Micro Electro Mechanical Systems for mechanical engineering applications

Lecture 4:

MEMS fabrication II: surface micromachining (1)

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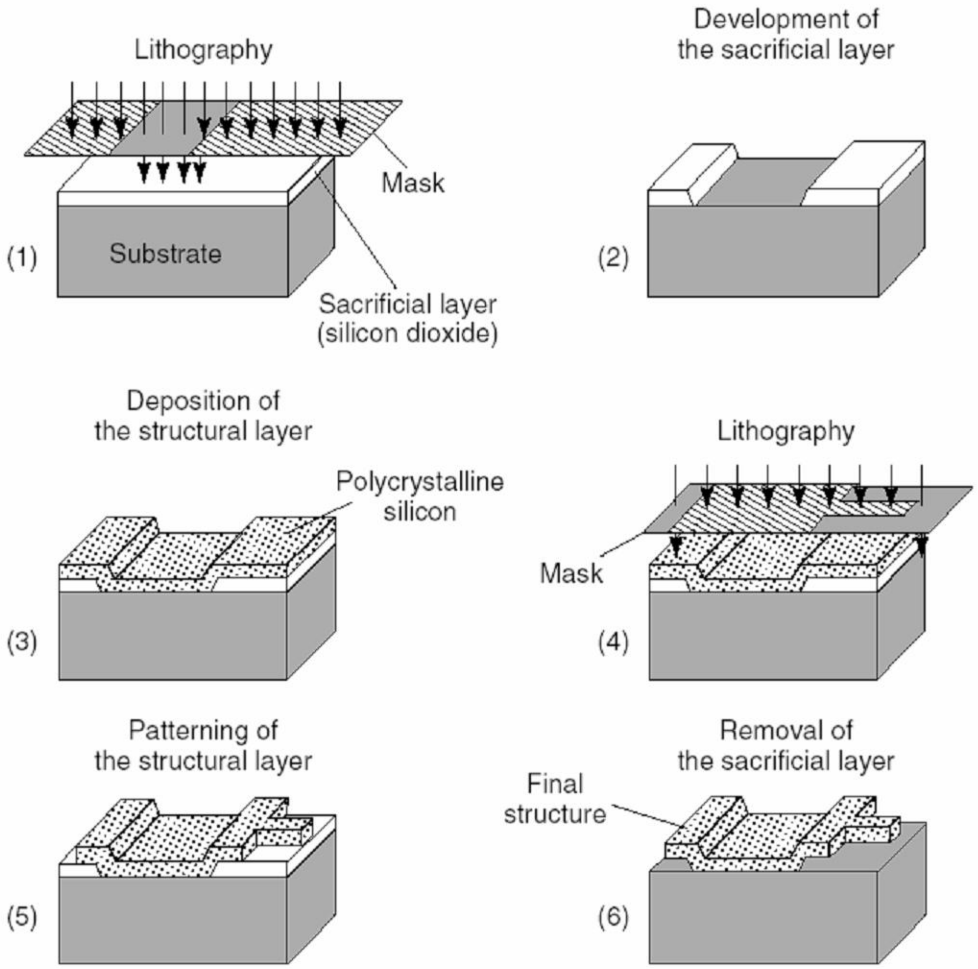
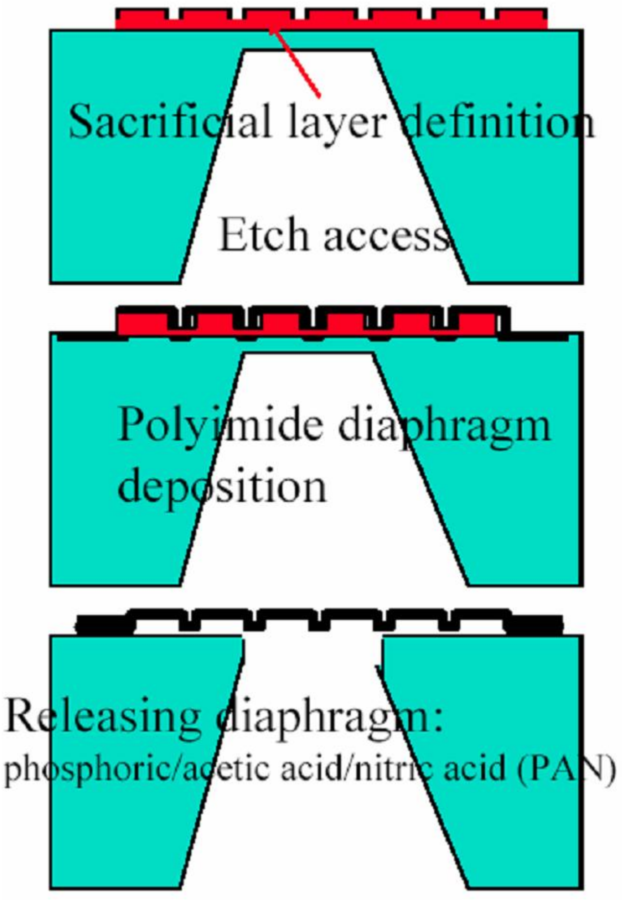
Bulk vs. Surface Micromachining

- Typical surface micromachining



- Bulk + surface



Surface Micromachining (1)

- What is surface micromachining ?
  - Surface micromachining is characterized by the fabrication of micromechanical structures from deposited thin films
  - Originally employed for integrated circuits
  - Used films: low-pressure chemical-vapor-deposition polycrystalline silicon, silicon nitride, silicon dioxide

- In the surface micromachining
  - Dry etching defines the surface features in the x, y plane, and wet etching released them from the plane by under cutting
  - Shapes in x, y plane are unrestricted by the crystallography of the substrate

Surface Micromachining (2)

- *Key parameters for thin-films in micromachining applications.*

(1) Deposition temperature (trying not to destroy underlying materials/devices).

(2) Intrinsic stress/strain (and gradients) of the film can wrap microstructures.

(3) Step coverage.

(4) Resistance to micromachining etchants.

(5) Resistance to ion penetration(defects will cause breakdown or failure during etching).

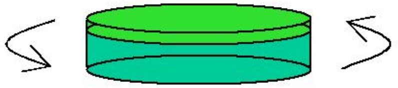
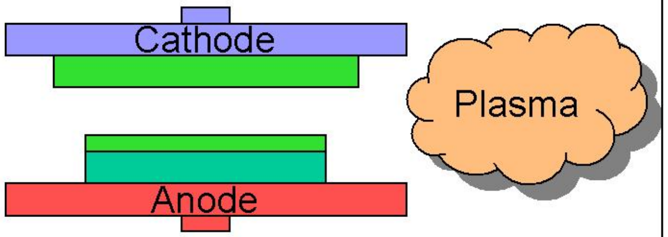
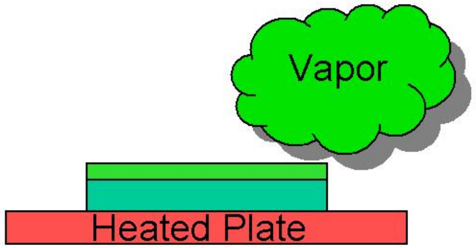
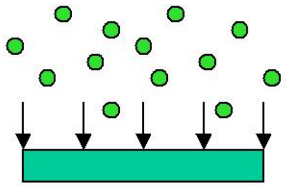
Thin Film Deposition (1)

- **Deposition**
  - The transformation of vapors into solids, frequently used to grow solid thin film and powder materials

- **Physical Vapor Deposition (PVD)**
  - Direct impingement of particles on the hot substrate surface
  - Electron-beam Evaporation, Sputtering

- **Chemical Vapor Deposition (CVD)**
  - Convective heat and mass transfer as well as diffusion with chemical reactions at the substrate surfaces
  - More complex process than PVD
  - More effective in terms of the rate of growth and the quality of deposition
  - LP/AP CVD, Thermal/PE/Ph/La CVD

Thin Film Deposition (2)

Type	Materials	Physics
Spin-on	Organic	
Sputtering	Metals	
Chemical Vapor Deposition	Silicon Compounds	
Doping	Conductors	

Considerations

Thickness

Time

Uniformity

Cost

Damage

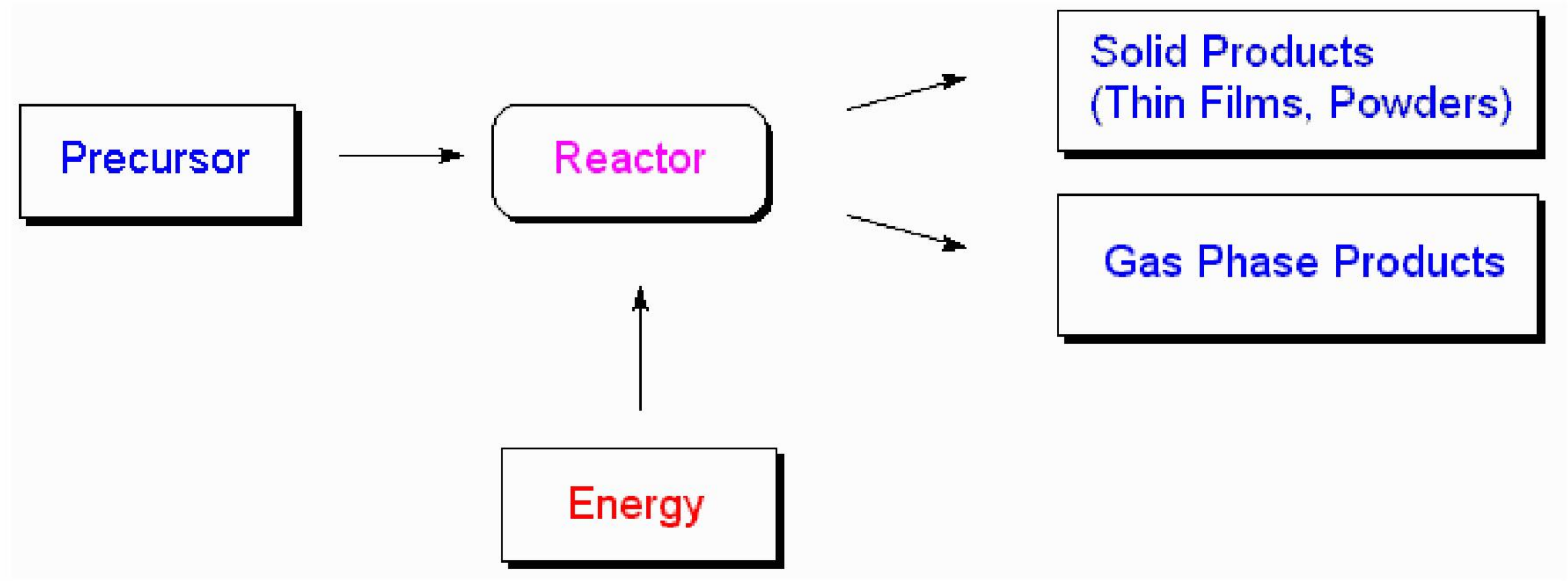
Contamination

Adhesion

Material Choice

Chemical Vapor Deposition (1)

- **What is Chemical Vapor Deposition?**
  - **Chemical reactions which transform gaseous molecules, called precursor, into a solid material, in the form of thin film or powder, on the surface of a substrate**



Chemical Vapor Deposition (2)

- **Types of CVD reaction**
  - Pyrolysis
    SiH_4 -> Si + $2H_2$ (600 ~ 1100 ˚C)
  - Reduction
    $WF_6 + 3H_2$ -> W + 6HF (300 ˚C)
  - Oxidation
    $SiH_4 + O_2$ -> $SiO_2 + 2H_2$ (400 ˚C)
  - Nitridation
    $3SiH_4 + 4NH_3$ -> $Si3N_4 + 12H_2$ (700 ~ 800˚C)
  - Carburization
    $2SiH_4 + C_2H_4$ -> $2SiC + 6H_2$
  - Synthesis Reaction
    (CH)3Ga + AsH_3 -> GaAs + $3CH_4$ (700 ˚C)

Chemical Vapor Deposition (3)

- **Types of CVD**
  - Reactor Temperature
    - Hot wall CVD
    - Cold wall CVD

  - Reactor Pressure
    - Atmospheric Pressure CVD (APCVD)
    - Low Pressure CVD (LPCVD)

  - Enhanced Energy
    - Thermal CVD
    - Plasma Enhanced CVD
    - Photo-assisted CVD
    - Laser-assisted CVD

Chemical Vapor Deposition (4)

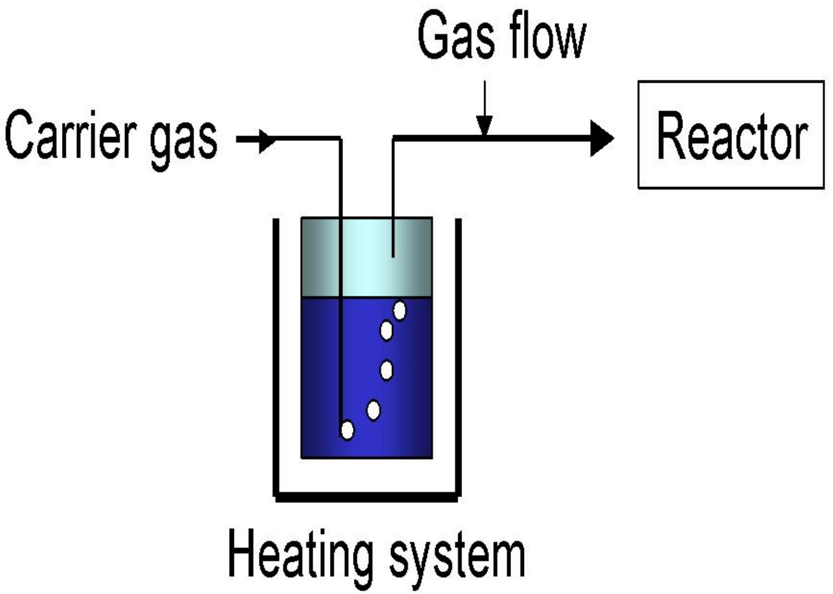
- **Types of CVD (Cont'd)**
  - Reaction Temperature
    - High temperature CVD
    - Low temperature CVD

  - Precursor
    - Conventional CVD: non-organic gas source
    - Metal Organic CVD (MOCVD): organometallic source

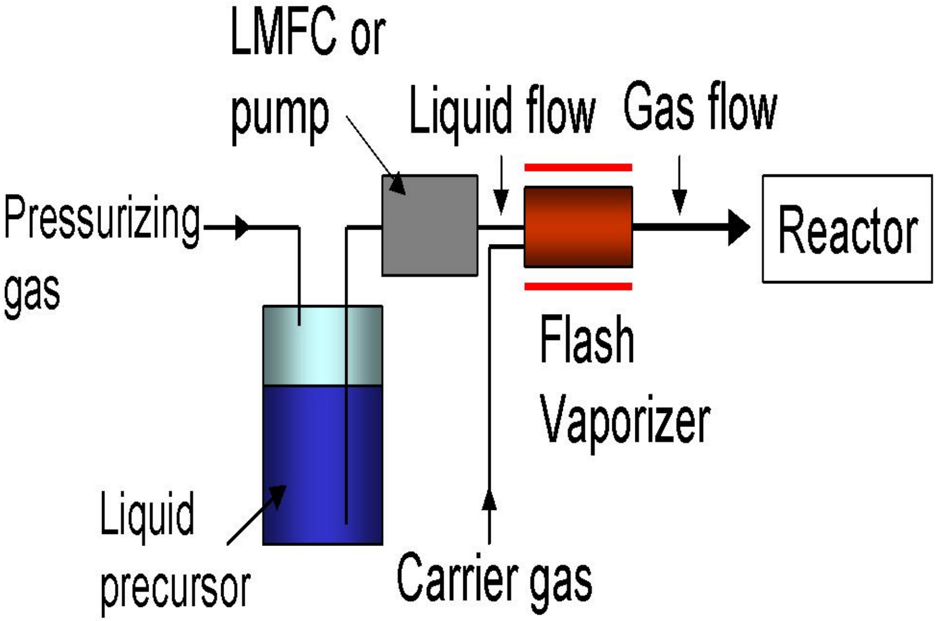
  - Precursor Delivery
    - Conventional gas delivery system: gas source, bubbling
    - Liquid delivery system: liquid pump or LMFC + flash vaporizer

Chemical Vapor Deposition (5)

- **Type of precursor delivery**



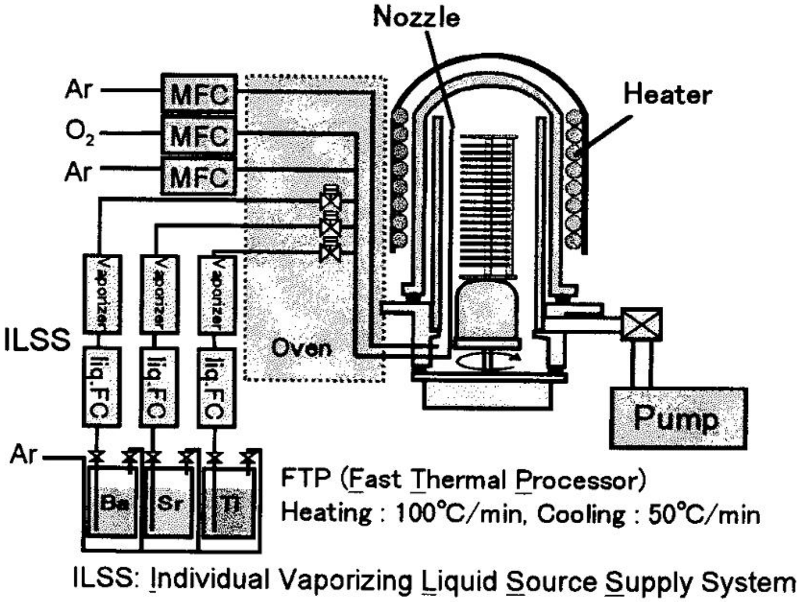
<Conventional bubbling delivery system>



<Liquid delivery system>

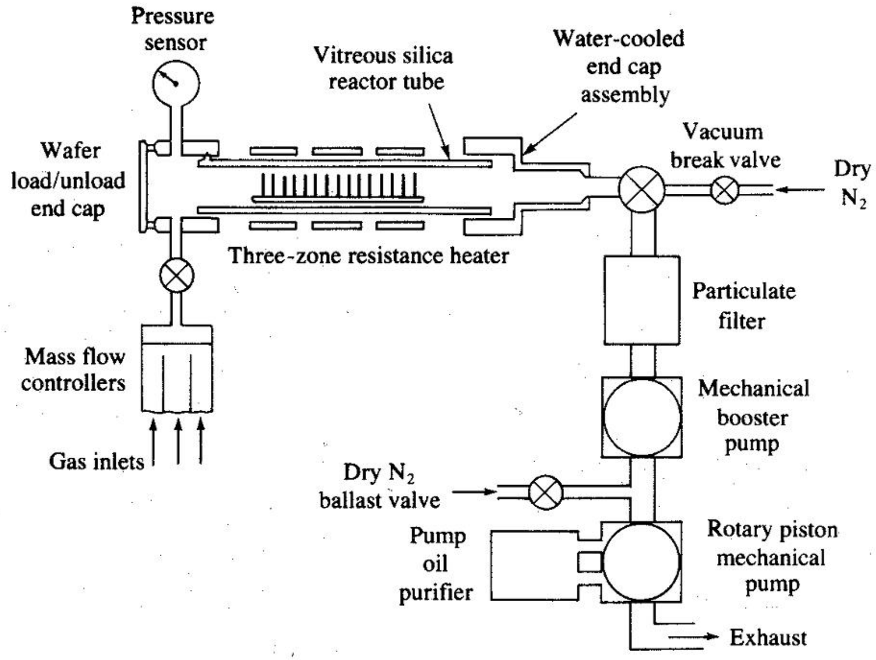
Chemical Vapor Deposition (6)

- **Type of reactor**
  - Tube type



FTP (Fast Thermal Processor)
Heating : 100°C/min, Cooling : 50°C/min

ILSS: Individual Vaporizing Liquid Source Supply System

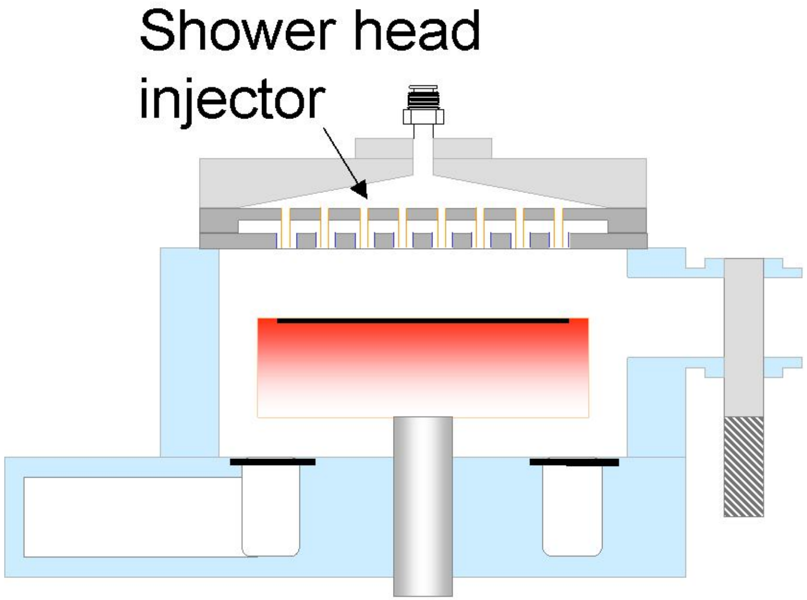


<Vertical CVD Reactor>

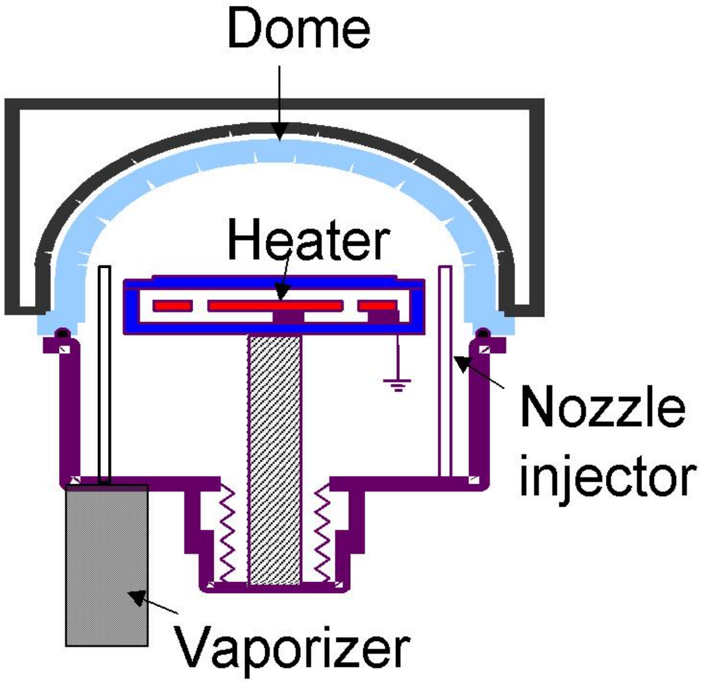
<Horizontal CVD Reactor>

Chemical Vapor Deposition (7)

- **Type of reactor (Cont'd)**
  - Wall type



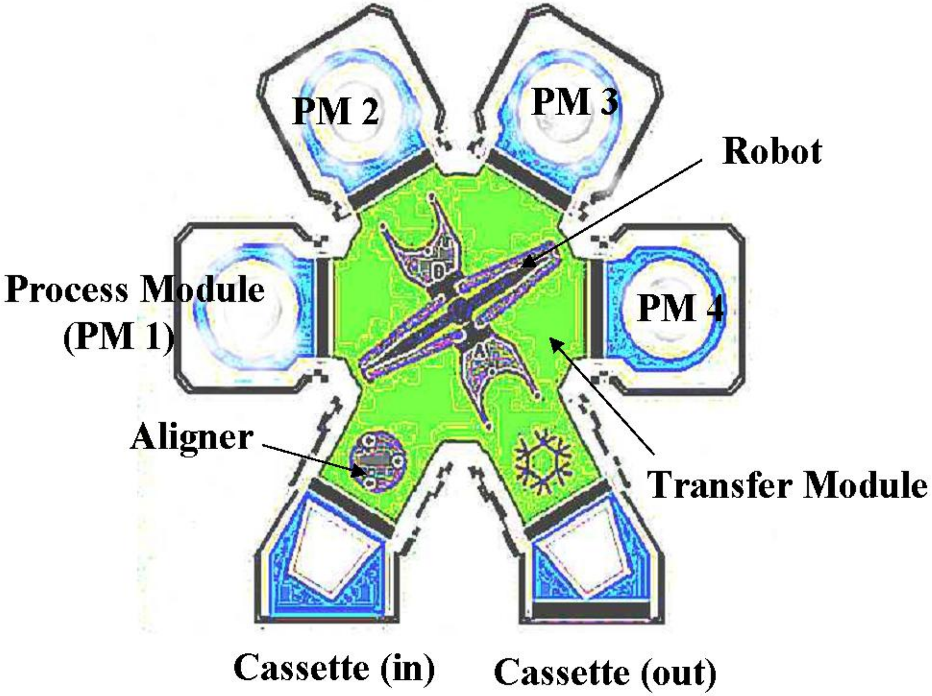
<Injector>



<Shower Head>

Chemical Vapor Deposition (8)

- **CVD system for mass production**



<Schematic>

<Picture of Equipment>

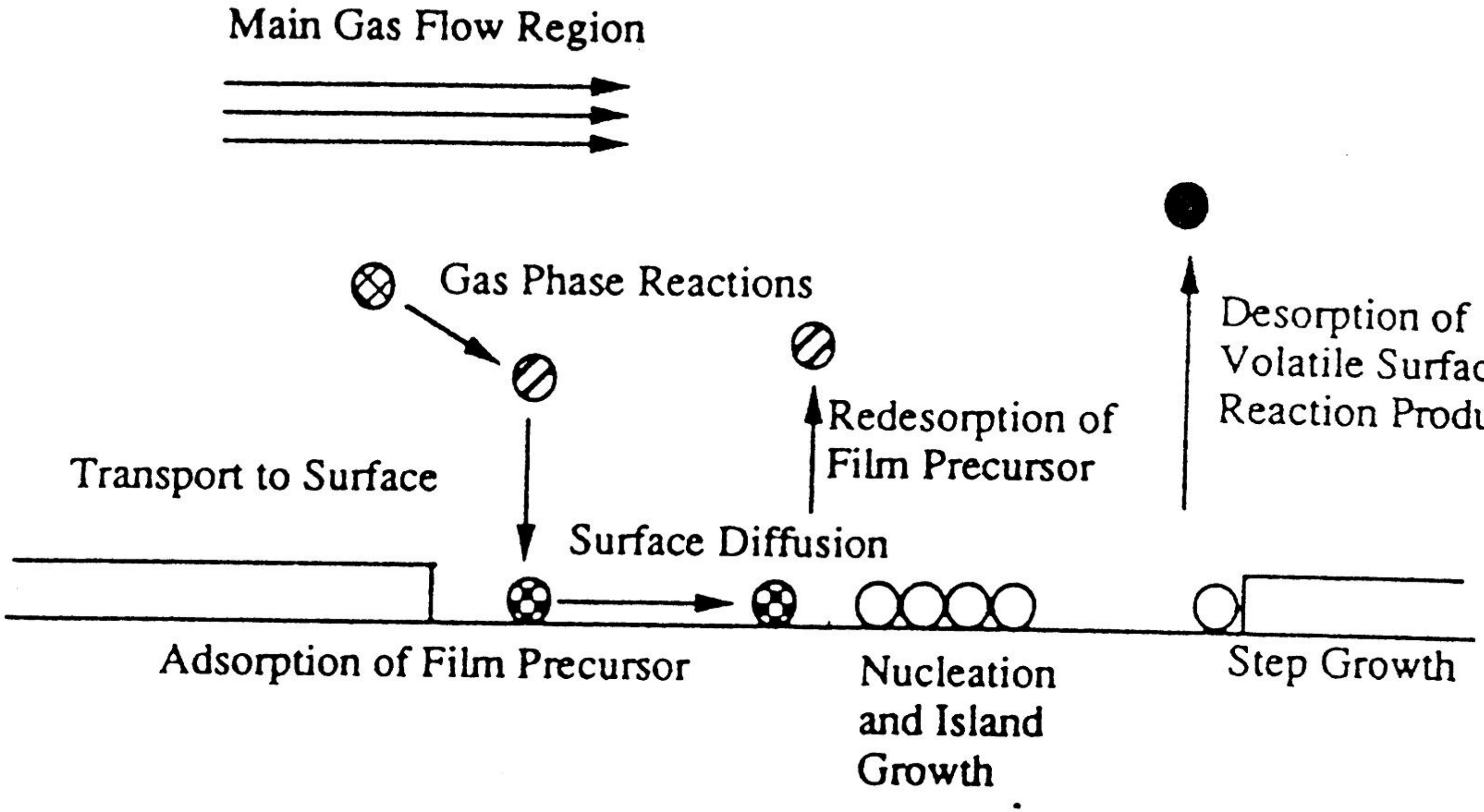
CVD Kinetics (1)

- **Chemical Vapor Deposition Process**

  1. Vaporization and Transport of Precursor Molecules into Reactor
  2. Diffusion of Precursor Molecules to Surface
  3. Adsorption of Precursor Molecules to Surface
  4. Decomposition of Precursor Molecules on Surface and Incorporation into Solid Films
  5. Recombination of Molecular Byproducts and Desorption into Gas Phase

CVD Kinetics (2)

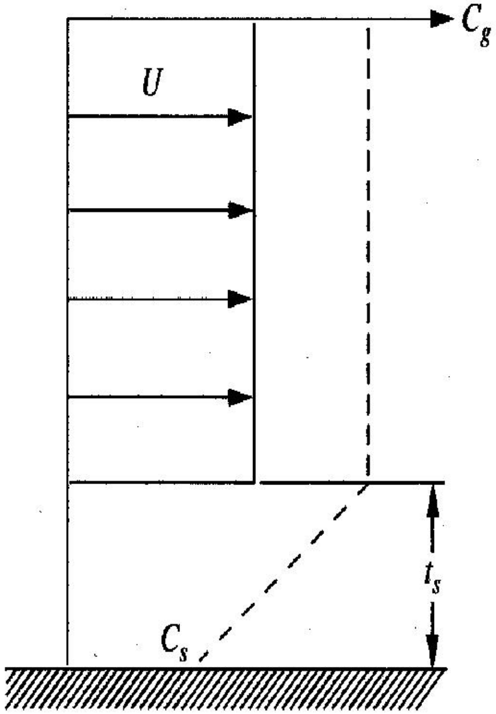
- **Schematic of CVD kinetics**



http://chiuserv.ac.nctu.edu.tw/~htchiu/cvd/home.html

CVD Kinetics (3)

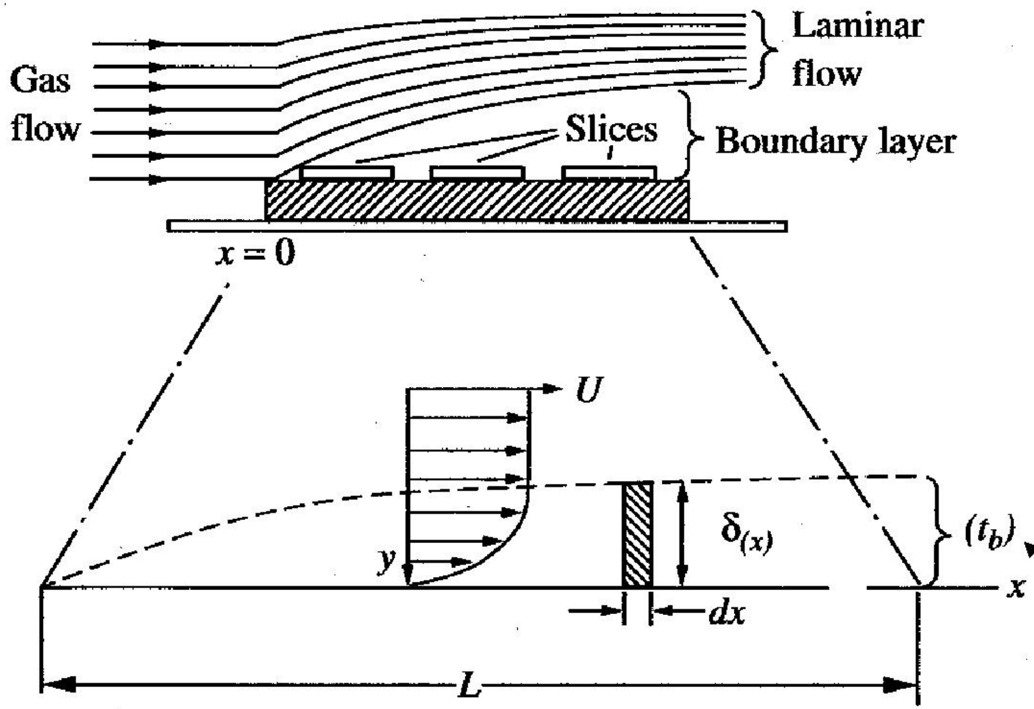
- **Transport in gas phase**
  - Stagnant layer
    - Similar idea with Boundary layer
    - At velocity U, thickness t_s layer is formed



<Stagnant layer model>

CVD Kinetics (4)

- **Boundary layer**
  - Properties of fluid above the substrate distinguish two layers.



At gas phase mass transfer, boundary layer model

CVD Kinetics (5)

- **Boundary layer (Cont'd)**
  - Properties of fluid (V, T, C) above the substrate

$$\delta(x) = \sqrt{\frac{\mu\, x}{\rho\, v_{\max}}}$$

$$<\delta(x)> = \frac{2}{3}\frac{L}{\sqrt{R_e}}$$

$$R_e = \frac{\rho L v_{\max}}{\mu}$$

δ(x) : boundary layer thickness

ρ: ***gas density***

v : *gas velocity*

μ: ***gas viscosity***

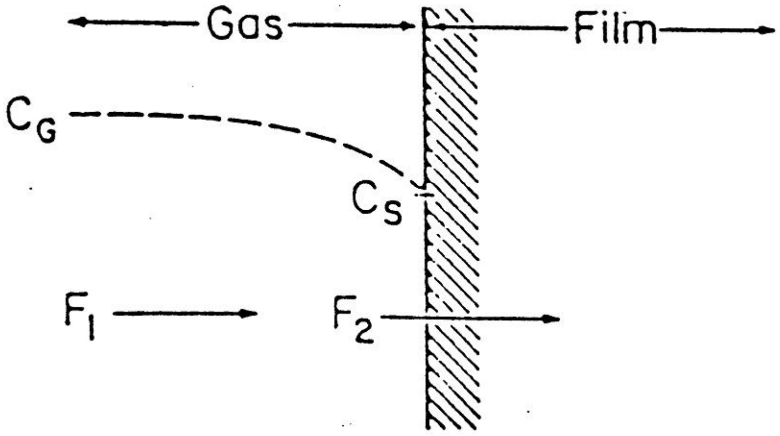
L : *susceptor Length*

$v_{max}\uparrow$ -> Re$\uparrow$ -> < δ(x)>$\downarrow$

Limit on v_{max} due to the onset of turbulence

CVD Kinetics (6)

- **CVD modeling**



CVD modeling

$$F_1 = D\frac{dc}{dy} \qquad (\mathrm{D:diffusion\ constant})$$

$$\cong D\frac{(C_G - C_S)}{\delta}$$

$$= h_G(C_G - C_S)$$

$$F_2 = k_S C_S$$

F: fluid velocity, C_S: surface concentration, C_G: gas bulk concentration, h_G: mass transport coefficient

$$steady-state \ : \ F_1 = F_2 \ \Rightarrow \ C_S = \frac{h_G}{(h_G + k_S)}C_G$$

CVD Kinetics (7)

- **CVD modeling (Cont'd)**

Growth Rate

$R_G = F_2/N_{Si}$ (N_{Si} : # of *Si atoms in a unit volume*)

$$R_G = \frac{1}{N_{Si}} \frac{h_G k_S}{h_G + k_S} C_G$$

Surface reaction limited

At $h_G \gg k_S$

$$R_G = \frac{1}{N_{Si}} k_S C_G$$

Diffusion limited

At $h_G \ll k_S$

$$R_G = \frac{1}{N_{Si}} h_G C_G$$

CVD Kinetics (8)

- **CVD modeling (Cont'd)**

Surface reaction rate

$$k_S = k_0 \exp(-\frac{E_A}{kT})$$

E_A : activation energy

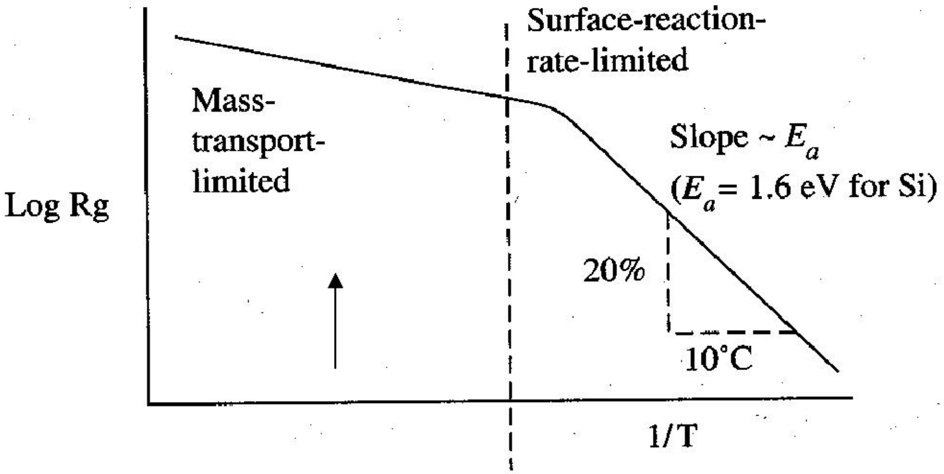
k : Boltzmann constant

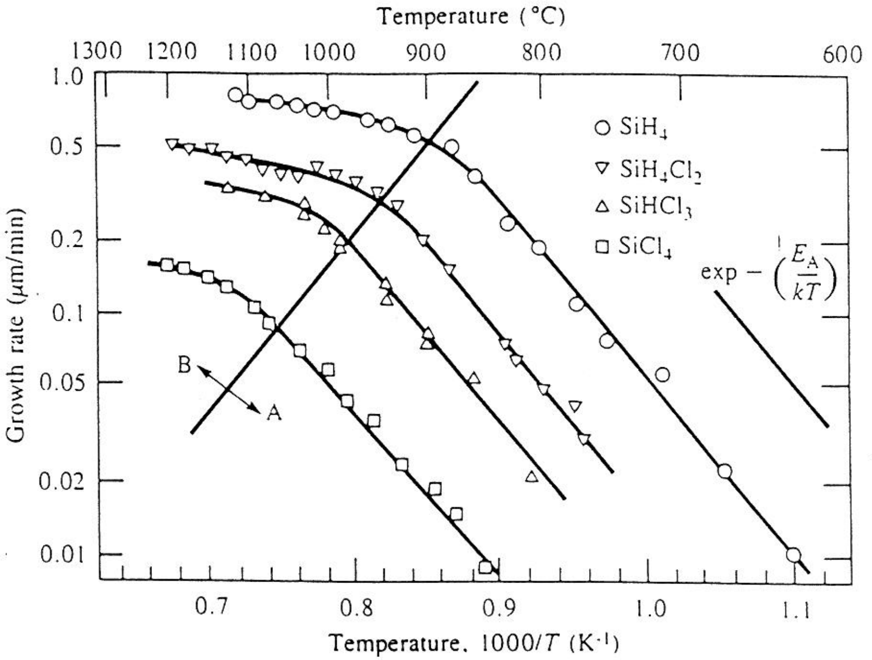
Reaction Temp. T ↑ —> k_S ↑ ==> diffusion limited

Reaction Temp. T ↓ —> k_S ↓ ==> surface reaction limited

CVD Kinetics (9)

- **CVD modeling (Cont'd)**



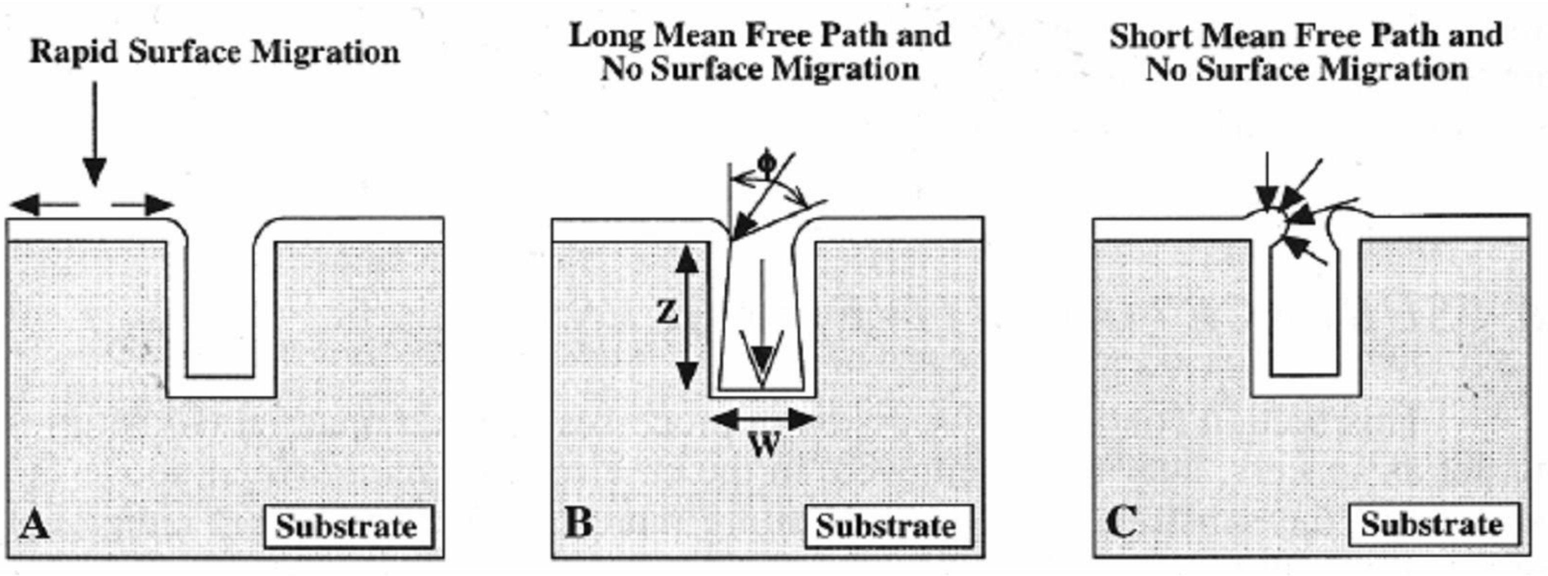


Growth rate vs. Temperature

Si film CVD process

Step Coverage Profile (1)

- **Step coverage profile**



A: Rapid surface migration process (before reaction), yielding uniform coverage since reactants adsorb and move, then react

B: Long mean free path process and no surface migration, with reactant molecule arrival angle determined location on features (local “field of view” effects are important)

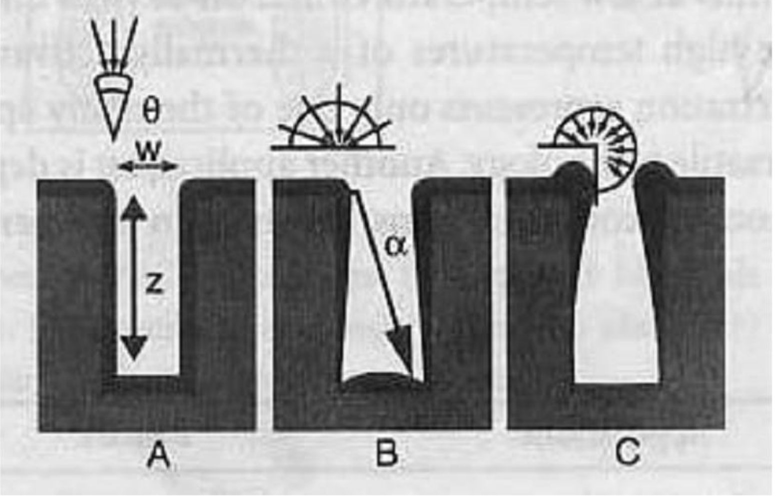
C: Short mean free path process with no surface migration, yielding nonconformal coating

Step Coverage Profile (2)

- Key Parameters
  - Mean Free Path
  - Surface Migration Energy ($E \propto$ Temperature)
  - Arrival angle

- For conformal step coverage
  - $\alpha < l$ (mean free path)

    where $\alpha = \arctan(w/z)$
  - High Surface Mobility

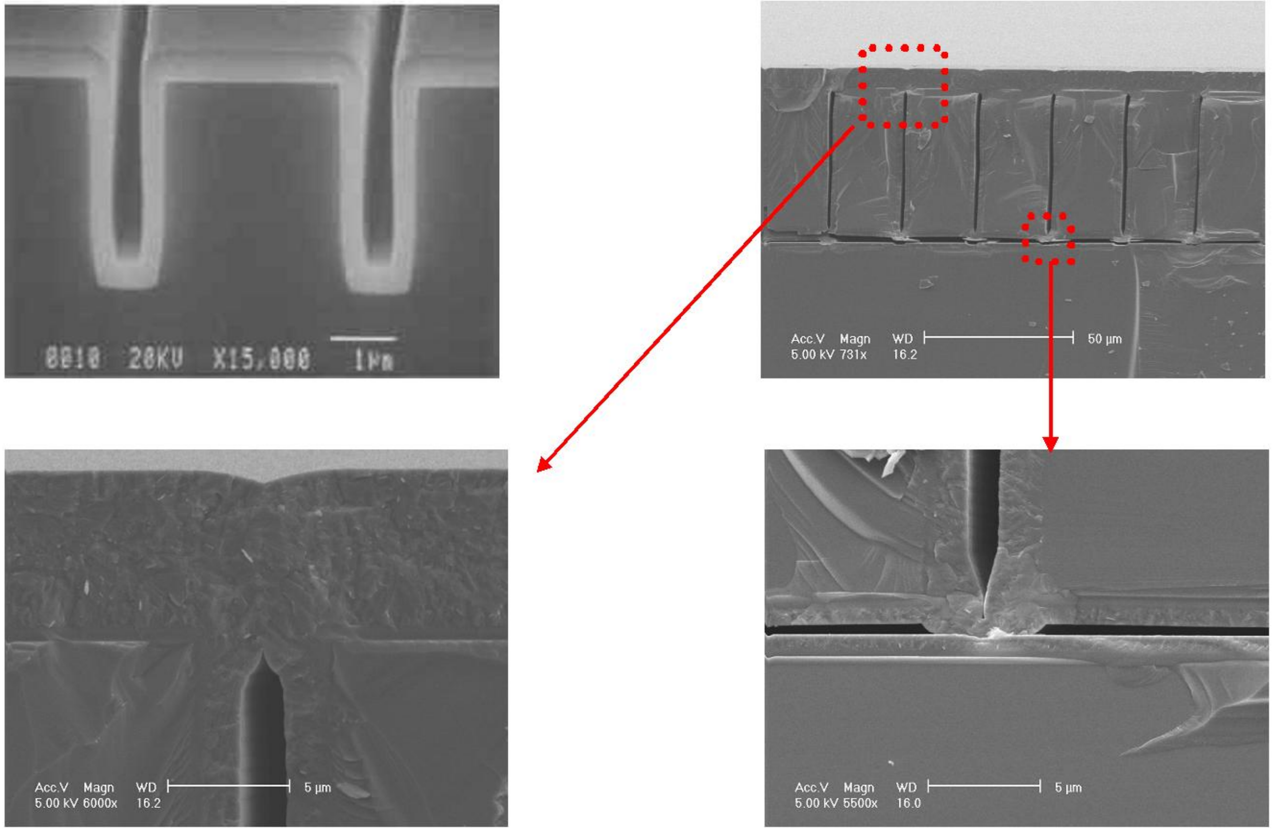


- Process tendency
  - A: LPCVD
  - B: PECVD

    Evaporated & Sputtered Metal

Step Coverage Profile (3)

- **Step coverage profile example**

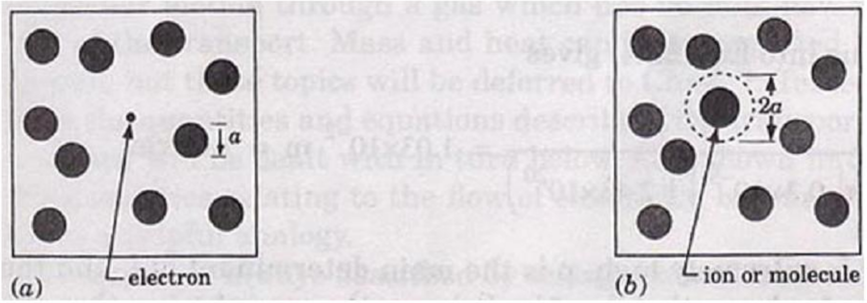


Good

Bad

Step Coverage Profile (4)

- **Mean free path**



- Electron's & ion Mean Free Path

$$l_e = \frac{1}{\sigma_m n} = \frac{1}{(\pi/4)a^2 n}$$

$$l_i = \frac{1}{\pi a^2 n}$$

$$l = \frac{1}{\sqrt{2}\pi a^2 n}$$

(Considering mean speed of mutual Approach in Ion Mean Free Path)

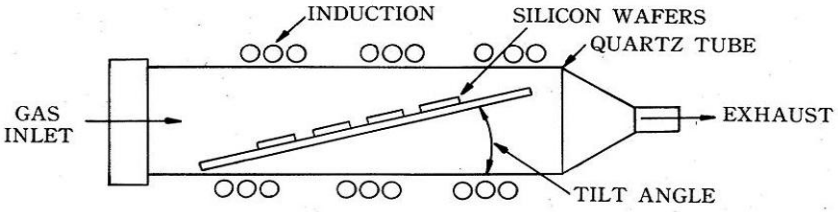
$$n = \frac{pNa}{RT}$$

(Unless T is extremely high , p is the main determinant of l)

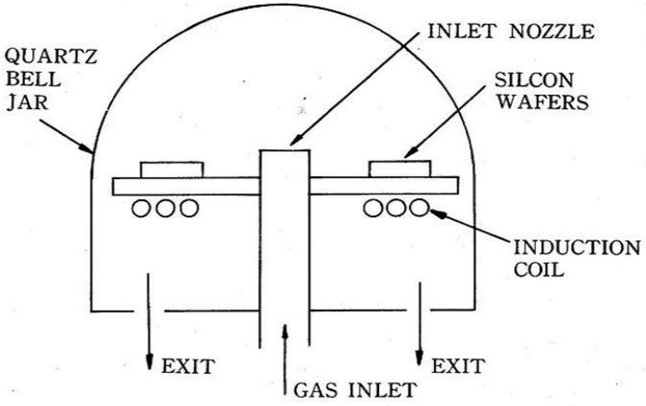
Knudsen number : $Kn = \frac{l}{L}$

Atmospheric Pressure CVD

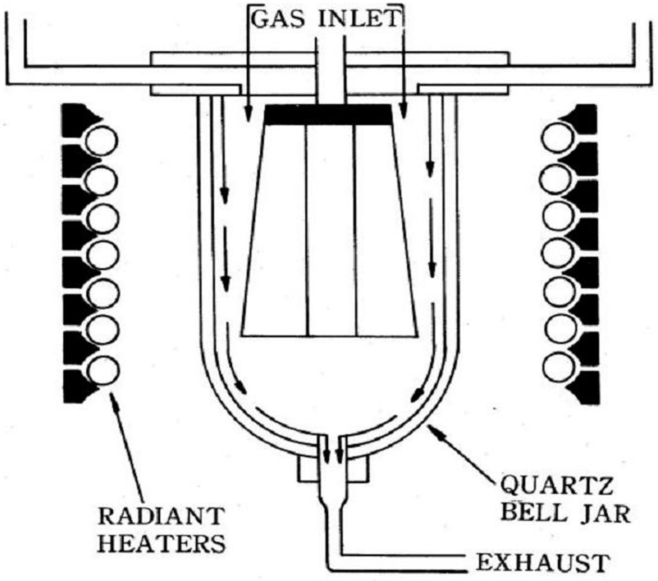
- **APCVD (Atmospheric Pressure Chemical Vapor Deposition)**
  - Material: epitaxial Si, poly-Si, Si_3N_4, SiO_2, etc.
  - Cold wall process



(a) INDUCTION HEATED HORIZONTAL REACTOR



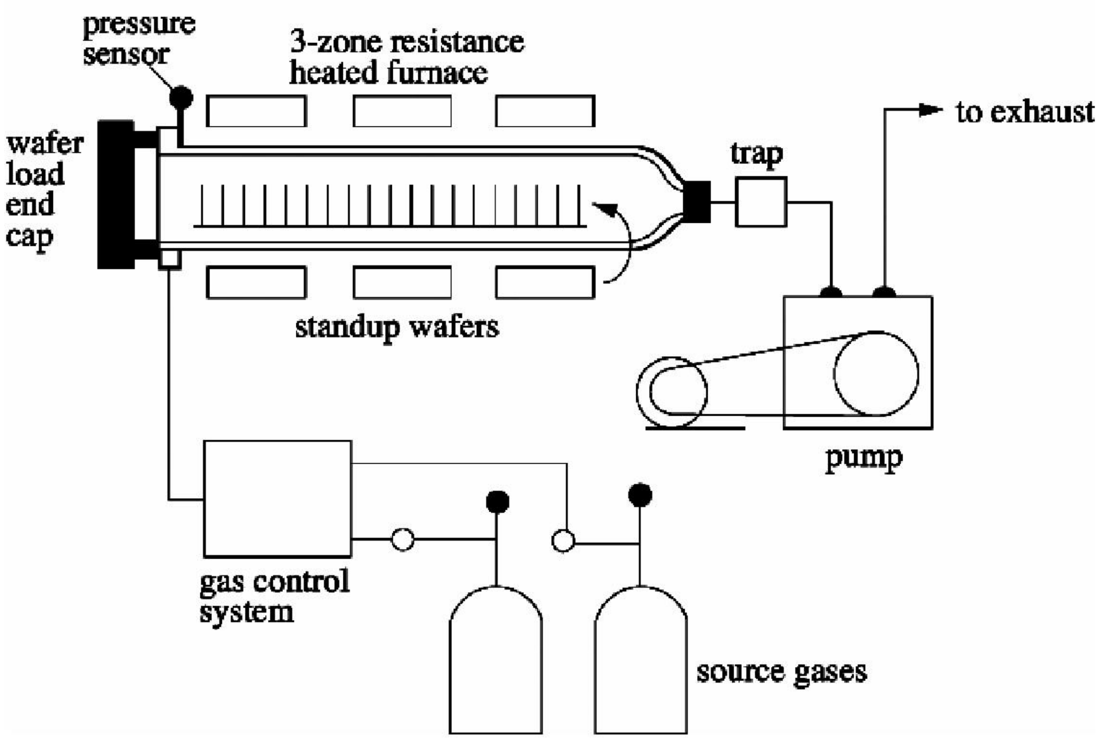
(b) INDUCTION HEATED VERTICAL REACTOR



(c) RADIANTLY HEATED CYLINDER REACTOR

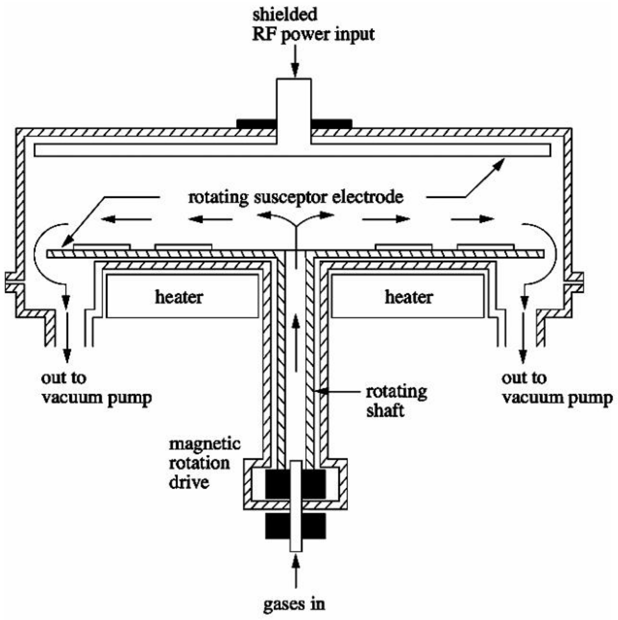
Low Pressure CVD

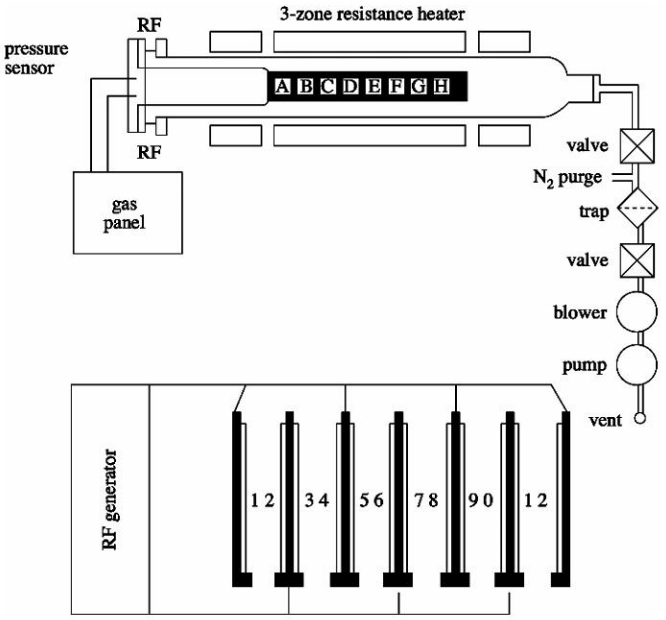
- **LPCVD (Low Pressure Chemical Vapor Deposition)**
  - Material: Si_3N_4, SiO_2, poly-Si, etc.
  - Good uniformity, property



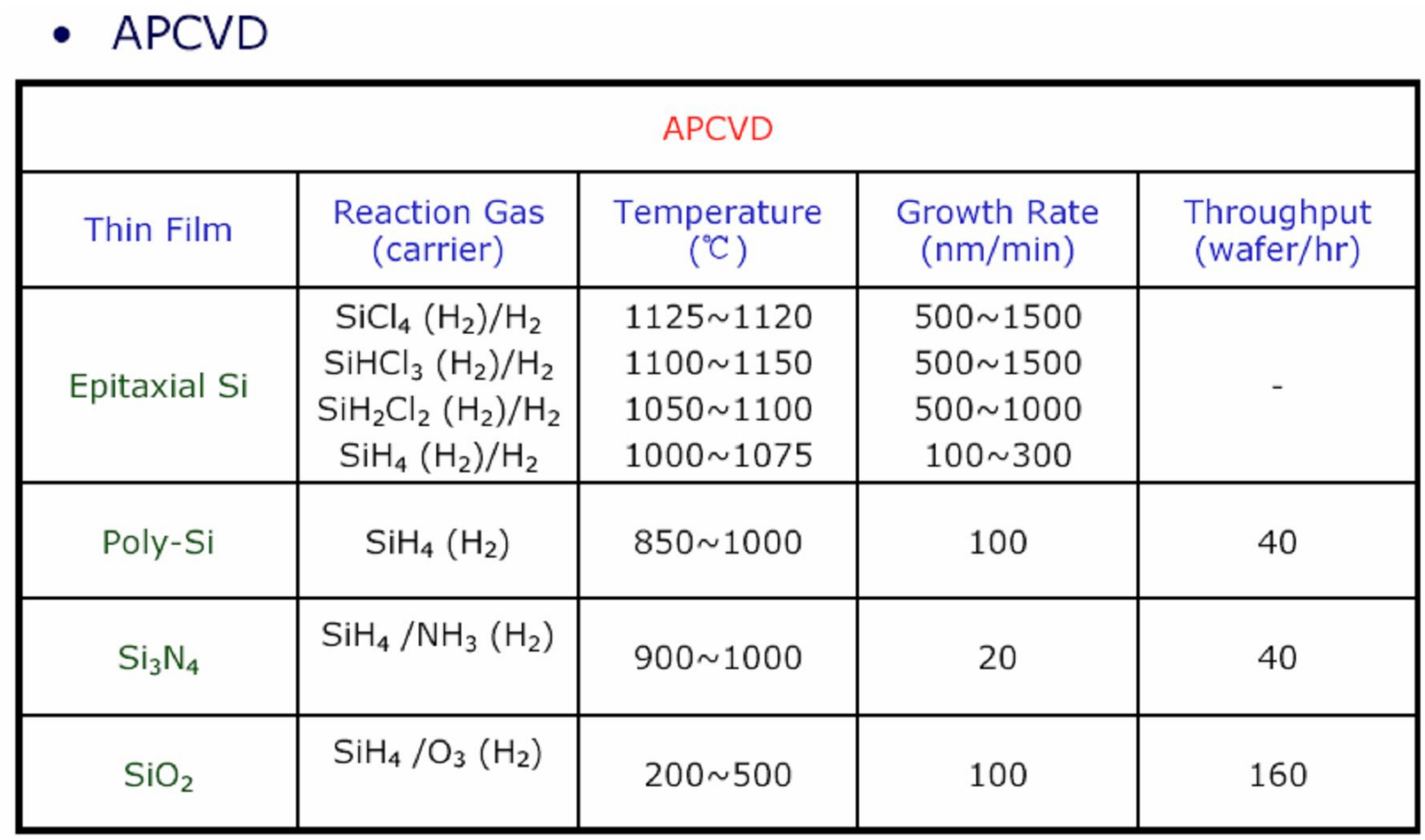
Plasma Enhanced CVD

- **PECVD (Plasma Enhanced Chemical Vapor Deposition)**
  - Material: Si_3N_4, SiO_2, amorphous-Si, etc.
  - Faster rate and lower deposition temperature than thermal CVD
  - Cracks, pin holes, and poor stoichiometry





CVD films and deposition conditions (1)



- APCVD

APCVD				
Thin Film	Reaction Gas (carrier)	Temperature (℃)	Growth Rate (nm/min)	Throughput (wafer/hr)
Epitaxial Si	$SiCl_4$ (H_2)/H_2 $SiHCl_3$ (H_2)/H_2 SiH_2Cl_2 (H_2)/H_2 SiH_4 (H_2)/H_2	1125~1120 1100~1150 1050~1100 1000~1075	500~1500 500~1500 500~1000 100~300	-
Poly-Si	SiH_4 (H_2)	850~1000	100	40
Si_3N_4	SiH_4 /NH_3 (H_2)	900~1000	20	40
SiO_2	SiH_4 /O_3 (H_2)	200~500	100	160

CVD films and deposition conditions (2)

- LPCVD

LPCVD				
Thin Film	Reaction Gas (carrier)	Temperature (℃)	Growth Rate (nm/min)	Throughput (wafer/hr)
Epitaxial Si	SiH_2Cl_2 $(H_2)/H_2$	1000~1075	100	-
Poly-Si	100% SiH_4 (0.2 torr)	620	100	100
Si_3N_4	23% SiH_4 (H_2) (0.1 torr)	640	19	150
	SiH_2Cl_2 $/NH_3$ (0.3 torr)	800	4	100
SiO_2	SiH_2Cl_2 $/N_2O$	900	8	-
SiO_2	SiH_4 $/O_3$	450	10	100
	SiH_4 $/PH_3$ $/O_3$ (0.7 torr)	450	12	50

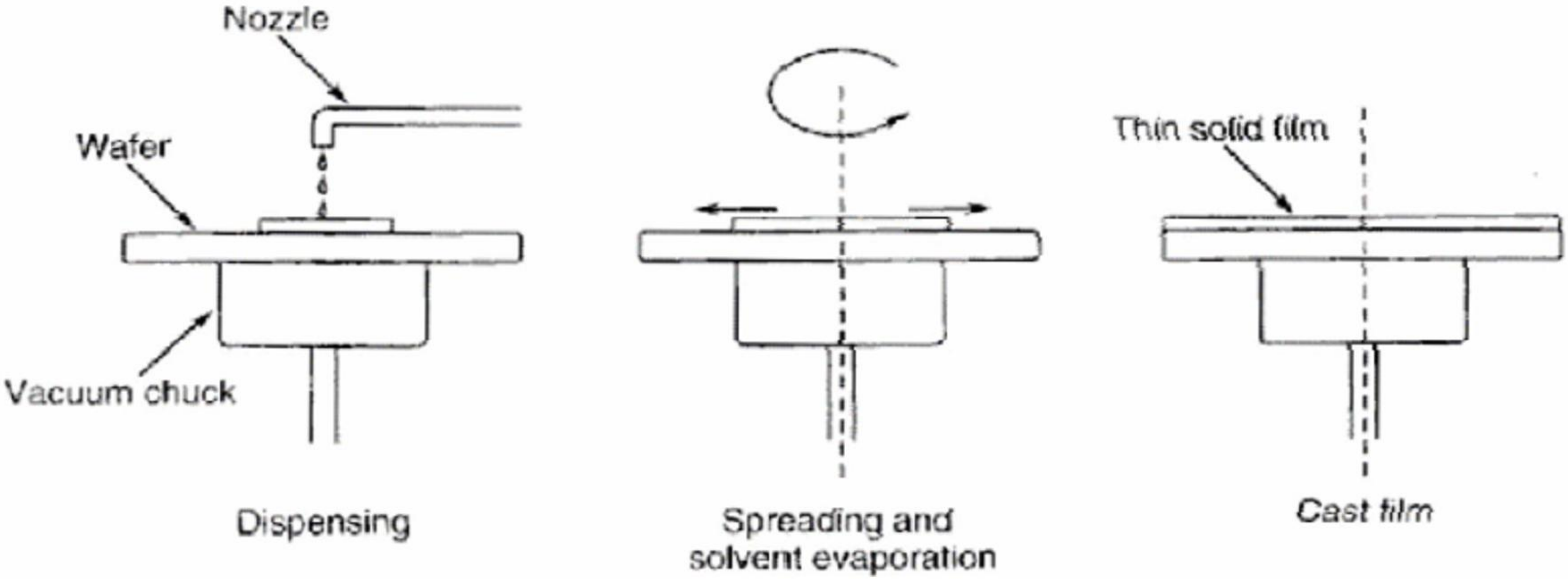
CVD films and deposition conditions (3)

- PECVD

PECVD				
Thin Film	Reaction Gas (carrier)	Temperature (℃)	Growth rate (nm/min)	Throughput (wafer/hr)
Si_3N_4	$SiH_4/NH_3(N_2)$ (0.3 torr)	300	10	-
SiO_2	SiH_2Cl_2 /N_2O	250	84	-
α-Si	SiH_4 /H_3 (0.1 torr)	300	6	-

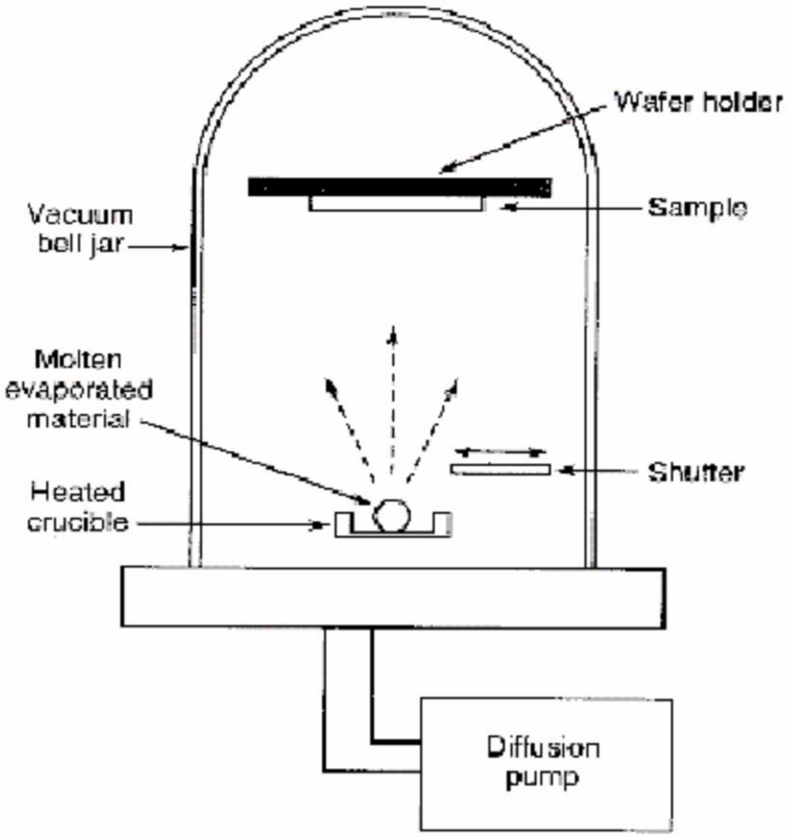
Other deposition methods (1)

- Spin casting
  - Material: PR, polyimide, spin-on-glass, PZT, sol-gel, etc.
  - Typical thickness: 0.1~50 um



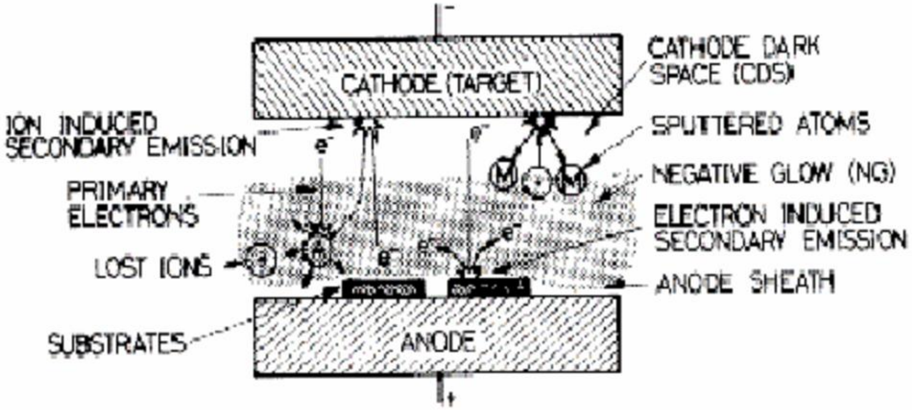
Other deposition methods (2)

- Evaporation
  - Material: Cr, Au, Cu, Ti, Ni, Mn, Al, etc.
  - Typical thickness: very thin (due to residual stress)
  - Deposition pressure : $10^{-6} \sim 10^{-7}$ Torr

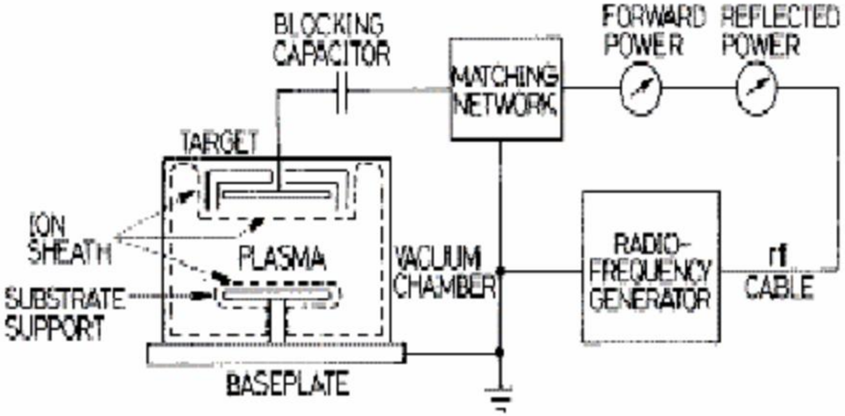


Other deposition methods (3)

- Sputtering
  - Material: almost all
  - Good uniformity, step coverage
  - 10-6~10-8 Torr, inert gas (eg. Ar, He) plasma (a few mTorr)



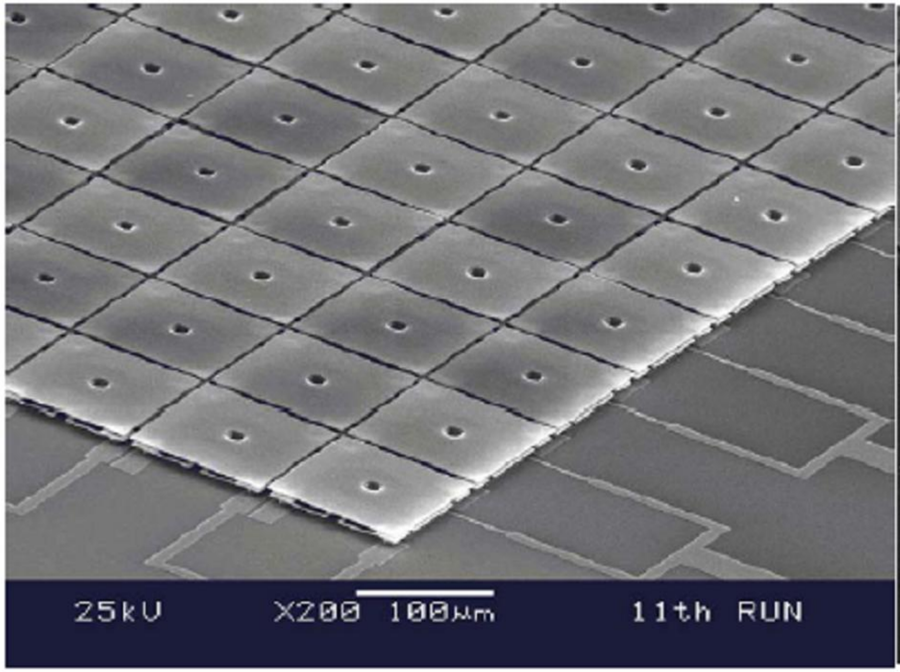
(a)



(b)

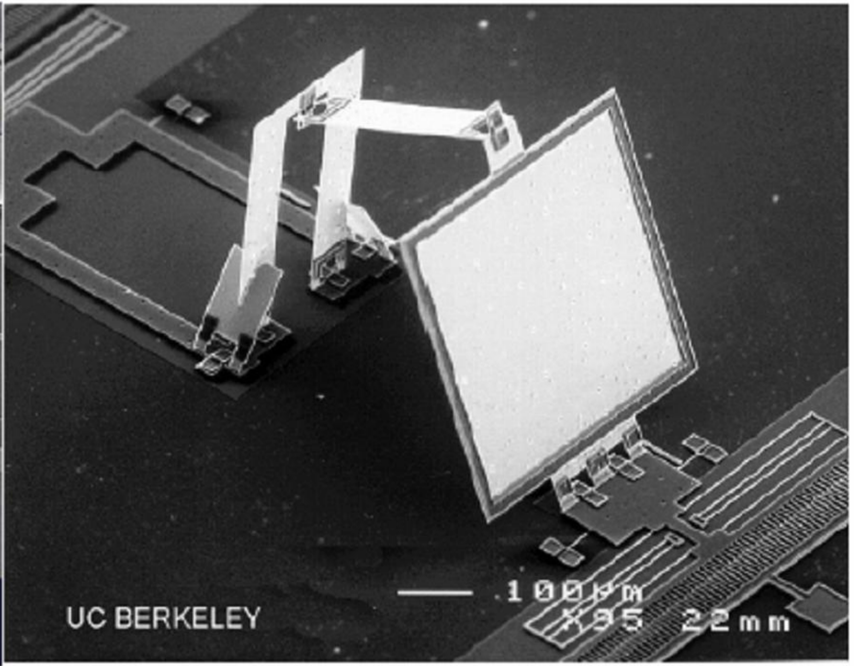
Surface micromachined devices (1)

- Optical system



Surface micromachined micromirror

(MiSA SNU)



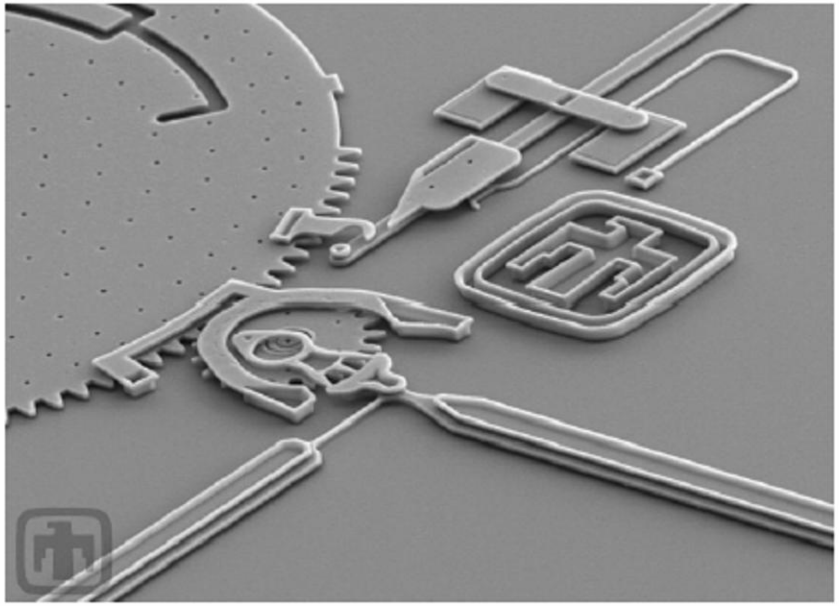
Actuated micromirror

for external cavity semiconductor lasers

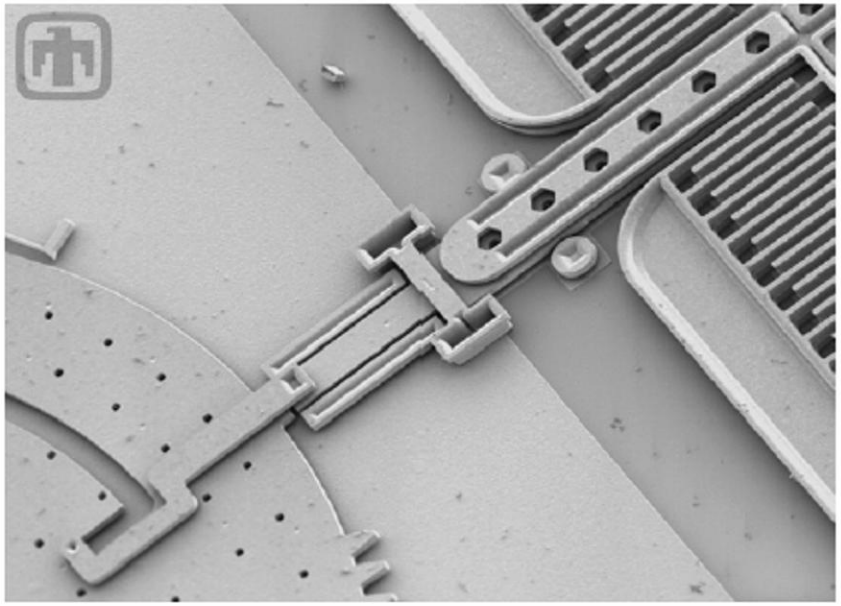
(UC Berkeley)

Surface micromachined devices (2)

- Microlock system



Microlock latch mechanism



Micromechanical lock pin actuator

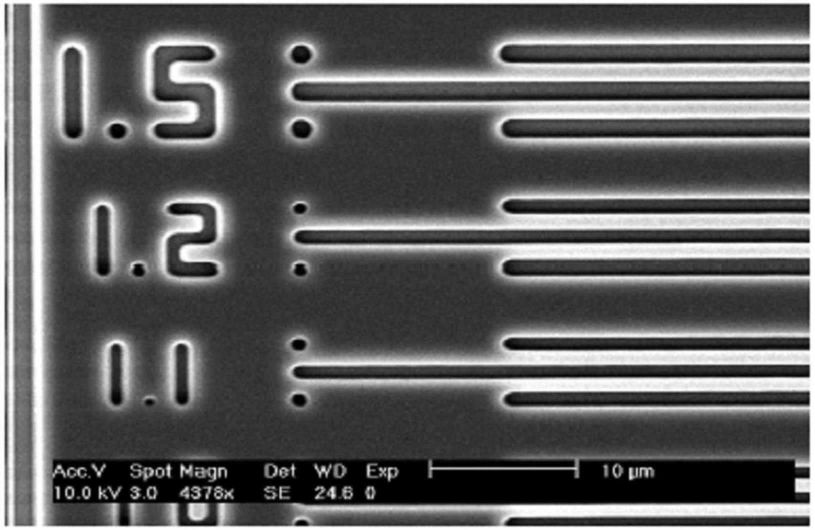
(Sandia National Laboratories)

Advantages and limitations (1)

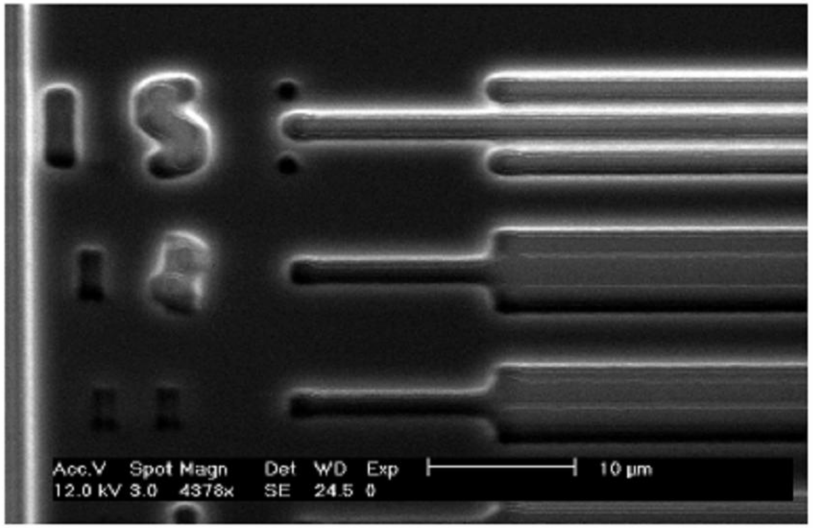
- Advantages of surface micromachining
  - multi layout structures
  - complex 2-D/3-D structures
  - multi-function devices
  - CMOS compatible
- Limitations of surface micromachining (I)
  - Material problems
    - hard to deposit thick films
    - deposited to polycrystalline or amorphous: residual stress, stress gradient, Young's modulus variation, fracture toughness variation
    - repeatability issue
  - Stiction
    - must be solved for commercialization

Advantages and limitations (2)

- Limitations of surface micromachining (II)
  - Photolithographic limitations
    - Micromachined structures are not planar: step height of several um
    - Not compatible with CMOS-based lithography technology: confined to C.D. of 2um



Photolithography process results at δ =0 um



Photolithography process results at δ =5 um