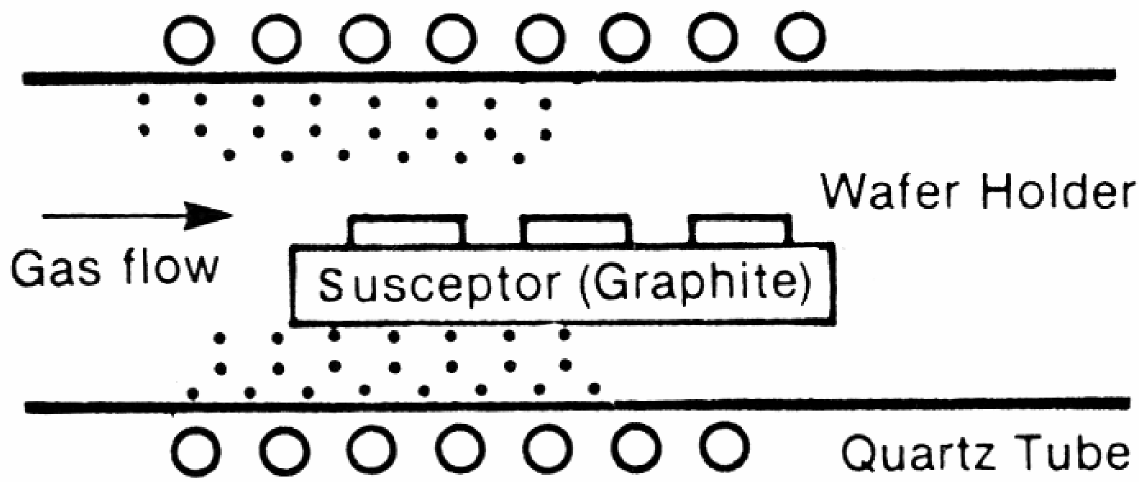


Figure 12.9 Cold-wall induction APCVD with horizontal susceptor.

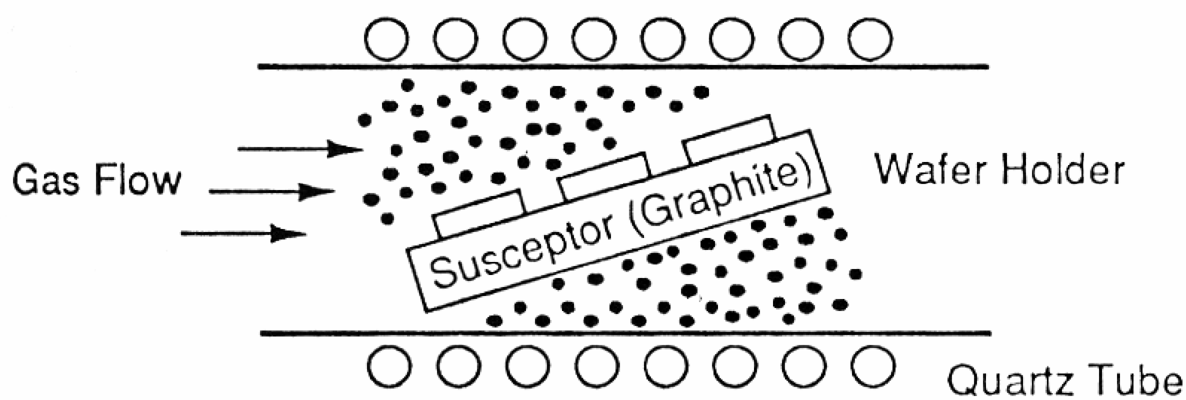


Figure 12.10 Cold-wall induction APCVD with tilted susceptor.

Cylindrical/Barrel CVD Reactor

- Used in large systems
- Wafers mounted on rotating graphite holder
- Heaters on outside

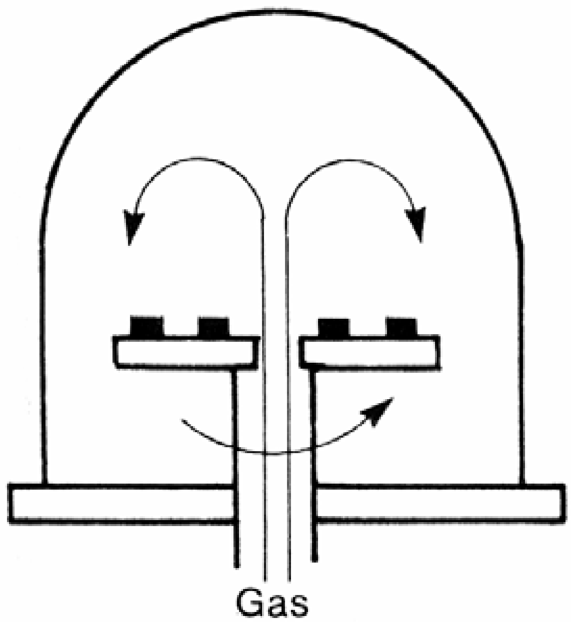
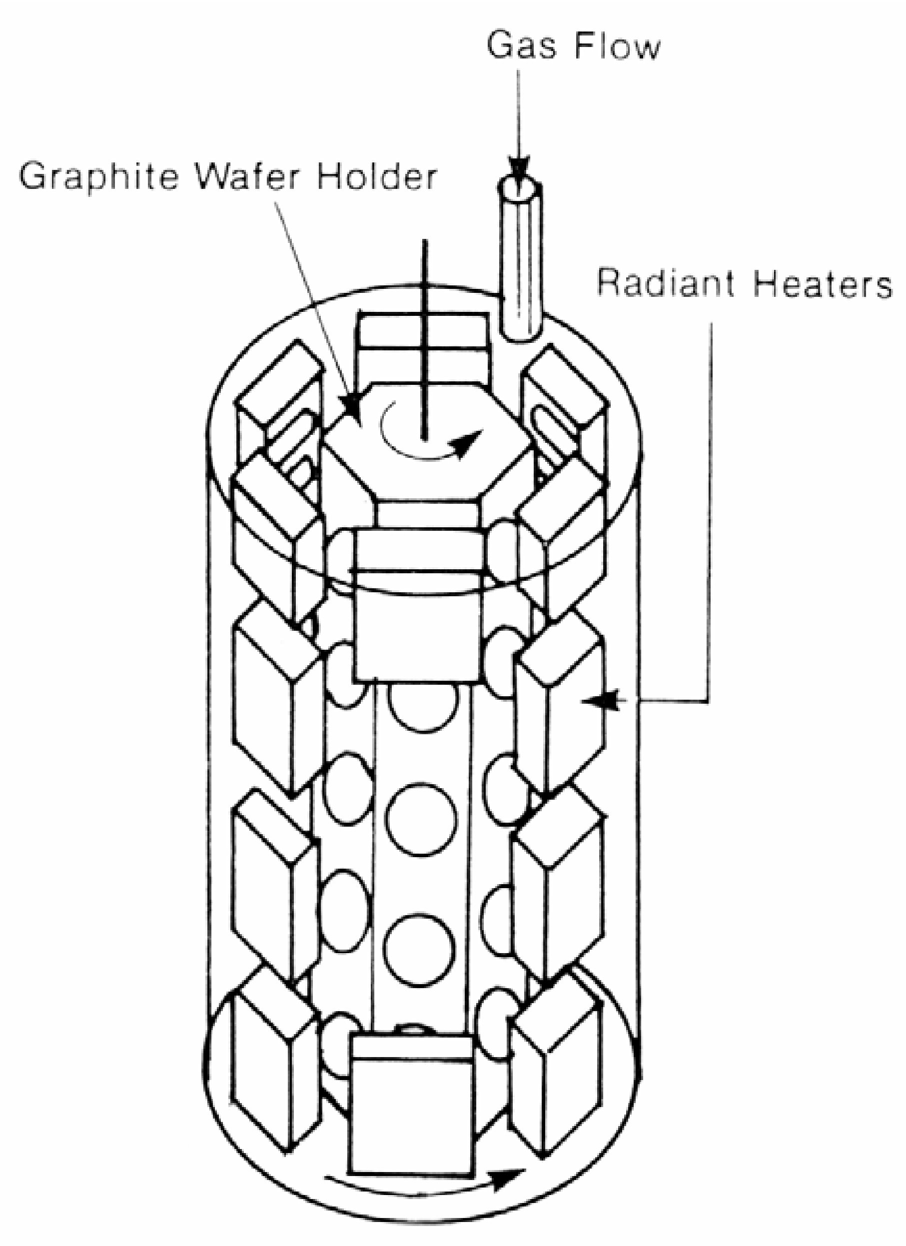


Figure 12.12 Rotating pancake APCVD.

Pancake Air Pressure CVD

- Gas distributed through centre
- palten rotates



Horizontal Flat Plate CVD

- Plates flat with heaters inside
- Gas flows over plates
- Or Gas distributed with "shower head"

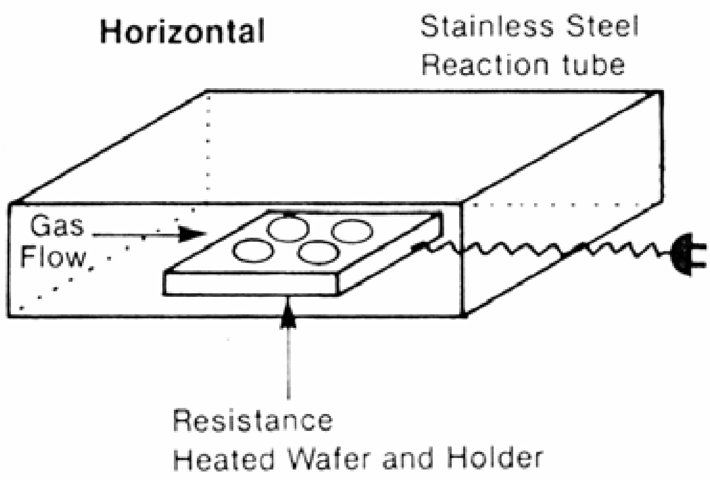


Figure 12.13 Hot-plate APCVD.

Moving Hot Plate Air Pressure CVD

- Move plate for uniform films
- Flat plate moved under shower head
- Continuous belt moved under gas plenum

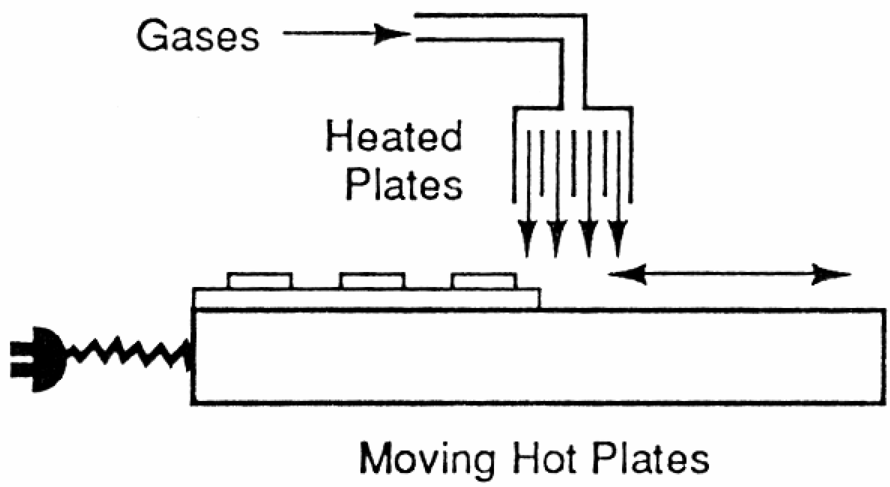


Figure 12.14 Moving hot-plate APCVD with shuttle.

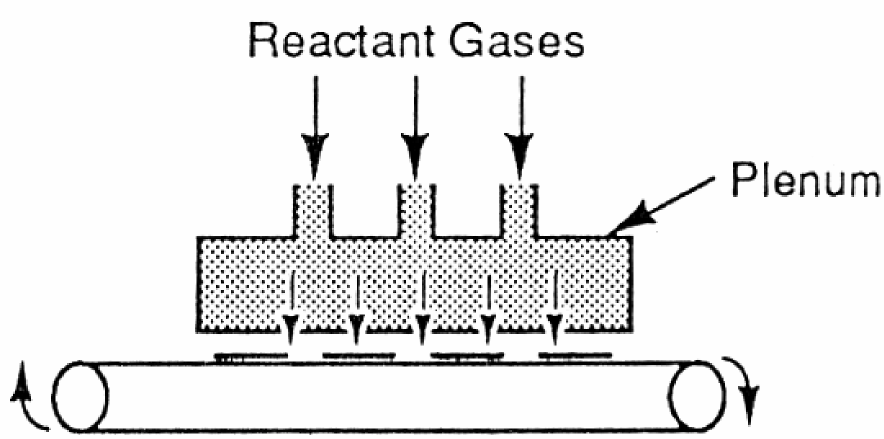


Figure 12.15 Continuous hot-plate APCVD.

Furnace or Horizontal Tube Low Pressure CVD

- Usually done in furnace tube
- Use furnace for temperature
- Must burn and exhaust gases

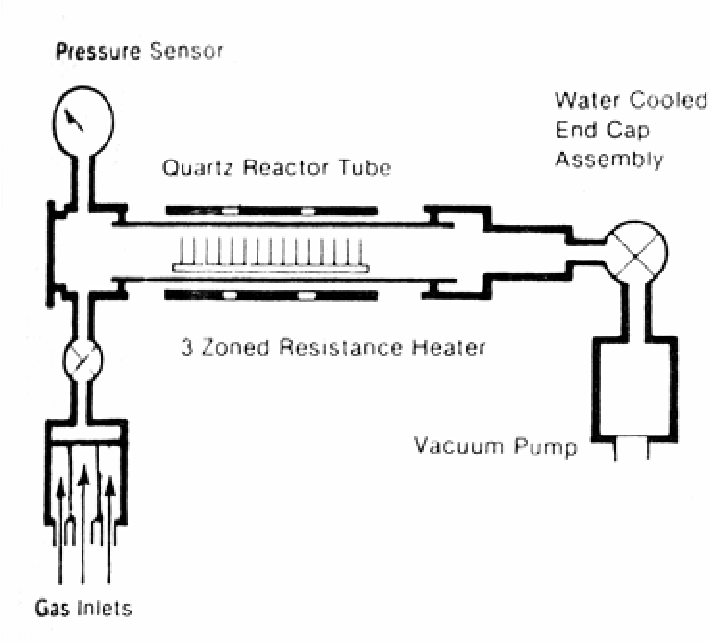


Figure 12.16 Horizontal hot-wall LPCVD system.

Vertical Isothermal CVD

- Use top/bottom heaters for uniformity
- Typically Bell Jar system

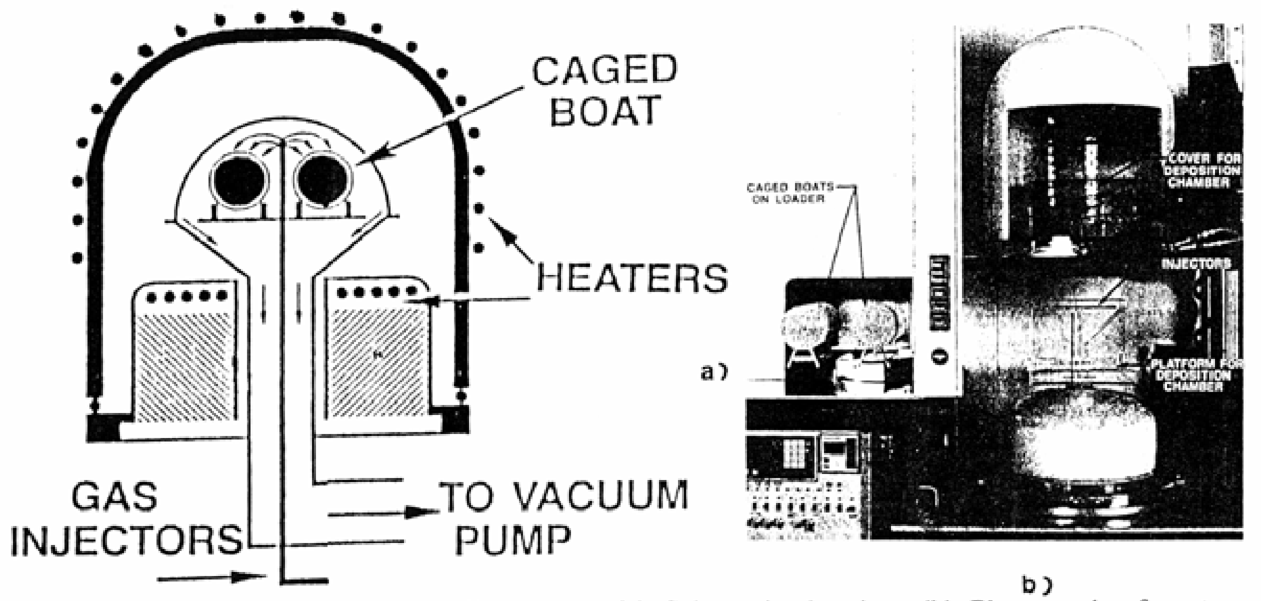


Fig. 7 Vertical isothermal LPCVD reactor. (a) Schematic drawing. (b) Photograph of system. Courtesy of Anicon, Inc.

Large Diameter wafers & Single chamber CVD

- for 150-300 mm wafers go to single chamber
- More control on each wafers

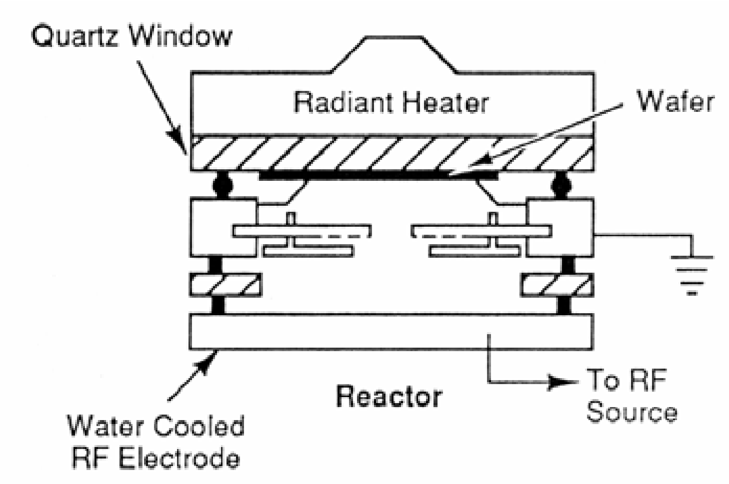


Figure 12.19 Single-chamber planar PECVD.

Plasma Enhanced CVD

- Use RF generated plasma
- Plasma breaks down reactants
- Done at low pressure for plasma (few torr)
- Typical: Vertical Flow pancake (table top) PECVD

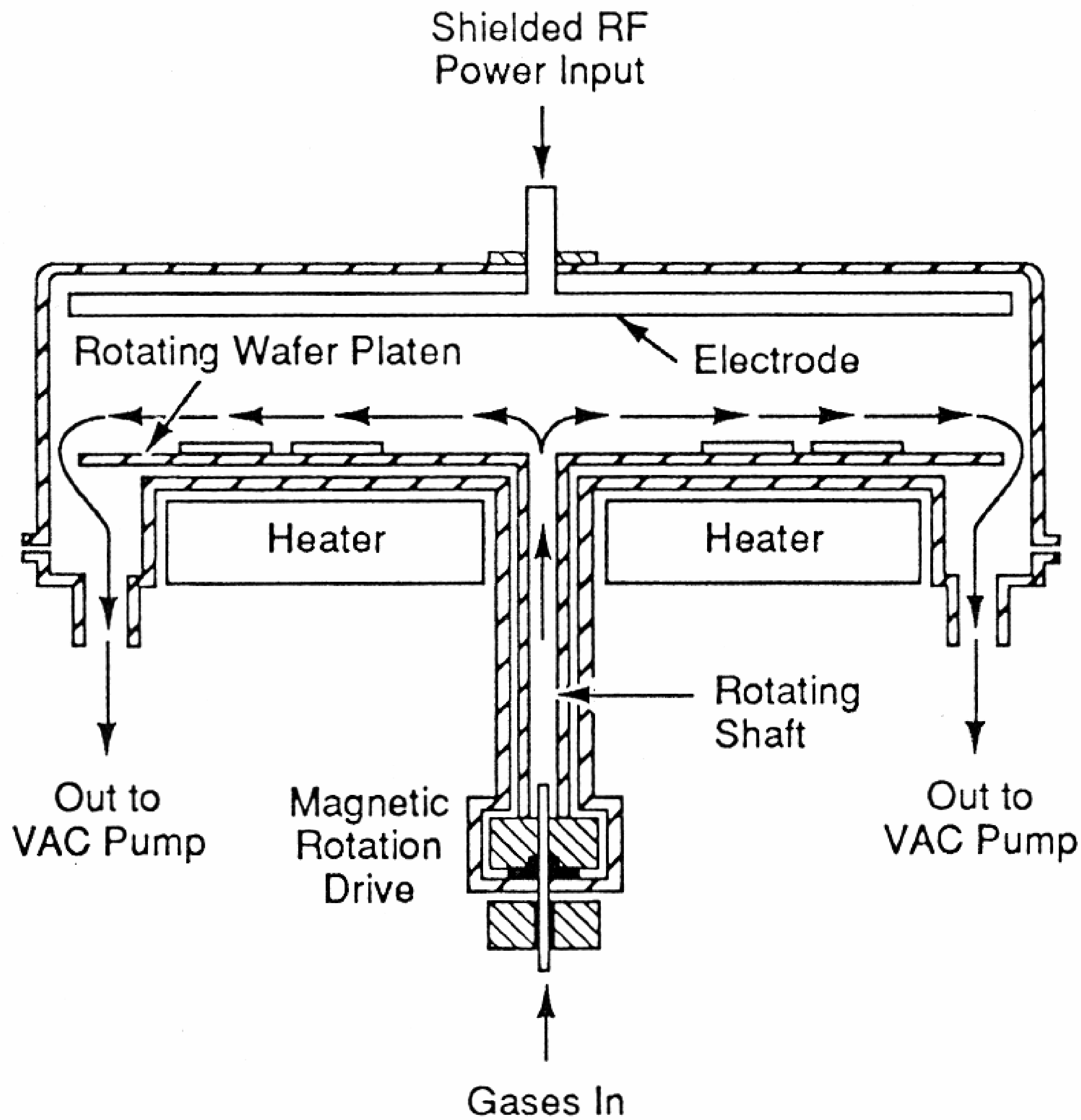


Figure 12.18 Vertical-flow pancake PECVD.

Furnace Tube PECVD

- Use graphite substrate as electrodes
- Wafers between RF antenna
- Use furnace as heater assistance

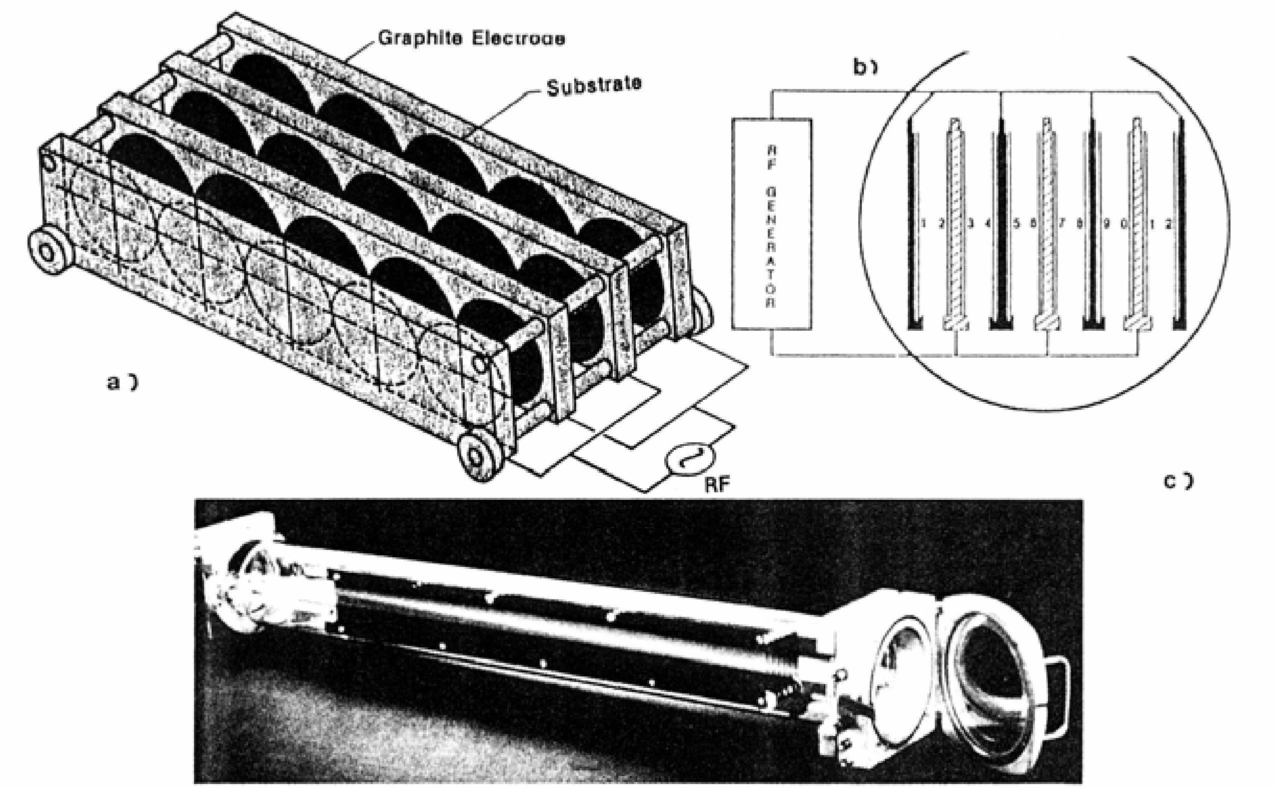


Fig. 9 (a) Long, multiple plate reactor generates plasma between the wafers facing each other on graphite electrodes[14]. (b) Cross section of electrode assembly and wafers shown in (a). Reprinted with permission of Solid State Technology, published by Technical Publishing, a company of Dun & Bradstreet. (c) Photograph of tubular PECVD reactor. Courtesy of Pacific Western Systems.

Typical Furnace PECVD system

- Temperature sets crystal size

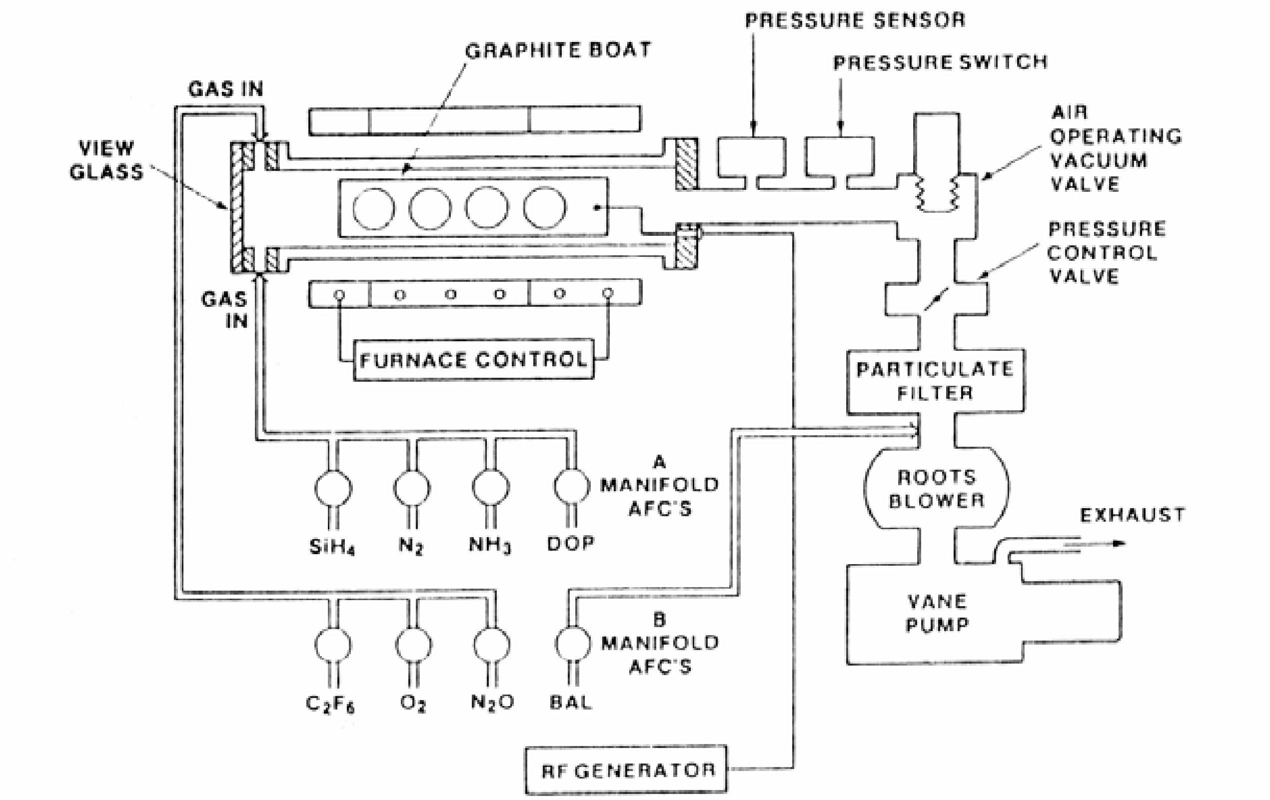


Fig. 2 Diagram of a typical commercial PECVD system. Courtesy of Pacific Western Systems.

Mass Flow Controller

- Want to control mass of material
- Feed back system needed: heats gas, measures temp. change
- Get mass flowing form gas heat capacity

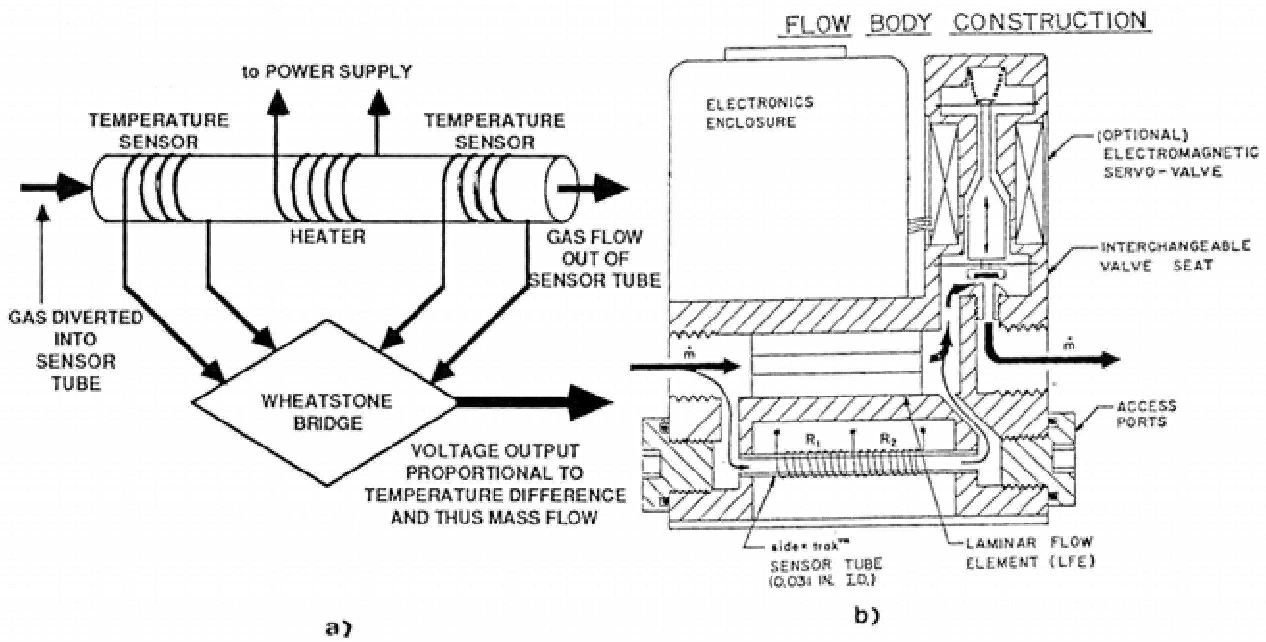


Fig. 3 (a) Operating principle, and (b) cutaway drawing of a mass flow controller. Courtesy of Sierra Instruments.

III-V compound hot CVD

- Use gallium source down stream of substrate
- Flow $AsCl_3$ over Gallium
- Deposit out GaAs

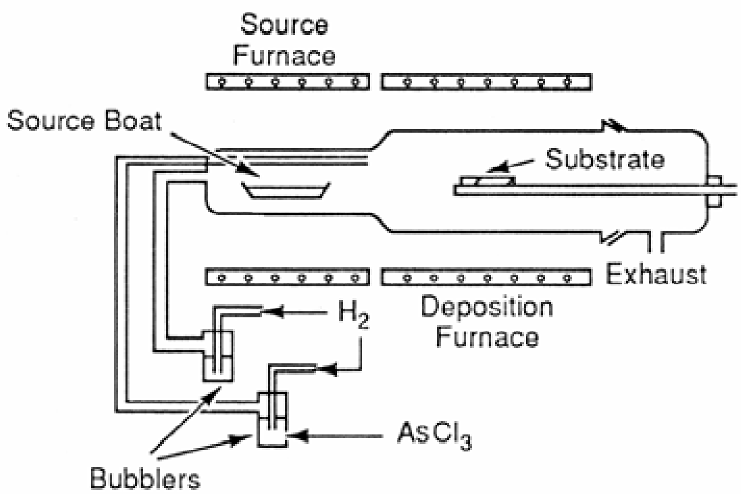


Figure 12.34 Diagram of gallium arsenide VPE deposition system.