

Ajay Kumar Gautam

Ast. Prof.

Electronics & Communication Engineering

Dev Bhoomi Institute of Technology & Engineering Dehradun



UNIT II



Syllabus

- **EPITAXIAL PROCESS:** Epitaxy and its concept, Growth kinetics of epitaxy, epitaxial growth, Low temperature epitaxy, Si-epitaxy- growth chemistry of Si epitaxial layer, auto-doping apparatus for epitaxial layer, apparatus for epitaxy, MBE system
- **DIFFUSION PROCESS:** Diffusion models of solid, Fick's theory of diffusion, Solution of Fick's Law, diffusion parameters measurements schemes,
- **ION IMPLANTATION:** Scattering phenomenon, range theory, channeling, implantation damage, ion-implantation systems, Annealing

Lecture Plan

UNIT-II EPITAXIAL PROCESS, DIFFUSION PROCESS, ION IMPLANTATION

1	Epitaxy and its Concept, Growth Kinetics of Epitaxy	1/55-63
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3	Auto-Doping Apparatus For Epitaxial Layer, Apparatus For Epitaxy	1/63-69
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EPITAXIAL PROCESS

Module 1



Epitaxy and its concept

- Epitaxy is the combination of 2 word.
 - Epi – upon
 - Taxis – ordered
 - It is the process of growing a thin crystalline layer on a crystalline substrate.
 - Epitaxial layer is always thinner than the substrate.
 - There is no chemical reaction between epitaxial layer & substrate layer.
 - 2 kind of epitaxy: Homo Epitaxy & hetero Epitaxy.
- 

Epitaxy

Homo Epitaxy


- Same material is grown on the substrate.
- Doping concentration & resistivity may be different.
- Ex: Si on Si.

Hetero Epitaxy

- Different material is grown in the substrate.
- Doping concentration & resistivity may/may not be different.
- Ex: GaAs on Si.



Techniques for Epitaxy

- In VLSI, there are 3 techniques to grow epitaxial layer.
 1. Liquid Phase Epitaxy (LPE)
 2. Vapor Phase Epitaxy (VPE)
 3. Molecular Beam Epitaxy (MBE)
 - In LPE & VPE, there are some chemical reactions involved but in MBE there is no chemical reaction involved.
 - MBE is a physical evaporation process.
 - In VPE, the material which we want to grow on the Si substrate must be in vapor form.
 - LPE mainly used to grow GaAs on Si.
- 



Epitaxial Growth

- The material which we want to grow on the substrate must be in vapor form.
- We use some gases & chemical reactants.
- Liquid with very high vapor pressure instead of gas may also be used.
- We have a graphite susceptor on which substrate (samples) are placed inside a reactor.
- Also, we have a flow of gas.
- The gas is containing the reactants.
- As the reactants flow over the samples, there will be deposition at the top of the samples.
- This process is called "***Vapor Phase Epitaxy***".

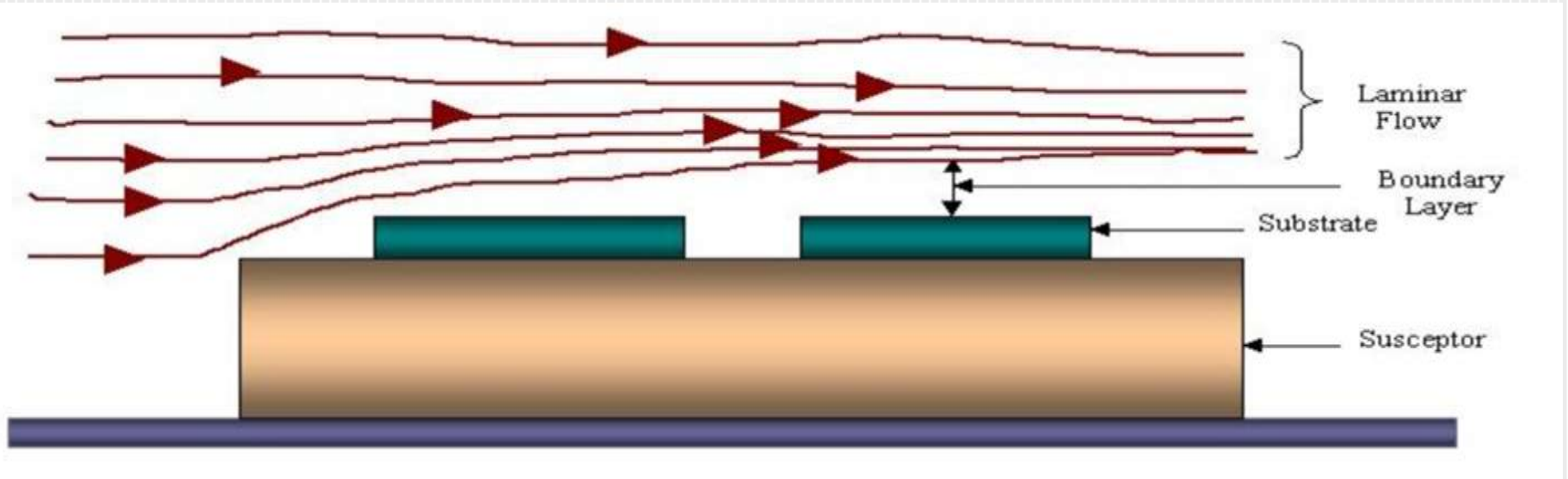


Fig: Growth Kinetics of Epitaxial Layer

- The material which we want to deposit is now on the samples.
- Samples are already present inside the reactor.
- The gas is flowing inside the reactor with a finite velocity.
- At the point of contact on the substrate, the velocity is zero.
- So, at other places the velocity of the gas is finite in the reactor.
- It means, inside the reactor the velocity of the gas at different regions is different.
- The velocity of the gas just right next to the first substrate is very low.
- It means reactants are not moving very fast.
- It means, we have a boundary layer.
- So for VPE the width of the boundary layer is very important.
- The flow of gas inside the reactor is characterized by Reynolds number R_e & is given by:

$$R_e = \frac{D_r v \rho}{\mu} \text{----- (1)}$$

- D_r is Diameter through which the gas is moving.
- V is velocity of the gas flow.
- ρ is the density of the gas.
- μ is the viscosity of the gas.

- Width of the boundary layer is related to the Reynolds number & is given by:

$$y = \sqrt{\frac{x\mu}{v\rho}} = \sqrt{\frac{D_r x}{\text{Re}}} \text{----- (2)}$$

- X is the distance along the reactor.
- From eq. (2), we can say that, when the gas moves along the reactor, the width of the boundary layer increases.
- Boundary layer means that the gas flow is not available there.
- So, if the boundary layer is varying from point to point, the growth rate will also vary from point to point.
- So, along the reactor on different substrates, we will have epitaxial layer of different thickness.

- The flux is the movement of the reactants in an unit area in an unit time &

is given by: $J_1 = \frac{D}{y}(N_G - N_S)$ ----- (3)

- ✓ N_G is reactant concentration in the gas.
- ✓ N_S is reactant concentration on the substrate.
- ✓ D is the diffusion constant.
- ✓ J is flux
- ✓ K_s is chemical reaction rate constant

- At the surface of the substrate the flux will be:

$$J_2 = K_S N_S$$
----- (4)

- Under steady state conditions, $J_1 = J_2$. So

$$\frac{D}{y}(N_G - N_S) = K_S N_S$$

$$N_s = \frac{N_G}{1 + \frac{K_s y}{D}} \text{----- (5)}$$

- Now consider the following cases:
- **Case 1:** when, $y \rightarrow 0, N_s \approx N_G$
 - ❖ It means, growth process will be dominated by surface chemical reaction.
- **Case 2:** when, $y \rightarrow \infty, N_s \approx 0$
 - ❖ It means, growth process will be dominated by diffusion.
- For uniform epitaxial layer, the boundary layer must be adjusted.
- The boundary layer can be adjusted by controlling the temperature & reactant concentration.
- By varying the thickness of the boundary layer, uniform epitaxial layer can be achieved.

Thickness of the epitaxial layer

- Since the boundary layer thickness is given by;

$$y = \sqrt{\frac{x\mu}{v\rho}}$$

- The y is the function of x; where, x is the path distance covered by the reactants.
- The epitaxial layer thickness is the average boundary layer thickness & is given by;

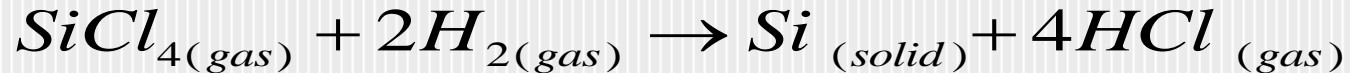
$$\bar{y} = \frac{1}{x} \int_0^x y dx$$

$$\bar{y} = \frac{1}{x} \int_0^x \left(\frac{x\mu}{v\rho} \right)^{1/2} dx$$

$$\bar{y} = \frac{2}{3} \sqrt{\frac{x\mu}{v\rho}}$$

Reaction chemistry of epitaxy

- Basically there are 4 Silicon sources used for epitaxial growth.
 - a) SiCl_4 – Silicon tetrachloride
 - b) SiHCl_3 – Trichlorosilane
 - c) SiH_2Cl_2 – Dichlorosilane
 - d) SiH_4 – Silane
- Out of these four, SiCl_4 is most widely used for industrial use.
- So, the overall reaction is the hydrogen reduction of the Silicon tetrachloride gas.



- During the epitaxial growth the Cl/H ratio remains constant because neither Cl nor H is incorporated into the epitaxial layer.



Cont...

- The epitaxial layer is growing it means, there is deposition of reactants (Si) from the gases on the surface of the substrate.
- The deposition rate is always –ve.
- The deposition rate is –ve; it means the concentration of the reactants outside the reactor is larger than that of at the reactor. i.e., $N_G > N_S$.
- It means reactants are moving from higher concentration region to lower concentration region.
- **So, epitaxial process takes place because of –ve deposition rate.**



Epitaxial Apparatus

- Basically we are having 3 reactors for epitaxial growth.
 - a) Horizontal reactor
 - b) Vertical reactor
 - c) Barrel reactor
- In **horizontal reactor**, we have an inclined sample holder as shown in fig.
- In this kind of reactor, we have parallel gas flow.
- In **vertical reactor**, gas flow is the normal to the surface of the sample.
- In vertical reactor, we can't place much more samples at a time.
- For mass production, the **barrel reactor** is used.

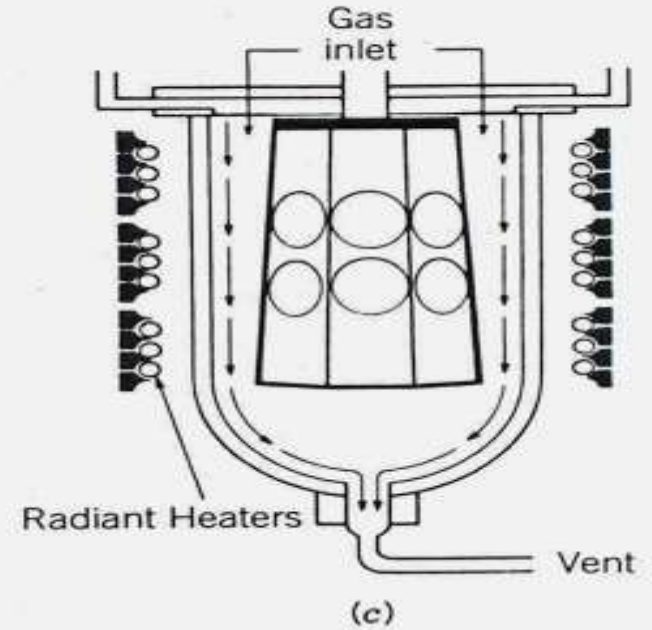
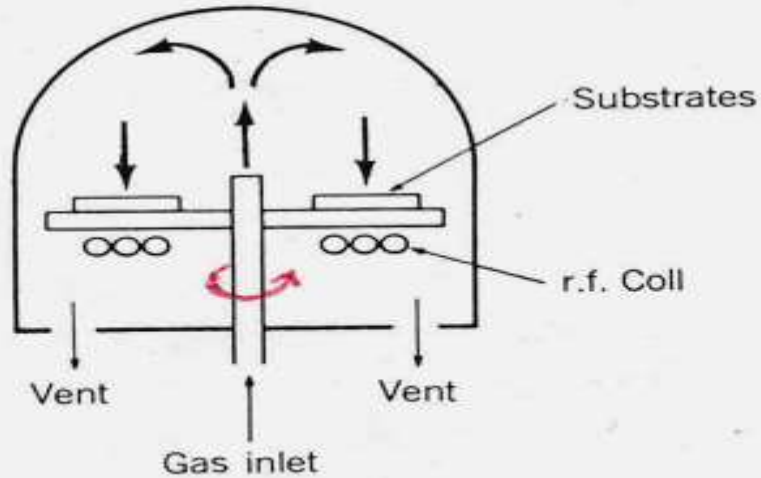
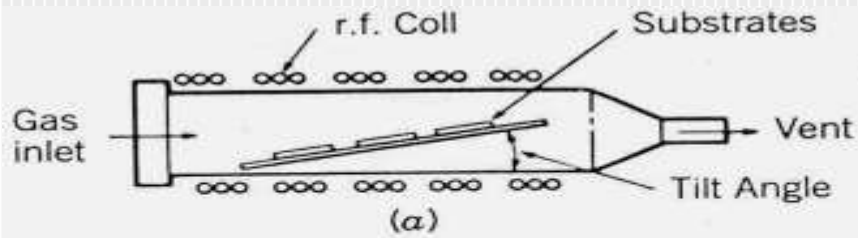



Fig: epitaxial reactors (a) horizontal (b) vertical (c) barrel



Cont . . .

- In this kind of reactor, the reactor the sample holder is a barrel or drum.
 - In this barrel, we are having small grooves.
 - In each of the grooves, the samples are placed.
 - The barrel can be rotate for uniform epitaxial growth.
 - The flow of the gas is parallel to the surface of the wafer.
 - In a barrel reactor, lot of samples can be placed in a same time.
 - Better growth can be achieved by rotating the barrel.
 - For the epitaxial reactor, there are **lot of steps**.
- 




Cont . . .

- **First step** is to filled up the reactor with hydrogen gas.
- Initially this hydrogen gas will clean the reactor. So, the hydrogen gas will react with the air & will form water.
- After that heating of the reactor is required through RF heaters.
- This will convert the water in vaporized form.
- After that the vaporized water can be taken out from the gas outlet.



Cont . . .

- **Next step** is to filled up the reactor with the silicon sources.
 - Growth process starts at a rate of $0.2 \mu\text{m}/\text{min}$ to $2.0 \mu\text{m}/\text{min}$.
 - When the epitaxial growth has completed, we need to shut off the power.
 - Remove the silicon sources & dopants.
 - Dopants may be n type or p type.
 - Reactor is cooled upto the ambient temperature.
 - Since the reactor may consist of some gases, so we need to filled up the reactor with some inert gases.
 - Usually the inert gas may be nitrogen, so that the reactor may be opened safely.
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Autodoping

- It is the process of transporting doping atoms from the substrate into the epitaxial layer.

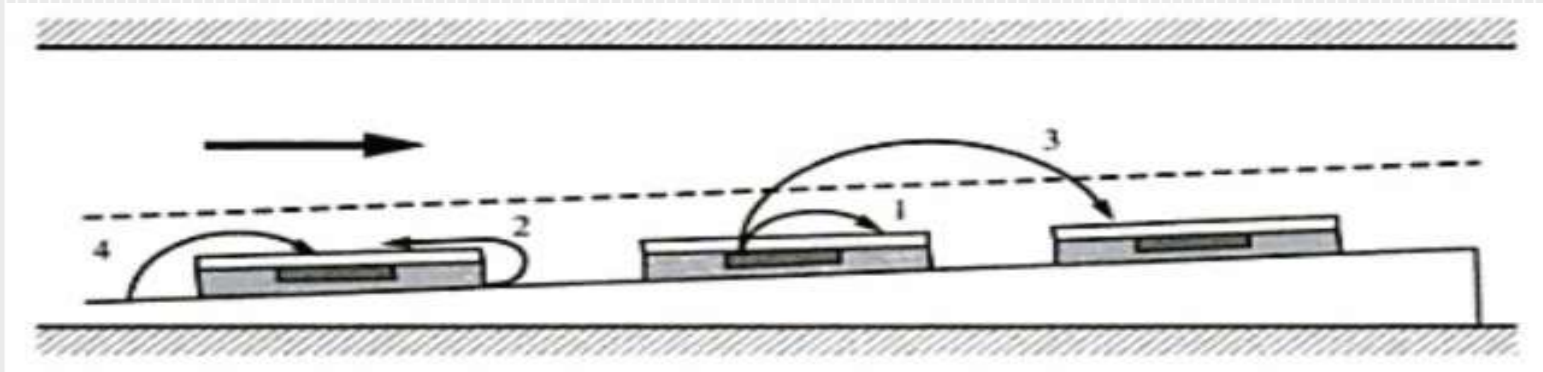
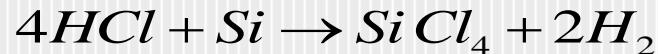



Fig: Auto Doping process in an epitaxial reactor
1 – wafer front side 2- wafer back side 3 – other wafer 4 - susceptor

- So, in auto doping unintentional dopants are incorporated from the substrate.
- This effect is called “**auto doping**”.
- These unintended impurities may come to the wafer from:
 1. wafer front side
 2. wafer back side
 3. other wafer
 4. Susceptor
- The auto doping can be removed by pre – epitaxial process inside the reactor.
- For this HCL etching takes place at 1200° C.





Low Temperature Epitaxy

- Epitaxial growth at low temperature is used to minimize the auto doping effect.
 - Lower epitaxial growth rate can be achieved even at low temperature.
 - Molecular Beam Epitaxy (MBE) is the example of low temperature epitaxy.
- 



Molecular Beam Epitaxy

- It is physical evaporation process, with no chemical reactions involved in it.
- The epitaxial layer, which we will be grown on Si substrate is usually Si in Silicon technology.
- The evaporation is done under very high vacuum condition.
- The heart of the MBE process is the ultra high vacuum pumping.
- After achieving the ultra high vacuum condition, next step is to evaporate the epitaxial species (Si).
- Since the Silicon (Si) has very high melting point, so it is very difficult the silicon by thermal heating.
- So, evaporation process of silicon is done with electron gun.

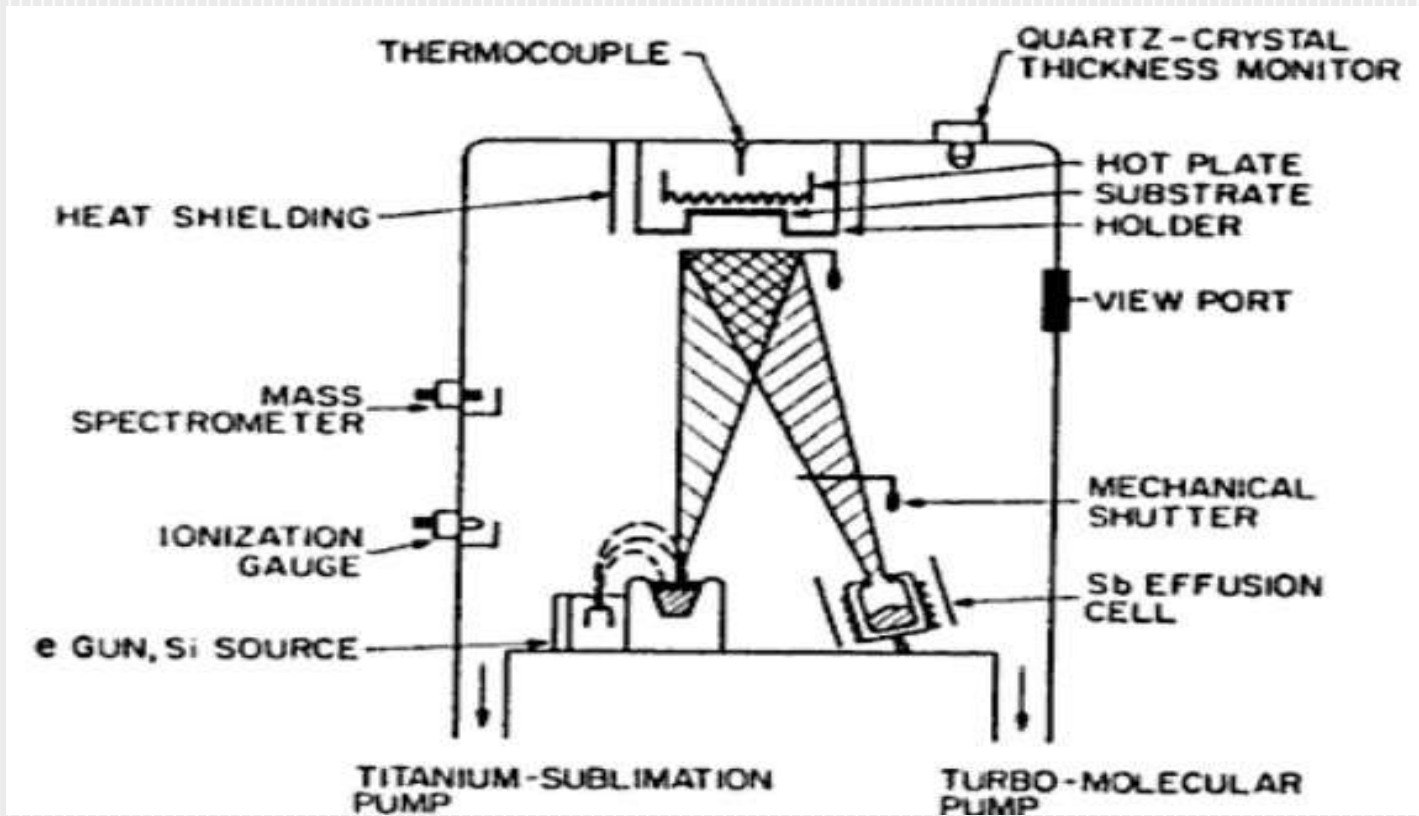


Fig: Molecular Beam Epitaxy (MBE) growth system

- The electron beam is focused on the silicon source, after that silicon is evaporated.
- In MBE system, we have 2 pumps.
- The pumps are used to achieve the ultra high vacuum condition.
- Also we have a silicon source.
- We have crucible in which the silicon is placed.
- e - beam is focused on the silicon source.
- From this silicon source, silicon is evaporated from the conical shape.
- Effusion cell is used to introduce the dopants.
- Effusion cell is the dopant holder, which is heated.
- There is a small opening at the mouth of the effusion cell, through which evaporated dopants come out.
- We have two shutters, these are controlled by microcontroller.
- The shutters are used to control the layer thickness and amount of dopants incorporated in the epitaxial layer.

- Sample holder supports the Silicon substrate.
- Additionally we have a heater and thermocouple.
- Thermocouple is used to measure the temperature of the substrate.
- Substrate temperature is usually kept 400°C to 800°C .
- So, we have the **following steps for MBE**.
 - 1) Create the ultra high vacuum condition with the help of pumps.
 - 2) Switch on the electron gun in order to evaporate the silicon.
 - 3) Heat the effusion cell in order to incorporate the dopant.
 - 4) Open the shutter at the top of two cones, dopants will be mixed with silicon.



Advantages of MBE over VPE

- 1. Low Temperature Process:** because of low temperature process, the auto doping effect can be minimized from substrate to epitaxial layer.
- 2. Precise Control of Doping:** this is because there is no chemical reaction involved. It is only physical evaporation process. Measured quantity of the dopants can be evaporated.
- 3. Growth Rate:** growth rate can be achieved as small as possible.
- 4. No Boundary (Stagnant) Layer Problem:** there is no boundary problem, so the growth rate is equal for all the substrate.



Disadvantages of MBE over VPE

1. Very costly equipment
2. Very complicated equipment



DIFFUSION PROCESS

Module 2

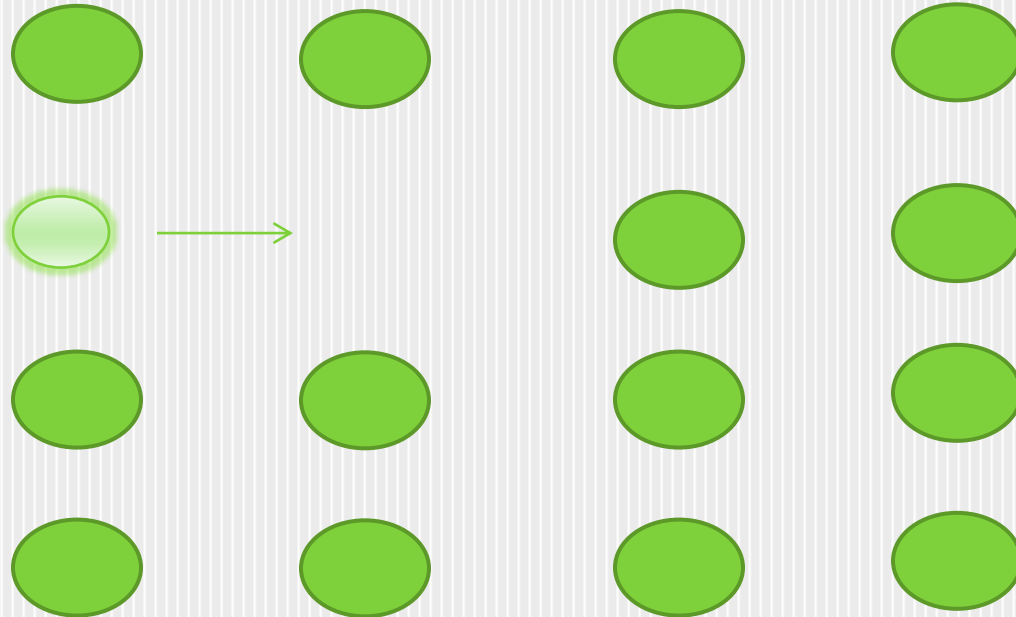


Diffusion Model of Solids

- Process by which controlled amount of impurities are introduced into the semiconductor.
- Impurities atoms moves inside the silicon crystal because a concentration gradient exists inside the crystal.
- Under this concentration gradient, impurity atoms move inside the crystal.
- If the crystal has lot of vacancies, then its very easy for impurity atoms to go inside and occupy the vacant space.
- Diffusion process may be divided into 3 categories.
 1. Substitution
 2. Interstitial
 3. Interstitialcy

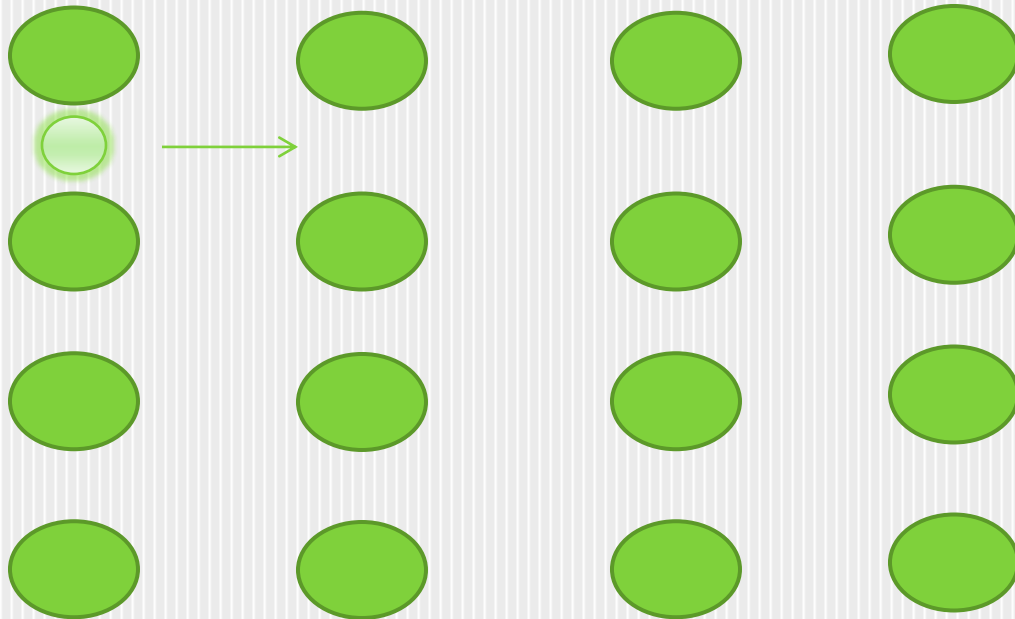
Substitution Diffusion

If the vacancy exists in the real crystal, so because of concentration gradient and vacancy, the dopant atom can now move into the vacant site.



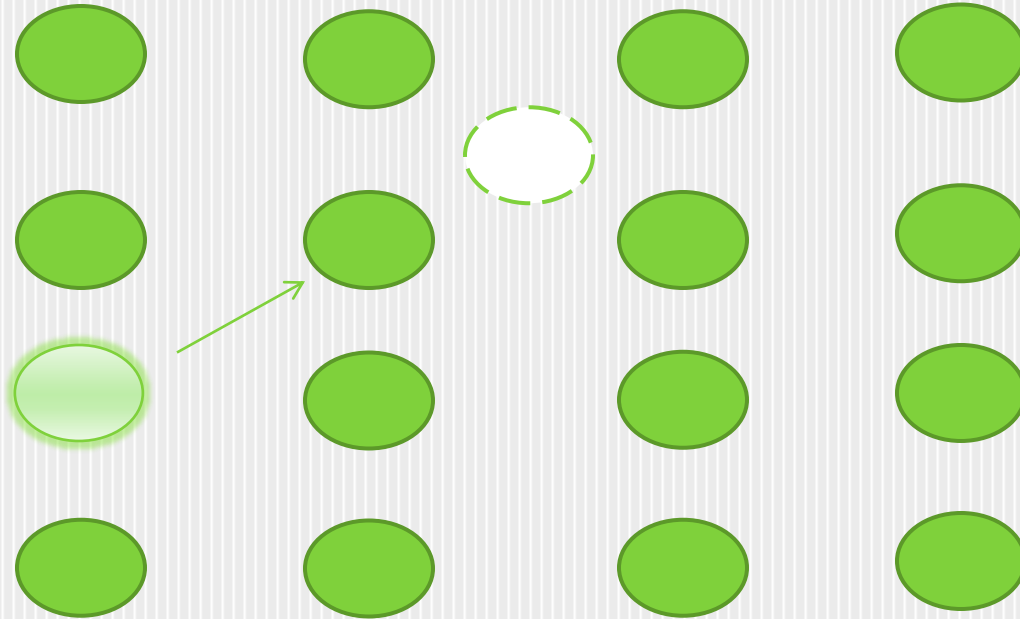
Interstitial Diffusion

The empty space in between the regular array of atom is known as **interstitial space**. The impurity atom will diffuse through the interstitial spaces available.



Interstitialcy Diffusion

If the interstitial diffusion is already done and, if the dopant atom try to push the host atom into the interstitial site.

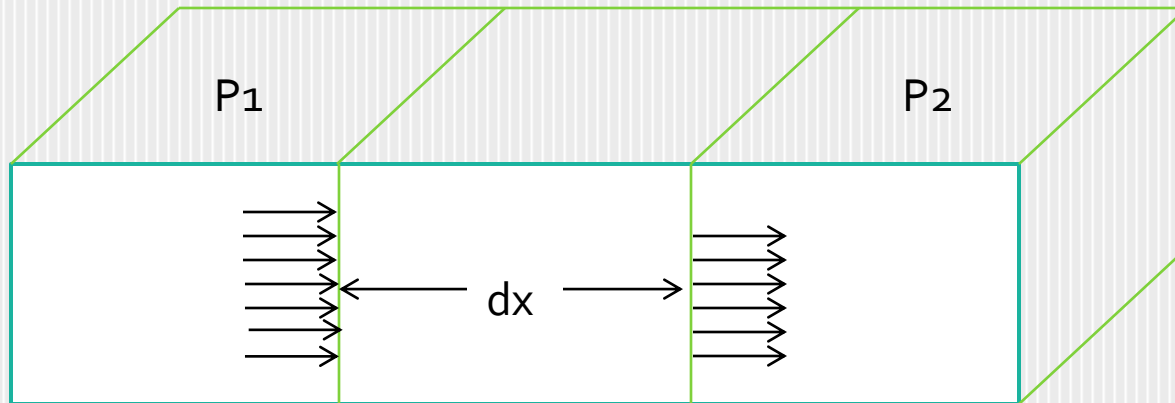


Fick's Law

- Fick's Law is given by:

$$J = -D \frac{\partial C}{\partial x} \text{----- (1)}$$

- J is flux & C is concentration of the dopants.
- This is called Fick's 1st Law.



- The movement of dopants is from higher concentration region to lower concentration region that's why -ve sign is used in eq (1).
- Imagine we have a crystal, in which dopant atoms are moving from left to right.
- P₁ & P₂ are the two planes in the crystal.
- The dopant atoms are crossing the plane P₁ & moving towards plane P₂.
- Let planes P₁ & P₂ are separated by a distance dx. then the rate of accumulation of dopant atoms in between these two planes is given by:

$$\frac{\partial C}{\partial t} \cdot A \cdot dx = A \cdot [j(x) - j(x + dx)]$$

- So,
$$\frac{\partial C}{\partial t} = - \left[\frac{j(x + dx) - j(x)}{dx} \right]$$

- For, small incremental distance, dx tends to 0; so

$$\frac{\partial C}{\partial t} = -\frac{\partial J}{\partial x}$$

- Now, put J from equation (1), we get;

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right) \text{-----} (2)$$

- Eq. (2) is the Fick's second Law. Now if diffusion coefficient is constant, then;

$$\frac{\partial C}{\partial t} = D \left(\frac{\partial^2 C}{\partial x^2} \right) \text{-----} (3)$$

- Eq. (3) is called Fick's second Law in simplest form.



Solution of Fick's Law

- The Fick's Law can be solved in the following ways. Let D is constant i.e., we have **Constant Diffusivities**.



Constant Diffusivities

- Three cases are there:
 - A. Constant surface concentration
 - B. Constant total dopant
 - C. Sheet resistance of a diffused layer

a. Constant surface concentration

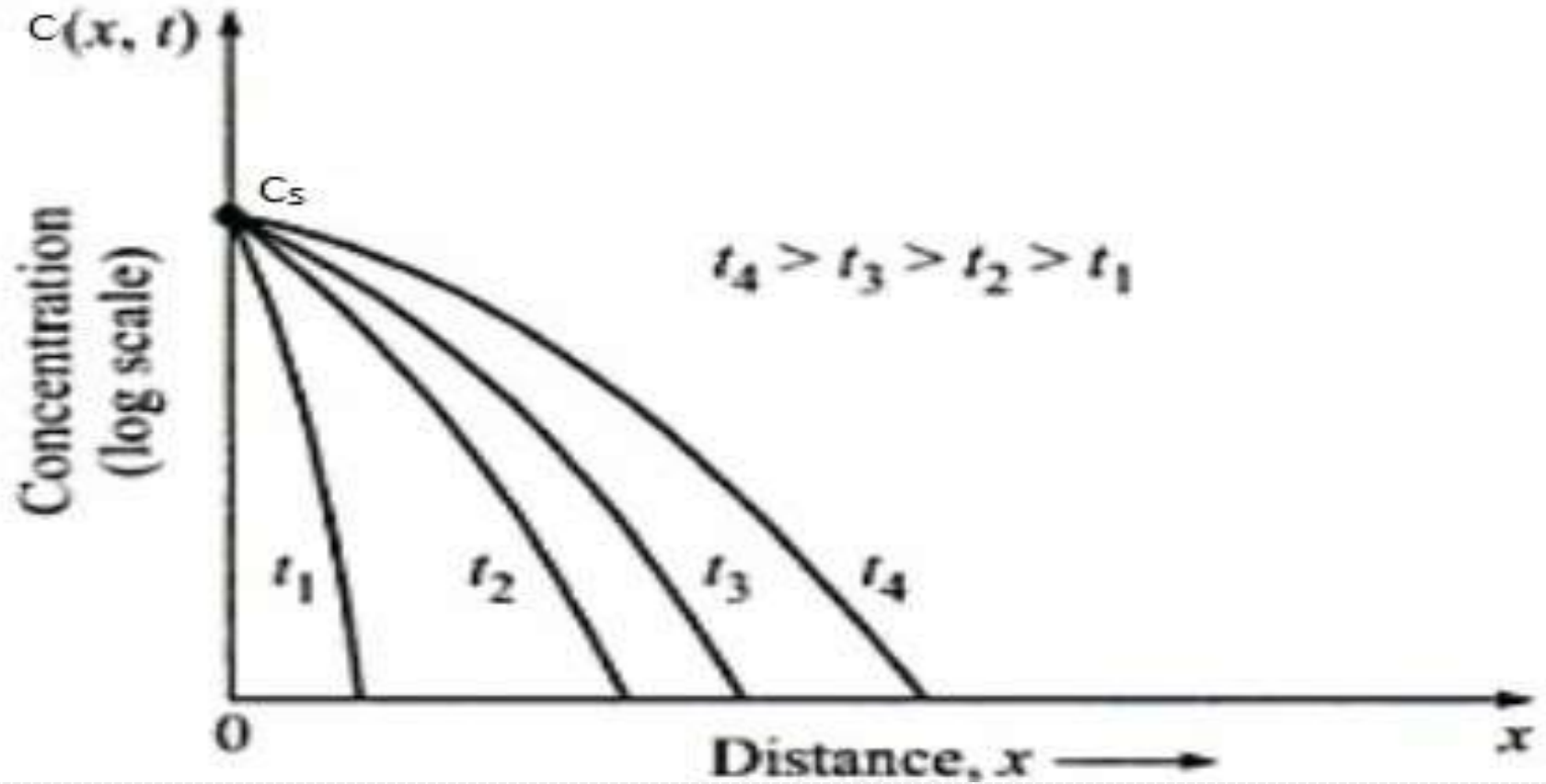
- Concentration of dopants at the surface of the substrate at $x = 0$ is; $C(0, t) = C_s$
- Concentration of dopants at the infinite distance will be 0;

$$C(\infty, t) = 0$$

- When diffusion starts, then doping concentration at the surface of the substrate will be 0, i.e., at $t = 0$ so; $C(x, 0) = 0$
- So, we have the following 3 conditions;

$$\left. \begin{array}{l} C(0, t) = C_s \\ C(\infty, t) = 0 \end{array} \right\} \textit{Boundary Conditions}$$
$$C(x, 0) = 0 \} \textit{Initial Condition}$$

- Where,
$$C(x,t) = C_s \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$$
- This is the solution of Fick's first Law in simplest form, that satisfies the initial and boundary conditions.
- erfc is complementary error function. Where,
- $\operatorname{erfc}(x) = 1 - \operatorname{erf}(x)$;
- See figure at next slide, at any time all the curves starts from the same surface doping concentration, i.e., C_s .
- Also Note that,
$$\begin{aligned} \operatorname{erf}(0) &= 0 & \operatorname{erf}(\infty) &= 1 \\ \operatorname{erfc}(0) &= 1 & \operatorname{erfc}(\infty) &= 0 \end{aligned}$$
- where,
$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-z^2} dz$$



- Lets us see how boundary conditions and initial conditions satisfy the solution.

$$\begin{aligned}
 C(x, t)_{at\ x=0} &= C(0, t) \\
 &= C_s \operatorname{erfc}\left(\frac{0}{2\sqrt{Dt}}\right) \\
 &= C_s \operatorname{erfc}(0) \\
 &= C_s (1 - \operatorname{erf}(0)) \\
 &= C_s \cdot (1 - 0) \\
 &= C_s
 \end{aligned}$$

$$\begin{aligned}
 C(x, t)_{at\ x=\infty} &= C(\infty, t) \\
 &= C_s \operatorname{erfc}\left(\frac{\infty}{2\sqrt{Dt}}\right) \\
 &= C_s \operatorname{erfc}(\infty) \\
 &= C_s (1 - \operatorname{erf}(\infty)) \\
 &= C_s \cdot (1 - 1) \\
 &= 0
 \end{aligned}$$

$$\begin{aligned}
 C(x, t)_{at\ t=0} &= C(x, 0) \\
 &= C_s \operatorname{erfc}\left(\frac{x}{0}\right) \\
 &= C_s \operatorname{erfc}(\infty) \\
 &= C_s (1 - \operatorname{erf}(\infty)) \\
 &= C_s \cdot (1 - 1) \\
 &= 0
 \end{aligned}$$

b. Constant total dopant

- At time $t = t_1$, the total amount of dopant atoms Q_T is given by the area under the curve as shown in figure (Slide 42);

$$Q_T = \int_0^{\infty} C(x, t) dx$$

- t is the time of diffusion;
- The longer the period of the diffusion, the more impurity will be introduced.
- As the D has unit of cm^2/s , so \sqrt{Dt} will have unit cm , & this quantity is called ***junction depth*** or ***diffusion length***.
- The amount of total impurity Q_T is given by
 - $Q_T = \int_0^{\infty} C(x, t) dx$
- At very large distance from the surface, i.e., very much deep inside the surface, the dopant concentration is zero so,
 - $C(\infty, t) = 0$
- At the beginning of the diffusion, i.e., at $t = 0$; dopant concentration on the surface will be zero so,
 - $C(x, 0) = 0$
- So, we have following 3 conditions;

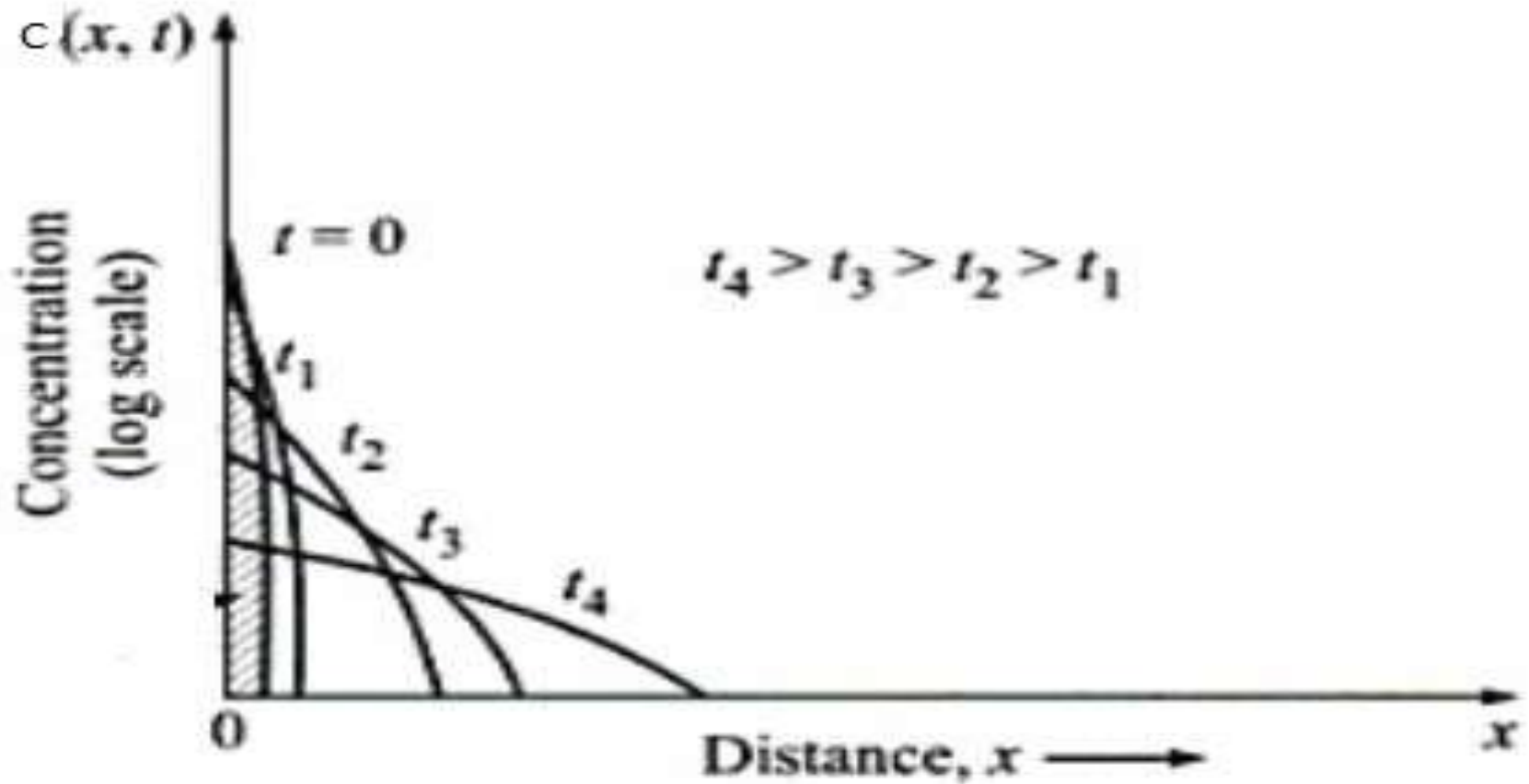
$$\left. \begin{aligned} \blacksquare C(\infty, t) &= 0 \\ \int_0^x C(x, t) dx &= Q_T \end{aligned} \right\} \text{Boundary Conditions}$$

$$C(x, 0) = 0 \} \text{Initial Condition}$$

- When, we solve Fick's Second law using these 3 conditions, we will have;

$$C(x, t) = \frac{Q_T}{\sqrt{\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right)$$

- This is Gaussian distribution function.
- See figure on slide 46.
- So, at $x = 0$, i.e., in the beginning of the diffusion, the dopant concentration at the surface is;
- $C_S = \frac{Q_T}{\sqrt{\pi Dt}}$, where $Q_T = \text{Total impurity in atoms/cm}^2$.



c. Sheet Resistance of a Diffused Layer

- The average sheet resistance R_s of a diffused layer is given by;

$$R_s = \frac{1}{q \int_0^{x_j} \mu C(x) dx}$$

- Where,
 R_s is sheet resistance
 X_j is junction depth
 μ is majority carrier mobility
 $C(x)$ is impurity distribution



Diffusion Parameters Measurements Schemes

- Four point Probe Method
- Vander Pauw Technique



Four Probe Point Method

- Already discussed during crystal growth

Vander Pauw Technique

- It is used to measure the sheet resistance of a sample for an irregular shape.
- It has four contact points along the periphery of a sample.
- The current is flowing into two adjacent contacts.
- The voltage is measured across other pair of contacts.
- The resistivity of a sample is, $\rho = \frac{\pi d}{\ln 2} \left(\frac{R_{12,34} + R_{23,41}}{2} \right) F(Q)$
- $F(Q)$ is correction factor, for square sample it is 1.
- d is the sample thickness.
- $Q = R_{12,34} / R_{23,41}$



ION IMPLANTATION

Module 3



Introduction

- Process of introducing energetic impurity atoms into substrate in order to change its conduction properties.
- During this process, an energetic ion beam of dopants is injected onto the surface of the substrate.
- Dopants have sufficient energy to penetrate the substrate to go inside.
- Dopants atoms are highly energized, they enter the substrate, collide with the silicon atoms, and gradually lose their energy.
- Finally dopant atoms come to the rest at some depth within the regular array of silicon.
- The average depth can be controlled by adjusting the acceleration energy of the dopants.




Advantages of Ion implantation

1. Less prone to contamination
2. Better control of total impurity
3. Low temperature process
4. Better flexibility



1. Less Prone to Contamination

- Major consideration in the **diffusion** are contamination.
 - For diffusion boron & phosphorus, same furnace can't be used.
 - Because inside the furnace, there will be lot of contamination.
 - Also same push rod can't be used for diffusion.
 - While, in **ion-implantation** is much less prone to contamination.
 - The same system can be used to implant various dopants.
 - **Ion-implantation is done under high vacuum condition.**
 - The high vacuum system is much more clean.
 - Because in order to create high vacuum condition, the contamination are pumped out.
- 



2. Better Control of Total Impurity

- In **Diffusion**, the control of doping profile is usually within 5% to 10% of the predicted value.
- It is because ambient conditions can't be adjusted accurately.
- In **ion implantation**, the control of doping profile is within -10% to +10%.
- It is because, in ion implantation, an ion beam is directed on to the surface of the substrate.
- So, the doors of the ion beam can be adjusted by simply adjusting the ion beam flow.

3. Low Temperature Process

- **Diffusion** is a high temperature process (**800 °C – 1200 °C**).
- So, for **diffusion**, **SiO₂** can be used as mask.
- While the ion implantation is **room temperature process**.
- But in **ion implantation photoresist** only can be used as mask.
- So, the thermal budget is reduced in ion implantation.

4. Better Flexibility

- In **diffusion**, surface concentration is given by $C_S = \frac{Q_T}{\sqrt{\pi D t}} = \frac{Q_T}{x_j \sqrt{\pi}}$ i.e., C_S is inversely proportional to the junction depth.
- It means, if the surface concentration is high, then we will have shallow junction.
- If the surface concentration is low then the junction depth will be large.
- So, it is not possible to form shallow junctions when we have low surface concentration.
- In **ion implantation**, ion dose and ion energy determines how deep the ions will go inside the substrate.




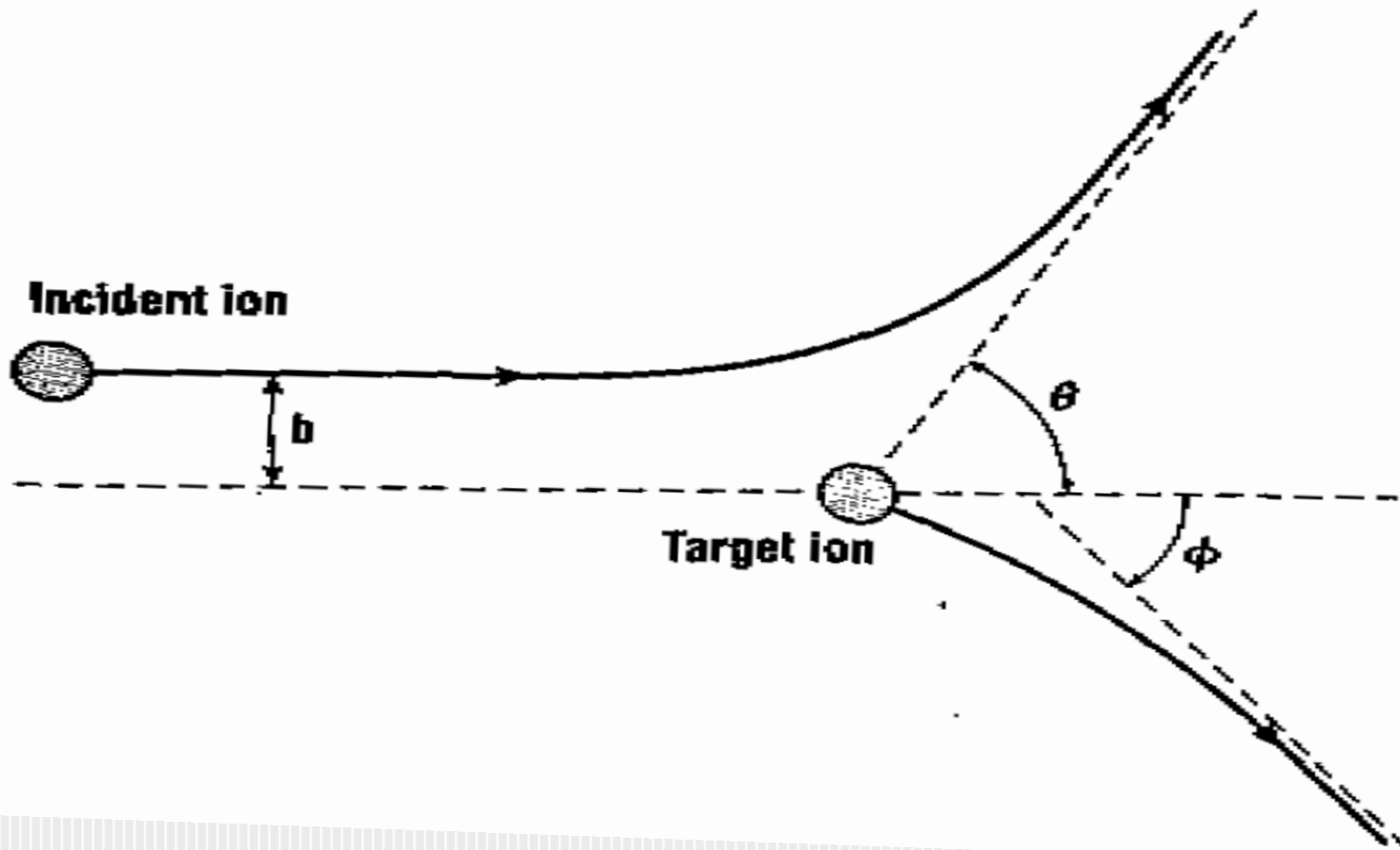
Disadvantages of Ion Implantation

- The equipment is expensive.
- This is much more complicated technique.
- Ion implantation creates damage to the semiconductor substrate.




Scattering Phenomenon

- Since, in ion implantation system, ions must have highly energized in order to penetrate the substrate.
 - The ion may collide with the target atom in the regular array of silicon & may displace it.
 - The target atom is initially at rest.
 - Let incident ion has incident velocity v and an impact parameter b as shown in figure.
 - As the incident ion has some energy, so when it will penetrate onto the silicon substrate, it will come on rest and will loose it energy gradually.
- 





Range Theory

- Since, during the ion implantation process, an energetic ion beam of dopants is injected onto the surface of the substrate.
 - Dopants have sufficient energy so as to penetrate the substrate.
 - Once the atoms go inside the substrate, they starts to loose their energy gradually.
 - The process of loosing their energy can be controlled by colliding with the lattice atom.
 - If dopants atoms have sufficient energy, then they can displace the lattice atom towards **interstitial site** or **substitution site**.
 - This is called **Nuclear Stopping**.
- 



Cond . . .

- So this collision of dopant atoms with lattice atoms create defects.
- The ion beam supplies energy to the bounded electrons.
- This is called **Electronic Stopping**.
- So, the ion beam is loosing energy by two processes, i.e., **Nuclear Stopping & Electronic Stopping**.
- The Range R is the distance traversed during which the ion energy has fallen from its initial energy E_0 to zero.

Cond...

- So, the average energy loss is given by:

$$-\frac{dE}{dx} = N(S_n(E) + S_e(E))$$

- The Range is thus given by:

$$\begin{aligned} R &= \int_0^R dx = -\frac{1}{N} \int_{E_0}^0 \frac{dE}{S_n(E) + S_e(E)} \\ &= \frac{1}{N} \int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)} \end{aligned}$$

- E_0 is the initial energy of the ion.



Implantation Damage

- During ion implantation, the energetic ions makes many collisions with the lattice atoms before coming to rest.
- When sufficient energy is transferred to the lattice, many of its atoms are displaced.
- Let we have a single energetic ion as it moves through the substrate & makes collisions with the target atoms.
- Let E_d , is the energy required to displace the target atom.
- If a lattice atom receives energy less than E_d , it will not be displaced.
- Similarly, if incident atom ion collide with lattice atom with energy less than E_d , then no atom will be displaced.
- So, **incident ion must have an energy of $2E_d$.**

Cond . . .

- The number of displaced atoms is:

$$N(E) = \frac{E_0}{2E_d}$$

- Where, E_0 is the initial energy of the ion.
- The implantation damage can be reduced by annealing.



Ion-Implantation Systems

- There are two key parameters for ion implants: **1. Ion energy** – which determines the penetration depth & **2. ion current** – which determines the implantation time.
- The basic feature of ion implantation system are – **ion source & acceleration** of high energy.
- **Mass analyzer** is used to select the single ion.
- All the ion sources, including their power supplies and control elements are controlled by remote.
- Rest of the system is kept on ground potential.
- Separate valves and pumps are provided in order to maintain the system under high vacuum condition at all the times.
- The cassette loader is required to handle the substrate.

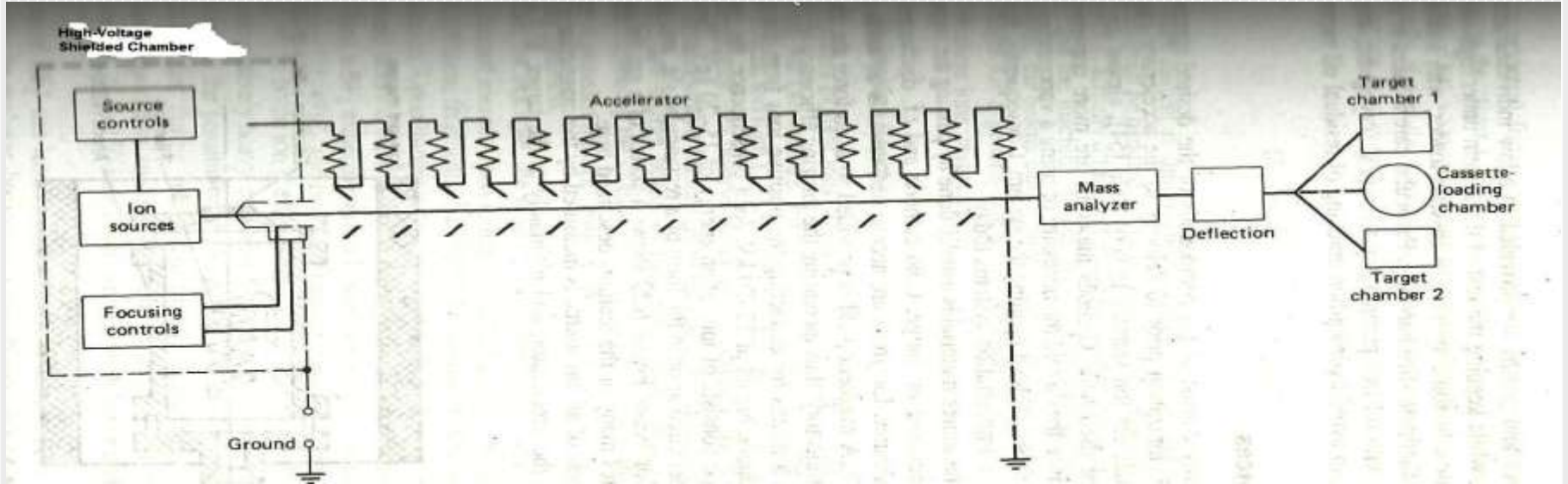


Fig: Block Diagram of Ion Implantation System

- **Ion Sources** usually consist of compounds of desired species.
- These species should ionize before they delivered to the accelerator column.
- Gaseous material are more convenient to use than solid because they avoid the necessity of using a vaporization chamber.
- Ionization of the source material is usually done by passing the vapor through a hot cathode electronic discharge.
- Electrons are accelerated towards an anode which is typically at 100 V.
- Magnetic field is provided to force the electrons to move in spiral filament.
- This will extract positive ions from this discharge.
- The outlet of this ionizer may be circular or rectangular slit.
- The **ion beam is energized** by passing it through **Accelerator**.
- The **accelerator is a tube** and its output end is usually kept at ground for safety reasons.
- The beam energy determines the projected range of an ion.

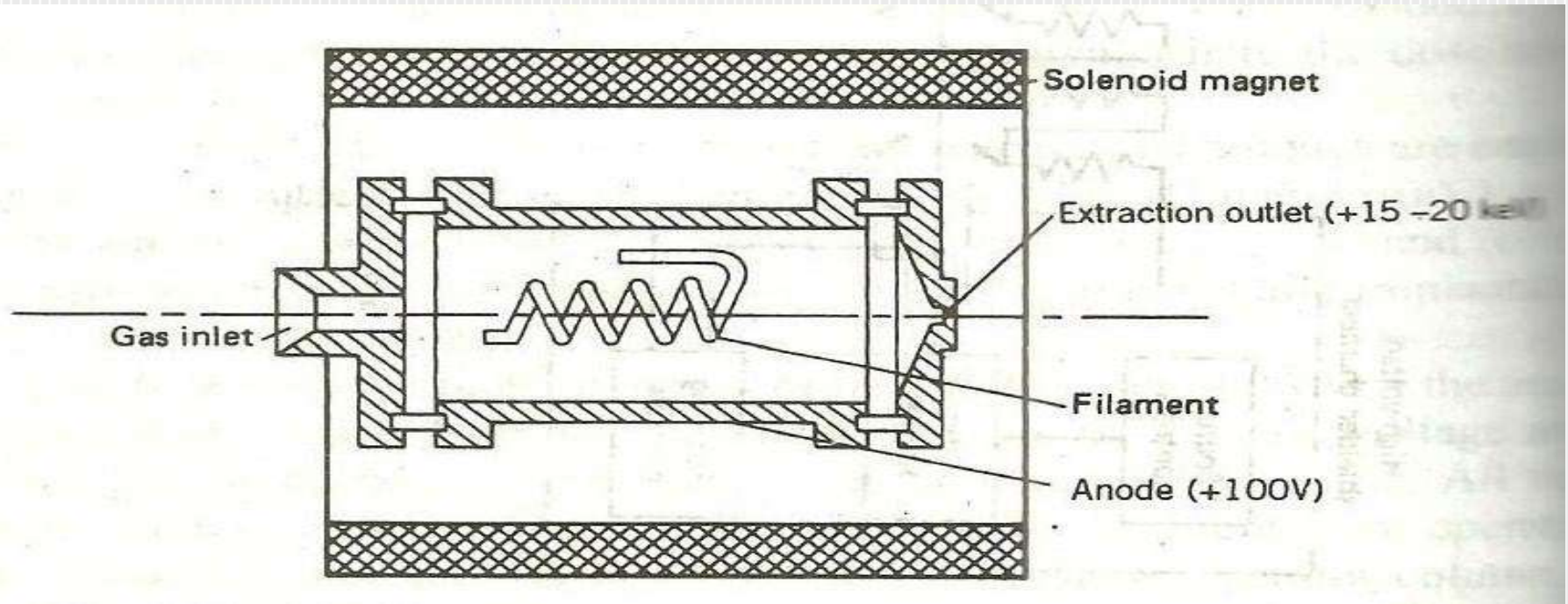


Fig: A Nelson-type gaseous source

- Raw output from an ion source may consists of contamination, produced by sputtering from its walls and filaments.
- So **mass separation** is necessary in practical ion implanter.
- The most common technique is a **homogeneous field magnetic analyzer**.
- Its principle is based on the dynamics of the charged particles.
- Let the charged particle has mass m and velocity v , is moving at right angles to a uniform magnetic field with a flux density B .
- The particle will experience a force F such that:

$$F = q(v \times B)$$

- This force will tend to move particles in a circular path of radius r , so creates a **centrifugal force**

$$mv^2/r.$$

- These forces must be equal in magnitude and opposite in direction.
- The velocity of the particles is related to their energy by:

$$\frac{1}{2}mv^2 = qV$$

- Where, V is the accelerating potential.
- Combining these relation, the radius of the ion path is given by:

$$r = \frac{1}{B} \left(\frac{2mV}{q} \right)^{1/2}$$

- So, the path radius is directly proportional to the square root of the mass.
- See figure on next slide, ions of any particular mass can be selected by the appropriate placement of an exit slit.

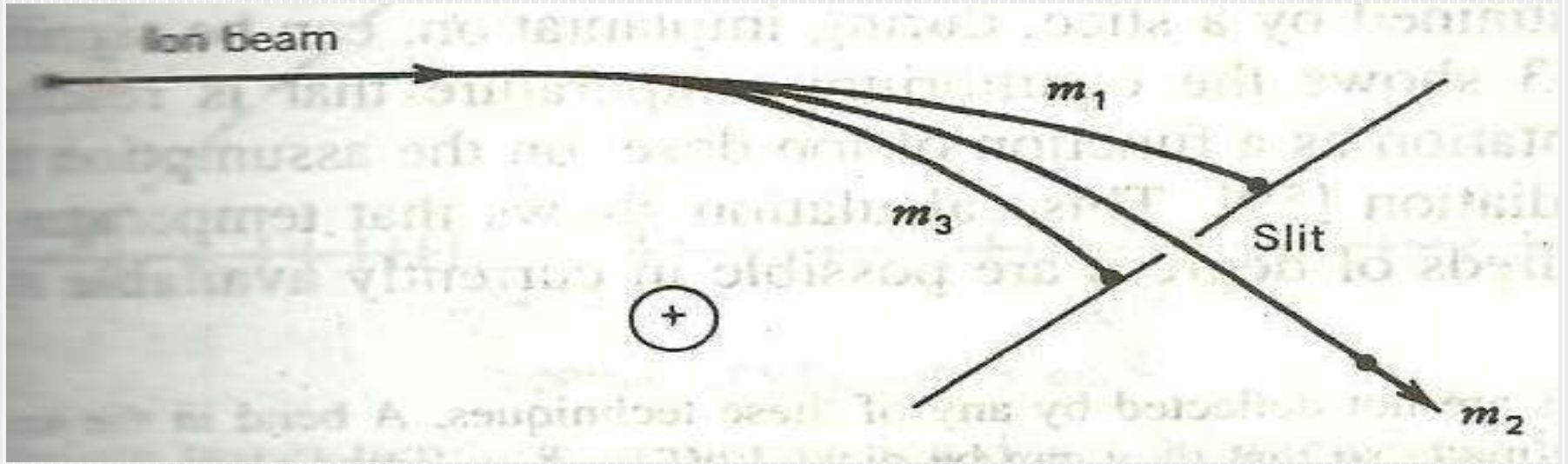


Fig: Mass Separation through a slit



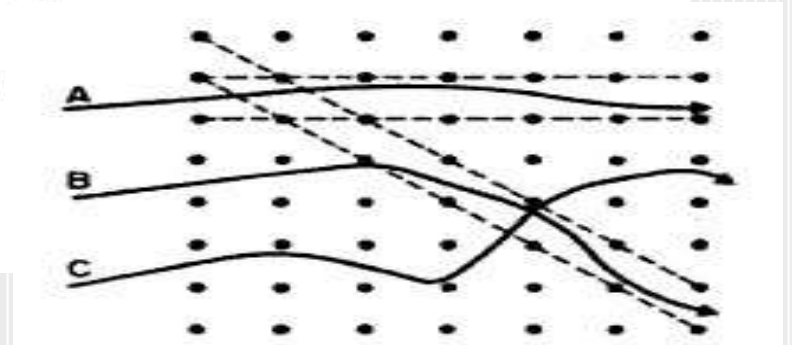
Channeling

- The substrate has crystalline structure with regular arrangements of atoms.
- The atoms rows may have open spaces through which ions can travel without significant scattering.
- The figure shows three ions entering a simple cubic lattice.

- **Ion A** is well aligned to the channel, so it suffers only small collision with the channel walls.
- **Ion B** scatters into a channel after a short distance, because of the lattice imperfection.
- **Ion C** is not channeled and has random collisions with the lattice atoms.
- Channeling is characterized by a critical angle Ψ .
- **The critical angle Ψ , is the maximum angle between ion and channel for an collision to occur.**


$$\Psi = 9.73 \sqrt{\frac{Z_i Z_t}{Ed}} \text{ (degree)}$$

- Where d is the atomic spacing along the ion direction.
- E is ion energy (keV)
- Z_i is atomic charge number of ions.
- Z_t is atomic charge number of target atoms.





Annealing

- The dopant atoms are introduced into a semiconductor in order to change its electrical properties.
 - During ion implantation atoms may displace and may create defects.
 - Annealing is required to repair the lattice damage and put dopant atoms on **substitutional sites** where they will be electrically active.
- 




Cond . . .

- The thermal anneal cycles are usually **15-30 minutes** in duration.
- During the anneal phase, displaced atoms tend to move in order to repair damages.
- **Anneal process takes place at temperature of 1200 °C.**

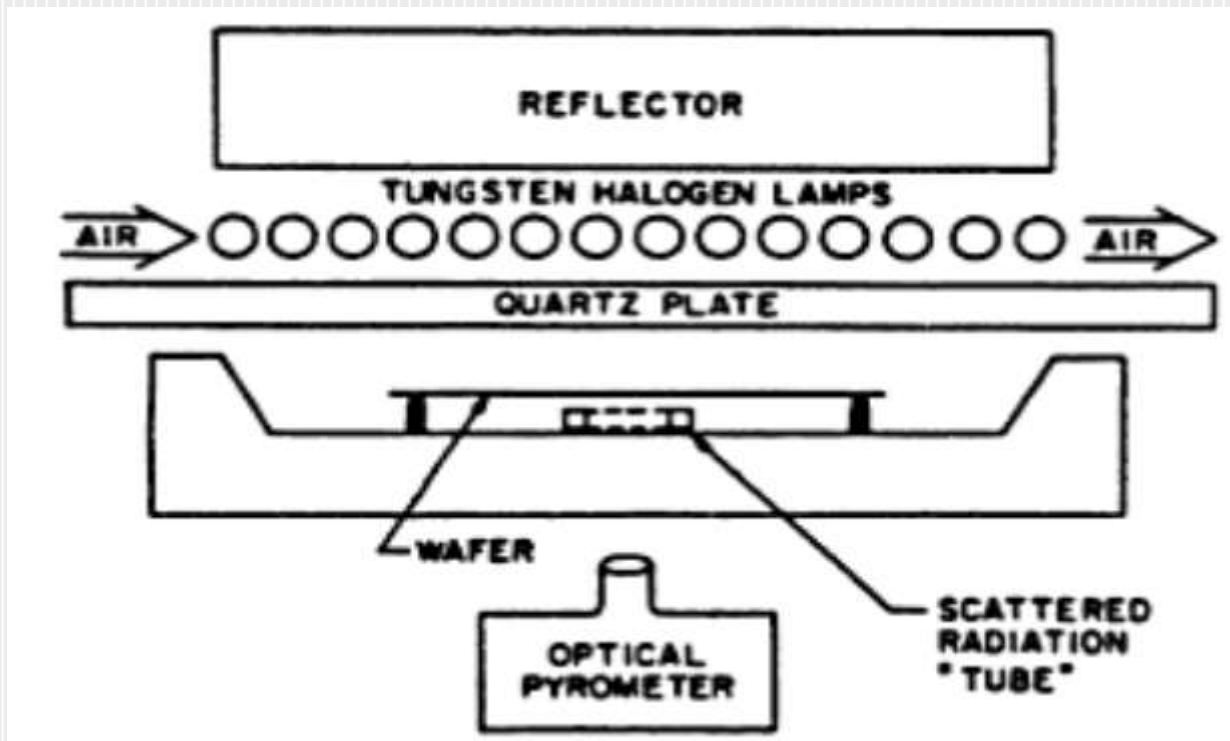


Cond . . .

- **Rapid Thermal Annealing:** The process usually takes place at a temperature of 1200°C .
 - The process of annealing takes place in order to dissolve the defects i.e., damages.
 - The lattice atoms have the energy of 5 keV.
 - These are associated with the diffusion of self-interstitials.
- 


Cond...

RTA System





Cond . . .

- A typical water cooled RTA system with tungsten halogen lamps is shown in figure.
 - The absorption of radiant heat is directly related to the free carrier concentration.
 - So, the heating rate for heavily doped material is more rapid than lightly doped materials.
- 




Cond . . .

- So, the temperature monitoring is very much necessary in this system.
- The optical pyrometers and thermocouples are used for this purpose.



Review questions

1. What is Epitaxy? Discuss Molecular Beam Epitaxy technique in brief. What are the advantages of MBE over VPE?
 2. Explain the kinetics of Epitaxy. Calculate epitaxial layer thickness.
 3. What are the sources of silicon in VPE?
 4. Why epitaxial layer of Si is necessary to grow? What are the functions of this layer in IC?
 5. What is Autodoping? What are the disadvantages of Autodoping? How it can be minimized?
- 

6. Derive the diffusion equation. How the depth of diffusion is controlled during diffusion process? Give the solution of Fick's Law?
7. Describe a typical ion implanter.
8. What are the advantages of ion implantation?
9. What is Ion Implantation? Explain the process with a neat diagram.
10. What do you mean by Annealing? Why it is required in IC fabrication process?
11. Compare ion implantation process with diffusion.



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