

Types :

1. Atmospheric Pressure CVD : APCVD
2. Low Pressure CVD : LPCVD
3. At. Pressure Low Temperature CVD
4. Plasma Enhanced CVD : PECVD
5. Atomic Layer Deposition : ALD
6. MBE : Molecular Beam CVD



CDEEP
IIT Bombay

EE 669 L 26 / Slide 13



CDEEP
IIT Bombay

EE 669 L 26 / Slide 14

In VLSI , we need to deposit

1. Dielectric Films : SiO_2, Si_3N_4, HfO_2 etc
2. Polysilicon Films : Self Aligned Gate and also for small Interconnect-
3. Metal films of Ti, W, Ta , Mo etc.

Further we also need At. Pressure CVD for growing Epitaxial Films.

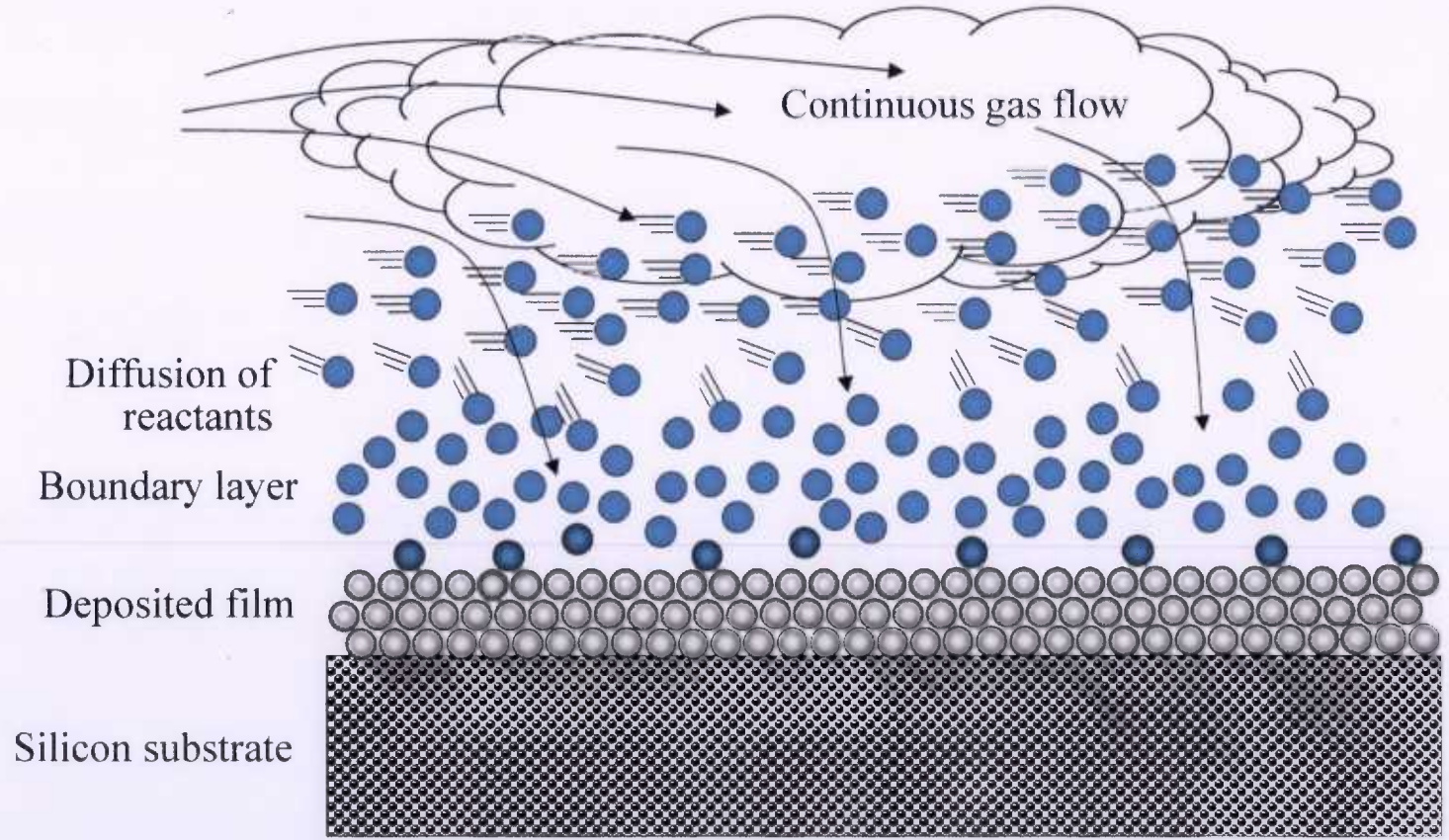
Thermal Budget and Quality of films desired decide the choice of Process.

CVD Chemical Reactions



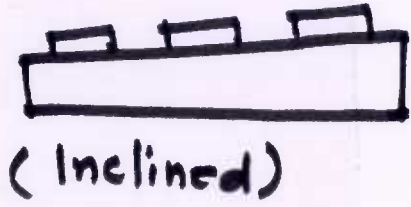
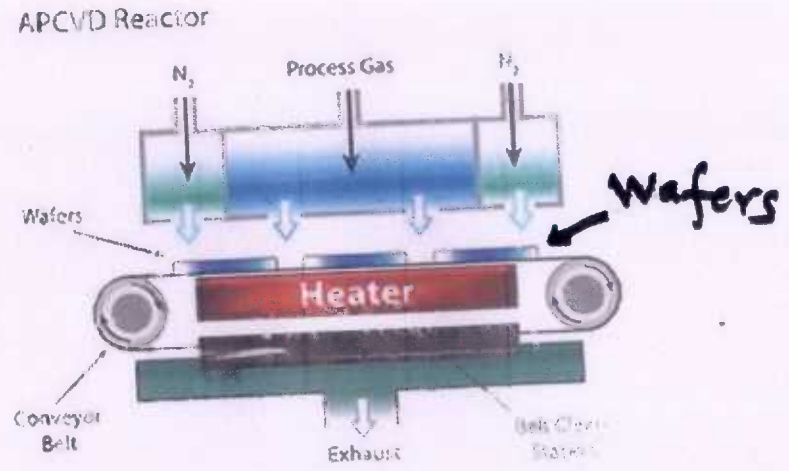
CDEEP
IIT Bombay

EE 669 L 26 / Slide 17





CDEEP
IIT Bombay



(copy from Dow Corning)

Steps in APCVD :-

- Ⓐ Reactants reaches deposition region where substrates are horizontally kept.
- Ⓑ From ambient Gas Stream the reactants diffused through ~~the~~ Boundary Layer (Stagnant layer)



CDEEP
IIT Bombay

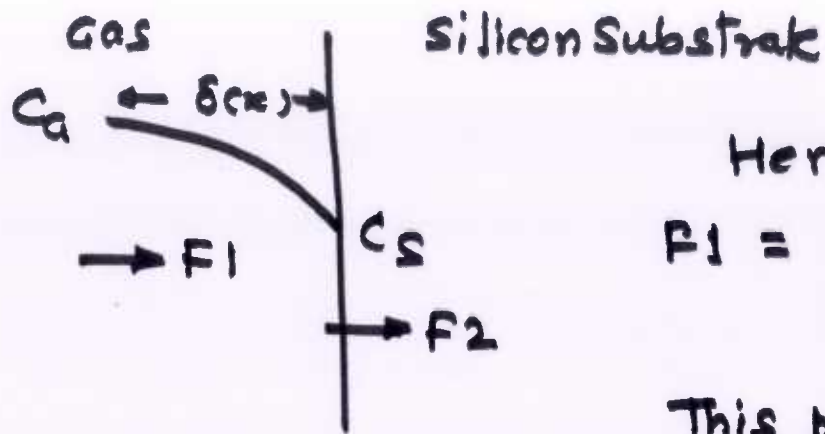
EE 669 L 26 / Slide 19

(c) Reactants are then adsorbed at water surface.

(d) Surface Reactions occur. Here chemical reactions take place, and deposition occurs conformally. Simultaneously emission and re-deposition too occurs.

(e) Unreacted reactants & Byproducts are desorbed. They transport through Boundary-Layer and are exhausted out of system.

We can have kinetics of such deposition, similar like Grove-Deal model for oxide growth.



Here

F_1 = Diffusion Flux of Reactant to the wafer

This process is Mass Transfer process



CDEEP
IIT Bombay

EE 669 L 26 / Slide 20

F_2 = Flux of Reactant consumed by surface reaction

Thus this process is Reaction rate limited

We have

$$F_1 = h_a (C_a - C_s) \quad h_a \text{ is Mass Transfer Coeff. (cm/sec)}$$

and $F_2 = k_s C_s$

In steady state $F = F_1 = F_2$



CDEEP
IIT Bombay

$$\text{or } h_a (C_a - C_s) = k_s C_s$$

$$\text{or } h_a C_a = (h_a + k_s) C_s$$

$$\text{or } C_s = \frac{h_a}{h_a + k_s} C_a = \frac{1}{1 + \frac{k_s}{h_a}} C_a$$

$$\text{or } C_s = \left(1 + \frac{k_s}{h_a} \right)^{-1} C_a$$

The Growth rate $V_y = \frac{u}{N}$

N is no of atoms incorporated on surface

$$\therefore V_y = k_s \left(1 + \frac{k_s}{h_a} \right)^{-1} \frac{C_a}{N}$$

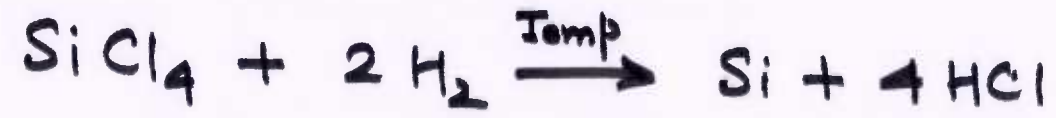
If C_T denotes conc. of all Molecules in Gas Phase, then C_a is fraction of C_T or Mole fraction $Y = C_a / C_T$



CDEEP
IIT Bombay

$$Y = \frac{C_A}{C_T} = \frac{P_A}{P_T} = \frac{P_{SiCl_4}}{P_{SiCl_4} + P_{H_2}}$$

Reaction used here is



$\Delta G = \Delta H - T \Delta S$ is Thermodynamic Statement.

The growth rate V_y is therefore written as

$$V_y = \frac{k_s h_a}{k_s + h_a} \cdot \frac{C_T}{N} \cdot Y \quad \left(\frac{1}{\frac{1}{k_s} + \frac{1}{h_a}} \right)$$

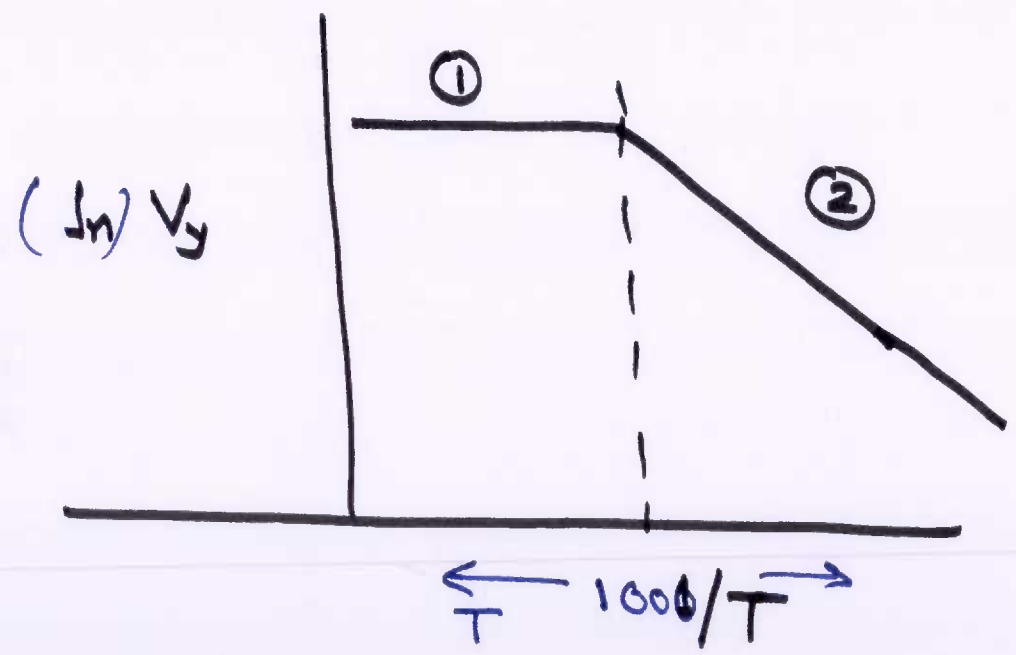
Two cases :- ① $k_s \ll h_a$, then $V_y = \frac{k_s C_T Y}{N}$ — (A)

② If ~~$h_a \ll k_s$~~ $h_a \ll k_s$, then $V_y = \frac{h_a C_T Y}{N}$ — (B)



CDEEP
IIT Bombay

Deposition rate V_y in CVD is a function of Temperature



① Mass Transfer Limited

② Reaction Rate Limited

We know reaction rate Constant

$$k_s = k_0 \exp(-E_s/kT)$$

or k_s is strong (exponential) function of T

However Mass Transfer Coefficient- h_c is

related to gas stream Pressure and its diffusivity through Boundary layer. Hence h_c is very weak function of Temp. and treated constant.

Clearly at Lower temperatures, we can have $k_s \ll h_c$

and V_y will show exponential temperature dependence.

However at higher Temperature $k_s \gg h_c$, and then

V_y becomes constant with temperature.

APCVD and LPCVD uses these two cases in their system



CDEEP
IIT Bombay

EE 669 L 27 / Slide 10

Epitaxial Deposition of Silicon on Silicon substrate, Epi layer is crystalline layer which is like crystal growth.



CDEEP
IIT Bombay

Epi growth often is carried at higher Temperature and hence deposition will be Mass Transfer Limited ($h_a \ll k_s$)

Here $h_a = \frac{D_a}{\delta}$

where D_a is Diffusivity of Gas in Boundary Layer δ

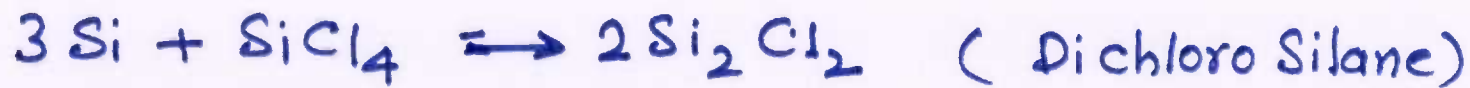
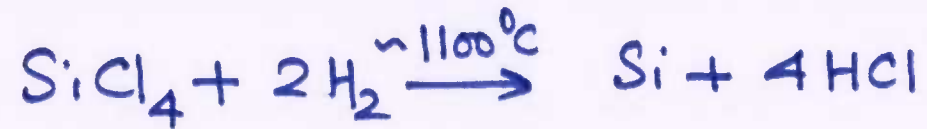
To keep δ constant, susceptor



wafers are kept on an inclined

This allows increased Gas velocity and hence reasonable const value of δ

Doping of Epi-film is easy as, one mixes dopant gas with SiCl_4 vapours.



CDEEP
IIT Bombay

EE 669 L 27 / Slide 12

In LPCVD case, the pressure of tube is reduced and that makes $k_s \ll h_c$. Hence Deposition is Temperature controlled

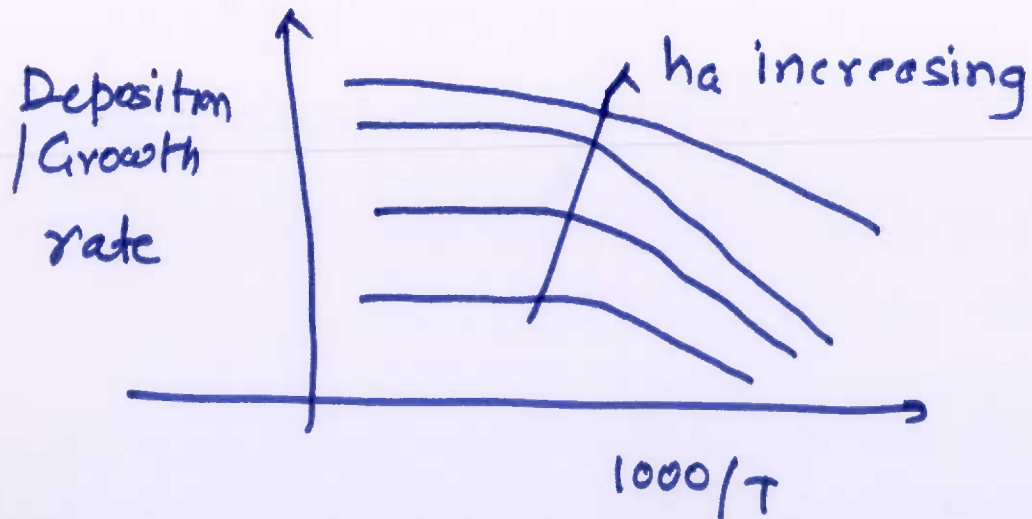


CDEEP
IIT Bombay

EE 669 L 27 / Slide 13

We have $h_c = \frac{D_a}{\delta}$; But $D_a \propto \frac{1}{P_{Total}}$

Clearly at low P_{Total} h_c is larger which allows $h_c \gg k_s$ possible.



We use Gas Laws to obtain condition of Process.

$$(a) D_a \propto \frac{1}{P_{Total}} ; D_a \propto T^{1.75} \rightarrow D_a \propto T^{0.5}$$

$$(b) \text{Viscosity } \mu \propto T^{2/3} \neq f(P_T)$$

$$(c) \text{ If } \rho \text{ is Atomic Mass Density } (P = \rho R T), \text{ then}$$
$$\rho \propto P_T ; \rho \propto T^{-1}$$

$$(d) \text{ Gas Stream Velocity } U \neq f(T) ; U \propto P_T^{-0.9} \approx \frac{1}{P_T}$$

Let P_T is reduced from 760 torr to 0.760 torr (1000 times) reduced

$$\therefore \frac{D_{a1}}{D_{a0}} = 10^3 ; \frac{U_1}{U_0} = \frac{C P_1^{-0.9}}{C P_0^{-0.9}} = \left(\frac{P_1}{P_0} \right)^{-0.9} \approx 500$$

$$\frac{\rho_1}{\rho_0} = 10^3 ;$$

$$PV = nRT$$
$$P = \rho R' T$$



CDEEP
IIT Bombay

EE 669 L 27 / Slide 14

As Gas Flows in a laminar fashion, one looks at the value of Reynold no. $R_L = \frac{\rho U L}{\mu}$ where L is length of subceptor.

$$\therefore \frac{R_{L0}}{R_{L1}} = \frac{\rho_0 U_0 L}{\mu} \cdot \frac{\mu}{\rho_1 U_1 L} = \frac{\rho_0}{\rho_1} \cdot \frac{U_0}{U_1} = 2$$

The Boundary layer $\delta = \frac{2}{3} \sqrt{\frac{L}{R_L}}$

$$\therefore \delta_0 = \frac{2}{3} \sqrt{\frac{L}{R_{L0}}} < \delta_1 = \frac{2}{3} \sqrt{\frac{L}{R_{L1}}}$$

$$\therefore \frac{\delta_1}{\delta_0} = \sqrt{\frac{R_{L0}}{R_{L1}}} = \sqrt{2}$$

$$\therefore \frac{h_{a1}}{h_{a0}} = \frac{D_{a1}}{D_{a0}} \cdot \frac{\delta_0}{\delta_1} = \frac{1000}{1.41} \approx 700$$

Hence if Pressure in system is reduced from 1 Atm to 760 millitor then h_a increases by around 700 times



CDEEP
IIT Bombay

EE 669 L **27** / Slide **15**

Hence it is imperative that h_a increase will make it possible to have $h_a \gg k_s$.

Similar analysis is done for Temperature of Deposition.

We have $D_a \propto \frac{1}{P}$ & $D_a \propto T^{1.75}$

$$\mu \propto T^{1/2} \quad (T^{0.66} \rightarrow T^{2/3})$$

$$l \propto P \quad ; \quad l \propto \frac{1}{T}$$

If Temperature lowers by factor of 2, we can show that

$$\frac{h_{a1}}{h_{a0}} = \frac{1}{2} \cdot 2\sqrt{2} = 1.41 \text{ times}$$

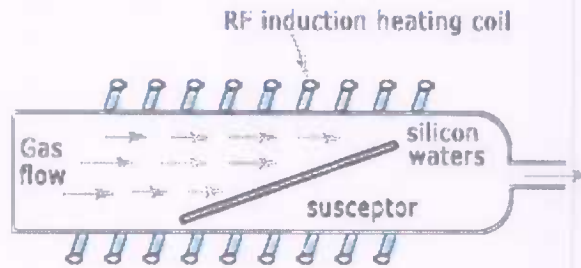
Hence h_a has weak Temperature dependence



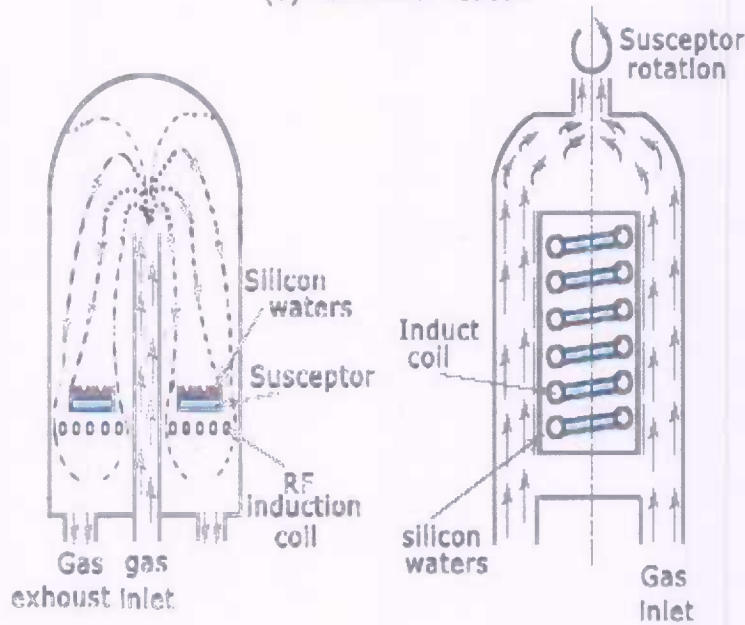
CDEEP
IIT Bombay

EE 669 L 27 / Slide 16

Epitaxial Reactors



(a) Horizontal reactor



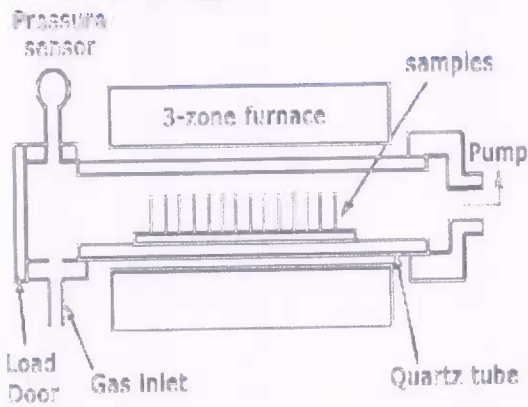
(b) Vertical reactor

(c) Cylindrical reactor

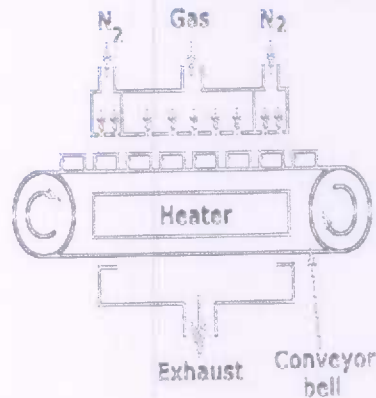
LP-CVD

CVD Reactors

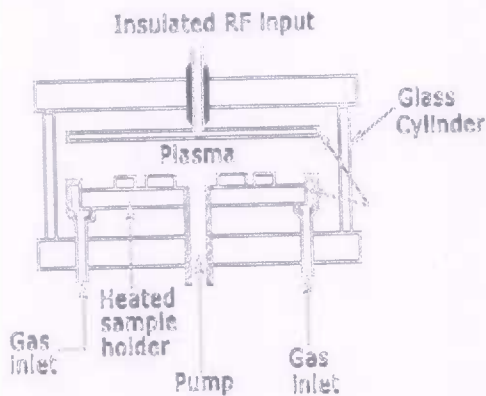
AP-CVD



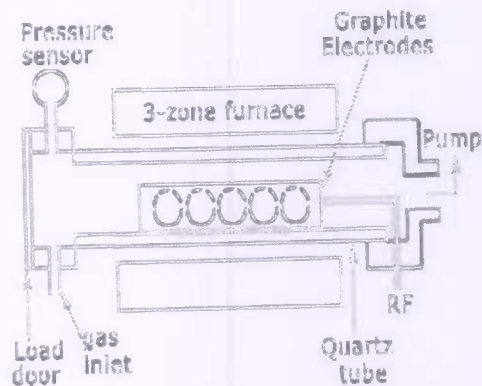
(a) Hot-wall reduced pressure reactor



(b) Continuous atmosphere pressure reactor



(c) parallel-plate plasma-deposition reactor



(d) hot-wall plasma-deposition reactor

www.CircuitsToday.com

PECVD

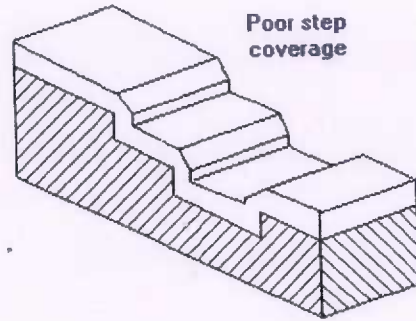
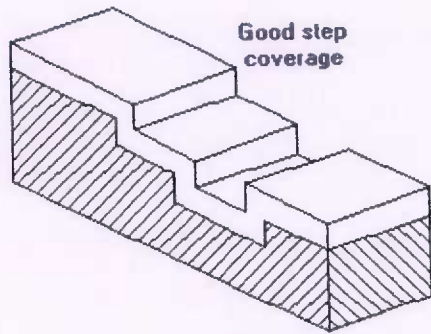
Low Temp - PECVD

AP-CVD :- Mass Flow Limited Deposition.
 Low Temp. depositions are ^{not} possible ($k_s \gg h_g$)
 (Hot wall plasma could be possible also)
 Wafers are kept horizontally flat.

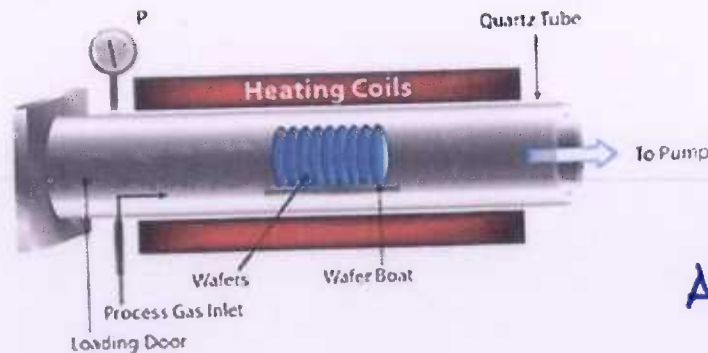
Adv :- Good Uniformity, Larger Dia Wafers

Disadvantages: High flow rates

LPCVD Depositions



LPCVD System



(Copyright Dow Corning Corporation, Midland, MI)



CDEEP
IIT Bombay

EE 669 L 27 / Slide 19

LPCVD used for SiO_2 , Si_3N_4 and Polysilicon films.

$T = 300^\circ\text{C}$ to 900°C

$P = 30 - 250$ Pascal

Vertical Wafers ; 5% accuracy

Advantages : Excellent Uniformity
Large Load (200-300 wafers)
Larger Dia. Wafers

Disadv. : - Low Deposition Rate
Toxic gases are required

Some details of Units

$$\textcircled{a} \quad 1 \text{ eV} = 1.6 \times 10^{-19} \text{ Joules} = 1.6 \times 10^{-12} \text{ ergs} \\ = 3.872 \times 10^{-38} \text{ calories} = 23.05 \text{ kcal/mol}$$

$$\textcircled{b} \quad 1 \text{ Joule} = 10^7 \text{ ergs}$$

$$\textcircled{c} \quad 1 \text{ gm cal} = 4.18 \text{ Joule}$$

$$\textcircled{d} \quad 1 \text{ Watt-sec} = 1 \text{ Joule} = 0.24 \text{ cal}$$

Pressure

$$\textcircled{a} \quad 1 \text{ Atm} = 760 \text{ mm of Hg} = 760 \text{ Torr} \\ = 1.013 \times 10^6 \text{ dynes/cm}^2 = 14.7 \text{ lbs/inch}^2$$

$$\textcircled{b} \quad 1 \text{ Torr} = 1333 \text{ dynes/cm}^2 = 133.3 \text{ Pascals}$$

$$1 \text{ Dyne/cm}^2 = 7.502 \times 10^{-4} \text{ mm. of Hg}$$

$$\textcircled{c} \quad 1 \text{ Pa} = 1 \text{ N/m}^2 = 0.0075 \text{ torr} \quad \text{d) } 1 \text{ Bar} = 7.502 \times 10^2 \text{ torr} \\ 1 \text{ Bar} = 10^6 \text{ dynes/cm}^2$$



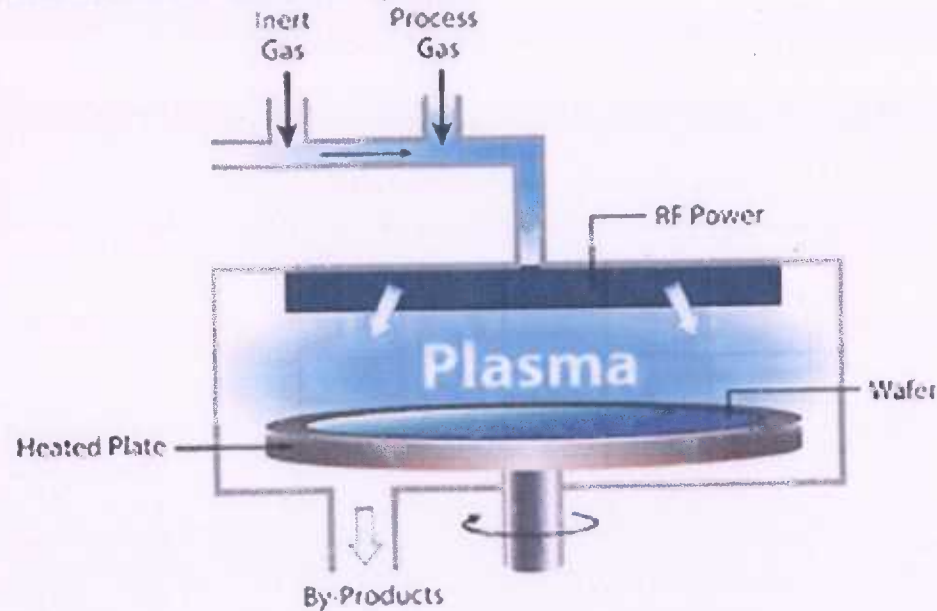
CDEEP
IIT Bombay



CDEEP
IIT Bombay

EE 669 L 27 / Slide 21

Plasma Enhanced CVD System



(Copyright Dow Corning Corporation, Midland, MI)

Advantages

- i Lower Pressure as Vacuum at lower temperature produces Uniformity of layer
- ii Multiple use of this System

Disadvantage

- i Many More variables to control
- ii Costly system.



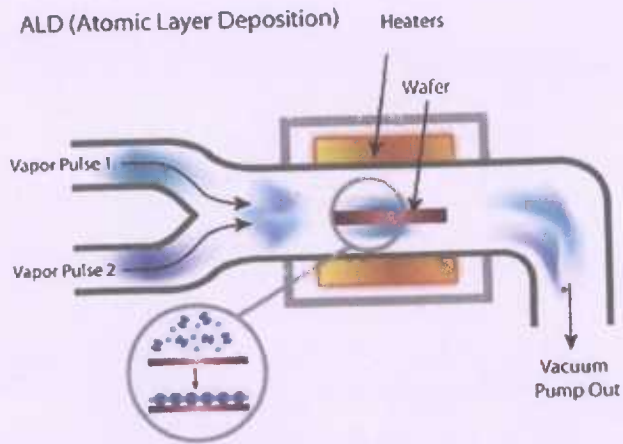
PECVD system



**CDEEP
IIT Bombay**

EE 669 L 27 / Slide 22

ALD System



(Copyright Dow Corning Corporation, Midland, MI)

In ALD, we have alternate cycles of Pulsing of Reactant gas and Purging of Unreacted Gas & byproducts. Steps are:

1. Pulse of Reactant Gas which is now at the Surface & Substrate
2. Purge excess Unreacted gas using Inert Gas
3. Pulse of a Second Precursor (Reactant gas) \rightarrow Reaction at Surface
4. Purge of Gaseous reaction by Products,



CDEEP
IIT Bombay

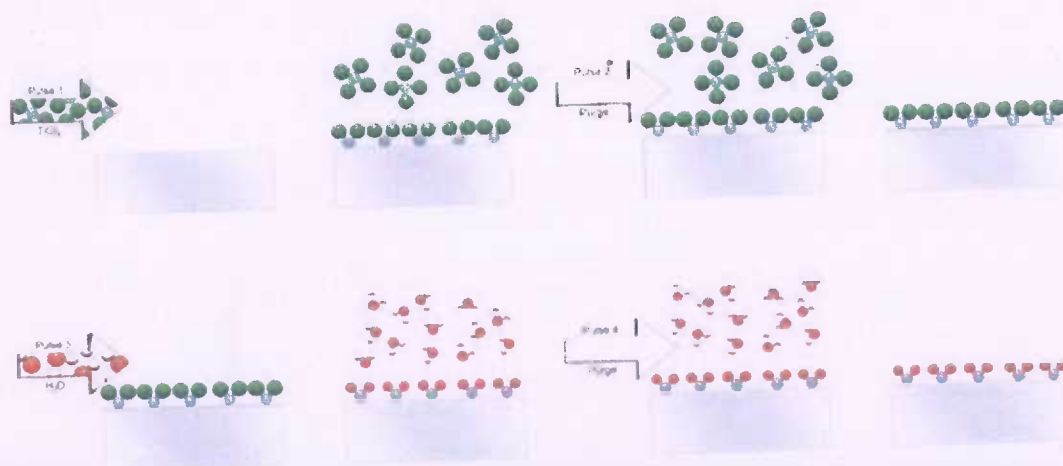
EE 669 L 27 / Slide 23



CDEEP
IIT Bombay

EE 669 L 27 / Slide 24

Atomic Layer Deposition



(Copyright Nanexa AB, Uppsala, Sweden)

Advantage

1. Accurate Thickness control on wide range
2. Large area Uniformity
3. Operates at Low Temp.
4. No Gas Phase reactions

Disadvantage

1. Low Deposition Rate
2. Reaction chemistry is complex
3. Poor Crystallinity due to Lower temp Deposition.



CDEEP
IIT Bombay

EE 669 L 27 / Slide 25

Etching in VLSI Processing

1. Wet Etching

2. Dry Etching

- Plasma Etching
- Reactive Ion Etching
- Sputter etch



L-28-32

Films to be etched :

- 1. SiO₂, 2. Si₃N₄, 3. Silicon, 4. Polysilicon

5 Metals like : Al, Ti, Mo, W, V & Copper

6 Alloys & compounds : TiO₂, TiN, silicides of Mo, Pt

EE 669 L 27 / Slide 26

A. Wet Etching



Poly is etched in ~~SiO₂~~: HF : HNO₃ : H₂O :: 6 : 100 : 40

(c) HCl + H₂O can etch Al

H₃PO₄ + HNO₃ + H₂O can etch Al.

In etching selectivity is major parameter to decide.

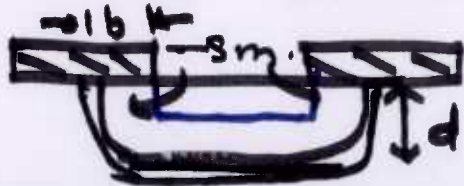
If r_1 is etch rate in film 1 and r_2 is the etch rate in film 2, then Selectivity

$$S = \frac{r_1}{r_2}$$

Higher the value of S , we can have ~~specification~~ specific film etched and other not affected.

Disadvantage of Wet Etching:

Wet Etching is Isotropic in nature and hence creates unwanted etched pattern.

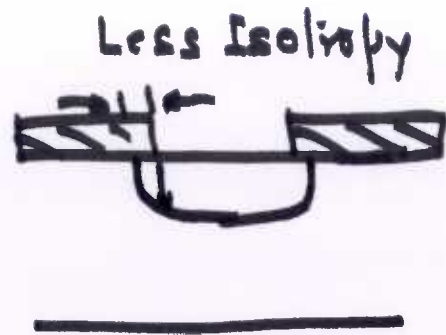
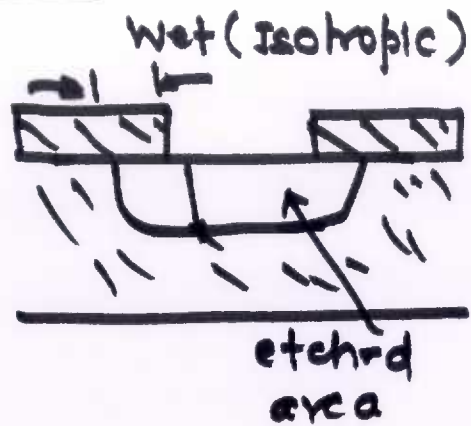


'b' is called Bias.



CDEEP
IIT Bombay

EE 669 L 27 / Slide 27



EE 669 L 27 / Slide 38

Anisotropy is defined as

$$A_f = 1 - \frac{\gamma_{\text{lateral}}}{\gamma_{\text{vertical}}} \quad \gamma \text{ is Etch rate}$$

From earlier figure if time of etching is t
then $b = \gamma_{\text{lateral}} \cdot t$ & $d = \gamma_{\text{vertical}} \cdot t$

$$\therefore A_f = 1 - \frac{b}{d}$$