



Course: EE3013/ Semiconductor Devices and Processing
School: School of Electrical and Electronic Engineering
Week 8 – Thermal Diffusion

Learning Objectives

At the end of this lesson, you will be able to:

- Explain the mechanisms and applications of thermal diffusion in semiconductor processing.
- Explain the different types of impurity diffusion in crystal.
- Explain the types of surface reactions and sources of impurities used for n and p type doping in silicon.
- Explain how diffusion is used to create pn junction and when to use it.
- Explain the potential dangers from the different types of impurities and why a scrubber system is needed in diffusion system.
- Explain the use of Fick's first and second law to derive an equation for the impurity concentration profiles.

Learning Objectives

- Explain what are constant source diffusion and limited source diffusion and their key associated parameters.
- Calculate the junction depth by source diffusion and limited source diffusion.
- Describe the different techniques for determining sheet resistance, impurity profiles, and junction depth.
- Describe the various types of diffusion systems.

Thermal Diffusion

- Thermal diffusion is a common example of diffusion but involves temperature.
- Diffusion will require a **concentration gradient**.



Applications of Diffusion in Semiconductor Processes

- **Diffusion** is the key process for introducing impurities in the selected regions of a semiconductor.
- It is most commonly used for:
 - base, emitter, and resistor in bipolar technology, and
 - source and drain regions, and doped polysilicon gate in MOS technology.

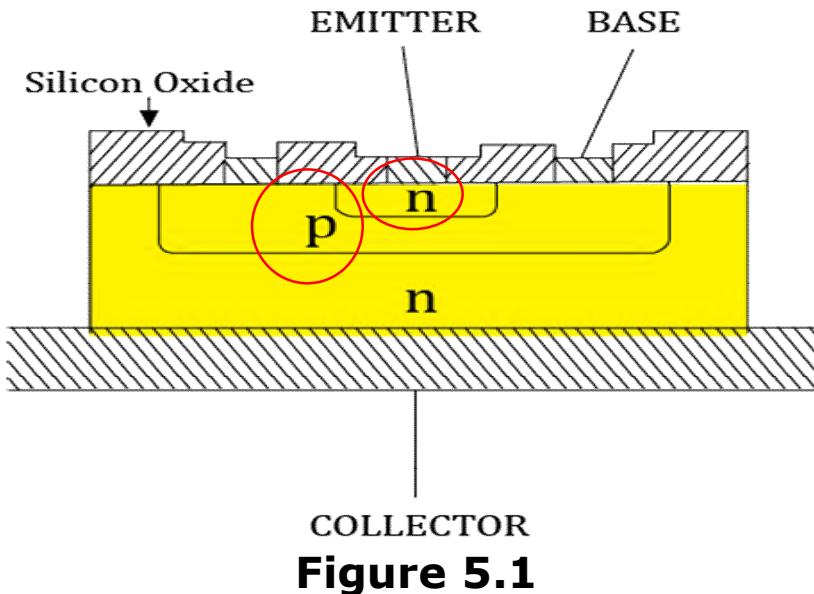


Figure 5.1

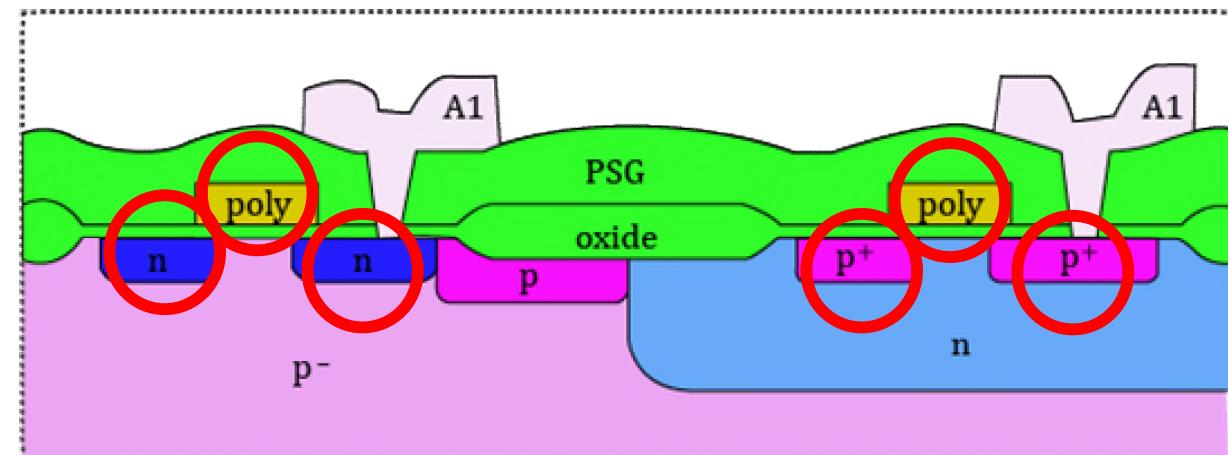


Figure 5.2

When to Use Diffusion Process?

- When **to use** it and when **not to use** it:
 - **To use** when damage from ion implantation is unacceptable, electrical junctions need to be very deep, or a cheap, easy solution is needed, and
 - **Not to use** for ultra-shallow junctions, or total impurity dose is critical.

Impurity Diffusion in Crystals

- Diffusion is the motion of impurity atoms in a crystal due to concentration gradient.
- There are two principal mechanisms for dopants to diffuse in the crystal.

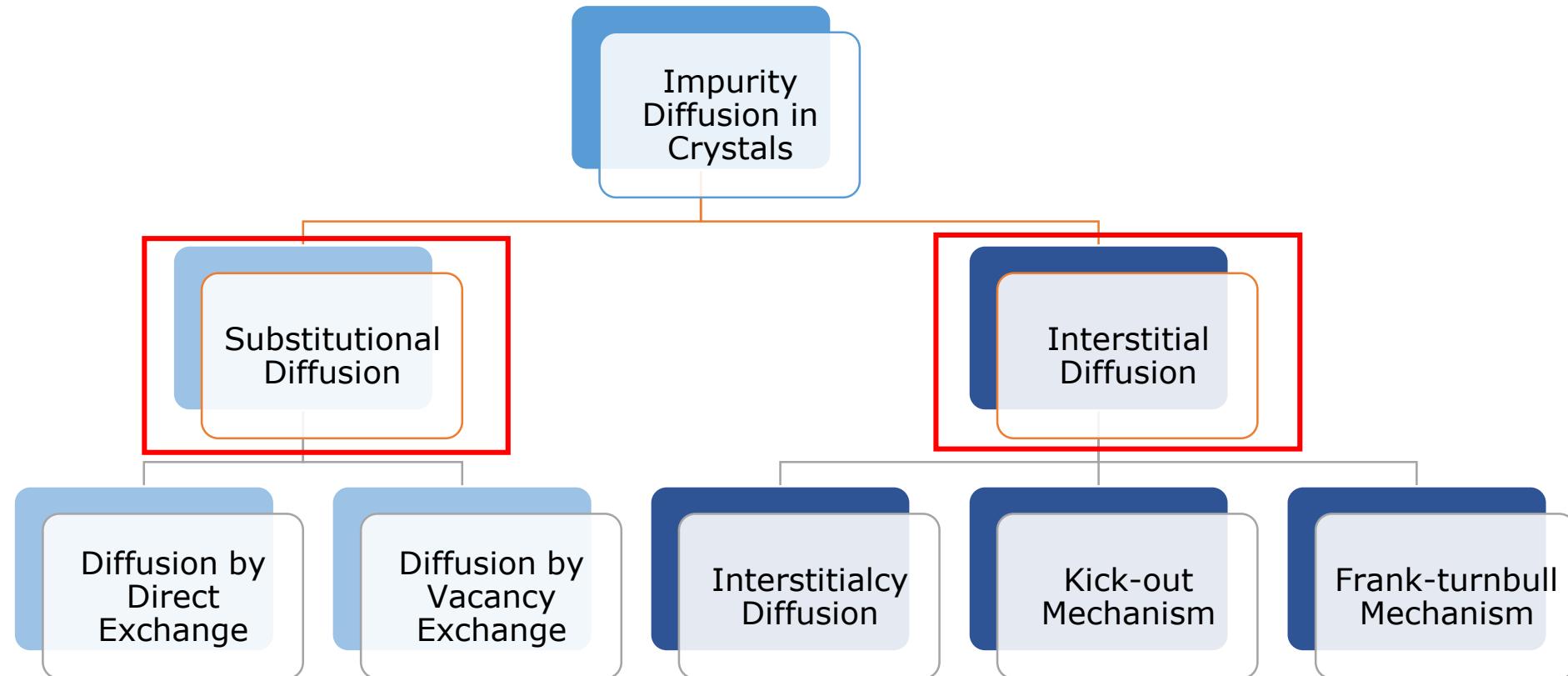


Figure 5.3

Substitutional Diffusion

- Impurity atoms jump from one lattice site to another lattice site.
- Since the number of lattice vacancies are limited, it is a **slow process**.
- Substitutional diffusion is **responsible for doping** effects.
- Some examples of dopants are **As, B, P, Al, Ga, Sb, and Ge**.

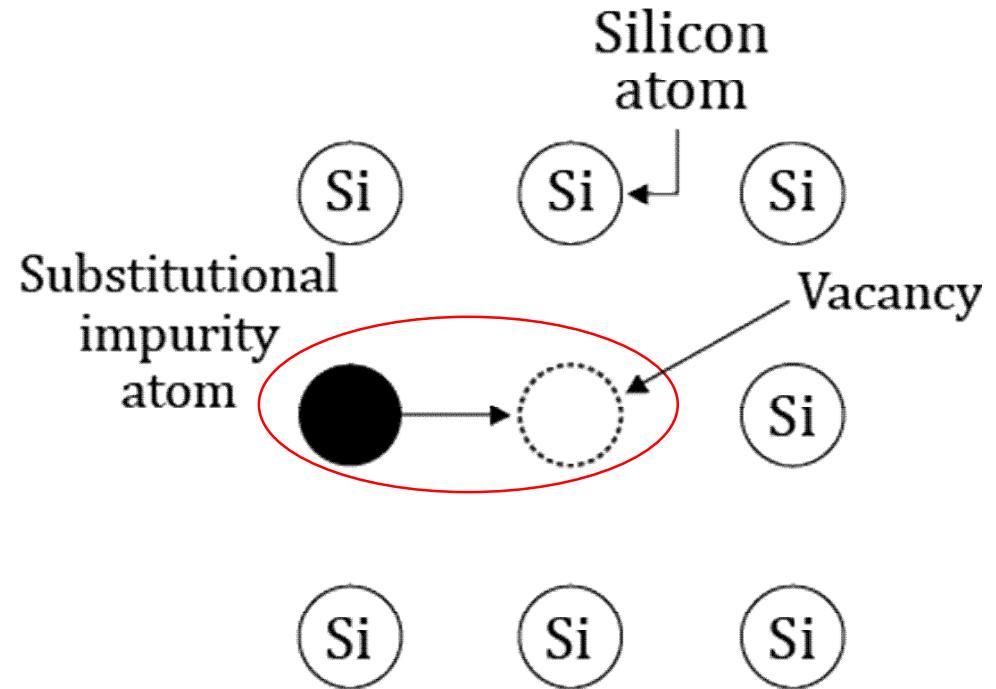
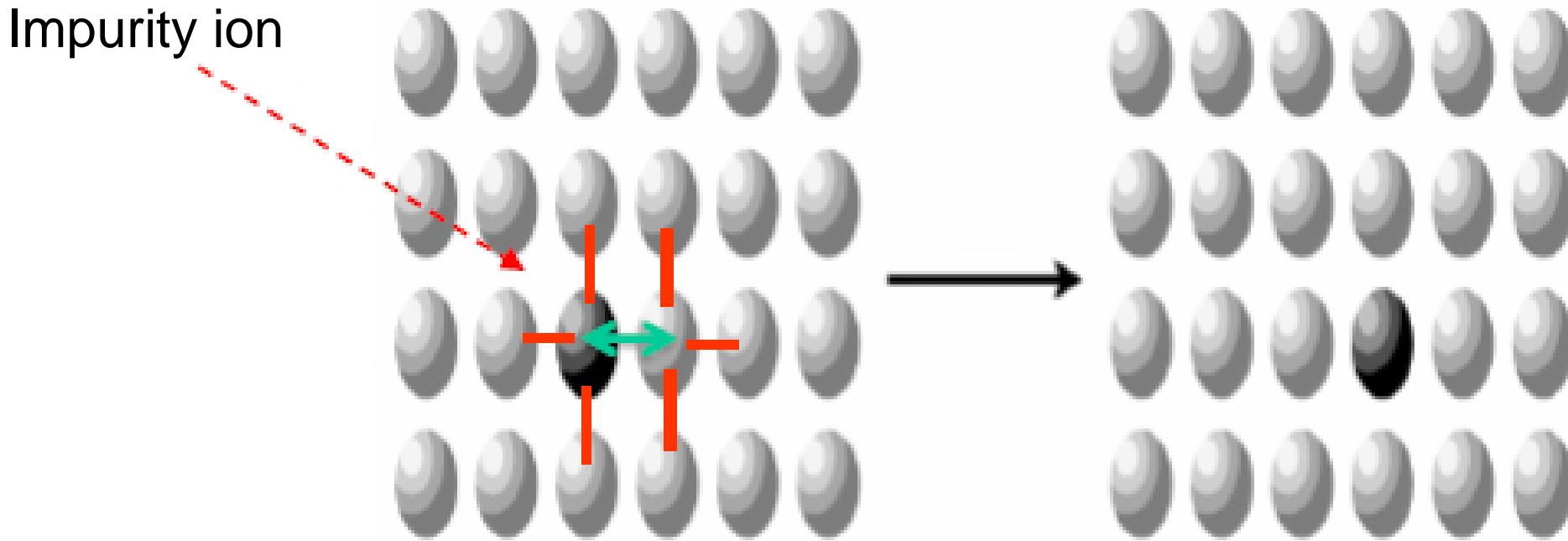


Figure 5.3

Types of Substitutional Diffusion

1. Diffusion by direct exchange

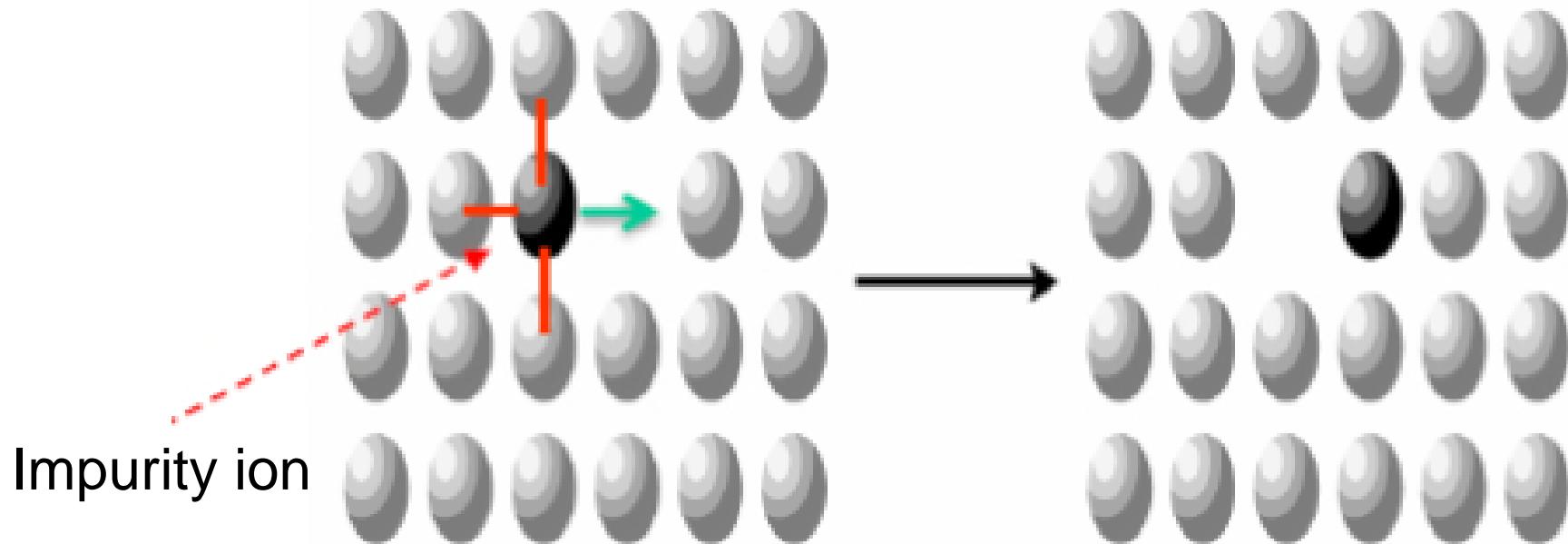
- The impurity ion exchanges site with its neighbor Si atom.
- Six covalent bonds must be broken for exchanging positions. So high energy is required.



Types of Substitutional Diffusion

2. Diffusion by vacancy exchange

- The impurity ion exchanges site with the neighbor vacancy.
- Only three bonds need to be broken for exchange. Lower energy is needed, thus a dominant diffusion mechanism.

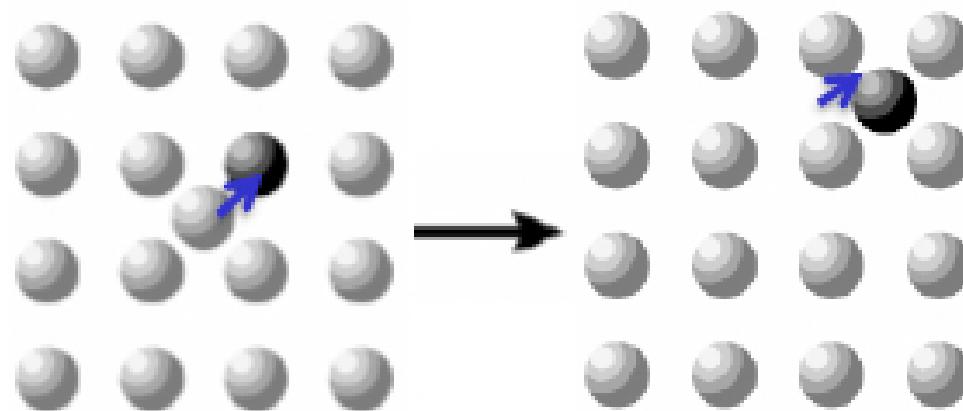


Types of Interstitial Diffusion

- Impurity atoms diffuse between interstitial spaces (do not replace atoms in the crystal lattice).
- They do not directly contribute to doping.
- Some examples are **O, Au, Fe, Cu, Ni, Zn, and Mg.**

1. Interstitialcy diffusion:

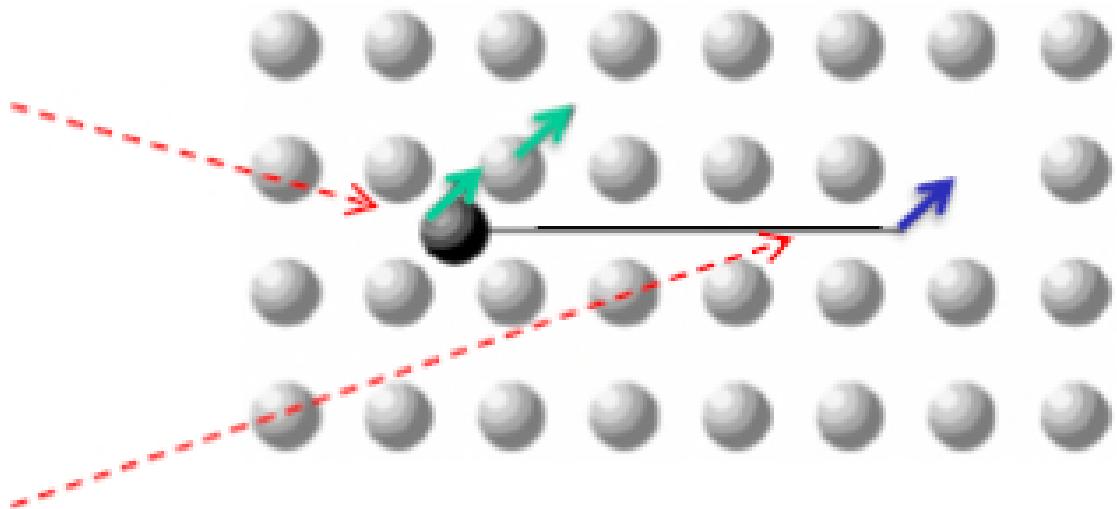
- An interstitial Si atom displaces a substitutional impurity, and drives it to an interstitial site.
- The impurity may diffuse some distance before it returns to a substitutional site. Some examples are **B, P, As.**



Types of Interstitial Diffusion

2. Kick-out mechanism:

- A fast moving interstitial impurity knocks out a host lattice atom and becomes a substitutional atom.



3. Frank-Turnbull mechanism:

- The impurity is captured by a vacancy.
Examples are Au and Pt.

Choice of Impurities

For p-type

- Aluminum and Gallium diffuse fast in SiO_2 and they can not be masked by SiO_2 .
- Indium is not used as it is a deep level acceptor.
- Boron is the best p-type dopant for Si.

For n-type

- Phosphorus, arsenic and antimony are all masked by SiO_2 .
- But phosphorus is used more often as it is less poisonous.

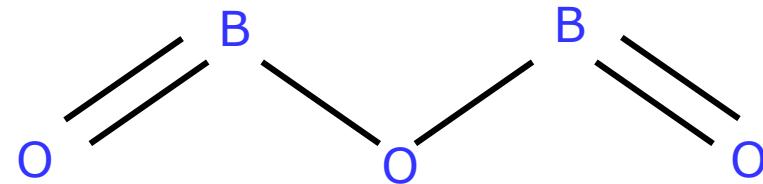
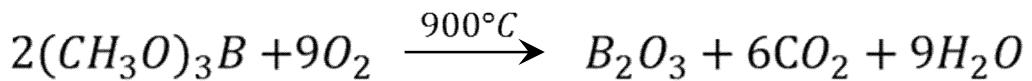
<i>IIIA</i>	<i>IVA</i>	<i>VA</i>	
5 B	6 C	7 N	
13 Al	14 Si	15 P	
31 Ga	32 Ge	33 As	
49 In	50 Sn	51 Sb	
p-type		n-type	

Figure 5.4

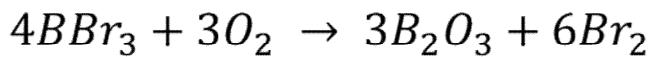
Boron Doping (p-type) by Diffusion

- **Surface reaction at Si surface:** $2B_2O_3 + 3Si \rightarrow 4B + 3SiO_2$
- **Sources of B_2O_3 :**

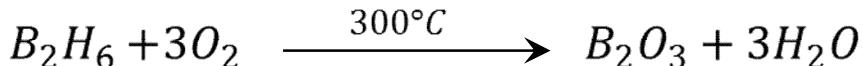
- **Solid source:** Trimethylborate (TMB) and boron nitride



- **Liquid source:** Boron tribromide BBr_3



- **Gaseous source:** Diborane B_2H_6 (extremely toxic)



Note: All systems need careful scrubbing for safety requirements!

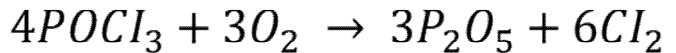
Phosphorus Doping (n-type) by Diffusion

- **Surface reaction:** $2P_2O_5 + 5Si \rightarrow 4P + 5SiO_2$
- **Sources of P_2O_5 :**

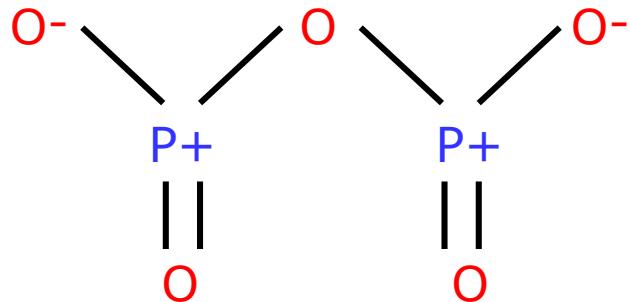
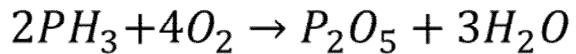
- **Solid source:**

- Phosphorus pentoxide, Ammonium monophosphate
 $NH_4H_2PO_4$
- Ammonium diphosphate $(NH_4)_2H_2PO_4$

- **Liquid source:** Phosphorus oxychloride $POCl_3$



- **Gaseous source:** Phosphine PH_3 (extremely toxic)



Note: All systems need careful scrubbing for safety requirements!

Arsenic and Antimony (n-type) Diffusion

- **Arsenic Surface Reaction:** $2\text{As}_2\text{O}_3 + 3\text{Si} \rightarrow 3\text{SiO}_2 + 4\text{As}$

- **Sources of $2\text{As}_2\text{O}_3$**

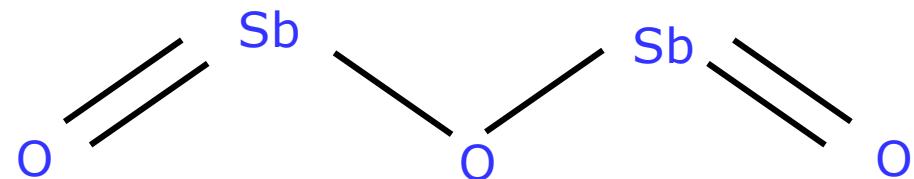
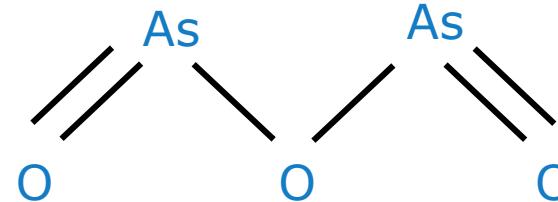
- **Solid source:**

- Possible – low surface concentrations

- **Gaseous source:** Arsine AsH_3 (extremely toxic)

- * **Antimony Surface Reaction:** $2\text{Sb}_2\text{O}_3 + 3\text{Si} \rightarrow 3\text{SiO}_2 + 4\text{Sb}$

- **Liquid source:** Antimony pentachloride Sb_3Cl_5



Note: All systems need careful scrubbing for safety requirements!

Why Gas Scrubber is Needed?

Table 5.1 : Threshold Limit Recommendations for Common Gaseous Sources [21]

Source	8-h exposure level (ppm)	Life-threatening exposure	Comments
	0.1	160 ppm for 15 min	Colourless, stickly sweet, extremely toxic, flammable
	0.3	400 ppm for 30 min	Colourless, decaying fish odour, extremely toxic, flammable. A few minutes' exposure to 2000 ppm can be lethal.
	0.05	6-15 ppm for 30 min	Colourless, garlic odor, extremely toxic. A few minutes' exposure to 500 ppm can be lethal.
	0.5	Unknown	Repulsive odor, burns in air, explosive, poorly understood.
	5.00	-	Colourless, flammable, toxic. Irritating odor provides adequate warning for voluntary withdrawal from contaminated areas.

PN Junction Formation: Diffusion Profiles

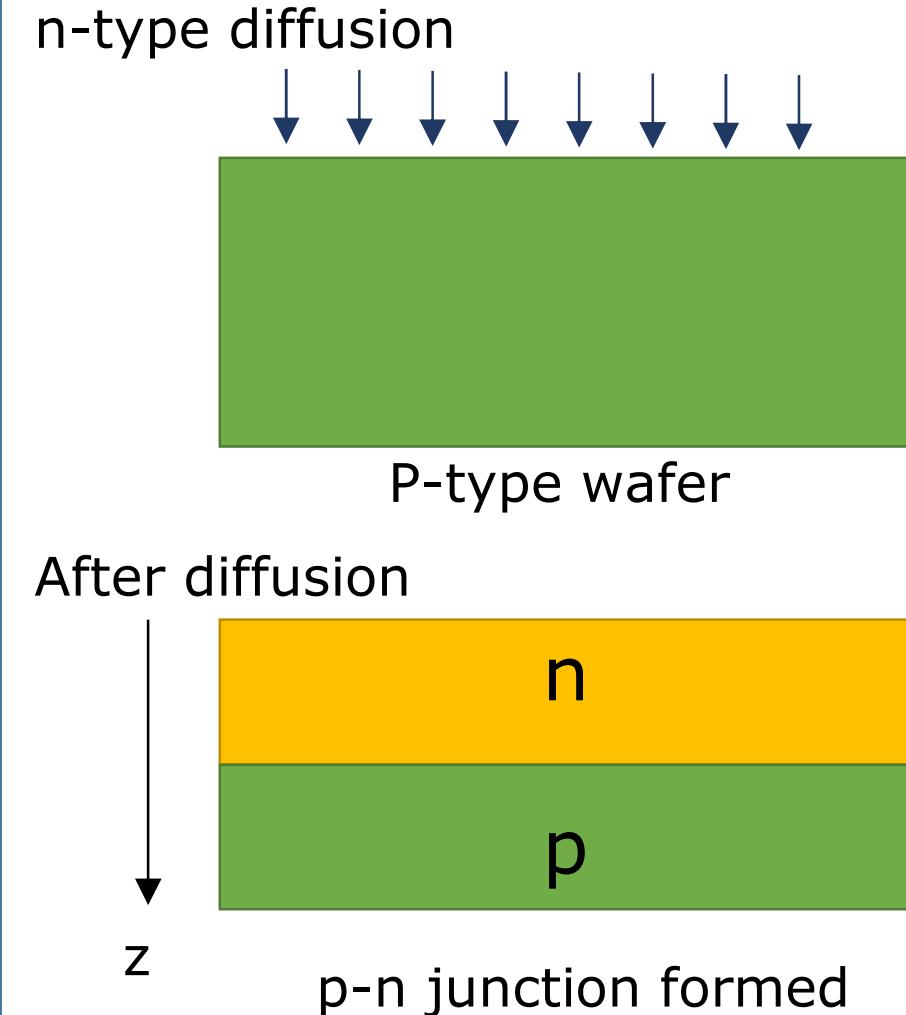


Figure 5.5

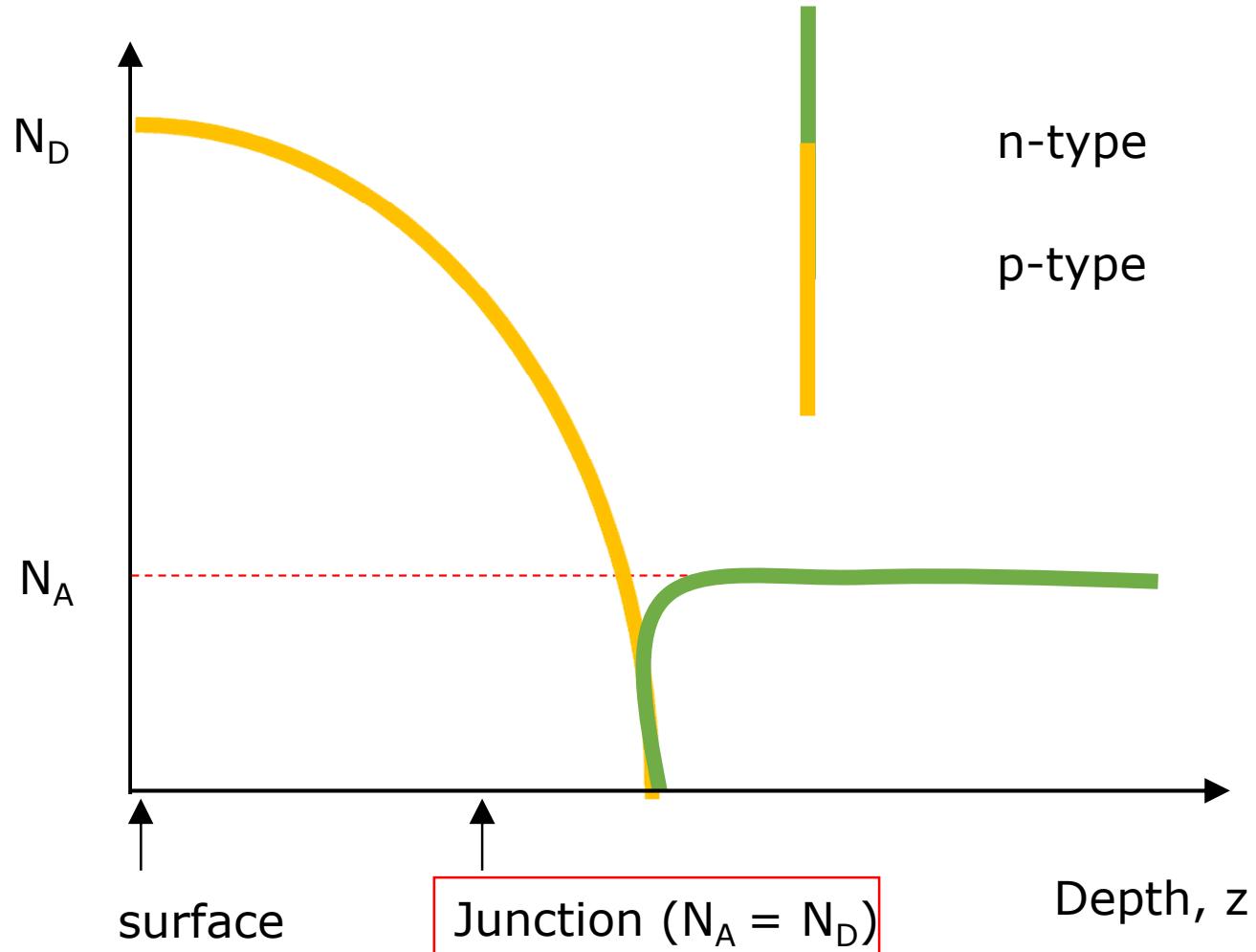


Figure 5.6

Theory Behind Diffusion - Fick's First Law

Fick's First Law:

$$J = -D \frac{\partial N(z, t)}{\partial z} \quad (\text{Equation 5.1})$$

where

J - Net impurity flux crossing the position z

N - Impurity concentration at a position z and time t

D - Diffusion coefficient

- The impurity concentration changes with distance and time.
- J is proportional to the negative gradient of the impurity concentration.
- **Negative sign:** Flux moves from a high concentration region to a low concentration region.

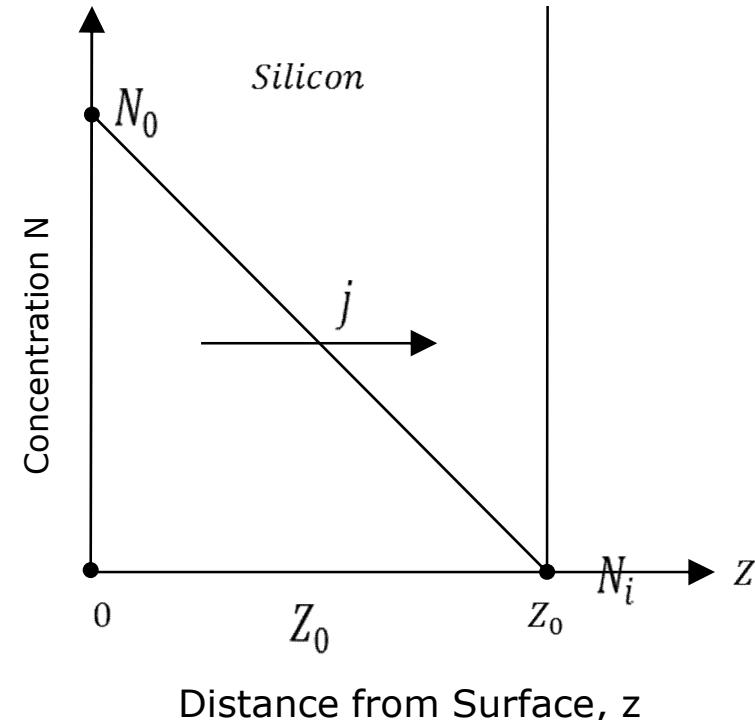


Figure 5.7

Theory Behind Diffusion - Fick's First Law (Cont'd.)

- Consider a small volume of length dz , then

$$\frac{J_2 - J_1}{Z_2 - Z_1} = \frac{J_2 - J_1}{dz} = \frac{\partial J}{\partial z} \quad (\text{Equation 5.2})$$

J_1 : flux entering the volume

J_2 : flux leaving the volume

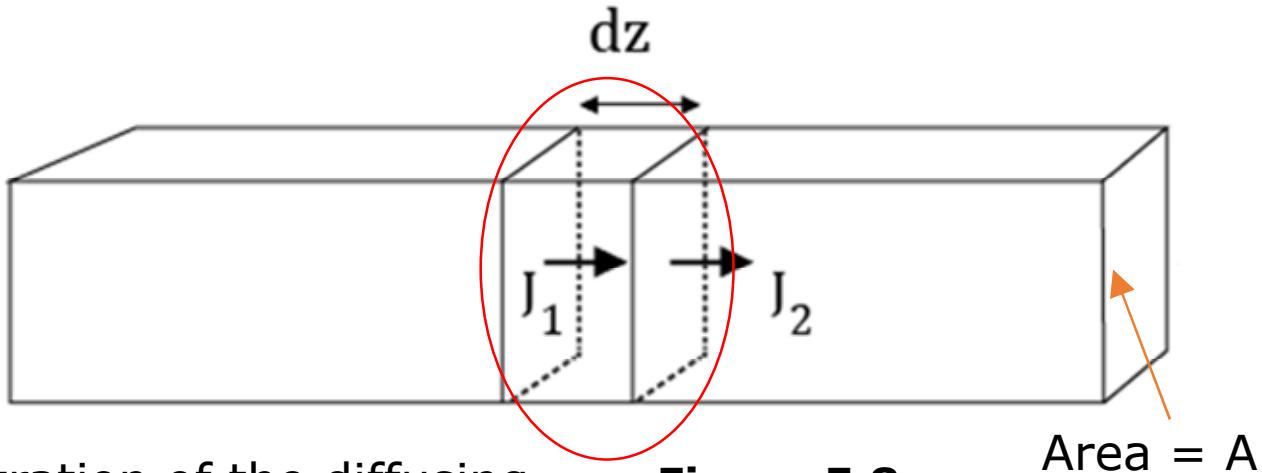


Figure 5.8

- If the fluxes J_1 and J_2 are different, the concentration of the diffusing impurities in the volume must change.
- Using equation 5.2, the continuity equation can be expressed as:

$$-A(J_2 - J_1) = -A dz \frac{\partial J}{\partial z} = Adz \frac{\partial N}{\partial t} \quad (\text{Equation 5.3})$$

or $\frac{\partial N}{\partial t} = -\frac{\partial J}{\partial z}$ *(Equation 5.4)*

Theory Behind Diffusion - Fick's First Law (Cont'd.)

- Using Fick's first law, $J = -D \frac{\partial N(z,t)}{\partial z}$, we get $\frac{\partial N}{\partial t} = -\frac{\partial J}{\partial z} := \frac{\partial}{\partial z} (D \frac{\partial N}{\partial z})$ (Equation 5.5)
- If D is independent of position, we have:

$$\frac{\partial N}{\partial t} = D \frac{\partial^2 N}{\partial z^2} \longrightarrow \textbf{Fick's Second Law} \quad (\textit{Equation 5.6})$$

- Fick's Second Law is a simple differential equation that can be solved subject to various boundary conditions

Impurity Concentration Profile

- Fick's second law (partial differential equation) can be used to find impurity distribution.
- There are two types of boundary conditions important in modeling the impurity diffusion in Si:
 1. Constant-source diffusion
 2. Limited-source diffusion

Constant Source Diffusion

- The impurity concentration at the surface of the solid remains constant, N_s (unlimited supply of excess impurity atoms is available at surface).
- As the time for impurity diffusion increases, the impurities can go deeper and deeper into the solid, but the concentration at surface remains unchanged.

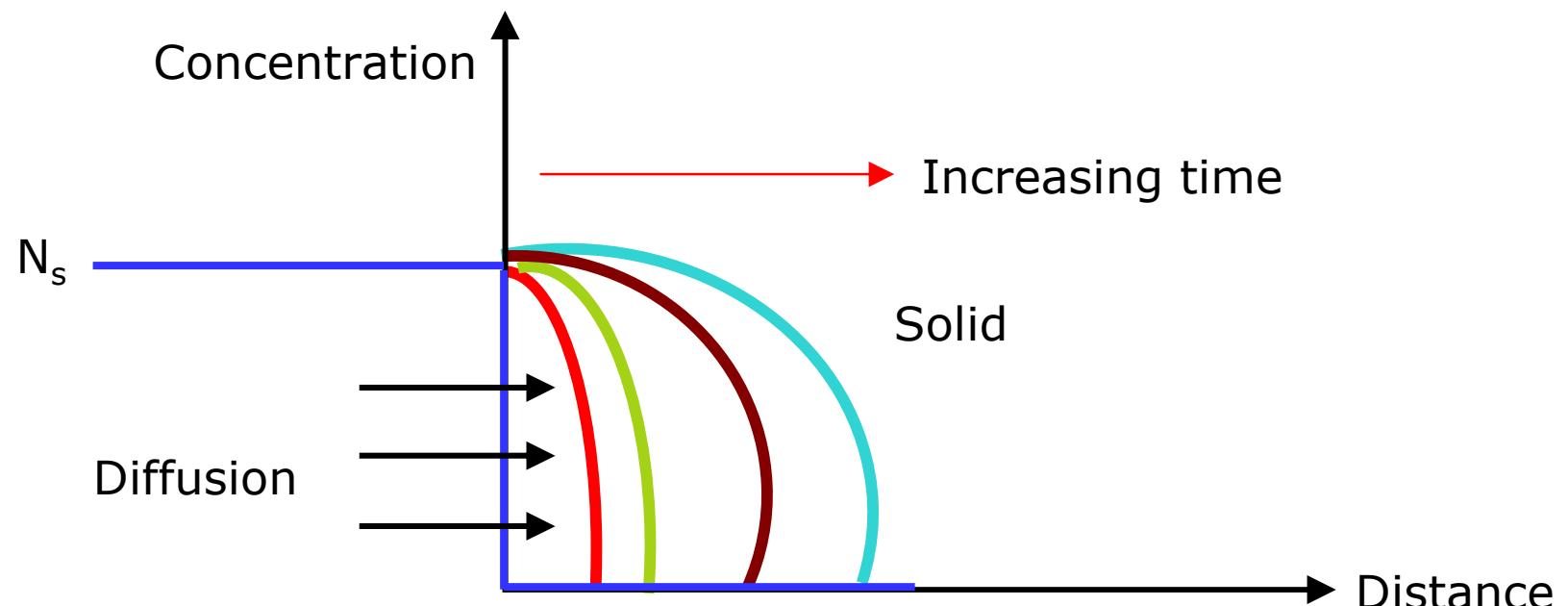


Figure 5.9

Constant Source Diffusion (Cont'd.)

Boundary conditions (One for time t and two for position z)

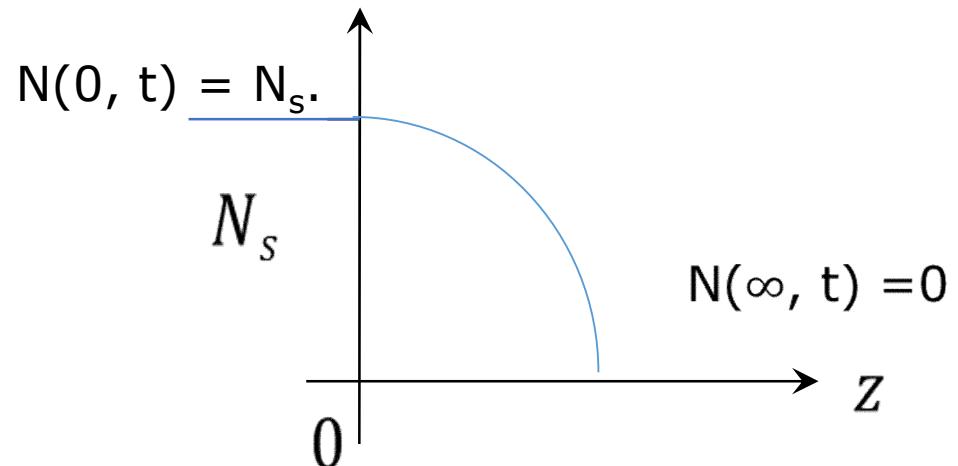


Figure 5.10

- The solution is:

$$N(z) = N_s \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right) \quad (\text{Equation 5.7})$$

where erfc : Complementary error function

\sqrt{Dt} : Characteristic diffusion length

Dose for Constant Source Diffusion

- Total number of the impurity atoms entered into the Si per unit area is called dose.

$$Q(t) = \int_0^{\infty} N_s \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right) dz \quad (\text{Equation 5.8})$$

$$Q(t) = \frac{2N_s}{\sqrt{\pi}} \sqrt{Dt} \quad (\text{Equation 5.9})$$

- Dose Q increases with $t^{1/2}$.

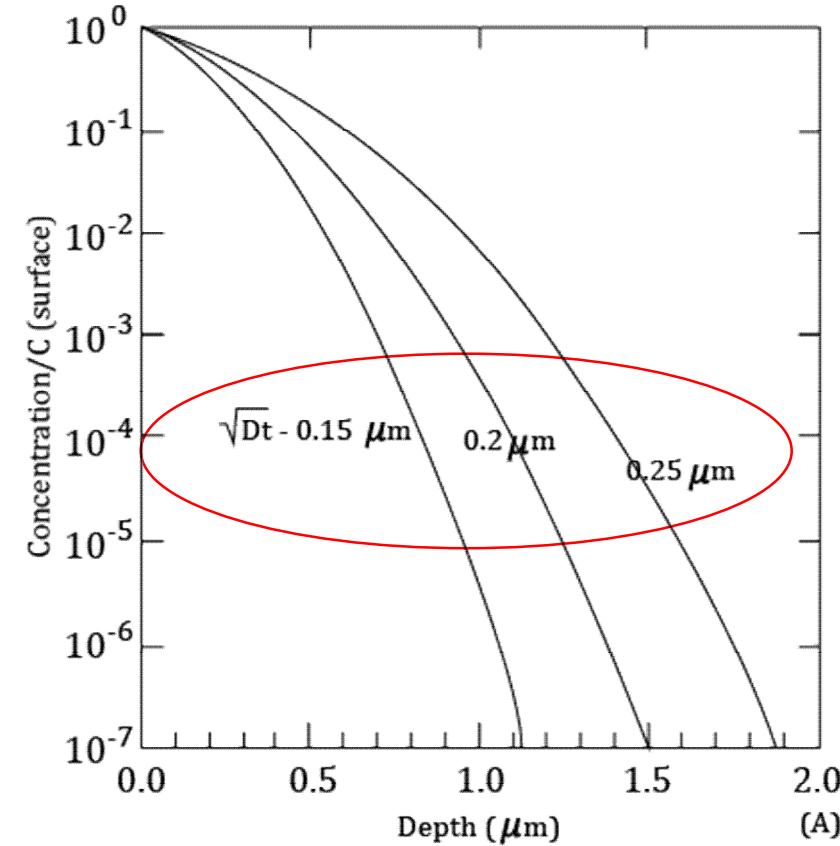


Figure 5.11

Diffusion Coefficient

- Diffusion coefficient D is a function of temperature:

$$D = D_0 \exp\left(-\frac{E_a}{kT}\right) \quad (\text{Equation 5.10})$$

- D_0 is called diffusion coefficient (cm^2/s) extrapolated to infinite temperature.
- E_a is the activation energy in eV.

TABLE 5.2 Typical Diffusion Coefficient Values for a Number of Impurities.

Element	$D_0(\text{cm}^2/\text{sec})$	$E_A(\text{eV})$
B	10.5	3.69
Al	8.00	3.47
Ga	3.60	3.51
In	16.5	3.90
P	10.5	3.69
As	0.32	3.56
Sb	5.60	3.95

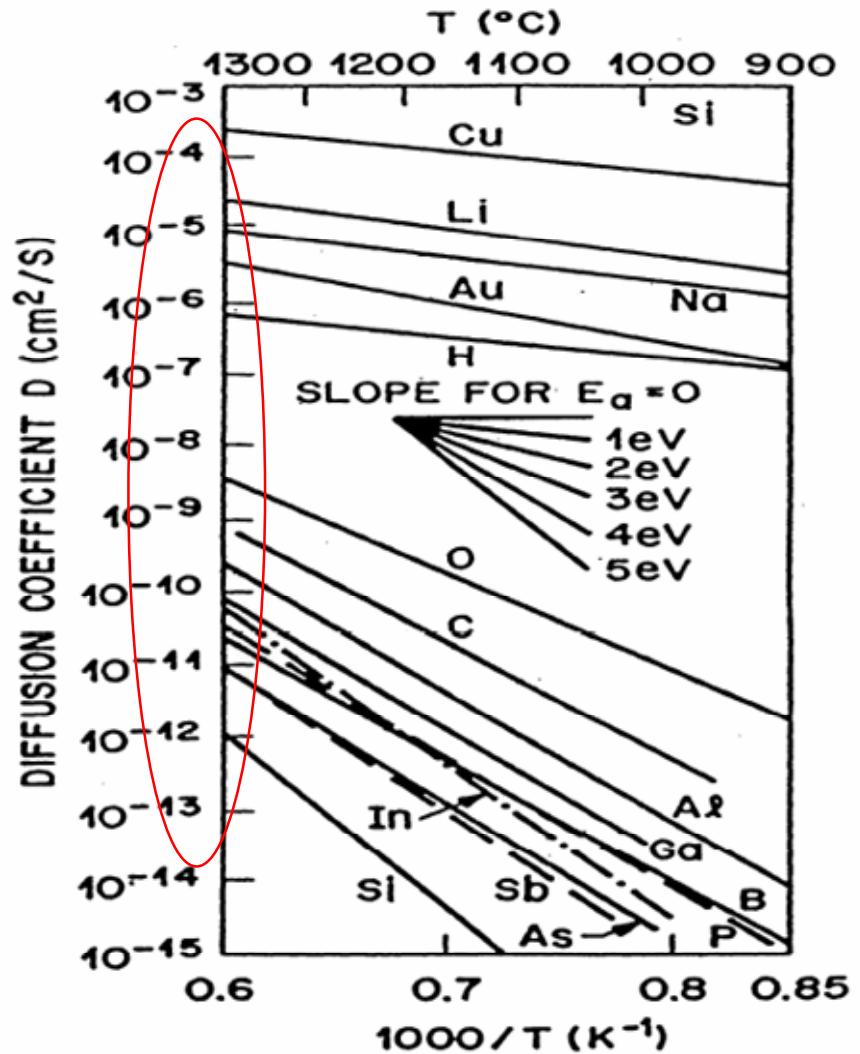


Figure 5.12

Diffusion Length

- Using Boron diffusion in silicon as an example, the same diffusion length can be achieved by different combinations of time and temperature.

Process	
	0.072
2 hours at 950°C	0.073
	0.076

Table 5.3

Some Properties of Error Functions

- **Error Function**

$$erf(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt \quad \begin{aligned} erf(0) &= 0 \\ erf(\infty) &= 1 \end{aligned} \quad (Equation \ 5.11)$$

- **Complimentary Error Function**

$$erfc(z) = \frac{2}{\sqrt{\pi}} \int_z^{\infty} e^{-t^2} dt \quad \begin{aligned} erfc(0) &= 1 \\ erfc(\infty) &= 0 \end{aligned} \quad (Equation \ 5.12)$$

$$erfc(z) = 1 - erf(z) \quad (Equation \ 5.13)$$

Error Function Table

z	$\text{erf}(z)$	$\text{erfc}(z)$	z	$\text{erf}(z)$	$\text{erfc}(z)$
0.00	0	1	1.3	0.9340079	0.0659921
0.05	0.056372	0.943628	1.4	0.9522851	0.0477149
0.10	0.1124629	0.8875371	1.5	0.9661051	0.0338949
0.15	0.167996	0.832004	1.6	0.9763484	0.0236516
0.20	0.2227026	0.7772974	1.7	0.9837905	0.0162095
0.25	0.2763264	0.7236736	1.8	0.9890905	0.0109095
0.30	0.3286268	0.6713732	1.9	0.9927904	0.0072096
0.35	0.3793821	0.6206179	2.0	0.9953223	0.0046777
0.40	0.4283924	0.5716076	2.1	0.9970205	0.0029795
0.45	0.4754817	0.5245183	2.2	0.9981372	0.0018628
0.50	0.5204999	0.4795001	2.3	0.9988568	0.0011432
0.55	0.5633234	0.4366766	2.4	0.9993115	0.0006885
0.60	0.6038561	0.3961439	2.5	0.999593	0.000407
0.65	0.6420293	0.3579707	2.6	0.999764	0.000236
0.70	0.6778012	0.3221988	2.7	0.9998657	0.0001343
0.75	0.7111556	0.2888444	2.8	0.999925	0.000075
0.80	0.742101	0.257899	2.9	0.9999589	0.0000411
0.85	0.7706681	0.2293319	3.0	0.9999779	0.0000221
0.90	0.7969082	0.2030918	3.1	0.9999884	0.0000116
0.95	0.8208908	0.1791092	3.2	0.999994	0.000006
1.00	0.8427008	0.1572992	3.3	0.9999969	0.0000031
1.20	0.910314	0.089686	3.5	0.9999993	0

Table 5.4

Complementary Error Function Table

Complementary Error Function Table											
x	erfc(x)	x	erfc(x)	x	erfc(x)	x	erfc(x)	x	erfc(x)	x	erfc(x)
0	1.000000	0.5	0.479500	1	0.157299	1.5	0.033895	2	0.004678	2.5	0.000407
0.01	0.988717	0.51	0.470756	1.01	0.153190	1.51	0.032723	2.01	0.004475	2.51	0.000386
0.02	0.977435	0.52	0.462101	1.02	0.149162	1.52	0.031587	2.02	0.004281	2.52	0.000365
0.03	0.966159	0.53	0.453536	1.03	0.145216	1.53	0.030484	2.03	0.004094	2.53	0.000346
0.04	0.954889	0.54	0.445061	1.04	0.141350	1.54	0.029414	2.04	0.003914	2.54	0.000328
0.05	0.943628	0.55	0.436677	1.05	0.137564	1.55	0.028377	2.05	0.003742	2.55	0.000311
0.06	0.932378	0.56	0.428384	1.06	0.133856	1.56	0.027372	2.06	0.003577	2.56	0.000294
0.07	0.921142	0.57	0.420184	1.07	0.130227	1.57	0.026397	2.07	0.003418	2.57	0.000278
0.08	0.909922	0.58	0.412077	1.08	0.126674	1.58	0.025453	2.08	0.003266	2.58	0.000264
0.09	0.898719	0.59	0.404064	1.09	0.123197	1.59	0.024538	2.09	0.003120	2.59	0.000249
0.1	0.887537	0.6	0.396144	1.1	0.119795	1.6	0.023652	2.1	0.002979	2.6	0.000236
0.11	0.876377	0.61	0.388319	1.11	0.116467	1.61	0.022793	2.11	0.002845	2.61	0.000223
0.12	0.865242	0.62	0.380589	1.12	0.113212	1.62	0.021962	2.12	0.002716	2.62	0.000211
0.13	0.854133	0.63	0.372954	1.13	0.110029	1.63	0.021157	2.13	0.002593	2.63	0.000200
0.14	0.843053	0.64	0.365414	1.14	0.106918	1.64	0.020378	2.14	0.002475	2.64	0.000189
0.15	0.832004	0.65	0.357971	1.15	0.103876	1.65	0.019624	2.15	0.002361	2.65	0.000178
0.16	0.820988	0.66	0.350623	1.16	0.100904	1.66	0.018895	2.16	0.002253	2.66	0.000169
0.17	0.810008	0.67	0.343372	1.17	0.098000	1.67	0.018190	2.17	0.002149	2.67	0.000159
0.18	0.799064	0.68	0.336218	1.18	0.095163	1.68	0.017507	2.18	0.002049	2.68	0.000151
0.19	0.788160	0.69	0.329160	1.19	0.092392	1.69	0.016847	2.19	0.001954	2.69	0.000142
0.2	0.777297	0.7	0.322199	1.2	0.089686	1.7	0.016210	2.2	0.001863	2.7	0.000134
0.21	0.766478	0.71	0.315335	1.21	0.087045	1.71	0.015593	2.21	0.001776	2.71	0.000127
										3.21	0.00000564

Table 5.5

Limited Source Diffusion

- A thin layer of fixed amount of dopant, (Q atoms / cm^2) is initially deposited onto the semiconductor surface, and then, diffusion is carried out. The total amount of impurity atoms at surface is fixed.

Boundary conditions:

1. $N(z, 0) = 0$ ($t = 0$) (No impurity inside Si but there are at surface)

2. $\frac{dN(0,t)}{dz} = 0$ ($z = 0$) (always maximum at surface)

3. $N(\infty, t) = 0$ ($z = \infty$) (No impurity at infinity)

Solution:

$$N(z) = \frac{Q}{\sqrt{\pi Dt}} \exp - \left(\frac{z}{2\sqrt{Dt}} \right)^2 \quad (\text{Equation 5.14})$$

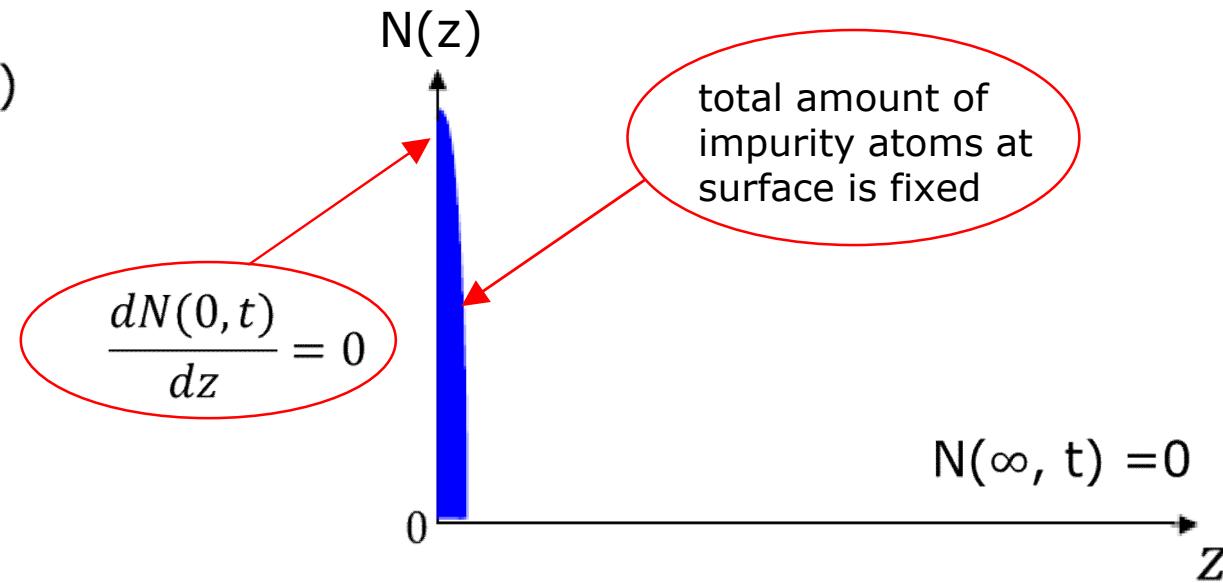


Figure 5.13

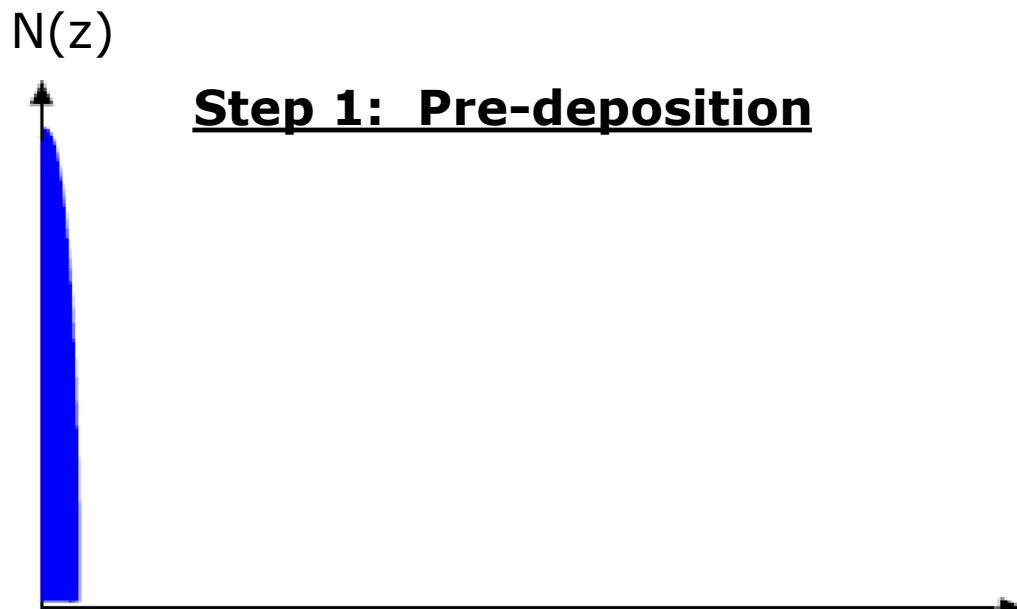
The surface concentration (at $z=0$) is: $N(0, t) = N_s = \frac{Q}{\sqrt{\pi Dt}}$

A limited source diffusion is a combination of two processes, pre-deposition and drive in.

Step 1: Pre-deposition:

- In pre-deposition, a thin layer with limited amount of dopants is deposited on surface at a short time t .
- The total amount gives a dose:

$$Q = 2N_s \sqrt{\frac{Dt}{\pi}} \quad (\text{Equation 5.15})$$



Step 1: Pre-deposition

Figure 5.14

Dose and Impurity Redistribution (Cont'd.)

Step 2: Drive in

- In drive in, the pre-deposited dopants on the surface (with fixed amount) are made to diffuse deeper into the solid, as requested.
- Drive in process makes the pre-deposited dopants **redistribute**.
- The redistributions of dopants follow the Gaussian profile.
- With the increase of diffusion time, the dopants go deeper and deeper. But the **total amount does not change**.

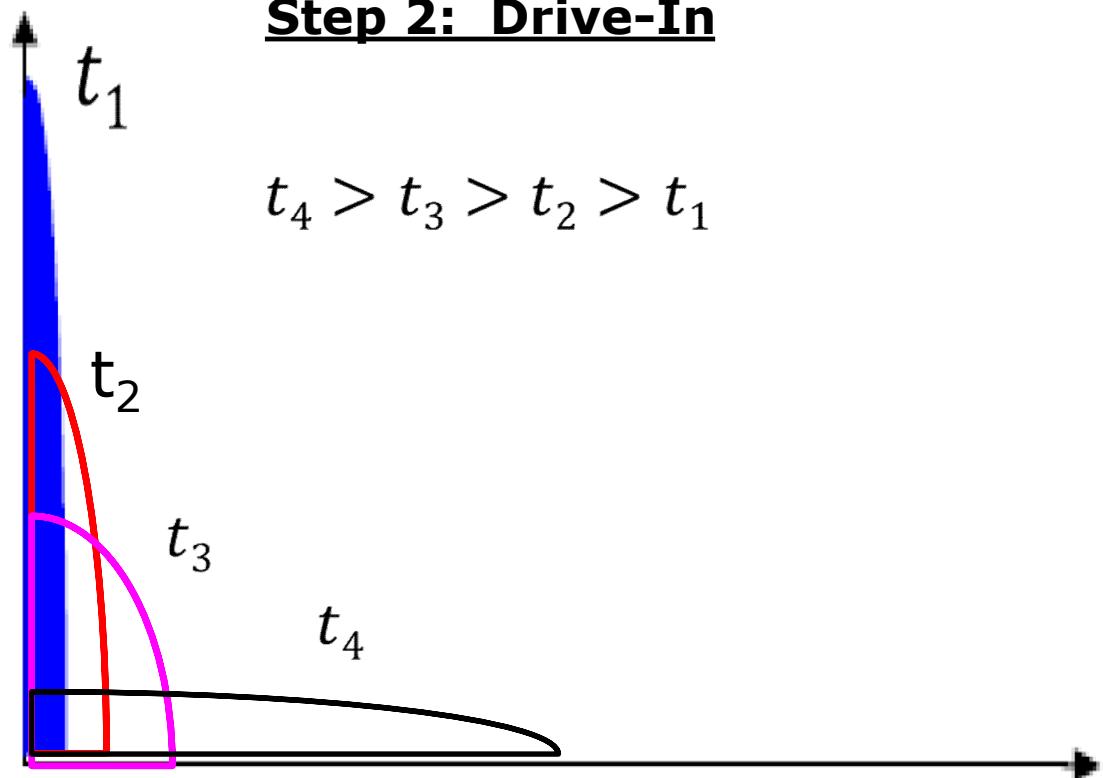


Figure 5.15

Solid Solubility Limits

- If the available impurity atoms are in excess, then the concentration of the impurity will be limited by the solid solubility of the impurity in the solid.
- Then, $N_s \leq \text{solid solubility}$.
- Solubility is a function of temperature.
- Some examples are (refer to figure):

$As, P > 10^{21} cm^{-3}$

$Sb: 2 - 7 \times 10^{19} cm^{-3}$

$B: 5 - 7 \times 10^{20} cm^{-3}$

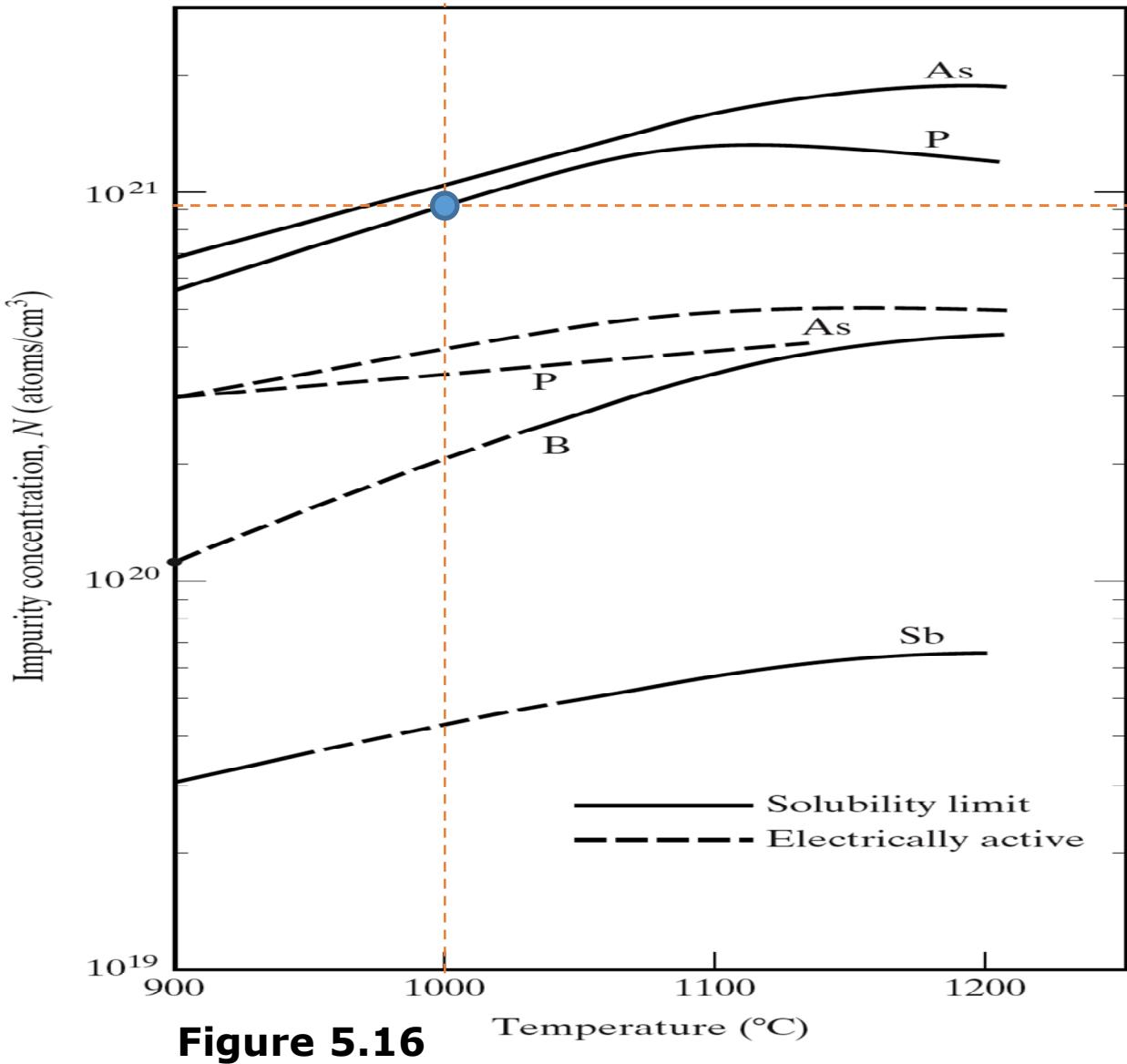


Figure 5.16

Junction Formation by Diffusion

- A pn junction can be fabricated by diffusing p-type impurities into an n-type wafer of uniform background concentration N_B .
- Effective doping concentration at any point is the difference between the acceptor and donor concentrations, whichever is larger.

p – type for $N(z,t) > N_B$

- Junction is located at z_j such that

$$N_s \operatorname{erfc} \left(\frac{z}{2\sqrt{Dt}} \right) = N_B \quad (\text{Equation 5.16})$$

Net carrier concentration Impurity concentration

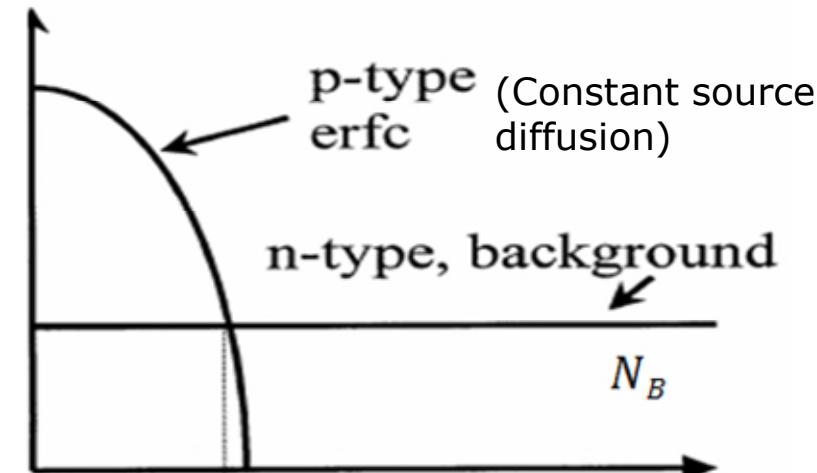


Figure 5.17 (a)

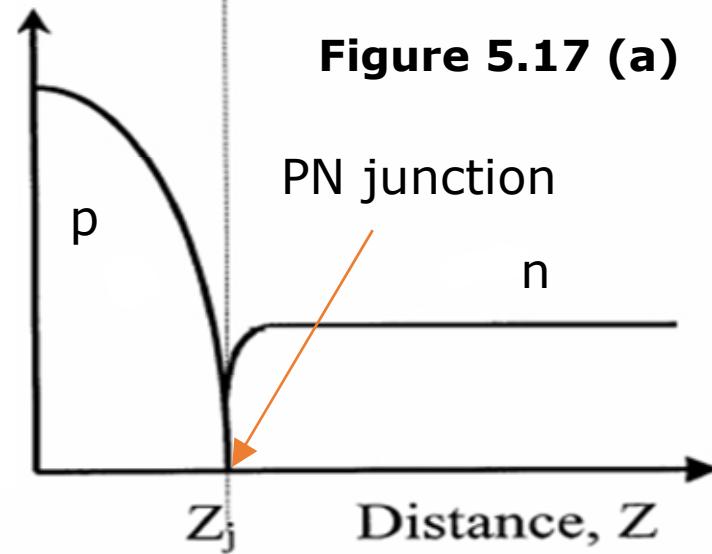


Figure 5.17 (b)

Analysis of Diffused Wafers

(A) Sheet Resistance Measurement

- To know the resistivity of the diffused layer, the best and simplest way is to measure sheet resistance R (Ω/\square) which eliminates the need for doping profile.
- There are two methods for measuring sheet resistance.

1. Four-point probe method

- Four probes are on one line, 2 for voltage and 2 for current.

$$R = \left(\frac{\rho}{t}\right) \left(\frac{L}{W}\right) = R_s \left(\frac{L}{W}\right)$$

If space $S \gg$ thickness t , then

$$R_s = \frac{\rho}{t} = \frac{\pi}{\ln 2} \frac{V}{I} \cong 4.53 \frac{V}{I} (\Omega/\square), \quad (\text{Equation 5.17})$$

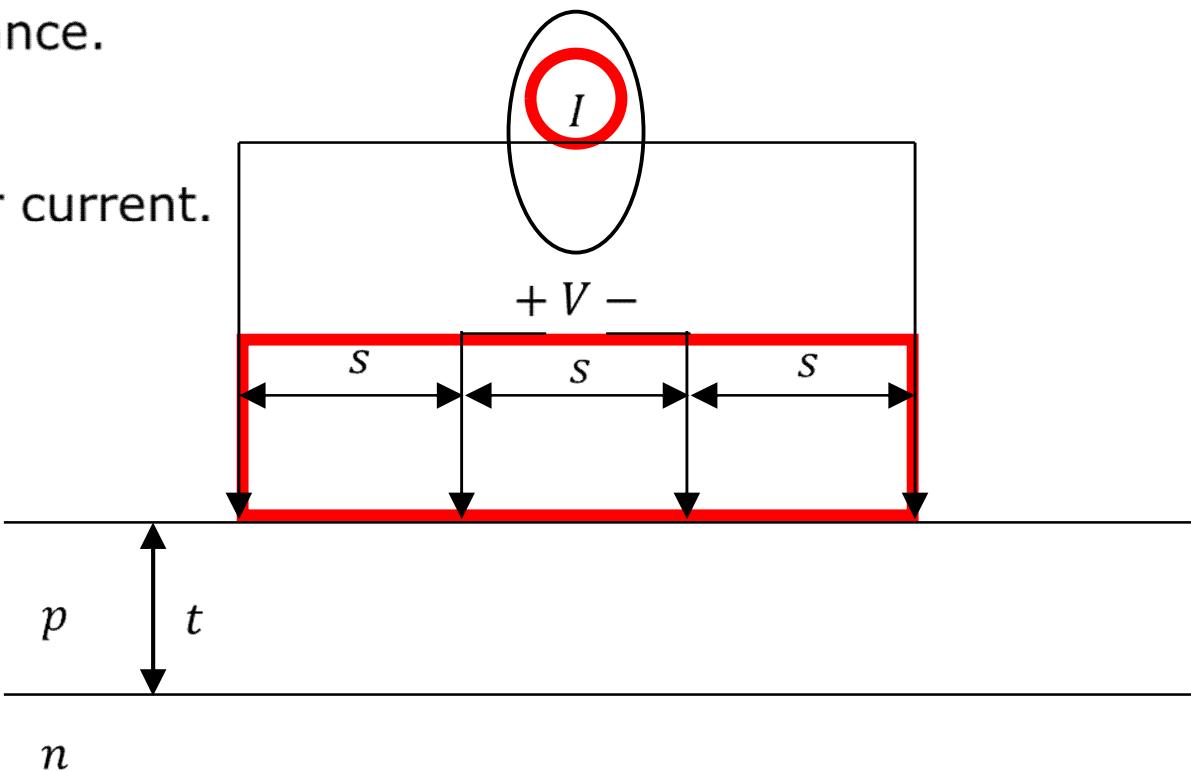


Figure 5.18

Analysis of Diffused Wafers (Cont'd.)

2. Van der Pauw's method

- The sample can be an arbitrary shape with four contacts on periphery of it.
- Two contacts to inject current and two to measure voltage.
- For symmetrical structure, a square or a circle,

$$R_s = \frac{\rho}{t} = \left(\frac{\pi}{\ln 2} \right) \frac{V_{CD}}{I_{AB}} \quad (\text{Equation 5.18})$$

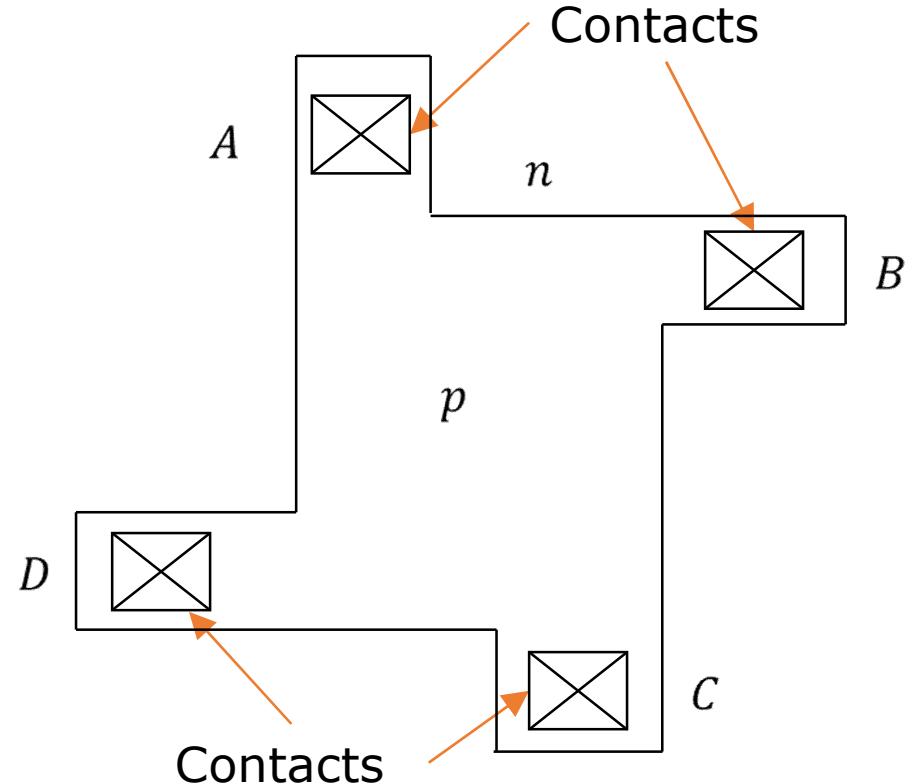


Figure 5.19

Angle-lap method

- The wafer edge is lapped at an angle of 1 to 5°, so that the junction region is visually magnified.
- An optically flat glass is placed over the lapped region.
- Illuminate the sample with monochromatic light.
- The number n of fringe is counted through a microscope.

$$X_j = d \tan \theta = n \frac{\lambda}{2} \quad (\text{Equation 5.19})$$

Light from sodium vapour lamp

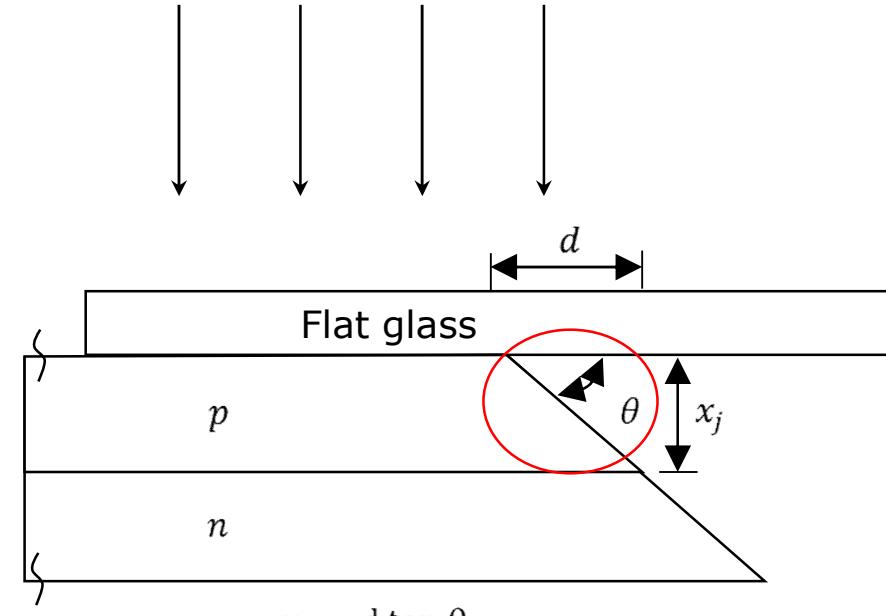


Figure 5.20 (a)

$$x_j = d \tan \theta$$

Fringe lines

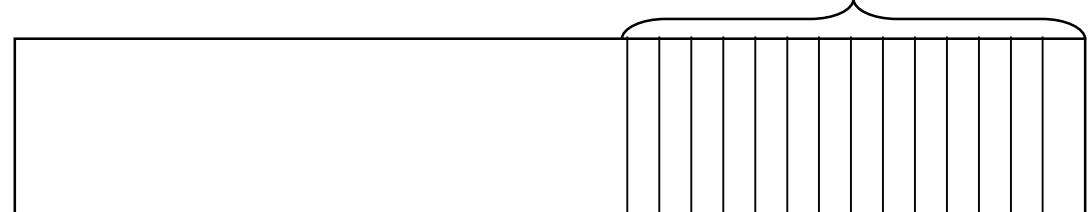


Figure 5.20 (b)

Junction Depth Measurements (Cont'd.)

Groove and stain technique

- A cylindrical groove in the wafer can be formed by the grinding wheel.
- Staining solution is applied to reveal the junction.
- Junction depth is expressed as, $x_j = \frac{(a+b)(a-b)}{2R}$ (Equation 5.20)

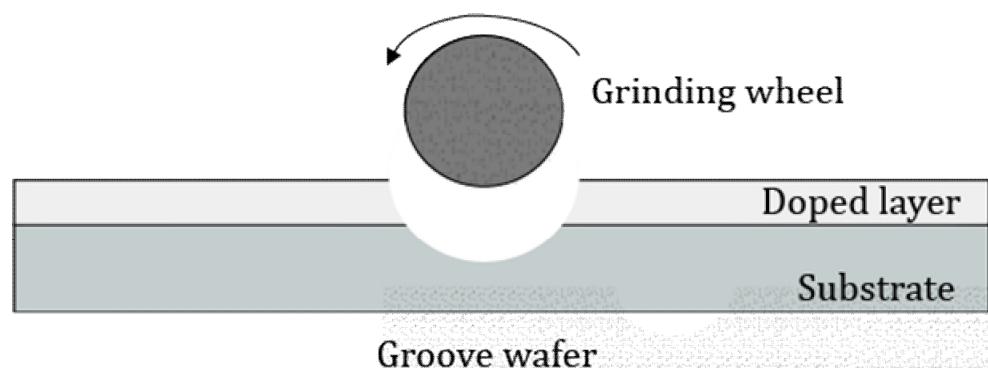


Figure 5.21 (a)

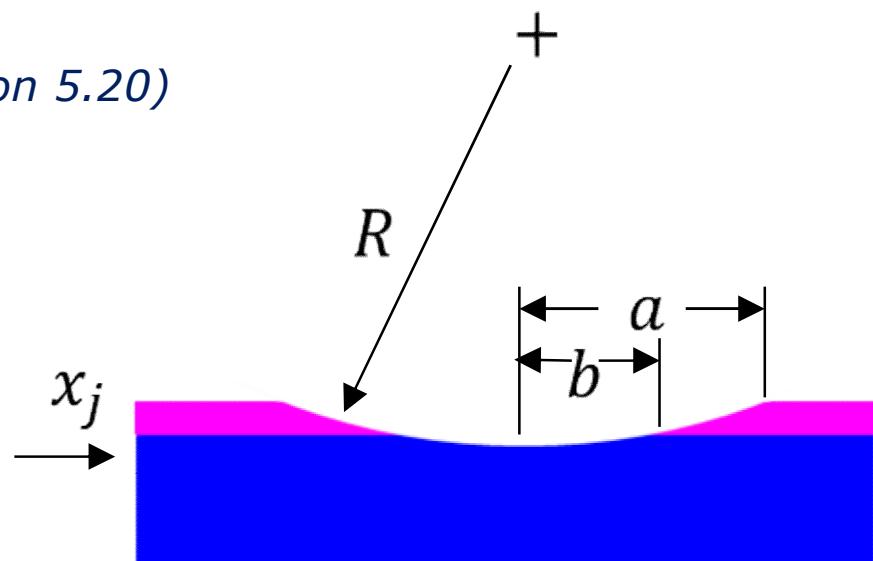


Figure 5.21 (b)

Impurity Profile Measurement

Secondary Ion Mass Spectrometry (SIMS)

- A low energy ($1 - 20 \text{ keV}$) ion beam sputters atoms from the sample, one or two atomic layer at a time.
- A small percentage of the removed atoms are ionised, collected and analysed by a mass spectrometer.
- A depth profile of atom is produced by continuous analysis.



Figure 5.22 (a)

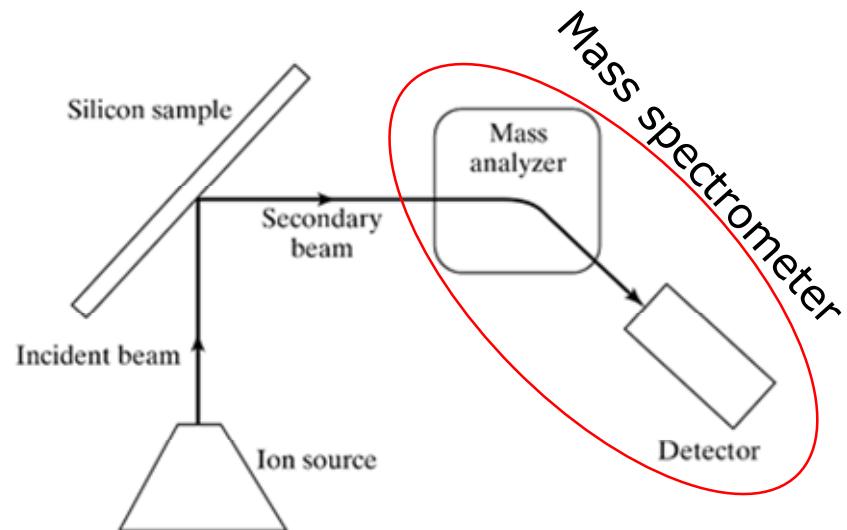


Figure 5.22 (b)

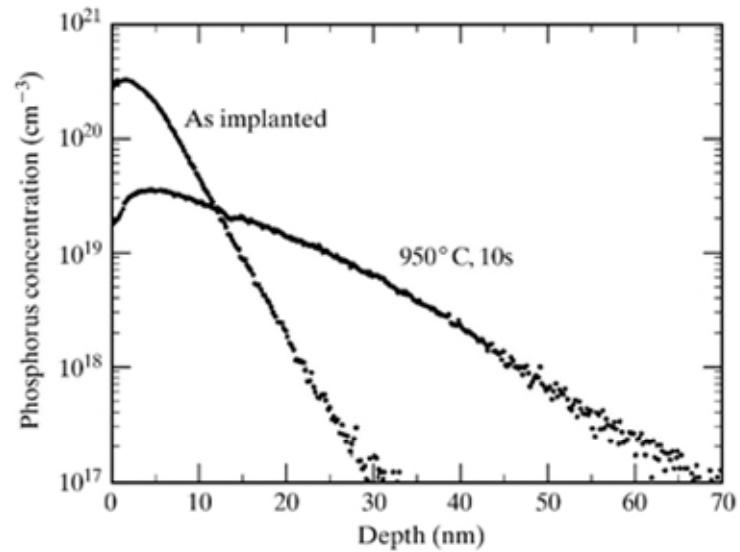


Figure 5.22 (c)

Impurity Profile Measurement (Cont'd.)

- SIMS is the best tool with the sensitivity needed for characterizing the impurity profiles in Si.
- The sensitivity is in the range of 10^{13} to 10^{17} cm^{-3} , depending on the impurity to be analyzed and the ion beam used.
- The depth resolution is in the range of 5 to 10 nm.

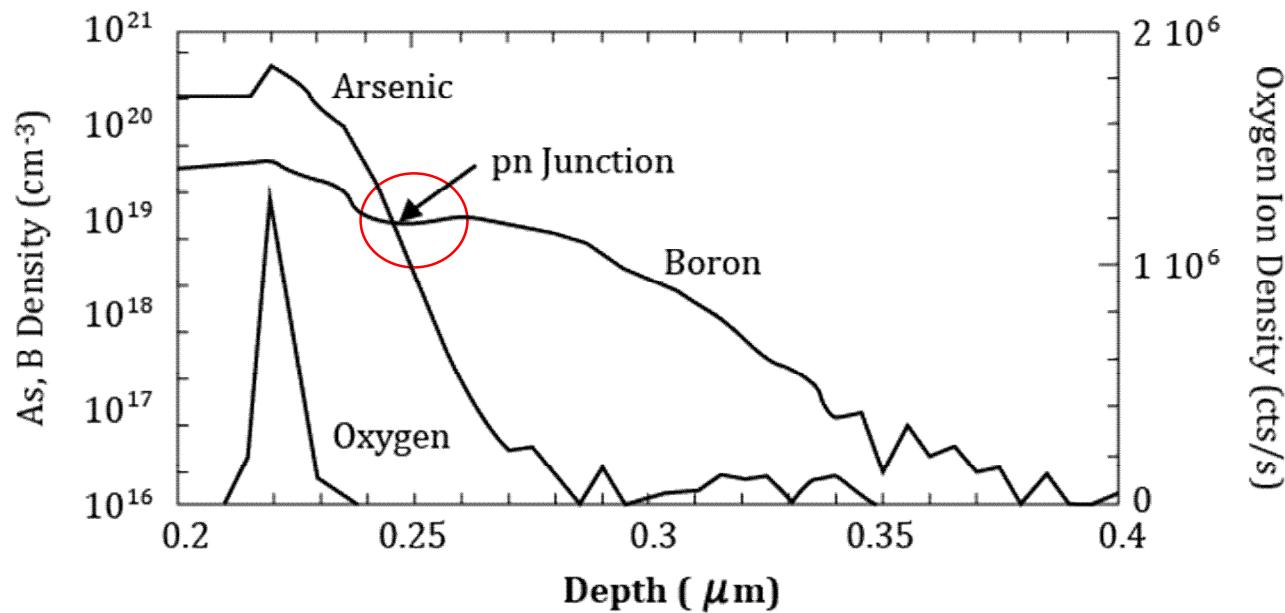


Figure 5.23

Diffusion Systems

- Open furnace tube systems
 - a) Solid source in platinum source boat
 - b) Liquid Source - carrier gas passing through bubbler
 - c) Gaseous impurity source
- Wafers in Quartz Boat
- Scrubber at Output

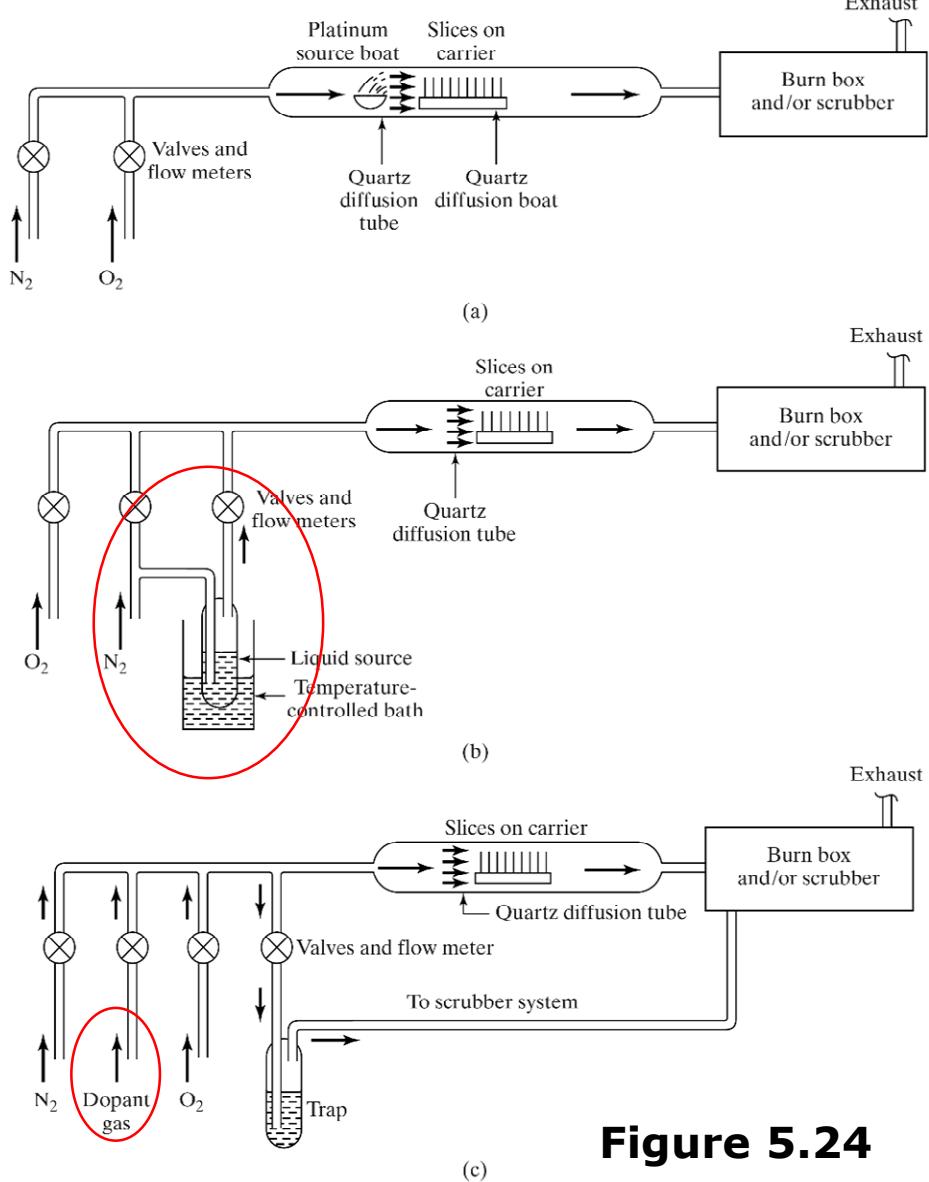
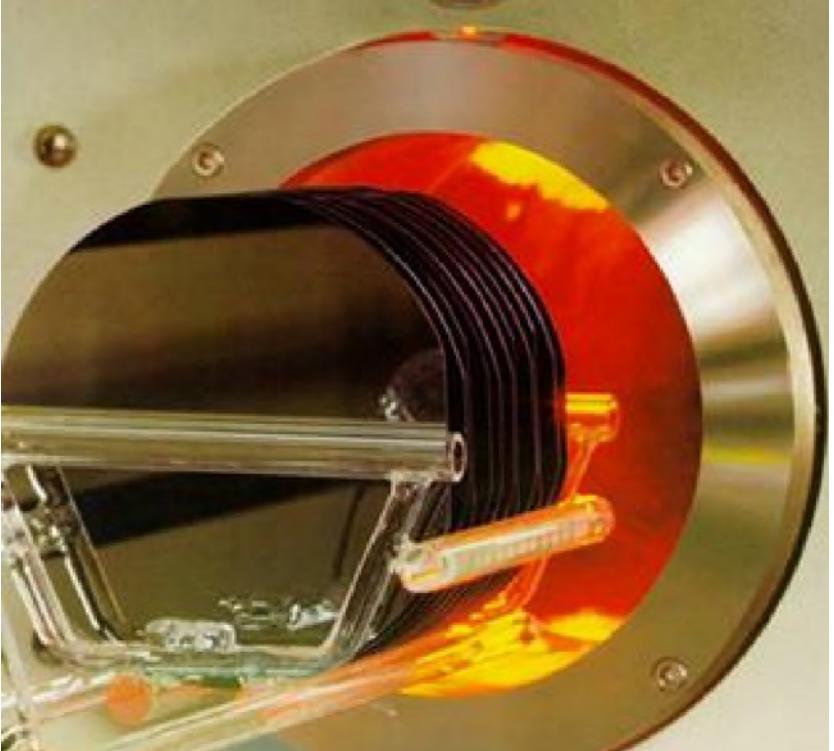


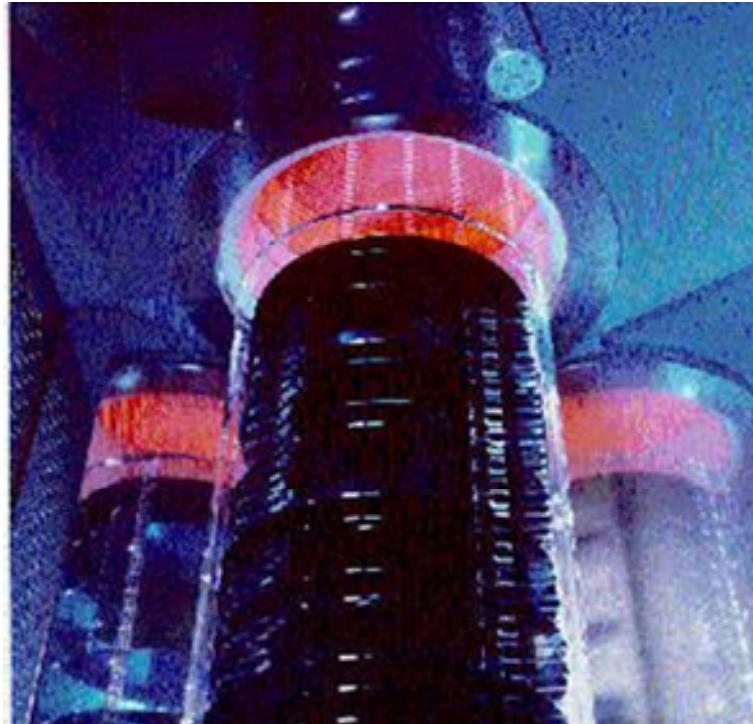
Figure 5.24

Diffusion Systems (Cont'd.)

- Furnace can be horizontal or vertical.



Horizontal furnace



Vertical furnace

Image 5.25

Lesson Summary

1. Diffusion will require a **concentration gradient**.
2. Diffusion is the key process for introducing impurities in the selected regions of a semiconductor.
3. Diffusion is used: little crystal damage, deep electrical junctions, cheap and easy solution.
Diffusion is not to use: for ultra-shallow junctions, or total impurity dose is critical.
4. Types of impurity diffusion in crystal:
 - Substitutional (direct exchange and vacancy exchange), and
 - Interstitial diffusion (Interstitialcy, kick-out and Frank-Turnbull).
5. Fick's Second Law: $\frac{\partial N}{\partial t} = D \frac{\partial^2 N}{\partial z^2}$.
6. Two boundary conditions for diffusion:
 - Constant source: $N(z) = N_s \operatorname{erfc}\left(\frac{z}{2\sqrt{Dt}}\right)$; $Q(t) = \frac{2N_s}{\sqrt{\pi}} \sqrt{Dt}$, and
 - Limited source: $N(z) = \frac{Q}{\sqrt{\pi Dt}} \exp - \left(\frac{z}{2\sqrt{Dt}}\right)^2$; surface concentration $N_s = \frac{Q}{\sqrt{\pi Dt}}$.

Lesson Summary

7. For limited source diffusion: pre-deposition (dose $Q = 2N_s \sqrt{\frac{Dt}{\pi}}$) and drive-in.

8. To find junction depth under:

- Constant source diffusion $\rightarrow N_s \operatorname{erfc} \left(\frac{z}{2\sqrt{Dt}} \right) = N_B$, and

- Limited source diffusion $\rightarrow \frac{Q}{\sqrt{\pi D_2 t_2}} \exp^{-\left(\frac{z}{2\sqrt{D_2 t_2}}\right)^2} = N_B$.

9. Sheet resistance measurement techniques:

- Four-point probe method $\rightarrow R_s = \frac{\rho}{t} = \frac{\pi}{\ln 2} \frac{V}{I} \cong 4.53 \frac{V}{I}$ (Ω/\square), and

- Van der Pauw's method $\rightarrow R_s = \frac{\rho}{t} = \left(\frac{\pi}{\ln 2} \right) \frac{V_{CD}}{I_{AB}}$.

Lesson Summary

10. Junction depth measurement techniques:

- Angle-lap method $\rightarrow X_j = d \tan \theta = n \frac{\lambda}{2}$, and

- Groove and stain method $\rightarrow x_j = \frac{(a+b)(a-b)}{2R}$.

11. High resolution impurity profile measurement: secondary ion mass spectrometry or SIMS.

12. Furnace systems: solid, liquid and gaseous impurity source; horizontal and vertical.