Lecture 12:

PECVD

(Plasma Enhanced Chemical Vapor Deposition)

Dong-Il "Dan" Cho

School of Electrical Engineering and Computer Science,
Seoul National University
Nano/Micro Systems & Controls Laboratory

Thin Film Deposition

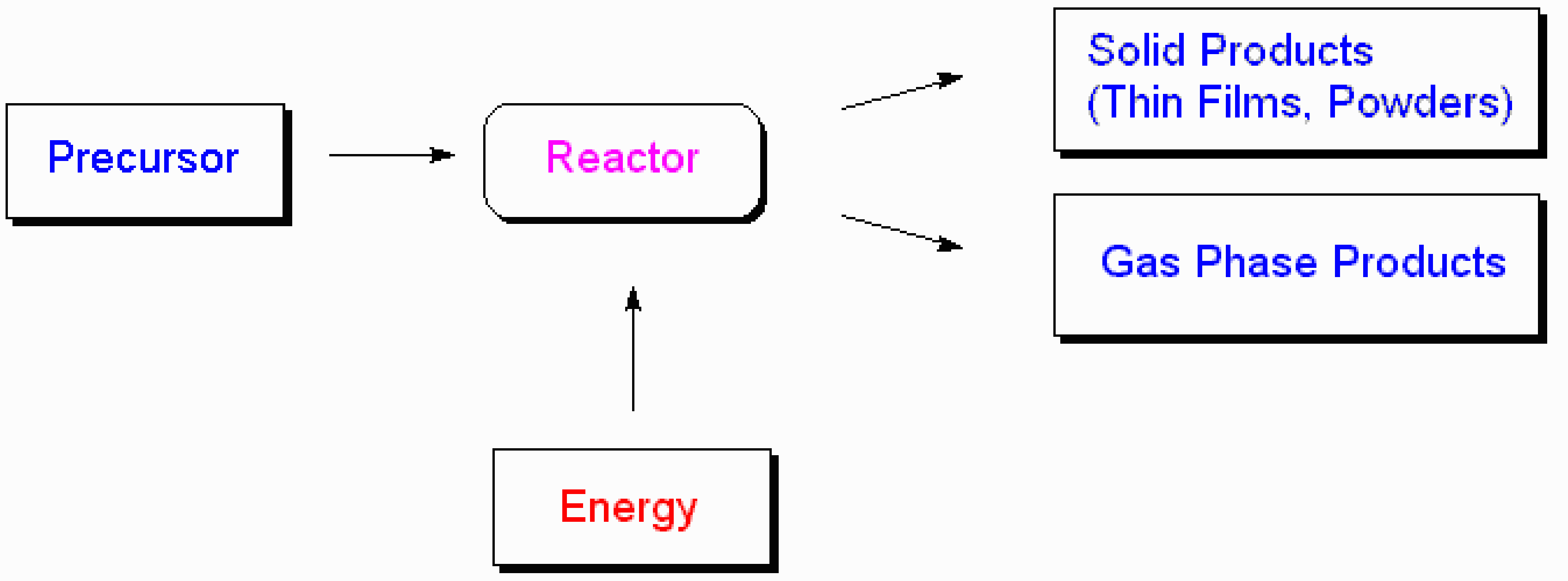
- Deposition
  - The transformation of vapors into solids, frequently used to grow solid thin film and powder materials

- 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/LC CVD

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)

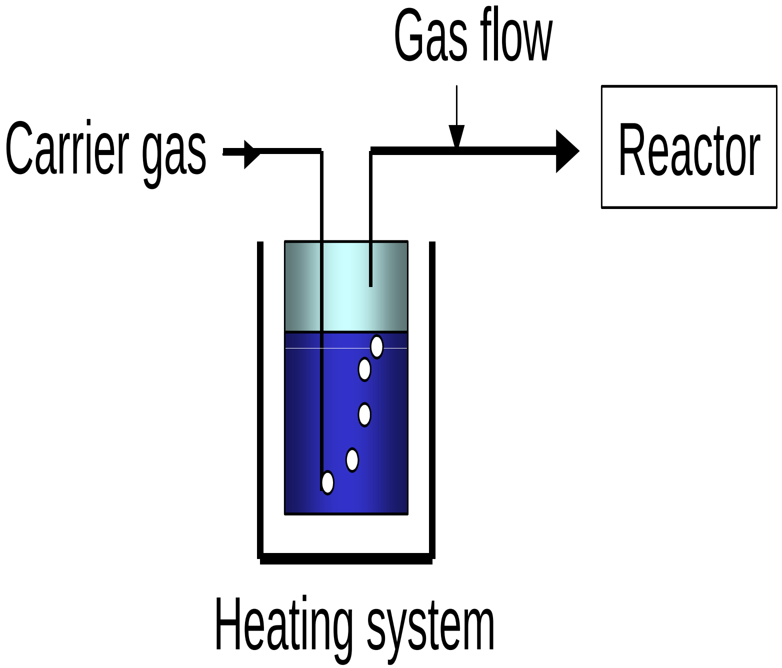
- Types of CVD (Cont'd)
  - Reaction Temperature
    - High temperature CVD
    - Low temperature CVD

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

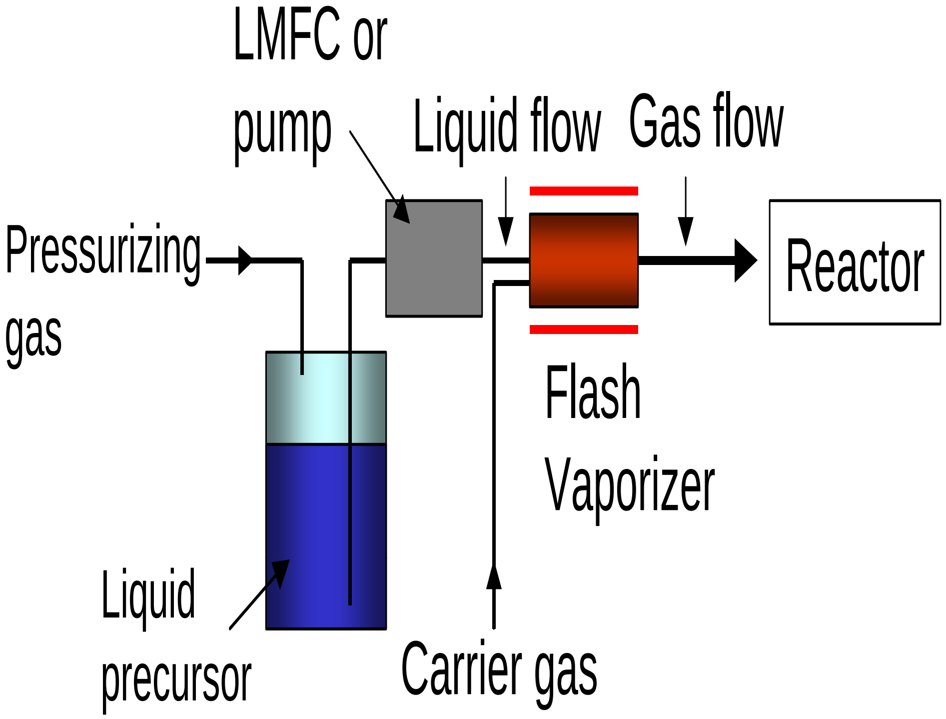
  - Precursor Delivery
    - Conventional gas delivery system: gas source, bublling
    - Liquid delivery system: liquid pump or LMFC + flash vaporizer

Chemical Vapor Deposition (5)

- Type of precursor delivery



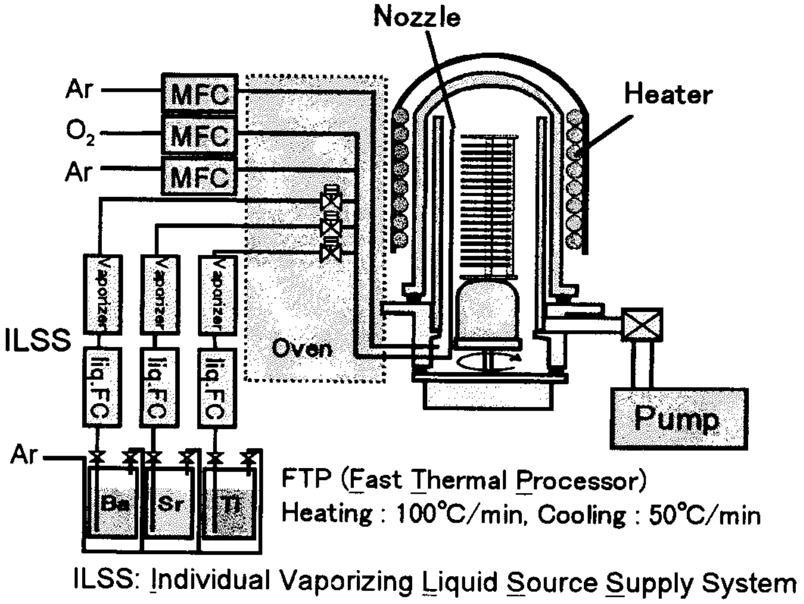
Conventional bubbling delivery system

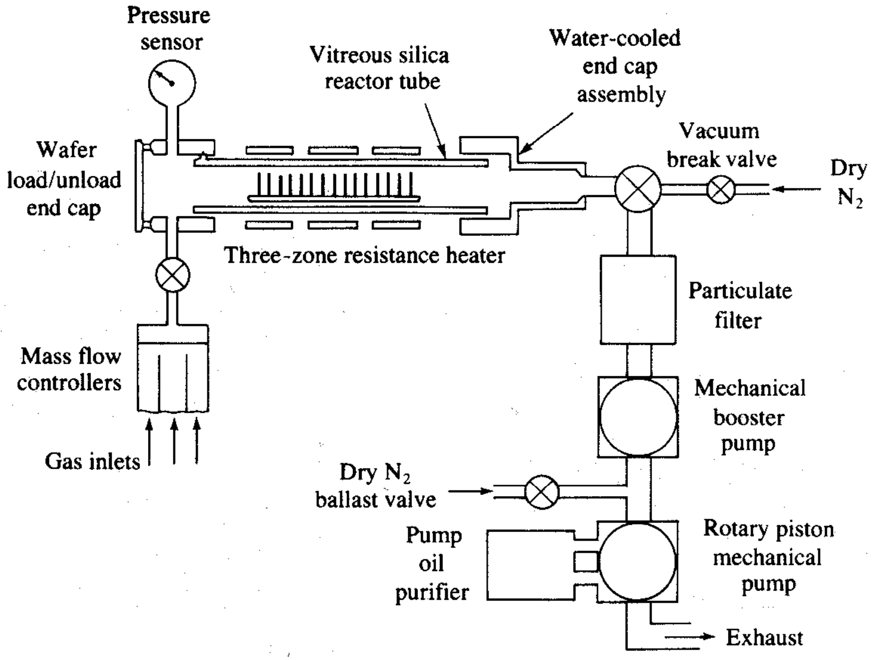


Liquid delivery system

Chemical Vapor Deposition (6)

- Type of reactor



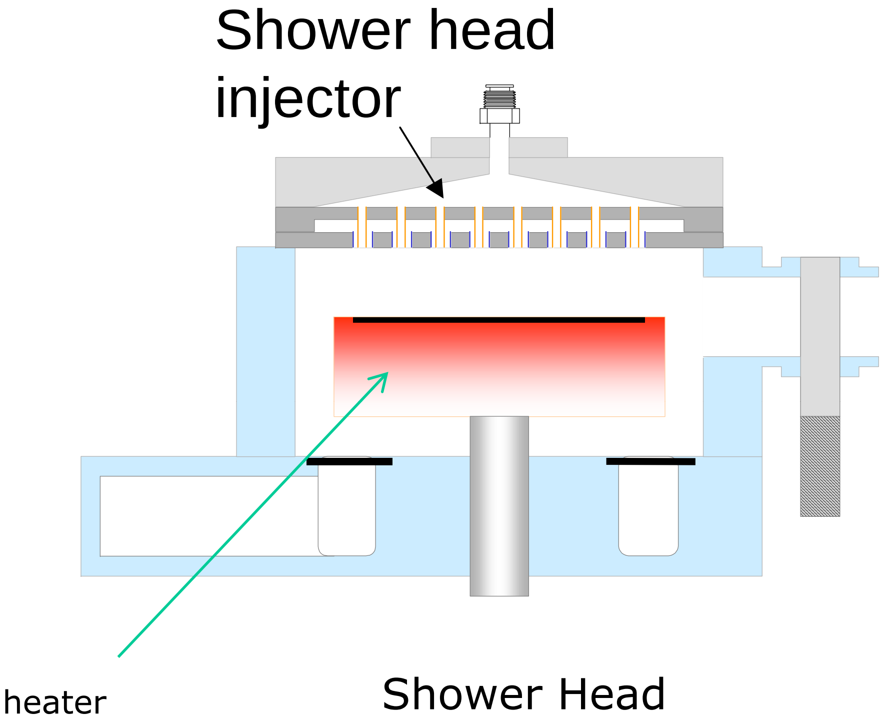


Vertical CVD Reactor

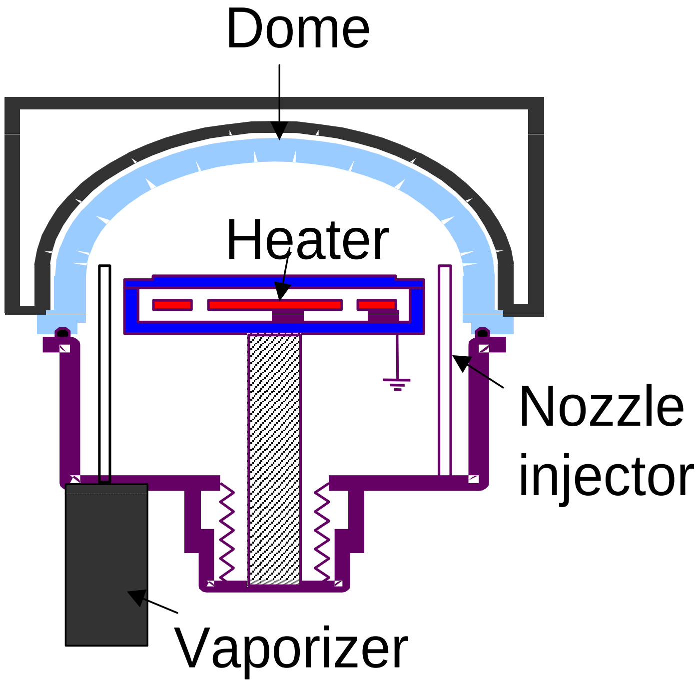
Horizontal CVD Reactor

Chemical Vapor Deposition (7)

- Type of reactor (Cont'd)



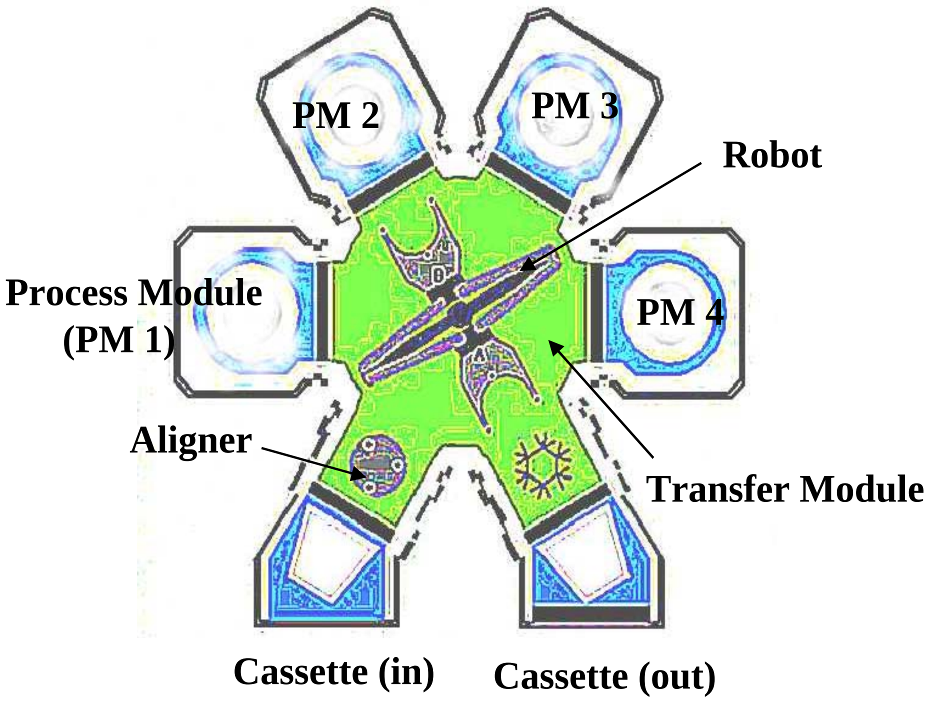
Shower Head



Injector

Chemical Vapor Deposition (8)

- CVD system for mass production



Schematic

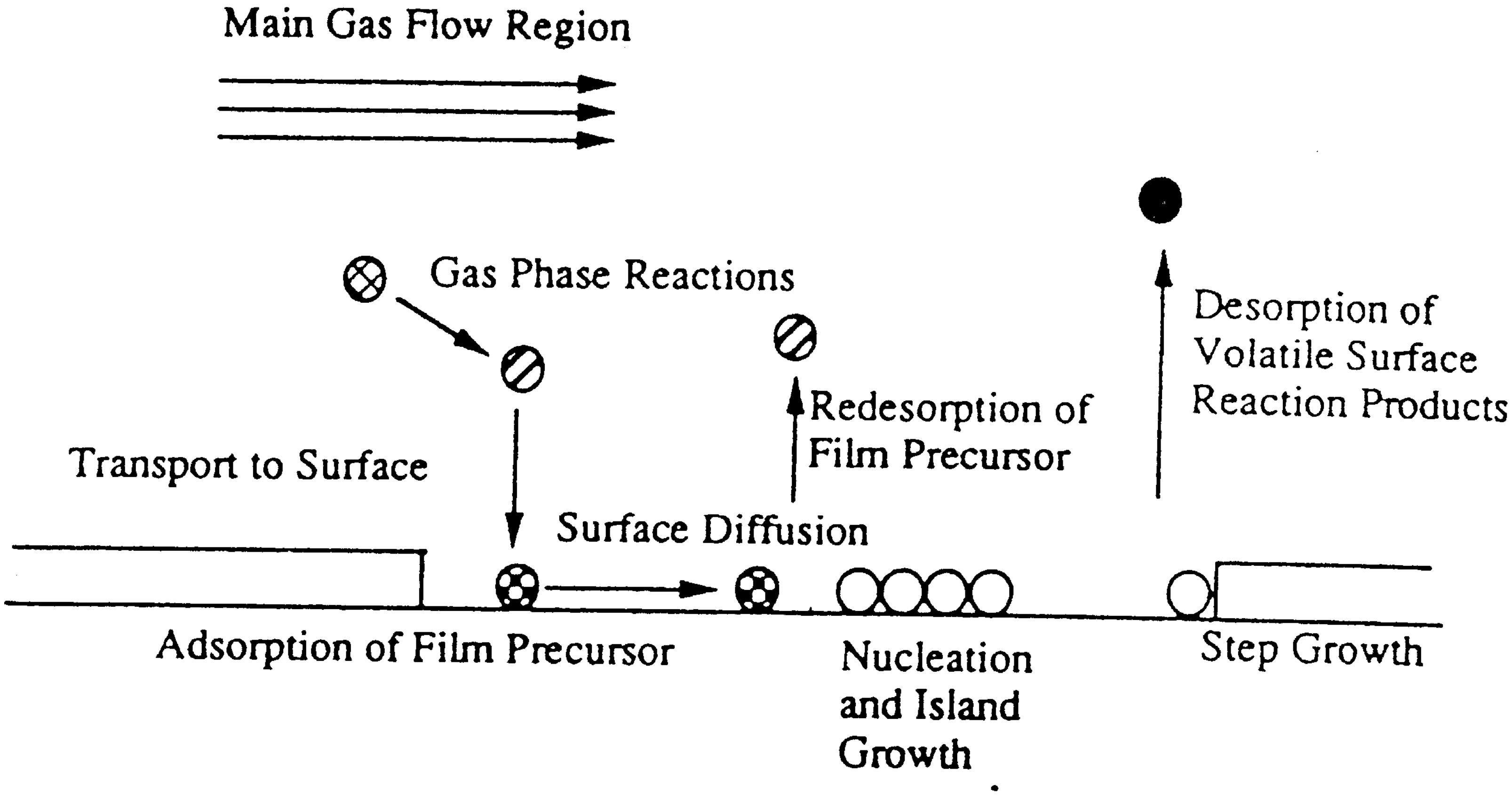
Picture of Equipment

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)

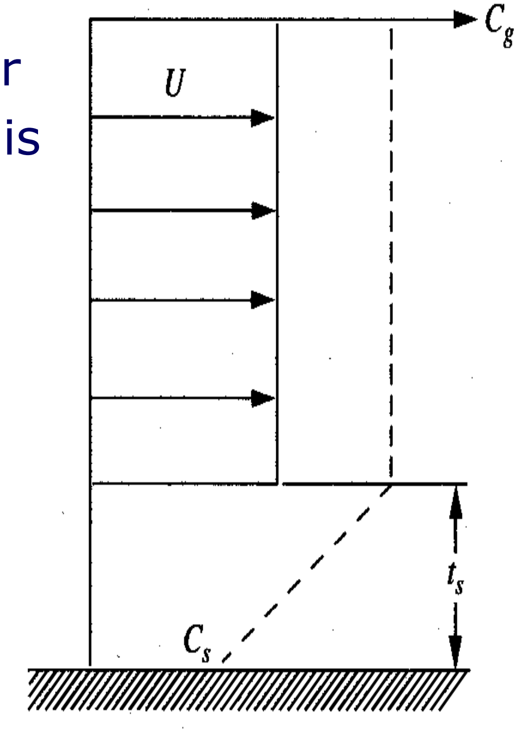
- Schematic of CVD kinetics



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

CVD Kinetics (3)

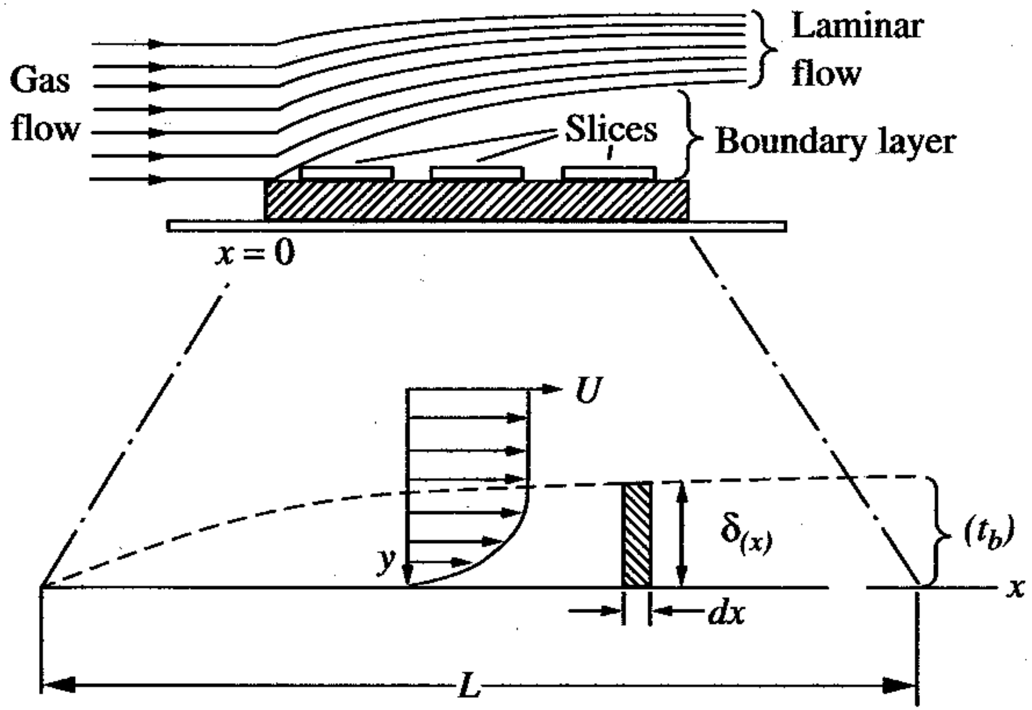
- Transport in gas phase
  - Stagnant layer
    - Similar idea with Boundary layer
    - At velocity U, thickness t_s layer is formed



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*

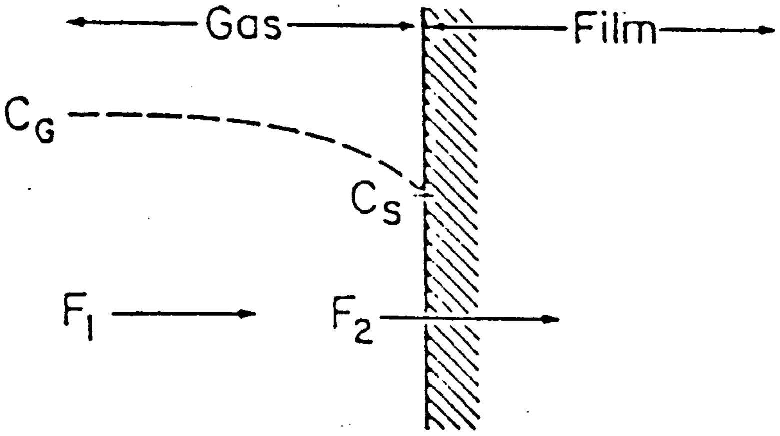
L : *susceptor Length*

$v_{max} \uparrow \rightarrow \mathrm{Re} \uparrow \rightarrow <\delta(x)> \downarrow$

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

CVD Kinetics (6)

- CVD modeling



CVD modeling

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

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

$$= h_G(C_G - C_S)$$

$$F_2 = k_S C_S$$

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 (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 (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 $h_G \gg k_S$

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

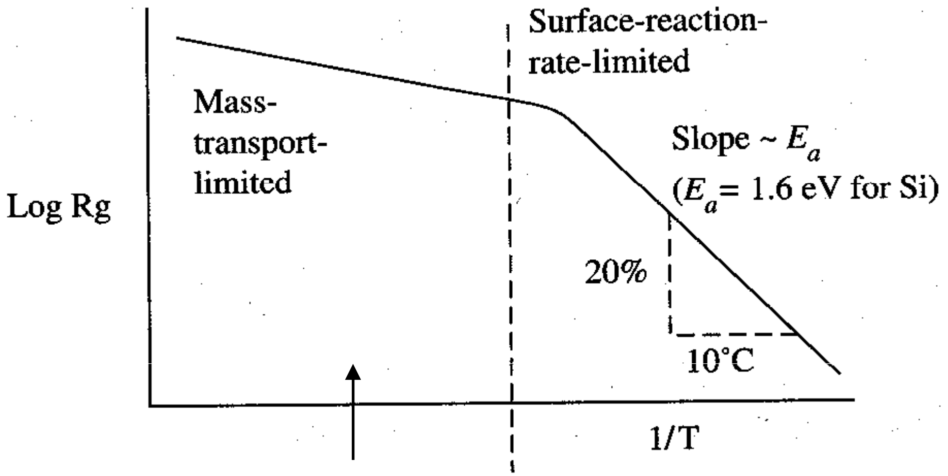
Diffusion limited

At $h_G \ll k_S$

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

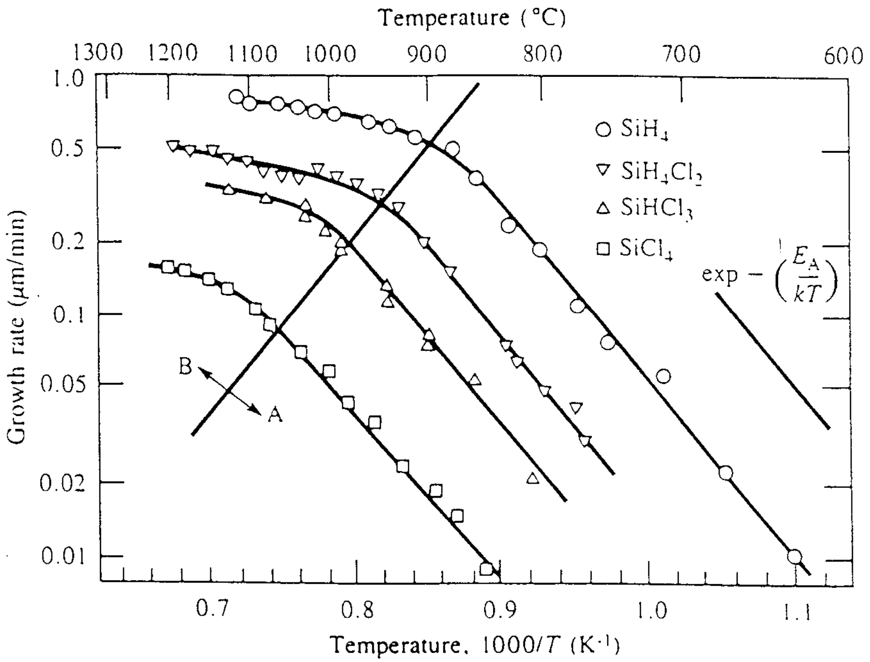
CVD Kinetics (9)

- CVD modeling (Cont'd)



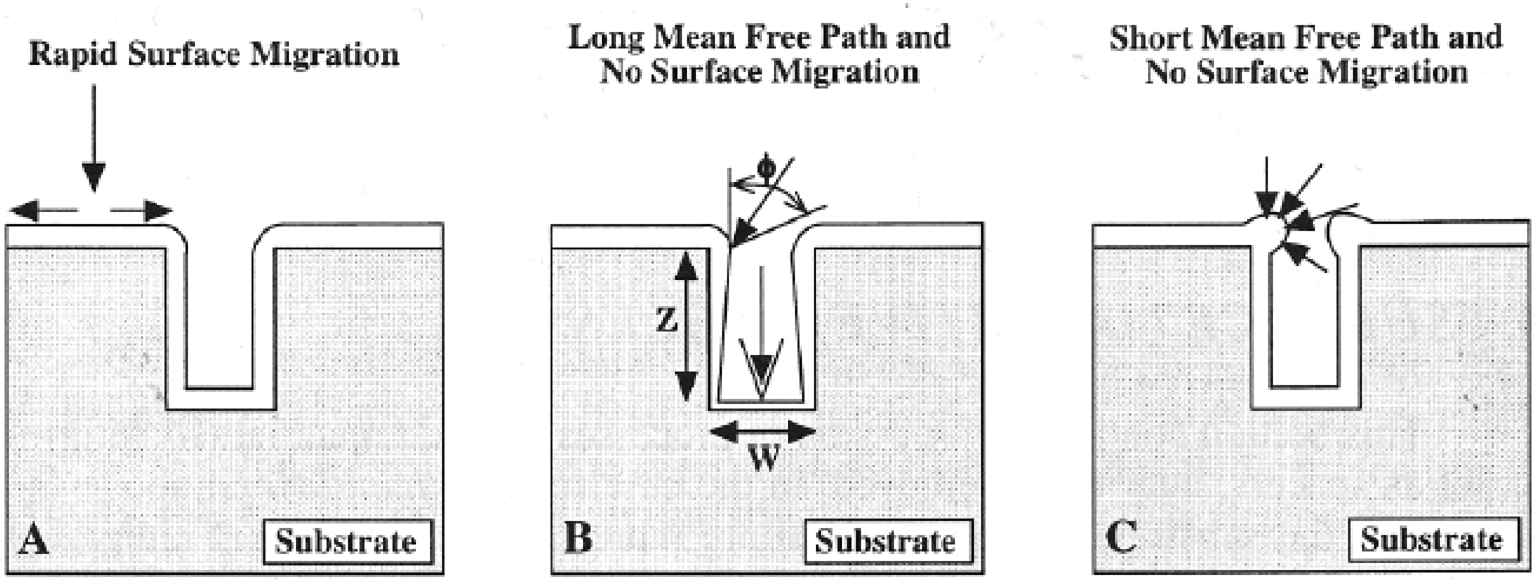
Growth rate vs. temperature

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

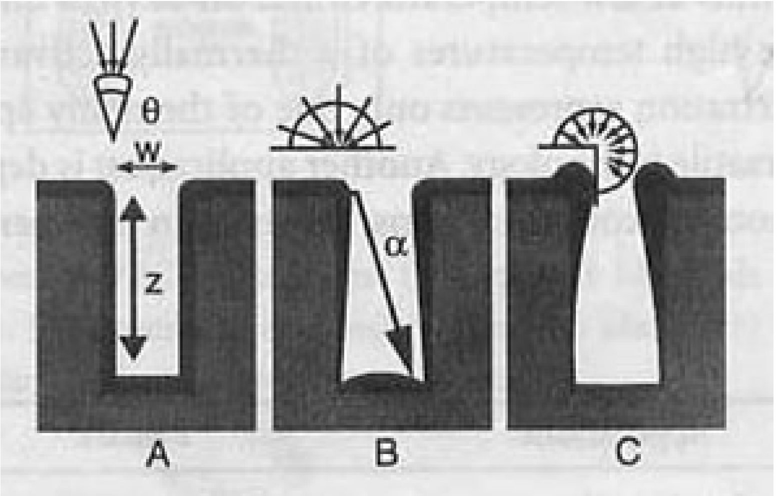
B: Long mean free path process and no surface migration, with reactant molecule arrival angle determined location on features (local “field of view” effects are important)

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 ∝ Temperature)
  - Arrival angle

- For conformal step coverage
  - $\alpha < l$ (mean free path)
  - $\alpha = \arctan(w/z)$
  - High Surface Mobility

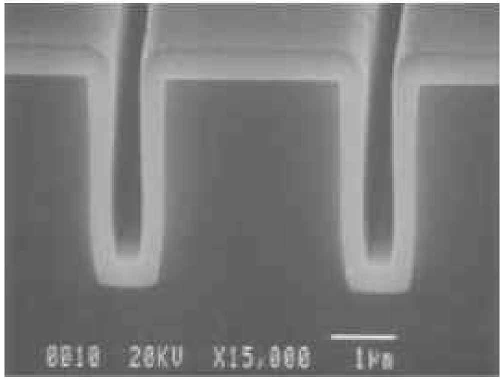


- Process tendency
  - A: LPCVD
  - B: PECVD

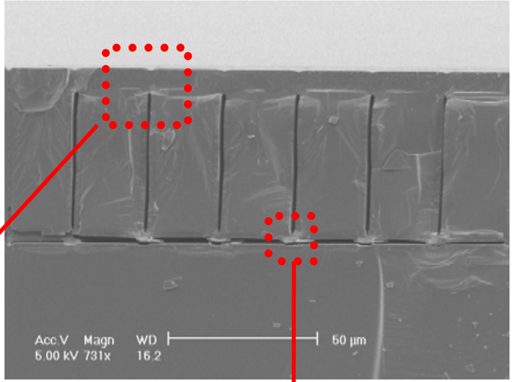
    Evaporated & Sputtered Metal

Step Coverage Profile (3)

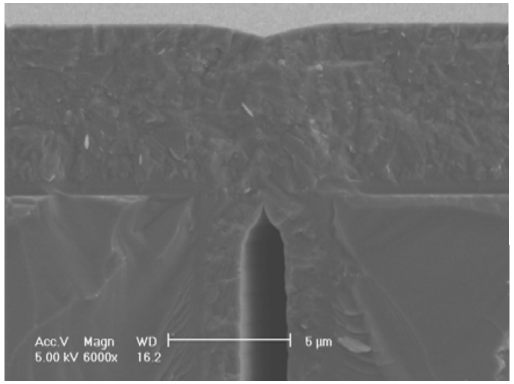
- Step coverage profile example

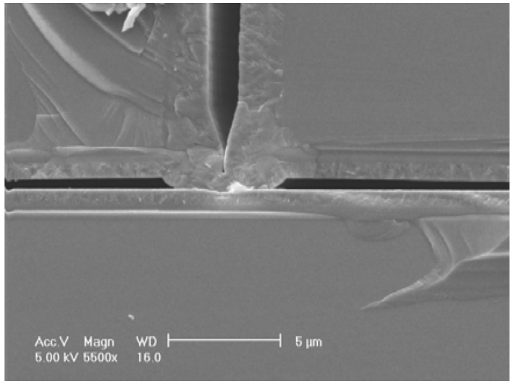


Good



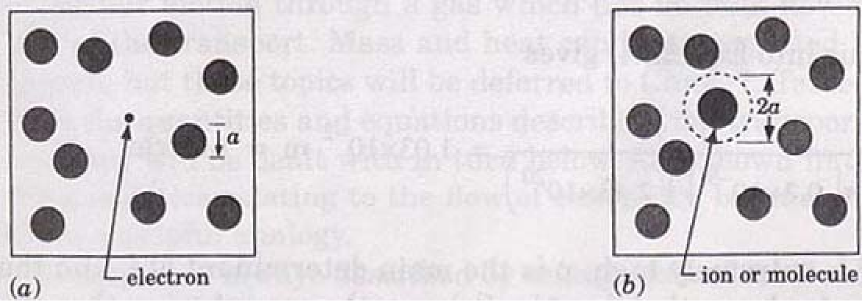
Bad





Step Coverage Profile (4)

- Mean free path



- Electron's & ion Mean Free Path

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

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

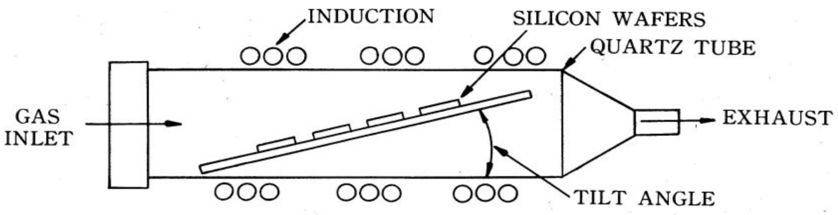
$$l = \frac{1}{\sqrt{2}\pi a^2 n}$$ (Considering mean speed of mutual Approach in Ion Mean Free Path)

$$n = \frac{pNa}{RT}$$ (Unless T is extremely high , p is the main determinant of l)

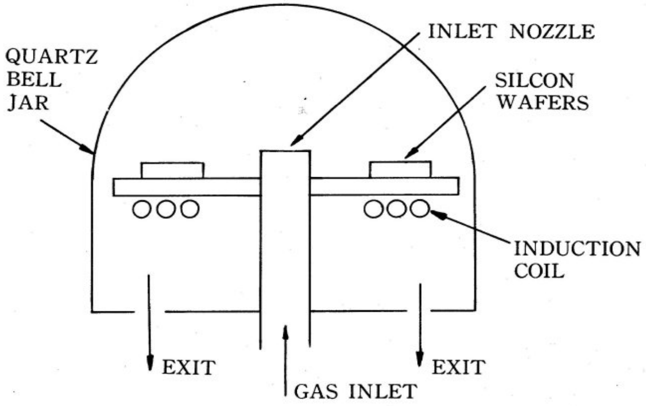
Knudsen number : $Kn = \frac{l}{L}$

Atmospheric Pressure CVD

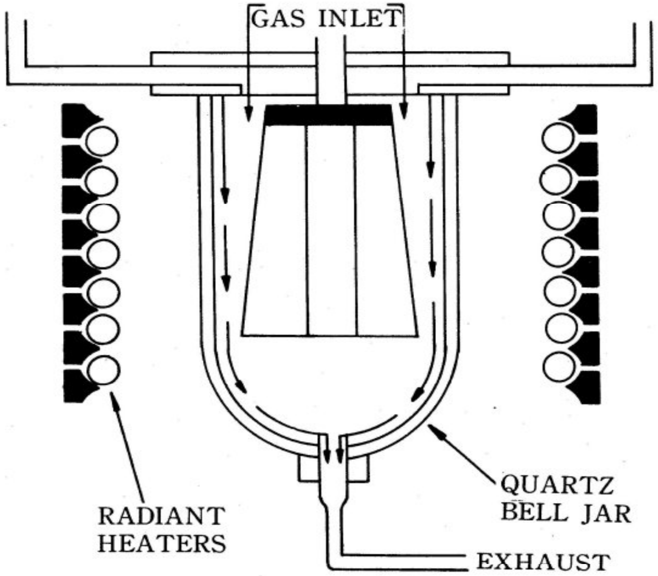
- APCVD (Atmospheric Pressure Chemical Vapor Deposition)
  - Material: epitaxial Si, poly-Si, Si_3N_4, SiO_2, etc.
  - Cold wall process



(a) INDUCTION HEATED HORIZONTAL REACTOR



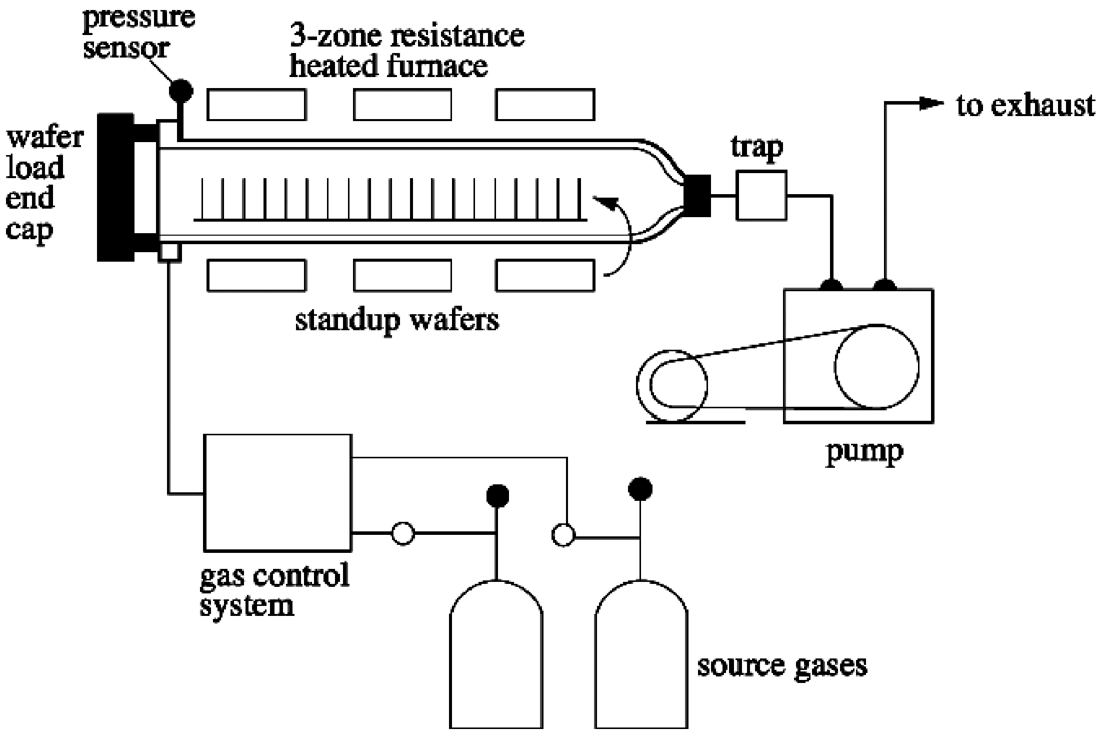
(b) INDUCTION HEATED VERTICAL REACTOR



(c) RADIANTLY HEATED CYLINDER REACTOR

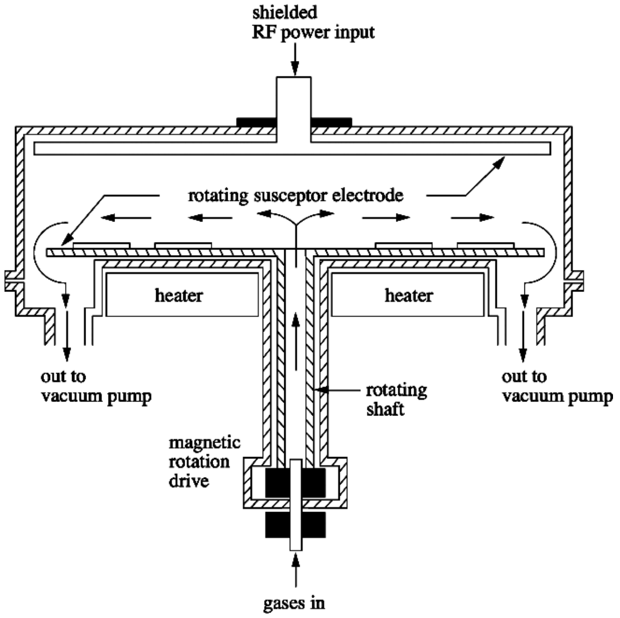
Low Pressure CVD

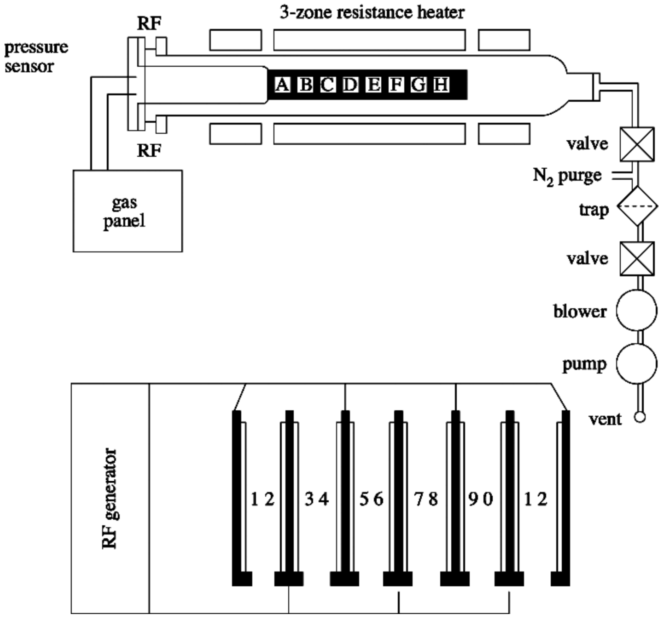
- LPCVD (Low Pressure Chemical Vapor Deposition)
  - Material: Si_3N_4, SiO_2, poly-Si, etc.
  - Good uniformity, property



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





PECVD (1)

- PECVD
  - Cold plasma
  - Low temperature deposition (< 300 °C)
  - High dep. rate
  - Inaccurate stoichiometry
  - Bad uniformity

PECVD (2)

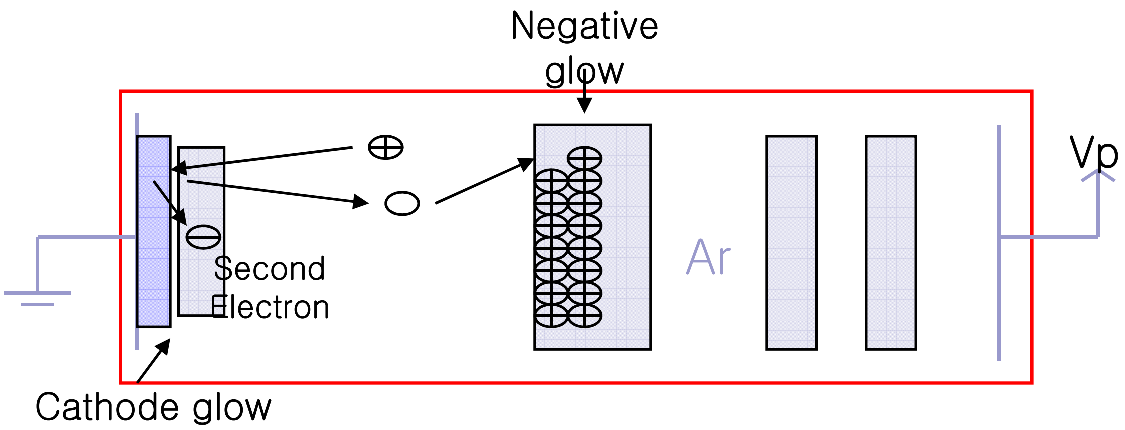
- PECVD process
  1. Reaction gas forming by glow discharge
  2. Diffusion of Precursor Molecules to Surface
  3. Adsorption of Precursor Molecules to Surface
  4. Decomposition of Precursor Molecules on Surface and Incorporation into Solid Films
  5. Recombination of Molecular Byproducts and Desorption into Gas Phase

PECVD (3)

- Plasma
  - Hot Plasma: Arc discharge
  - Cold Plasma: Low pressure glow discharge

PECVD (4)

- DC Glow Discharge



Plasma Condition :

- Energy of collision particle over the critical point
- Collision Number Between Particles
- Ionization process = recombination process

Cathode layer : Bombardment between accelerated ions and neutral gas by E-field
Second electron Generation

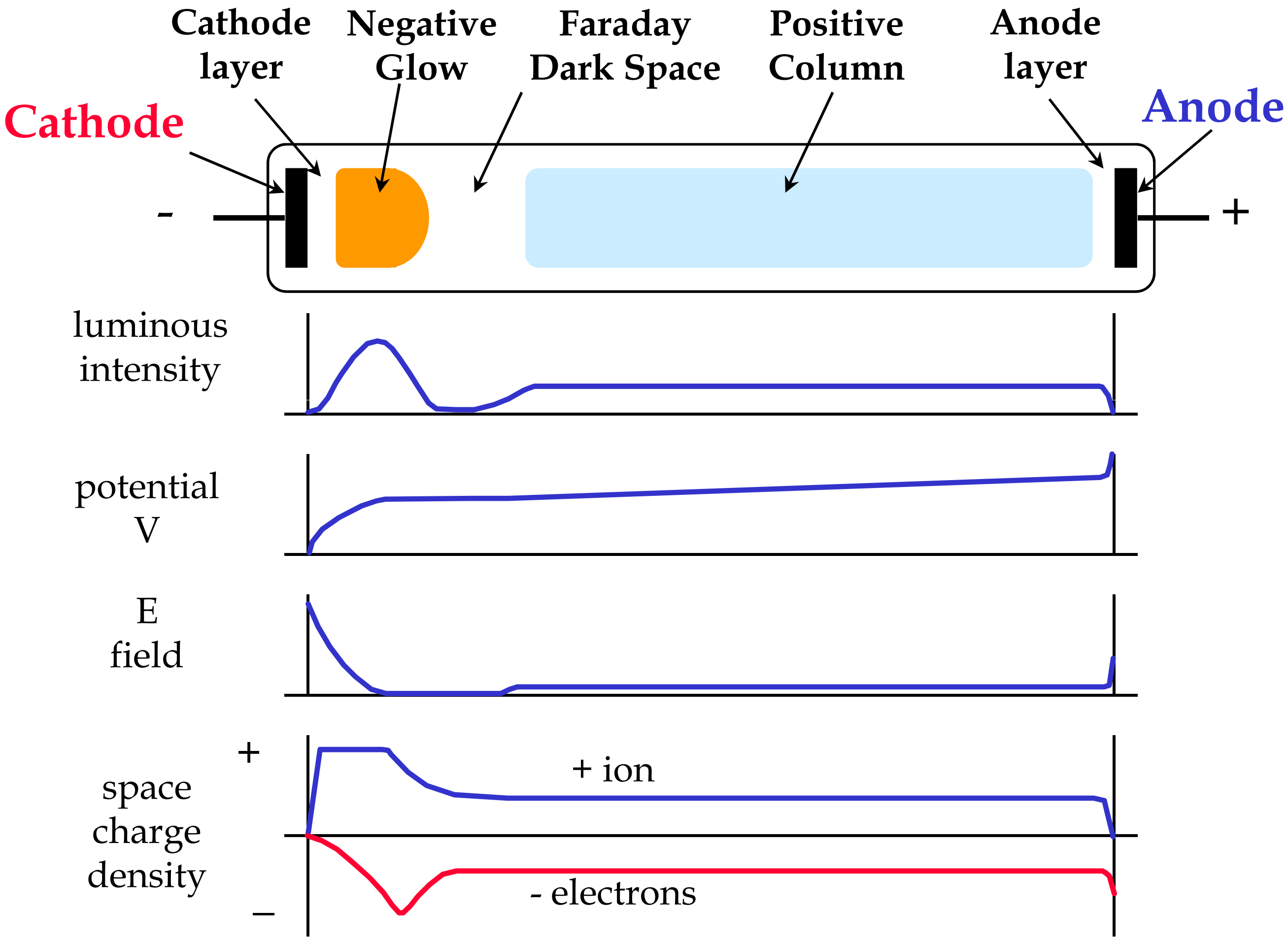
Negative Glow : Collision between accelerated electron/ neutralized atom and ion / atom

Typical parameter values for a glow discharge plasma

	Neutrals	Ions	Electrons
Mass	$6.6*10^{-23}$ g	$6.6*10-^{23}$ g	$9.1*10^{-28}$ g
Average Velocity	$4.0*10^{4}$ cm/sec	$5.2*10^{4}$ cm/sec	$9.5*10^{7}$ cm/sec

PECVD (5)

- DC Glow Discharge



PECVD (4)

- Glow discharge plasma
  - RF generation

$$V_p - V_f = \frac{kT_e}{2e}\log(MT_e / mT_i)$$

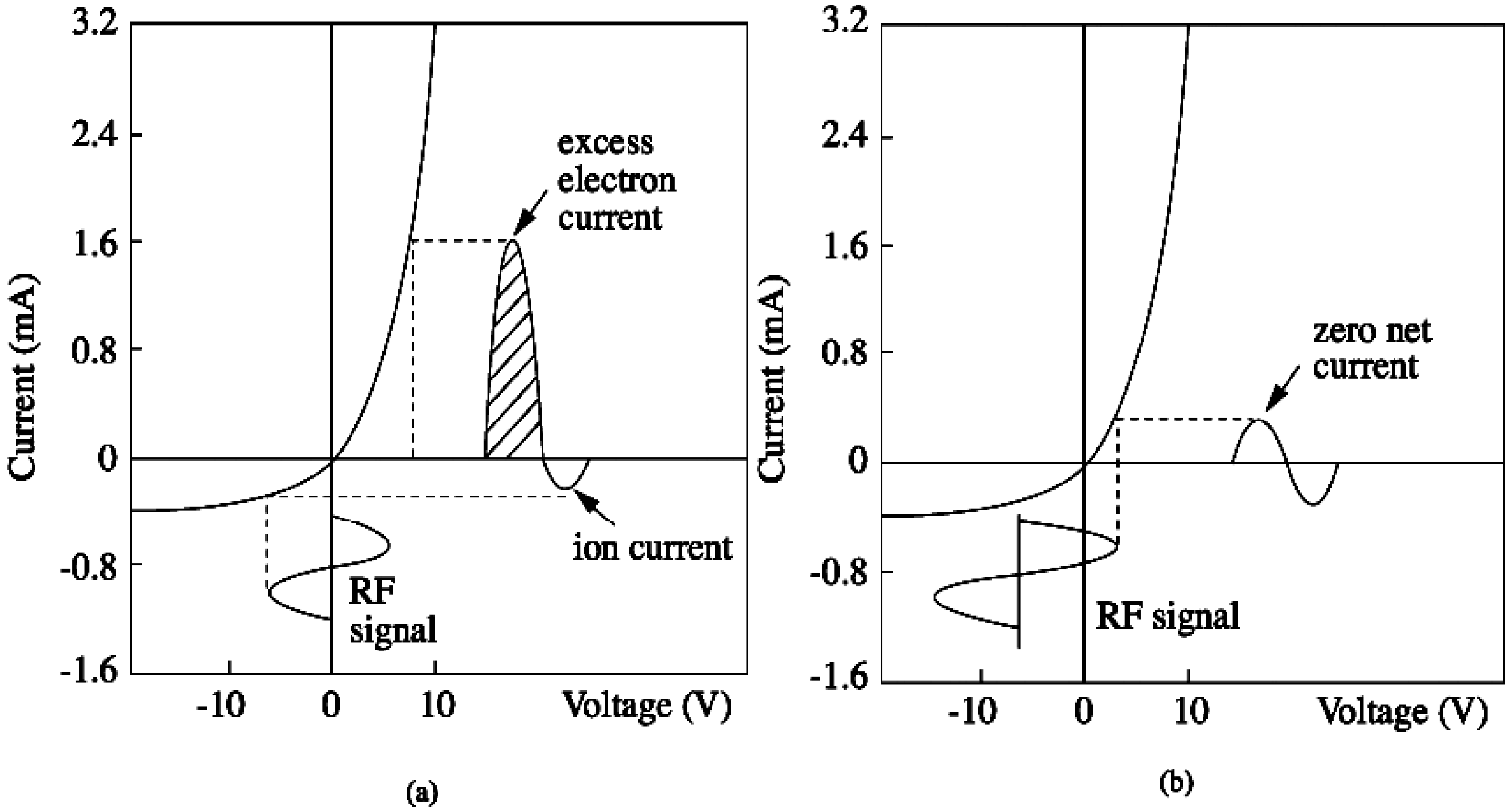
e : electric charge of electron
m: electron mass
T_e : electron temperature
M : ion mass
T_i : ion temperature
V_f : floating potential

  - Ion sheath (Dark Space)

: Area that ion is accelerated and negative ion is decelerated.

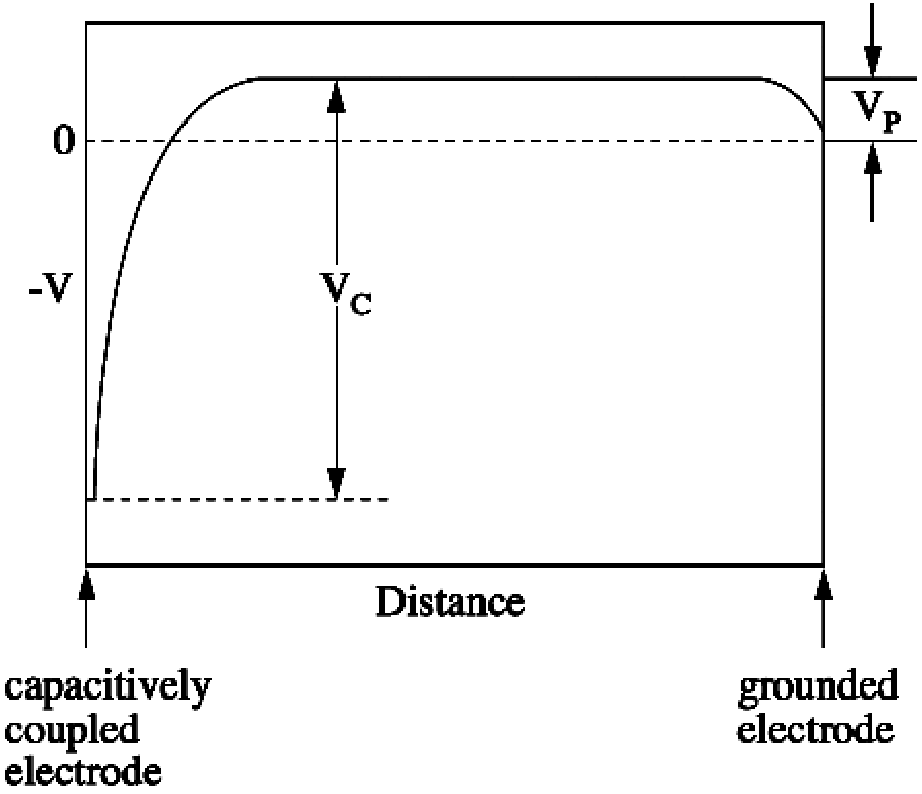
PECVD (5)

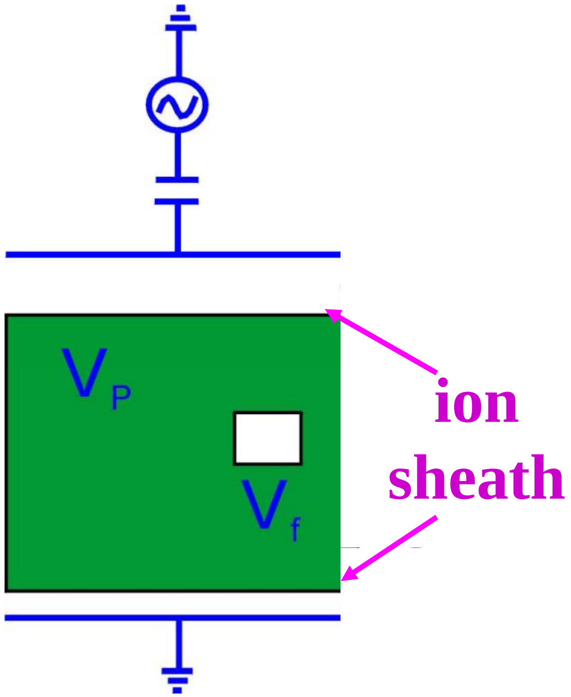
- I – V characteristic in RF glow discharge



PECVD (6)

- Charge distribution in RF glow discharge





Reference

- J.M. Bustillo, R. T. Howe, and R. S. Muller, "Surface micromachining for microelectromechanical systems ," Proceedings of the IEEE, Vol. 86, No. 8, pp. 1552-1574, 1998
- Marc J. Madou, "Fundamentals of MICROFABICATION," 2nd edition
- S. Lee, C. Cho, J. Kim, S. Park, S. Yi, J. Kim, and D. Cho, "The Effects of Post-deposition Processes on Polysilicon Young's Modulus," IOP J. of Micromechanics and Microengineering, Vol. 8, No. 4, pp. 330-337, 1998
- S. Lee, C. Cho, J. Kim, S. Park, S. Yi, J. Kim, and D. Cho, "Mechanical Properties of Phosphorus-doped Polysilicon Films", Journal of the Korean Physical Society, Vol. 33, pp. 392-395, 1998
- S. Lee, and D. Cho. "The Effects of Texture on the Young's Modulus of Polysilicon", 1998 MRS Spring Meeting, 1998.
- K. Lee, and Y Kim, "Uniformity Improvement of Micromirror Array for Reliable Working Performance as an Optical Modulator in the Maskless Photolithography System," Journal of Semiconductor Technology and Science, Vol. 1, No. 2, 2001

Reference

- G. Li, and A. A. Tseng, “Low stress packaging of a micromachined accelerometer,” Electronics Packaging Manufacturing, IEEE Transactions on, Vol. 24, No. 1, pp. 18-25, 2001
- P. Melvas, E. Kalvesten, and G. Stemme, “A surface-micromachined resonant-beam pressure-sensing structure,” Microelectromechanical Systems, Journal of , Vol. 10, No. 4, pp. 498-502, 2001
- K. Meng-Hsiung, O. Solgaard, R. S. Muller, and K. Lau, ”Silicon-micromachined micromirrors with integrated high-precision actuators for external-cavity semiconductor lasers,” Photonics Technology Letters, IEEE, Vol. 8, No. 1, pp. 95-97, 1996
- P. J. French and P. M. Sarro, “Surface versus bulk micromachining:the contest for suitable applications”, IOP J. of Micromechanics and Microengineering, Vol. 8, pp. 45-53, 1998
- Gregory T. A. Kovacs, “Micromachined Trensducers Sourcebook,” 1st edition
- J. D. Lee, “Silicon Integrated Circuit microfabrication technology,” 2nd edition

Reference

- http://chiuserv.ac.nctu.edu.tw/~htchiu/cvd/home.html
- http://www.plasmas.org
- Brian Chapman, "Glow Discharge Processes: Sputtering and Plasma Etching", John Wiley & Sons, 1980.
- Lieberman, "Principles of plasma discharges and materials processing" John Wiley & Sons, 1994