



Course: EE3013/ Semiconductor Devices and Processing
School: School of Electrical and Electronic Engineering
Week 9 – Ion Implantation

Learning Objectives

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

- Explain the applications of ion implantation in semiconductor processing.
- Explain the advantages and disadvantages of implantation.
- Describe the five major parts of a typical ion implantation system.
- Describe and apply the Gaussian distribution function to approximate the implantation profile.
- Determine the key parameters such as project range, straggle, dose for implantation.
- Describe the two main stopping mechanisms for implantation.
- Explain what is ion channelling in implantation and how to avoid them.
- Calculate the minimum mask thickness required for effective masking in implantation.
- Determine the pn junction depths using implantation technique.
- Explain why temperature annealing is needed for implantation.
- Explain what is the effect of annealing on the implant profile.
- Describe a typical rapid thermal annealing system used for implant annealing.

Application of Ion Implantation in CMOS Fabrication

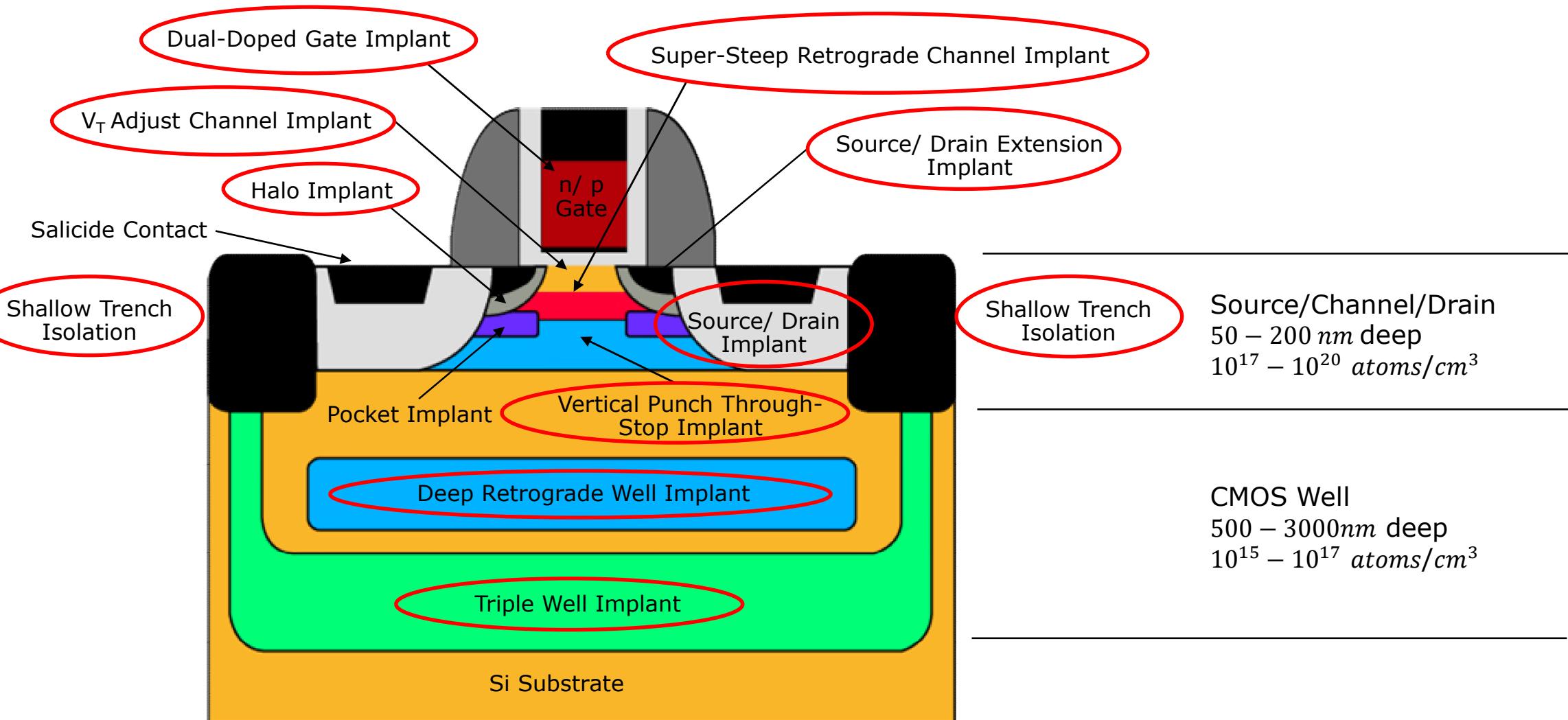


Figure 6.1

Advantages and Disadvantages

Advantages:

- Low-temperature process (can use photoresist as mask)
- Wide selection of masking materials, e.g. photoresist, oxide, poly-Si, metal
- Less sensitive to surface cleaning procedures
- Very fast (6" wafer can take as little as 6 seconds for a moderate dose)
- Complex profiles can be achieved by multi-energy implants

Disadvantages:

- Very expensive equipment (\$1M or more)
- At high dose values, throughput is less than diffusion (chemical source pre-deposition on surface)
- Ions damage the semiconductor lattice
- Not all the damage can be corrected by annealing
- Very shallow and very deep doping are difficult or impossible
- Masking materials can be 'knocked' into the wafer creating unwanted impurities, or even destroying the quality of the interface

Ion Implantation System

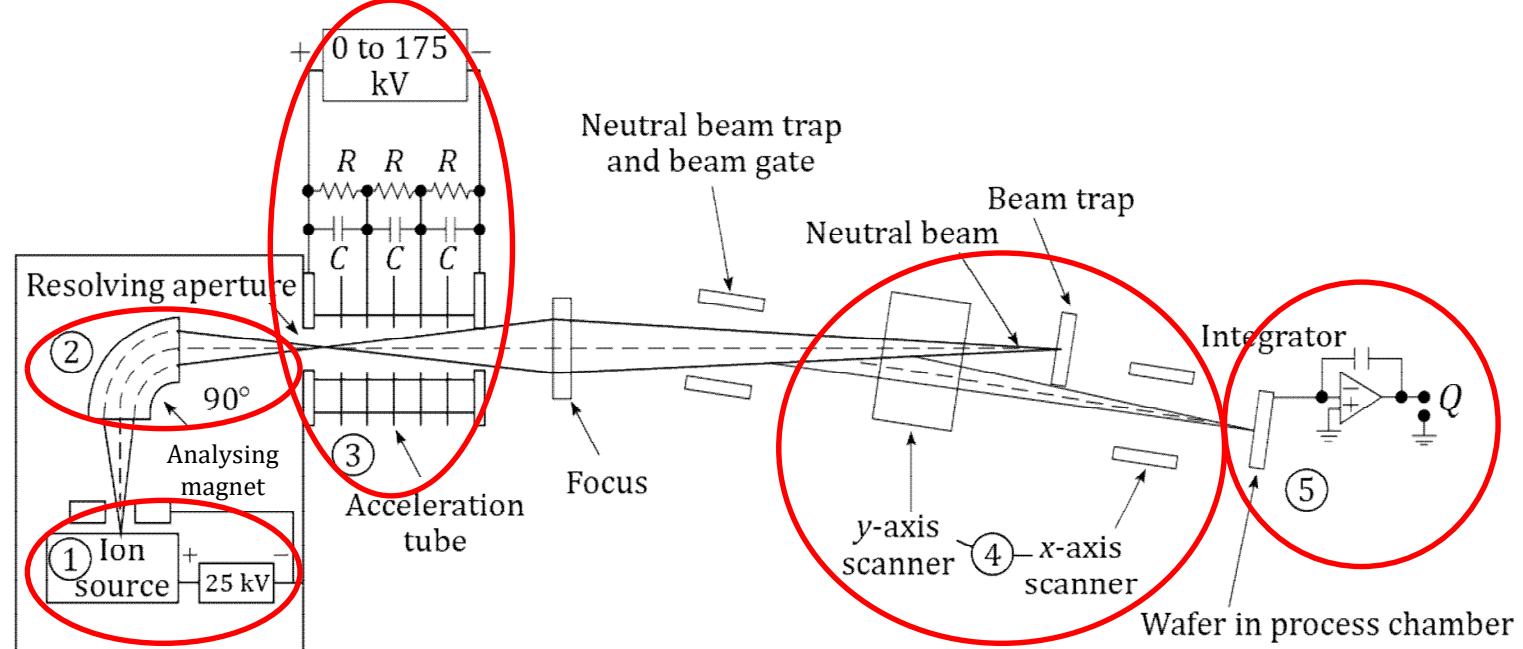


Figure 6.2

- ① Ion Source
- ② Mass Spectrometer
- ③ High-Voltage Accelerator (Up to 5 MeV)
- ④ Scanning System
- ⑤ Target Chamber



Ion Implantation System

Ion Implantation System (Cont'd.)

1. Ion source

- The ion source produces a plasma containing the desired impurity ions (and other undesired species).
- Arsine, phosphorus, and diborane are usually used as the sources.
- Solids can also be sputtered as ion sources if no gases available for the dopants.

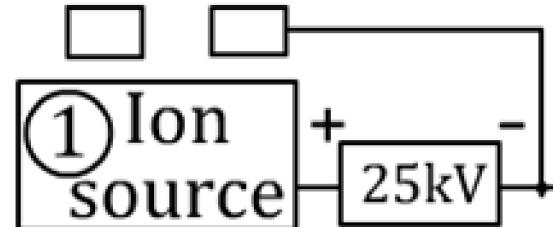


Figure 6.3

2. Mass spectrometer (or Analyser)

- An analyser magnet will bend the selected ions through a right angle.
- Hence, only selected ions can be passed to the accelerator.

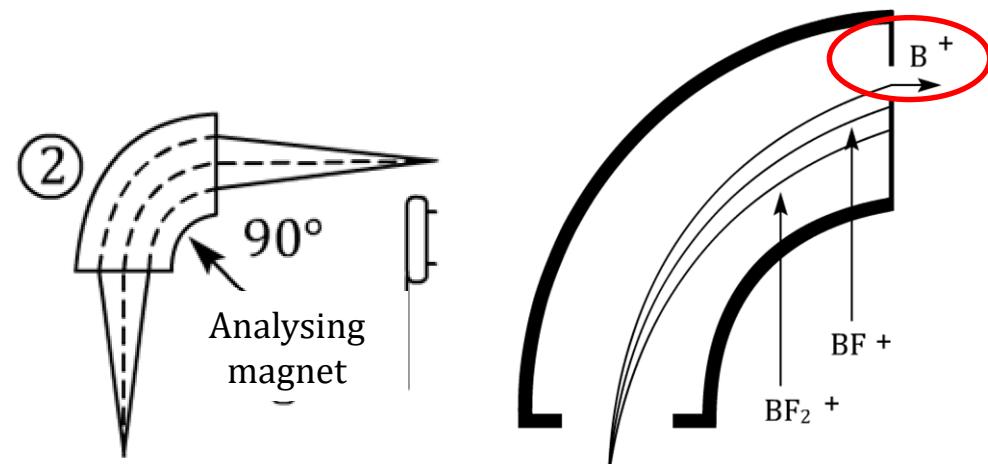


Figure 6.4

Ion Implantation System (Cont'd.)

3. Accelerator

- The accelerator adds energy to the ion beam.

4. Scanning system

- X- and y-axis deflection plates scan the ion beam across the wafer to produce uniform implantation and to get desired dose.
- The slight bending of beam is to prevent neutral particles from hitting the wafer.

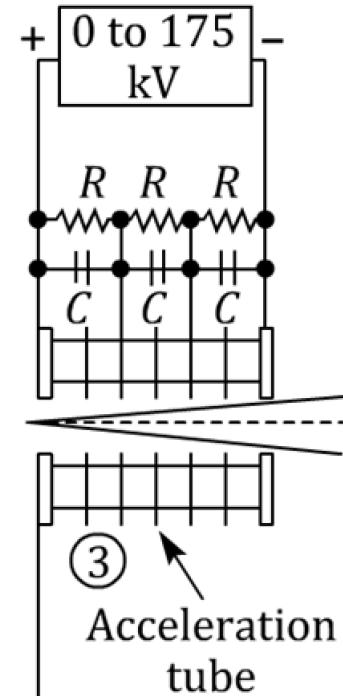


Figure 6.5

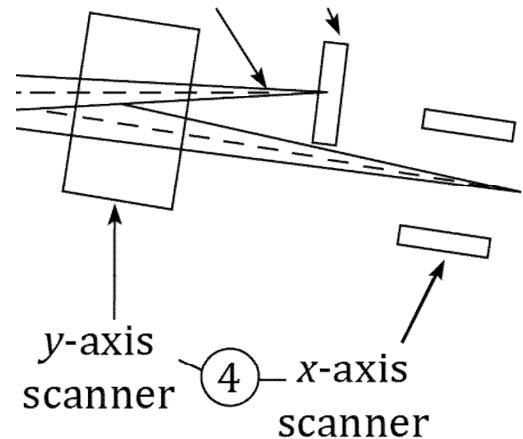
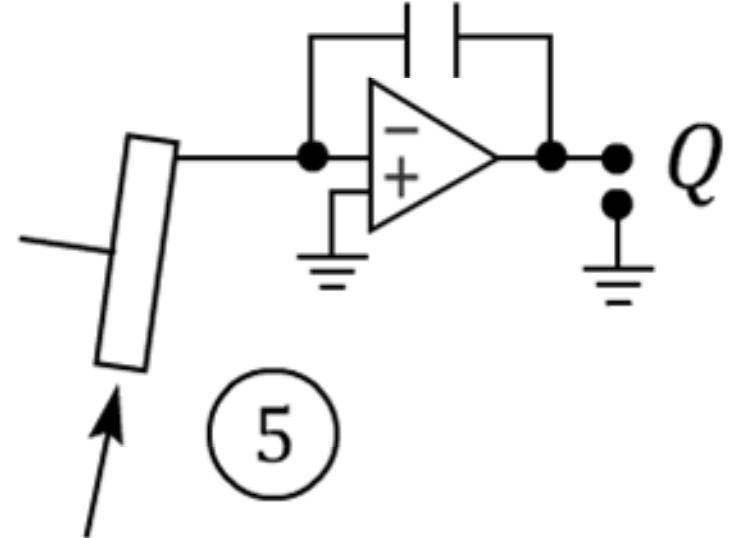


Figure 6.6

Ion Implantation System (Cont'd.)

5. Target chamber

- Si wafer is the target for ion beam.
- The wafer area is maintained near ground potential.



Wafer as a target

Figure 6.7

Magnetic Field for Selecting Ions

- Force on charged particle with velocity v

$$\bar{F} = q(\bar{v} \times \bar{B}) \quad (\text{Equation 6.1})$$

- If B is perpendicular to v , then

$$qvB = \frac{mv^2}{r} \quad (\text{Equation 6.2})$$

and energy $qV = \frac{mv^2}{2}$ (*Equation 6.3*)

- Hence, the magnetic Field for selecting ions with mass m is

$$|\bar{B}| = \sqrt{\frac{2mV}{qr^2}} \quad (\text{Equation 6.4})$$

where, m = mass of the ions

v = velocity

V = accelerator voltage

r = radius of the analyser magnet

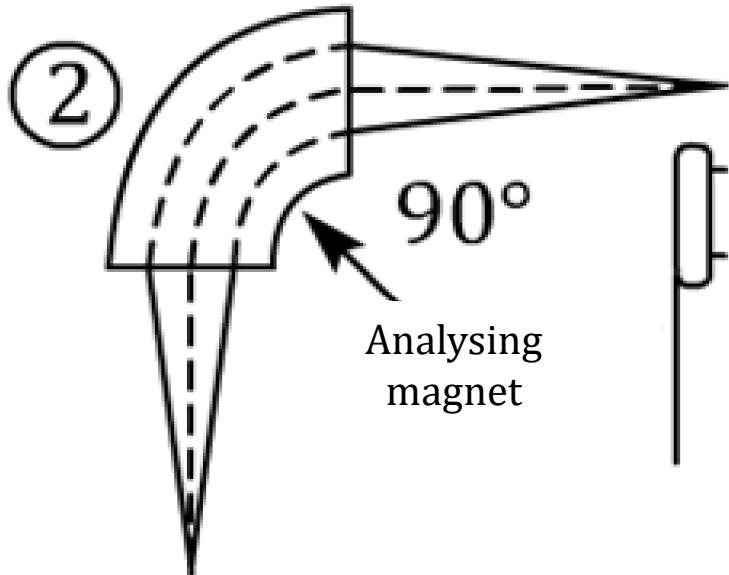


Figure 6.8

Implant Depth and Profile

- The higher the implantation energy, the larger the depth of the ions.

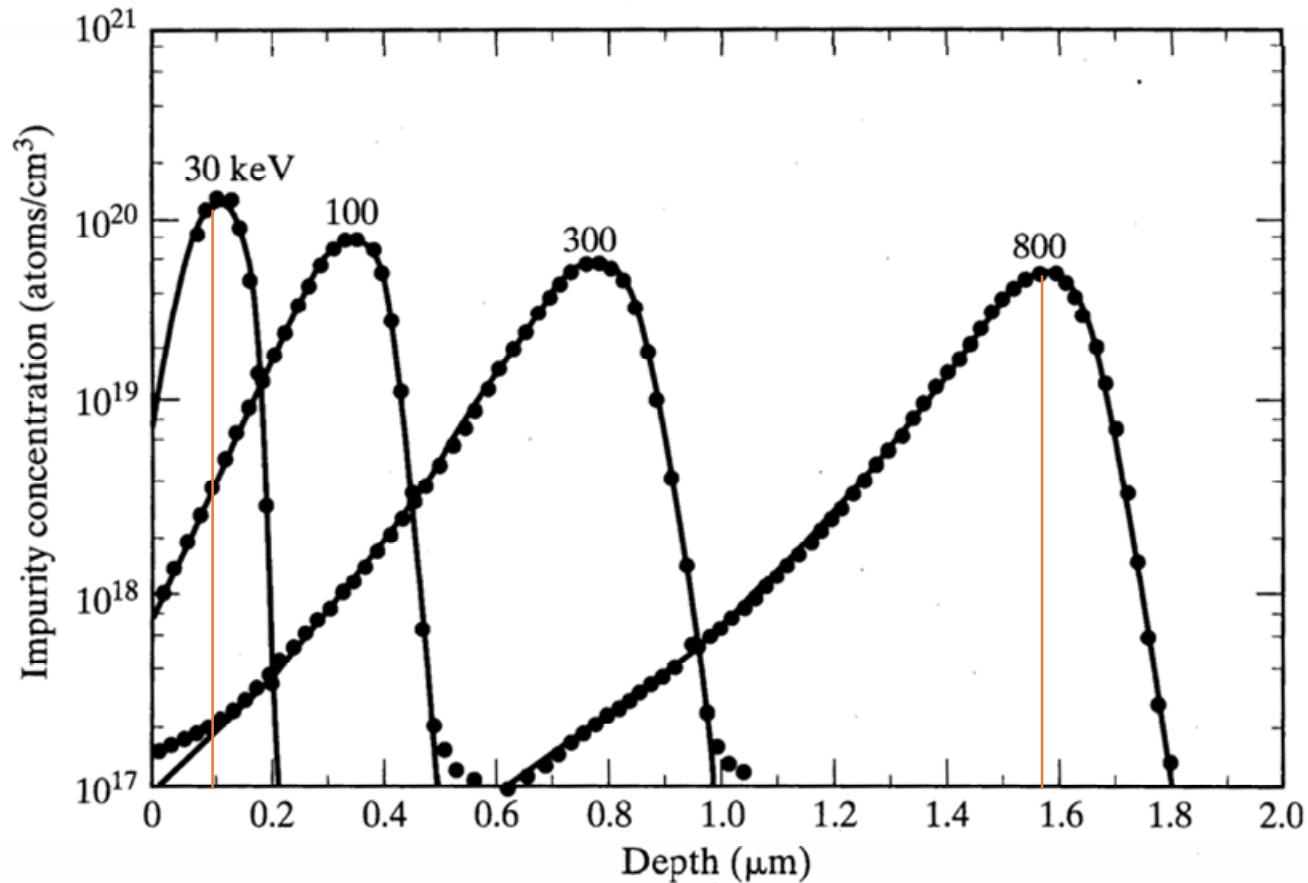


Figure 6.9

Implanted Dose

- Implanted Dose can be calculated from:

$$Q = \frac{1}{nqA} \int_0^t I(t)dt \quad (\text{Equation 6.5})$$

where,

I = beam current

A = wafer area

t = implantation time

n = 1 for singly ionised ions

2 for doubly ionised ions

Ion Distribution

- Impurity profile is approximated to a Gaussian distribution function along the axis of incidence.

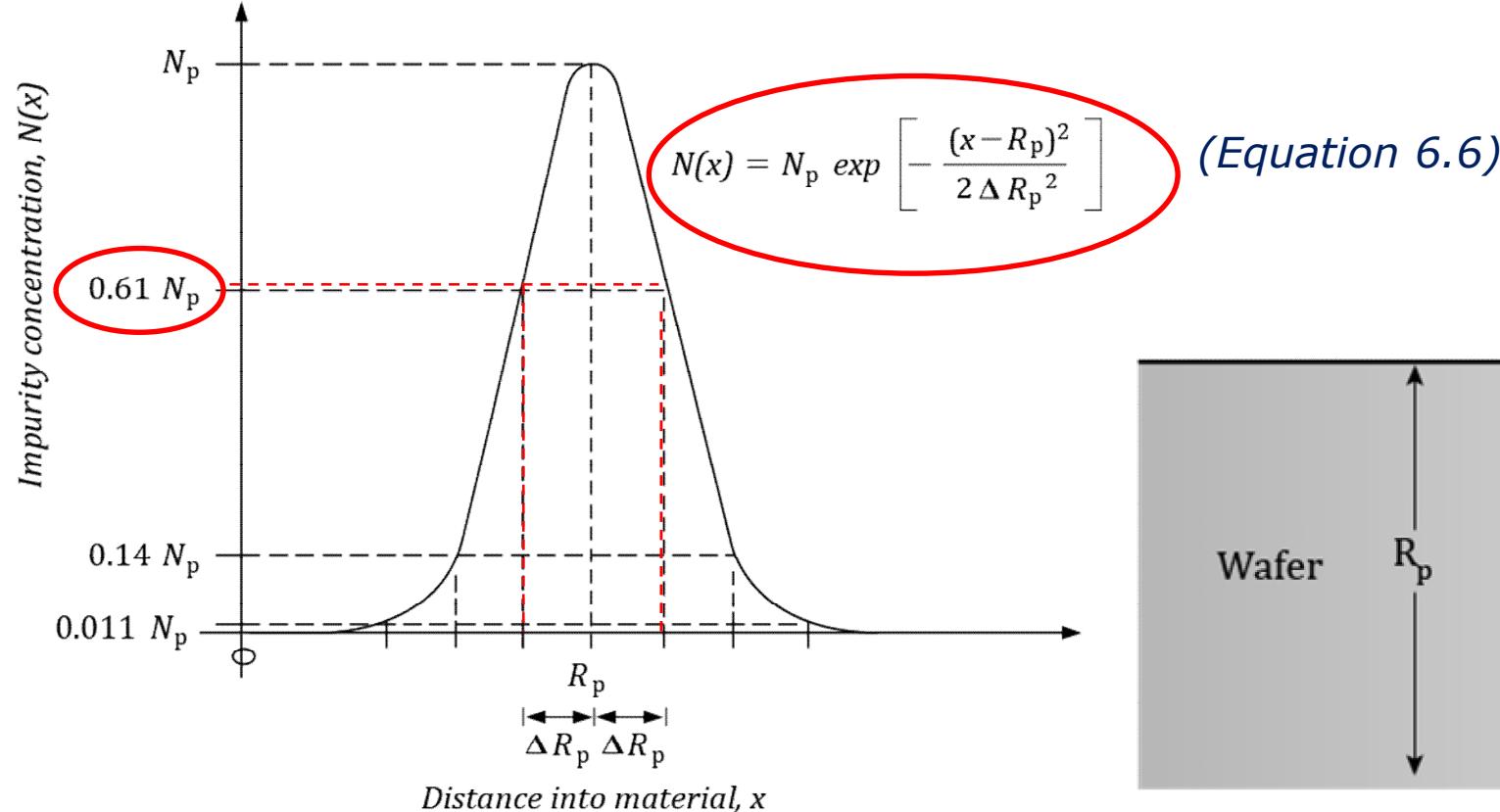


Figure 6.10

where R_p : Projected range (average distance an ion travels)

ΔR_p : Straggle (Standard deviation of the projected range)

$N(R_p)$: N_p (maximum ion concentration)

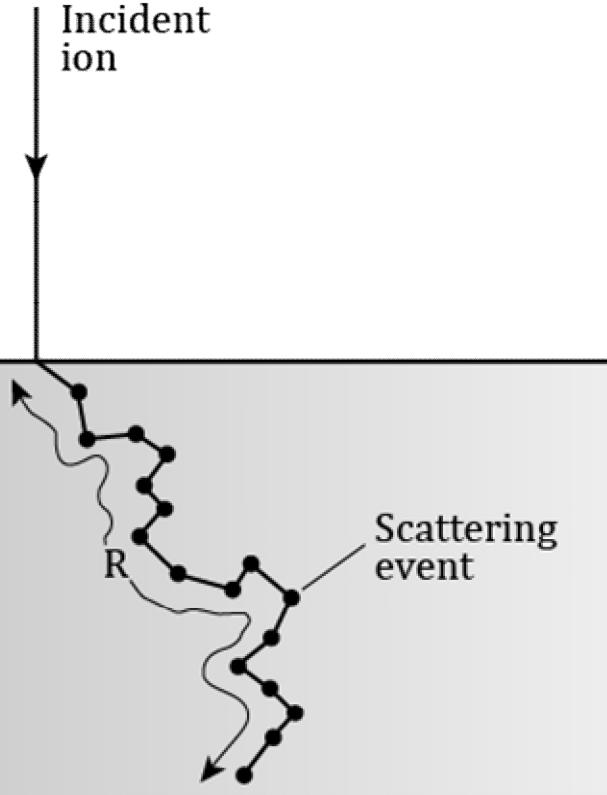


Figure 6.11

Ion Distribution (Cont'd.)

- The total ions implanted into the Si is dose, which, mathematically, is the area under the impurity distribution curve,

Dose
$$Q = \int_0^{\infty} N(x) dx = \sqrt{2\pi} N_p \Delta R_p \quad (\text{Equation 6.7})$$

- Hence
$$N(x) = \frac{Q}{\sqrt{2\pi} \Delta R_p} \exp \left[-\frac{(x-R_p)^2}{2\Delta R_p^2} \right] \quad (\text{Equation 6.8})$$
- Range of Q : $10^{10} - 10^{18} \text{ cm}^{-2}$

Ion Distribution in Three Dimension

Based on a theory developed by Lindhard, Scharff and Schiott (LSS theory)

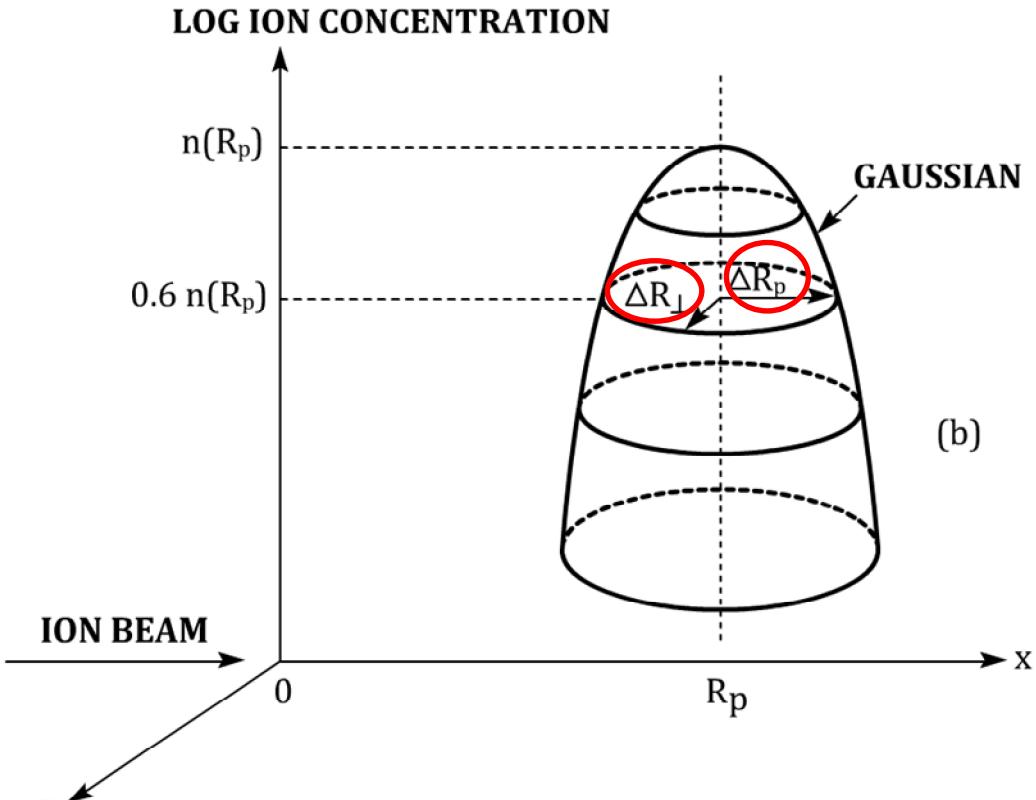


Figure 6.12

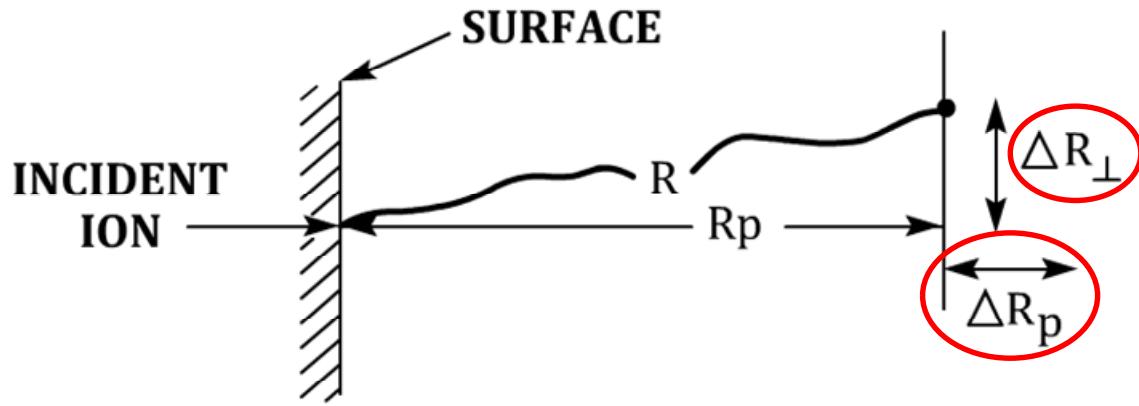


Figure 6.13

where R_p : Projected range

ΔR_p : Straggle along the axis of incidence x

ΔR_{\perp} : Straggle along the axis perpendicular to incidence

Projected Range

- R_p increases with acceleration energy.

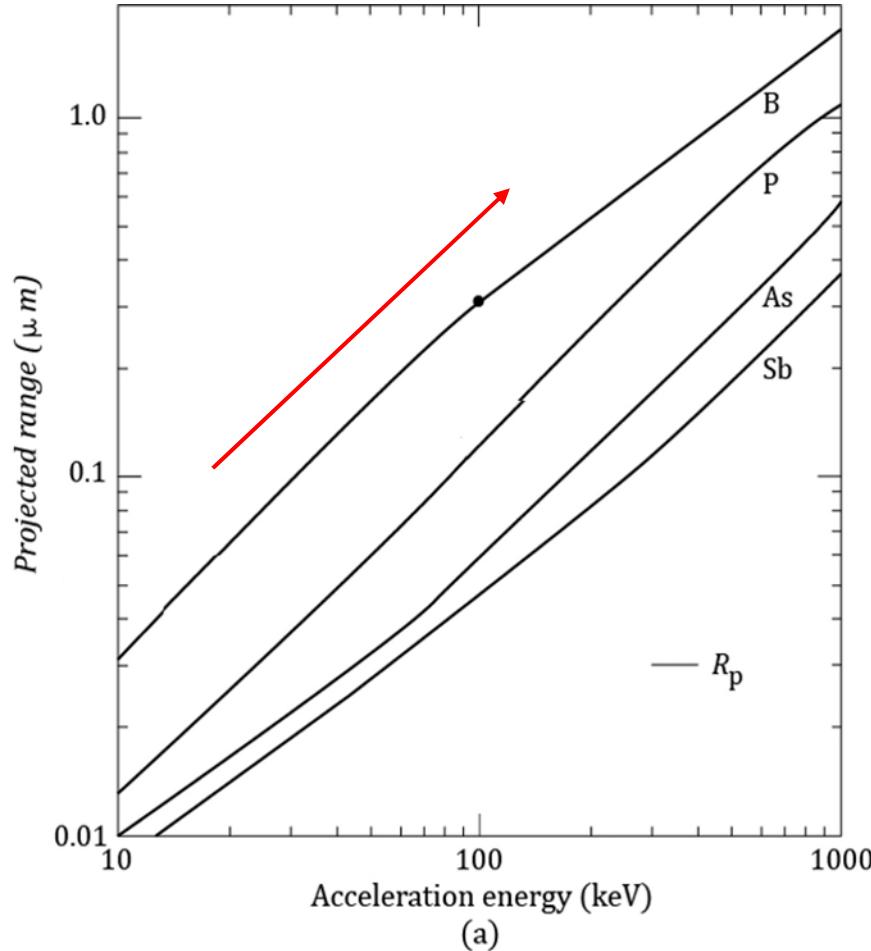


Figure 6.14

Straggle

- Both ΔR_p and ΔR_{\perp} increases with acceleration energy.

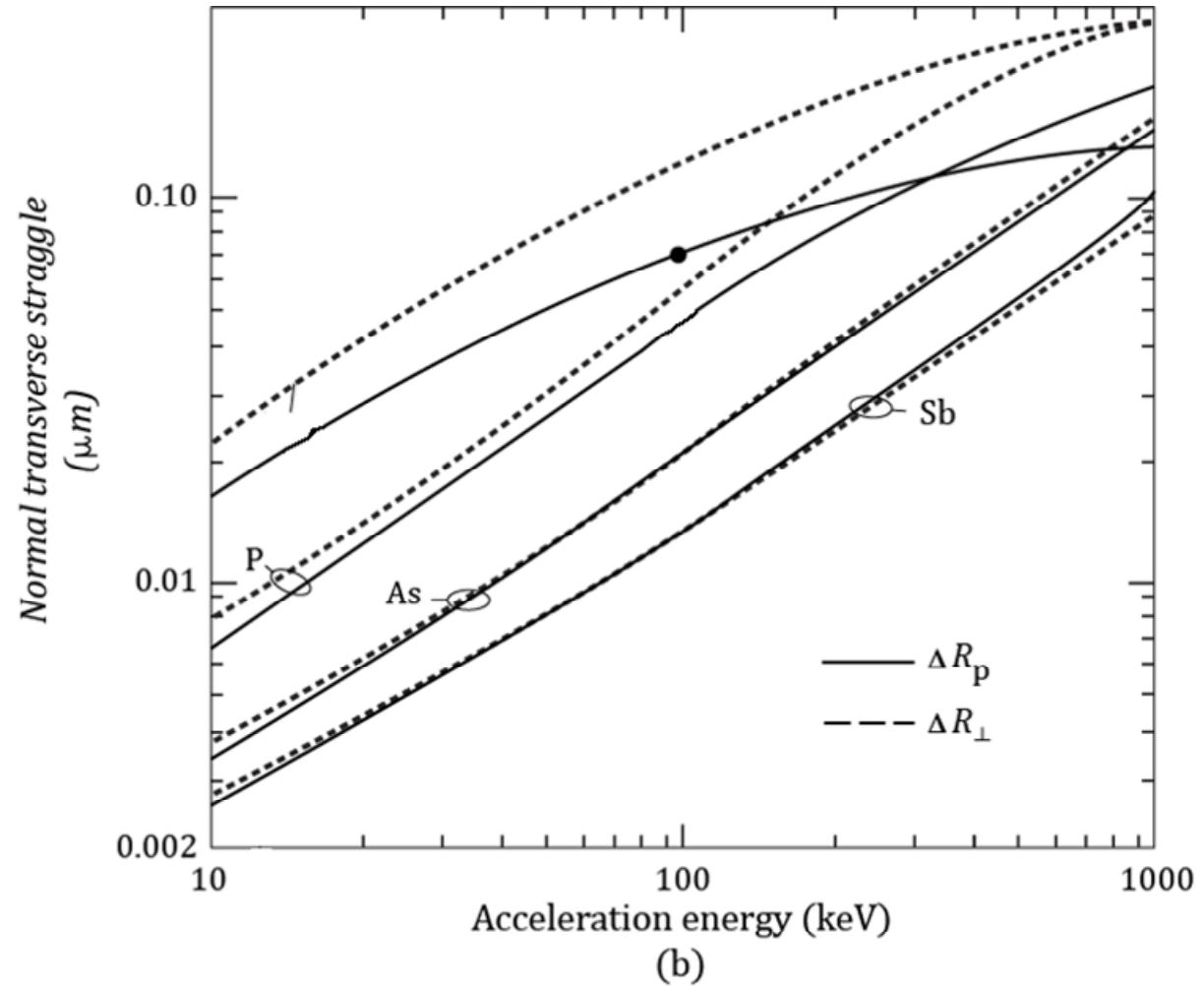


Figure 6.15

Example

Phosphorous ions with an energy of 100 keV are implanted into a silicon wafer.

- (a) What are the projected **range** and **straggle** associating with this implantation?
- (b) What should the **implanted dose** be if a peak concentration of $1.1 \times 10^{17}/\text{cm}^3$ is desired?
- (c) What length of time is required to implant this dose into a 200mm wafer using a $2\text{ }\mu\text{A}$ beam current with **singlly** ionised phosphorus.

Example (Cont'd.)

Solution:

- a) Using figures 6.14 and 6.15, we find that the projected range and straggle are **0.12 μm** and **0.045 μm** , respectively.

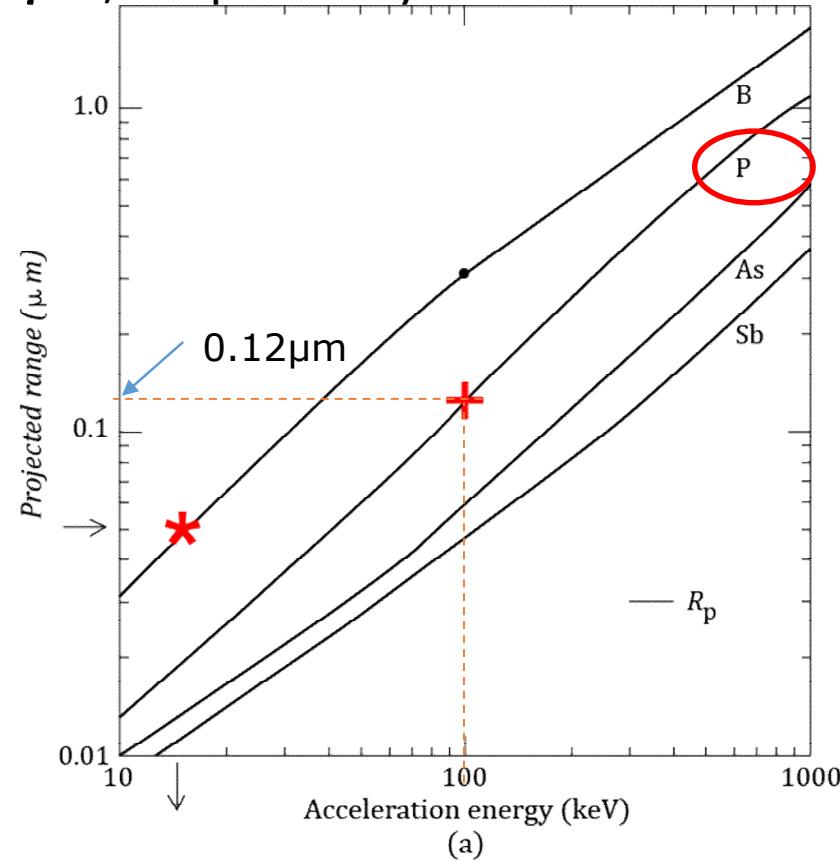


Figure 6.14

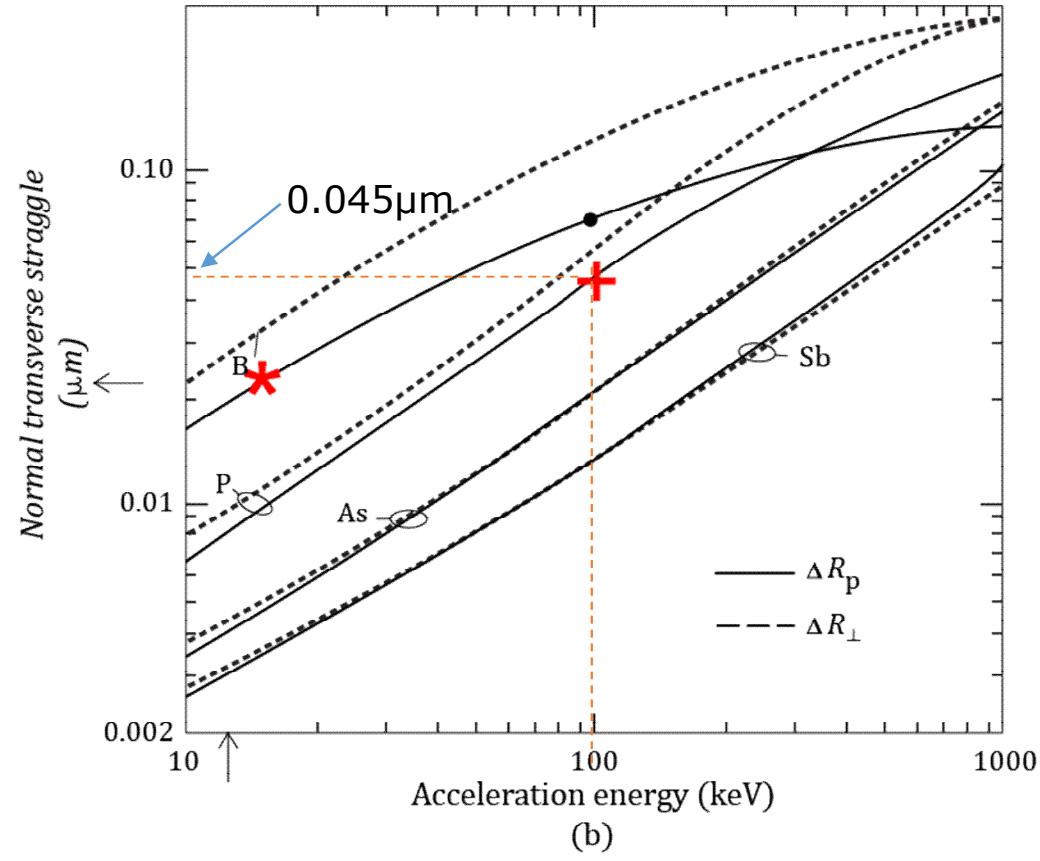


Figure 6.15

Solution (Cont'd.)

b) The dose and peak concentration are related by

$$Q = \sqrt{2\pi} N_p \Delta R_p = \sqrt{2\pi} (1 \times 10^{17}/cm^2)(4.5 \times 10^{-6} cm) = 1.13 \times 10^{12}/cm^2$$

c) From
$$Q = \frac{1}{nqA} \int_0^t I(t) dt = \frac{1}{nqA} t$$

$$t = \frac{nqAQ}{I} = \frac{(1)(1.6 \times 10^{-19} coul)(\pi)(10 cm)^2(1.13 \times 10^{-12}/cm^2)}{2 \times 10^{-6} coul/sec}$$

$$= 28.4 sec$$

Ion Stopping Mechanisms

Two stopping mechanisms by which the ion on entering the substrate can be brought to a rest.

(1) Nuclear stopping:

- Transfer of energy from the incoming nuclei (energy E_0 , mass M_1) to the target nuclei (initial energy zero, mass M_2).

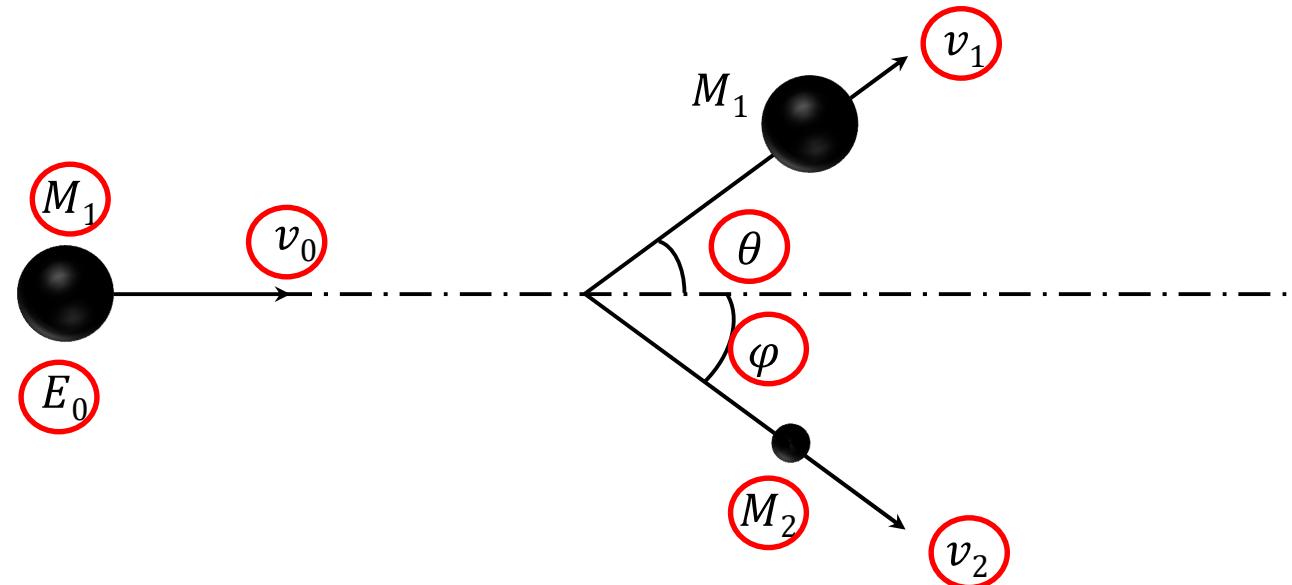


Figure 6.16. Collision of Hard Spheres

Ion Stopping Mechanisms

(2) Electronic Stopping:

- The interaction of the incident ion with the electronic cloud of the host atom. The ion loses energy by Coulombic interaction.

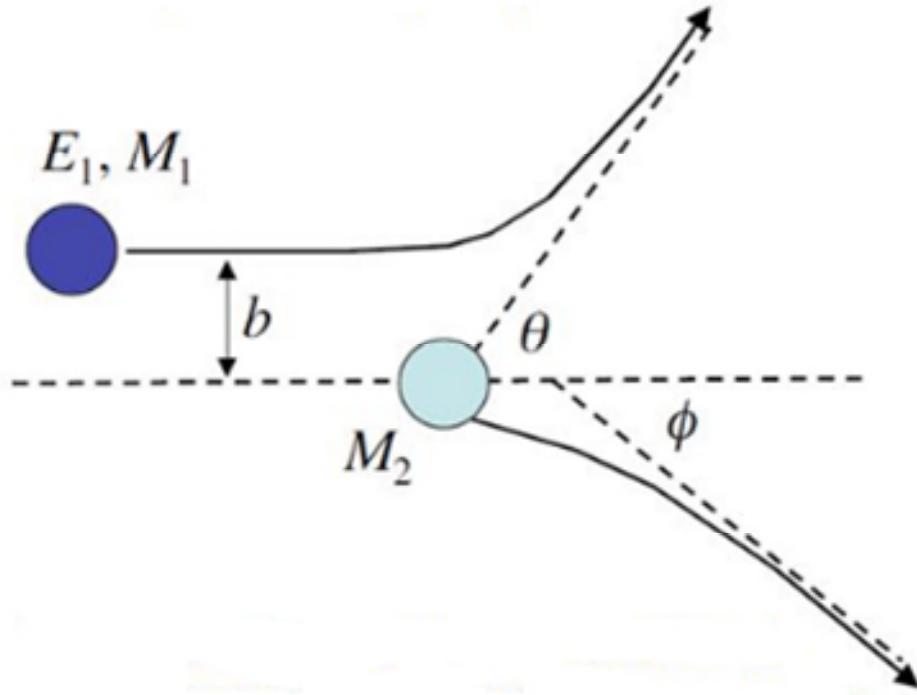


Figure 6.16 (b): Electronic stopping by Coulomb scattering

Ion Channelling

- Amorphous materials - implanting ion encounters the same number of atoms per unit distance while traveling.
- Single crystals - there are directions (e.g. $<110>$) in which no nuclei will be encountered and the only stopping mechanism is due to electrons. Thus, the project range will be considerably increased or channeled.

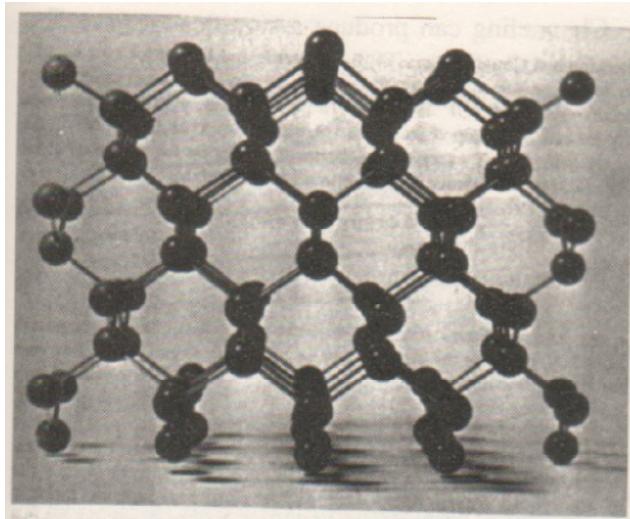


Figure 6.17 (a)

View of the diamond structure along a (a) major crystal axis $<110>$ and (b) along a random direction

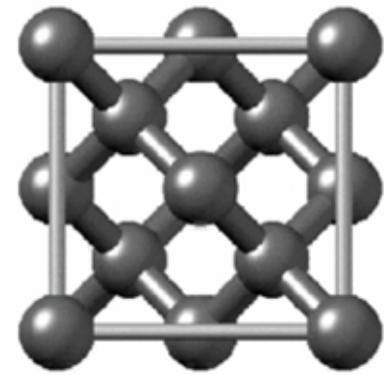


Figure 6.17 (b)

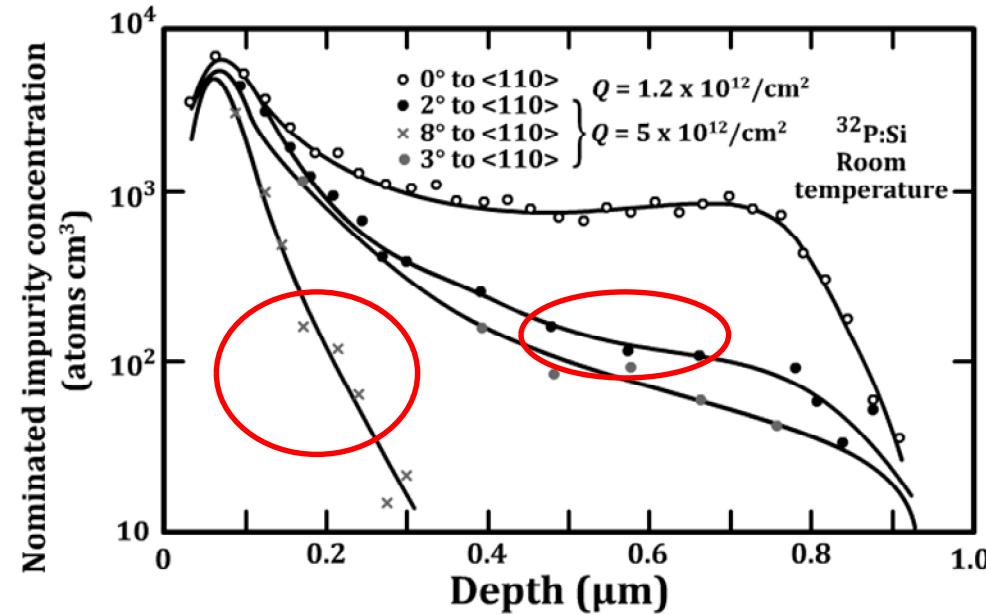


Figure 6.18

Phosphorus impurity profiles for 40 KeV implantations at various angles from $<110>$ axis

How to Avoid Ion Channeling?

1. Tilt

- To avoid channeling, the crystal can be misoriented by a small angle (7 to 10°), so that the ion beam is incident along a random direction.

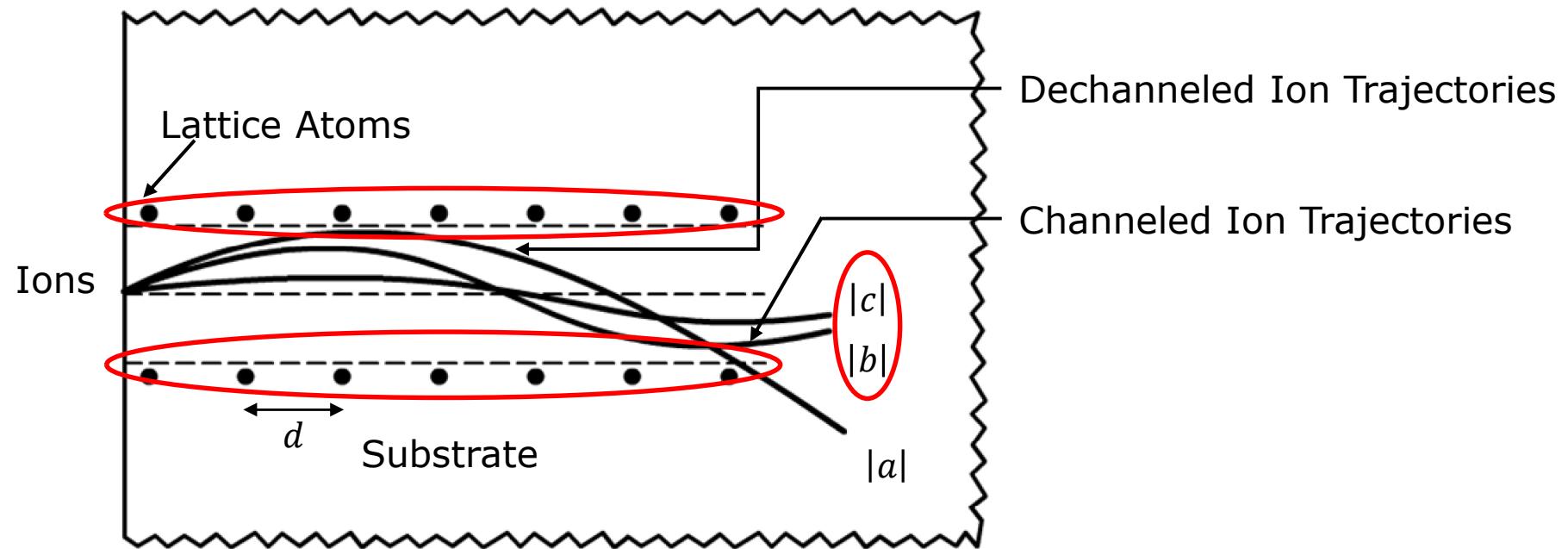


Figure 6.19. Trajectories of channeled particles in a crystallographic direction

How to Avoid Ion Channeling? (Cont'd.)

1. Tilt (Cont'd.)

- The extent of channeling depends on dose also.

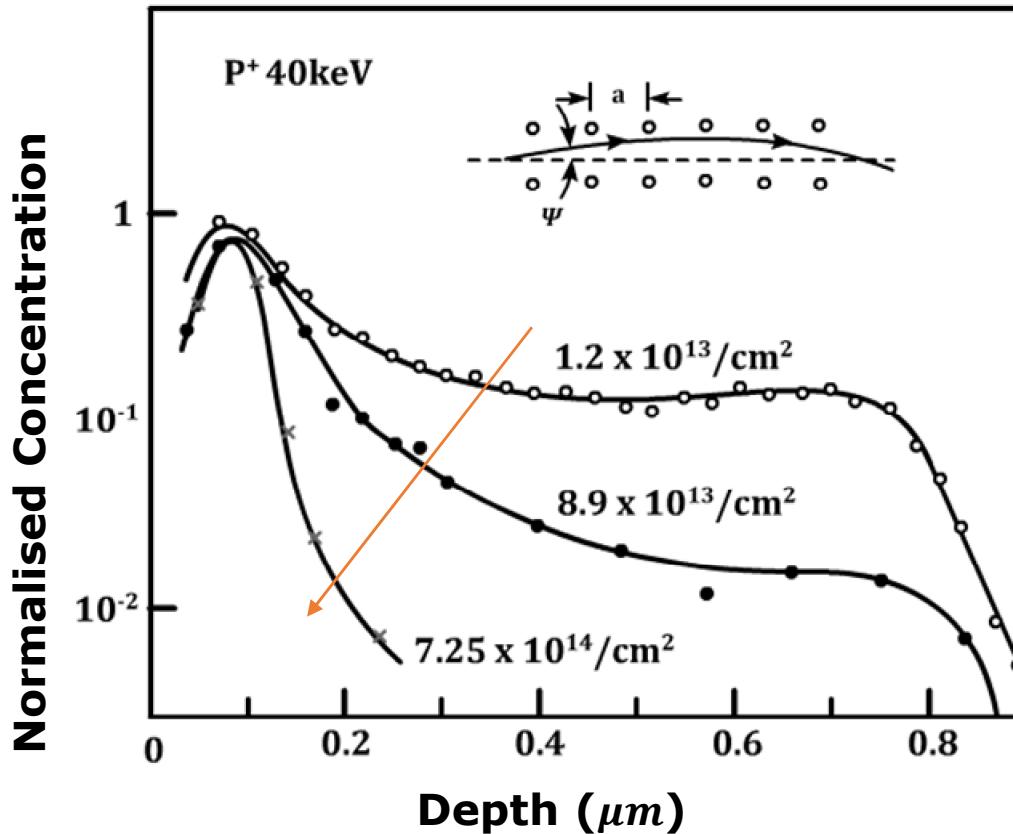


Figure 6.20

How to Avoid Ion Channeling? (Cont'd.)

2. Surface amorphise

- Another way to avoid channeling is to amorphise the crystal surface before implantation.

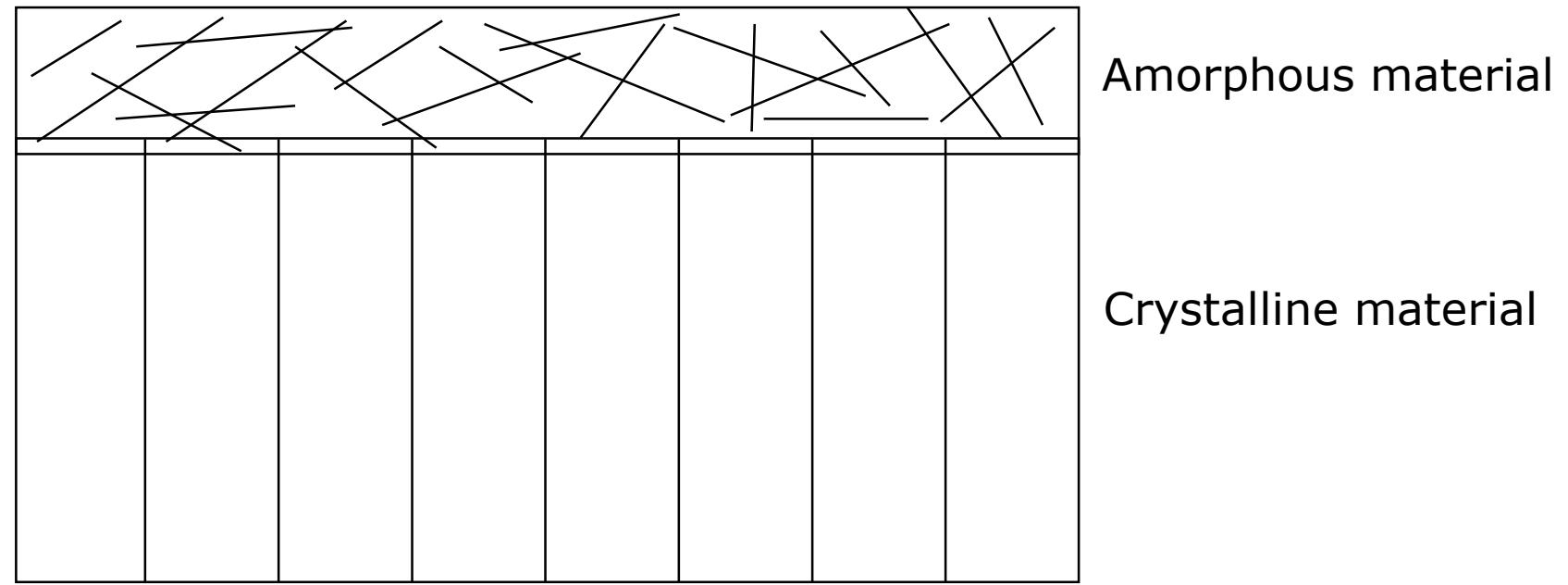
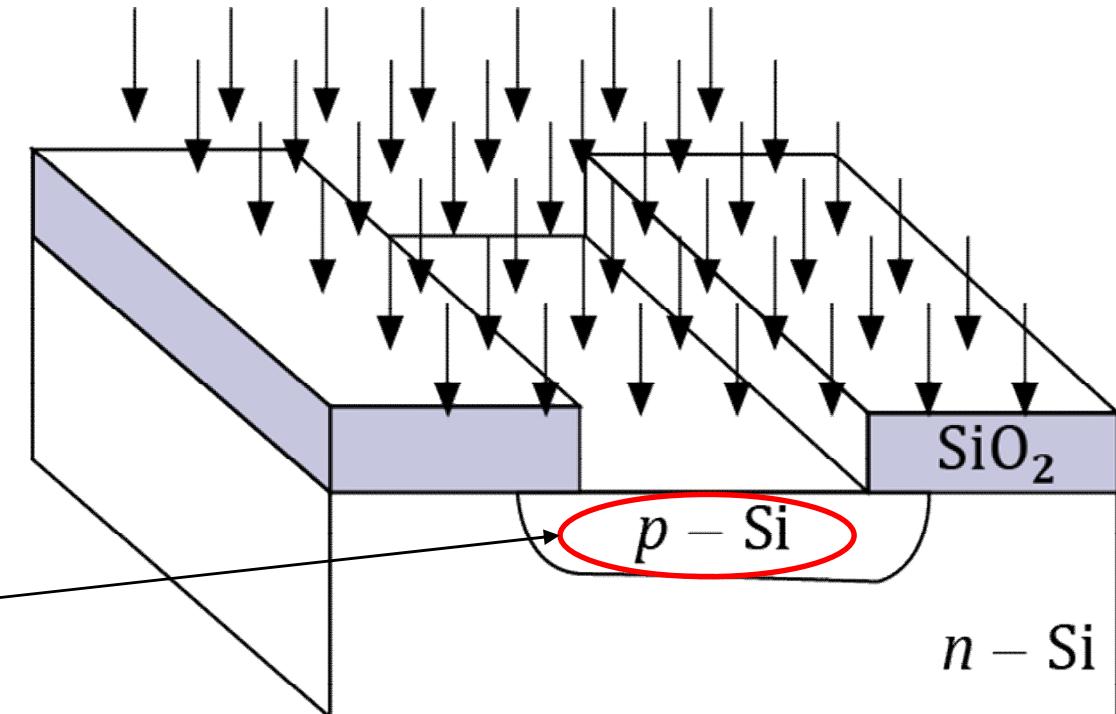


Figure 6.21

Selective Implantation

- In most cases, we want to implant impurity in a selective area.
- The rest areas where do not need implantation should be masked by a layer of SiO_2 (or other type of mask).
- The implanted concentration at the interface between SiO_2 and Si of the masked part should be $< 1/10$ the background concentration in Si .

$$N(t_{ox}) < N_B/10$$



where t_{ox} is the thickness of the oxide layer.

Figure 6.22

Masking During Implantation

- Since implantation is a low temperature process, a wide variety of masking materials can be used.
- The thickness required for masking is a function of stopping parameters of the **masking material**.
- The dose deposited in the wafer beyond depth d (shaded) is:

$$S(d) = \frac{S}{\sqrt{2\pi}\Delta R_p} \int_d^{\infty} \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^2}\right] dx$$

(Equation 6.9)

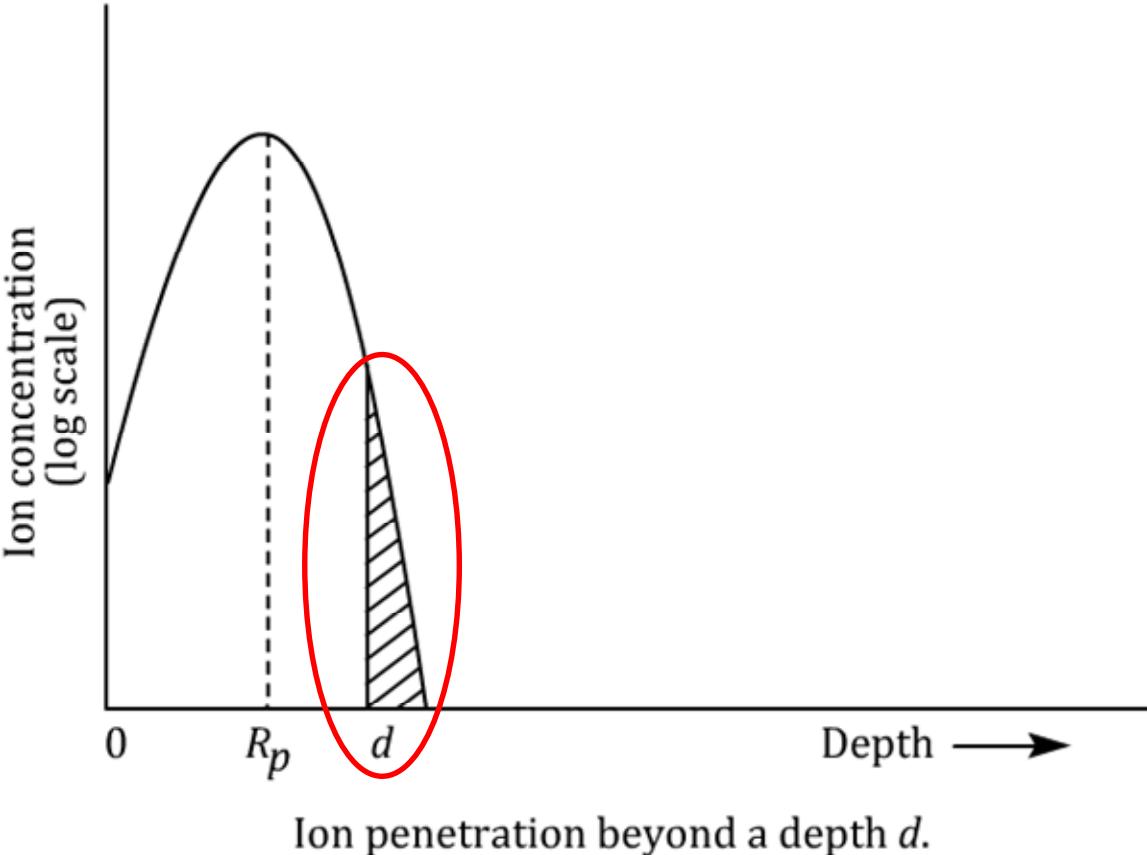


Figure 6.23

Masking During Implantation (Cont'd.)

Since

$$\int_d^{\infty} [-x^2] dx = \frac{\sqrt{\pi}}{2} \operatorname{erfc} d$$

(Equation 6.10)

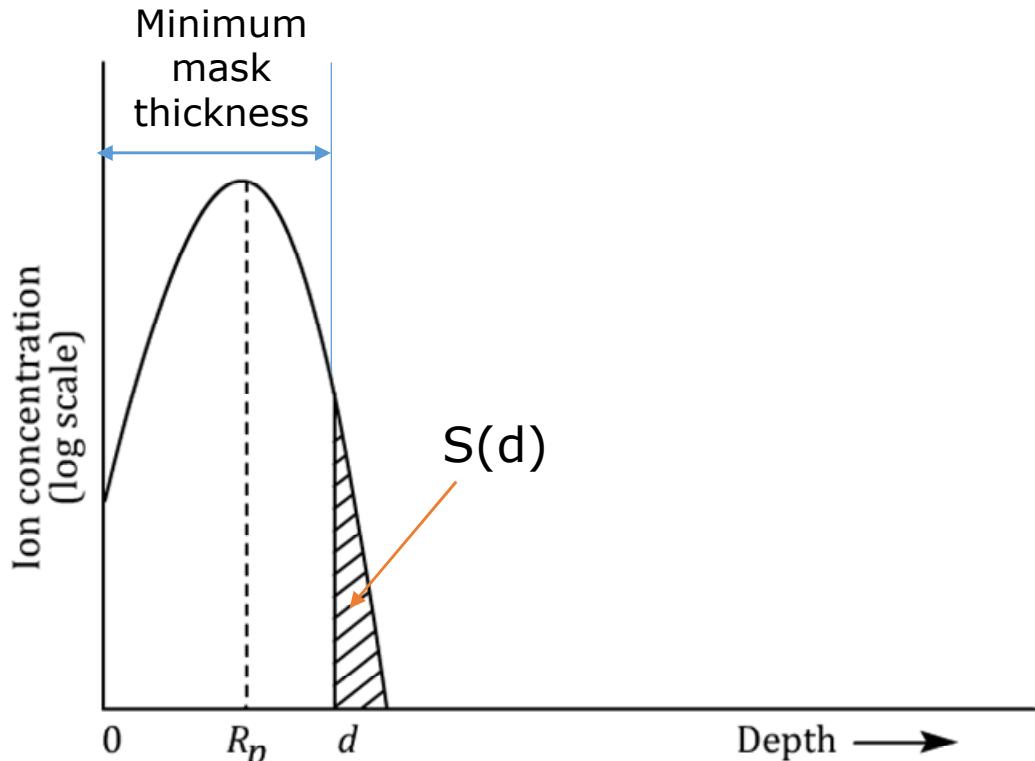
- Fraction of dose implanted beyond depth d is:

$$\frac{S(d)}{S} = \frac{1}{2} \operatorname{erfc} \frac{(d - R_p)}{\sqrt{2} \Delta R_p}$$

(Equation 6.11)

- To achieve masking effectiveness of 99.99%,

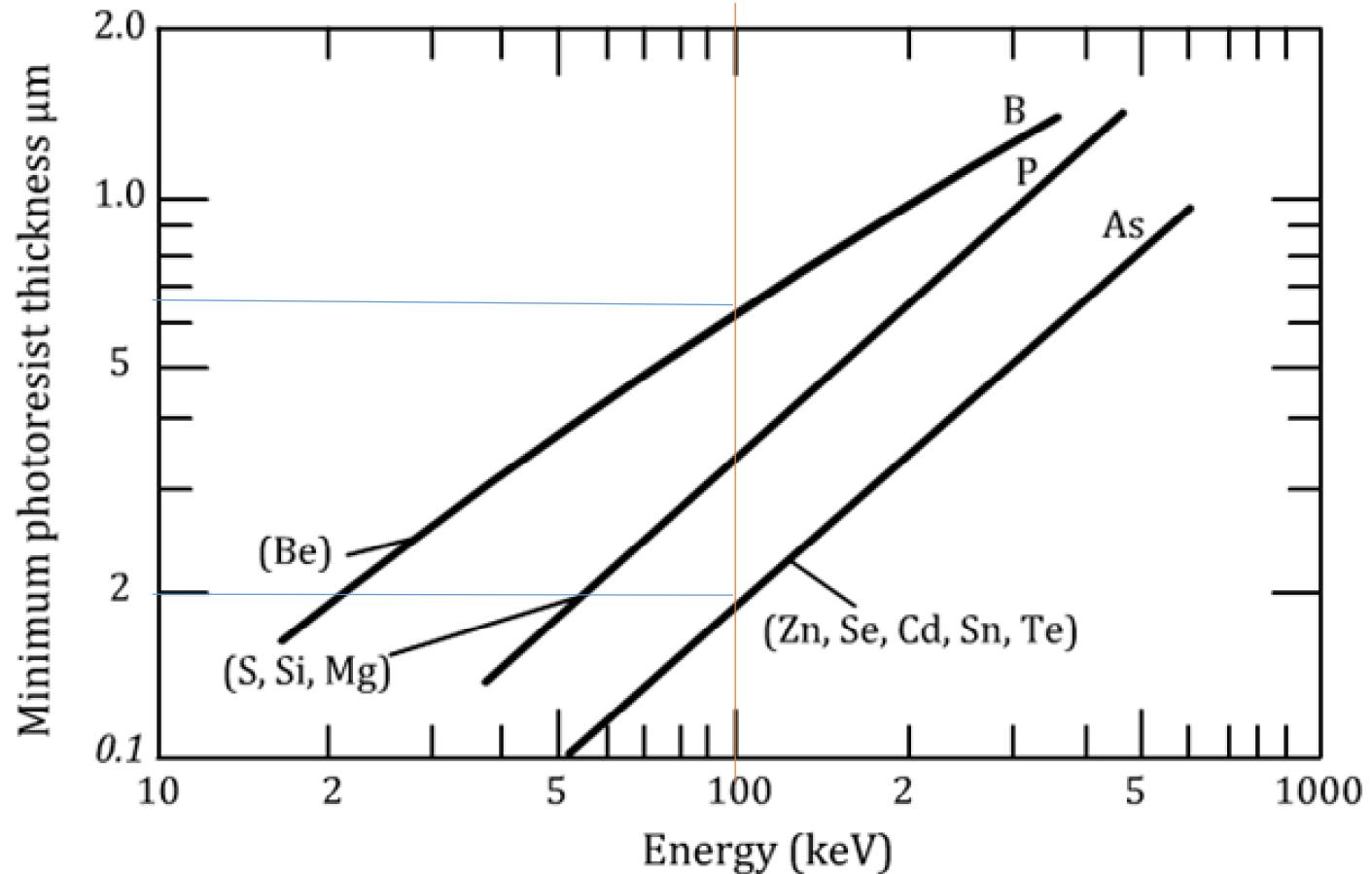
$$\text{Masking thickness } d = (3.72 \Delta R_p + R_p) \quad (\text{Equation 6.12})$$



Ion penetration beyond a depth d .

Figure 6.23

Photoresist for Masking



Minimum photoresist thickness for a masking effectiveness of 99.99%.

Figure 6.24

Silicon Oxide for Masking

- By letting the impurity concentration at interface,

$$N(t_{ox}) = N_p \exp \left[-\frac{(t_{ox} - R_p)^2}{2\Delta R_p^2} \right] < \frac{N_B}{10} \quad (\text{Equation 6.13})$$

- One can calculate the **required oxide thickness for the mask**

$$t_{ox} \geq R_p + \Delta R_p \sqrt{2 \ln \left(\frac{10N_p}{N_B} \right)} \quad (\text{Equation 6.14})$$

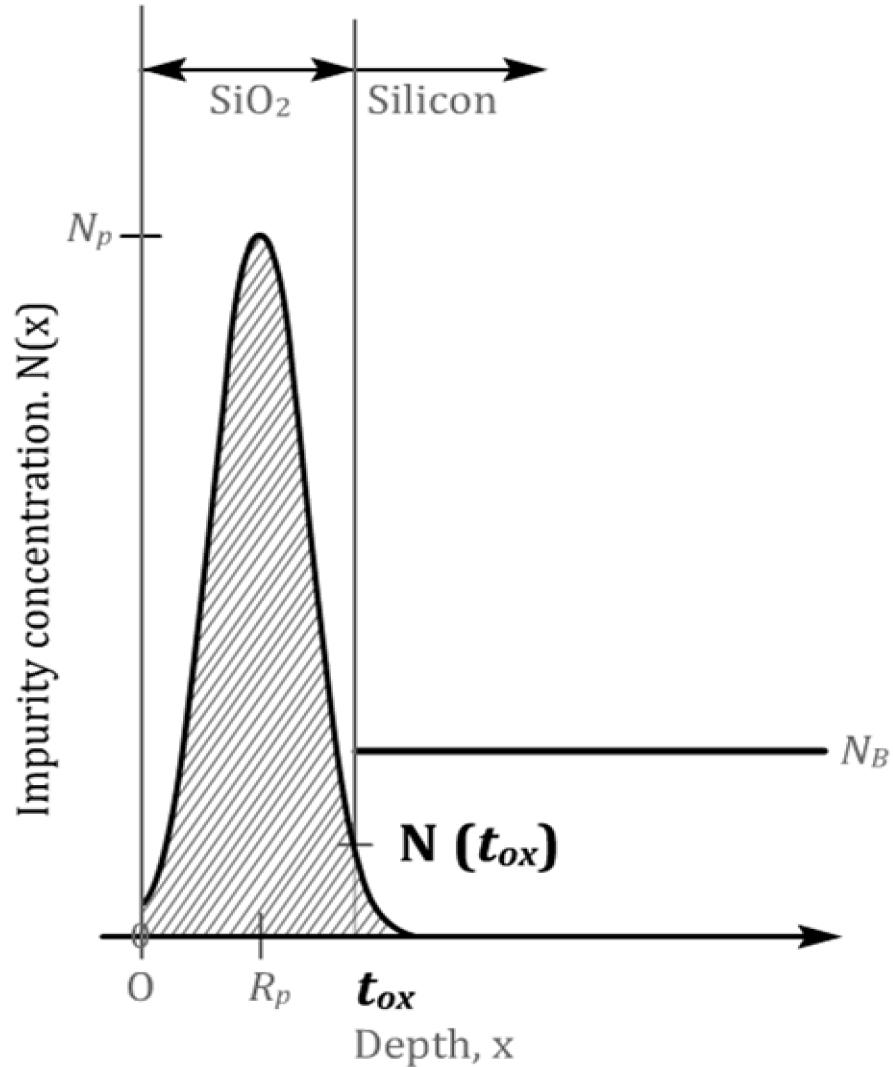
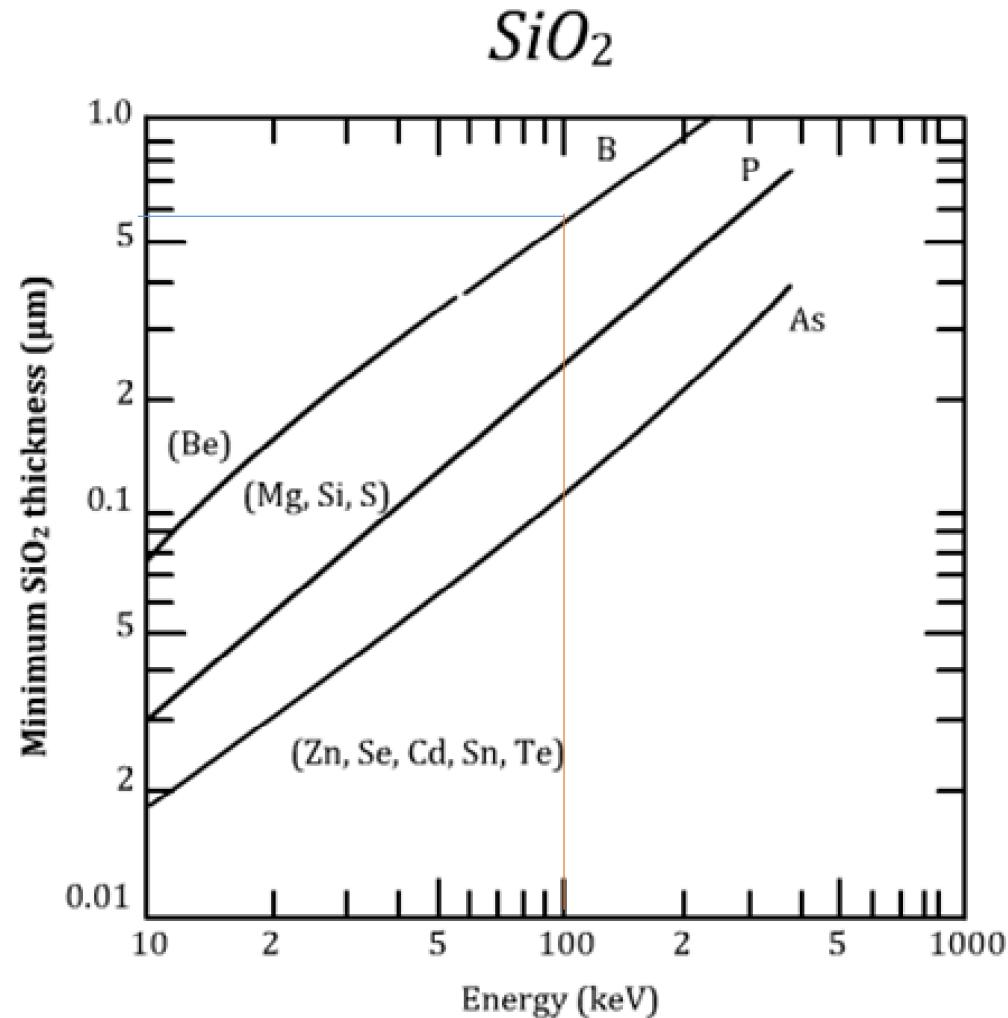


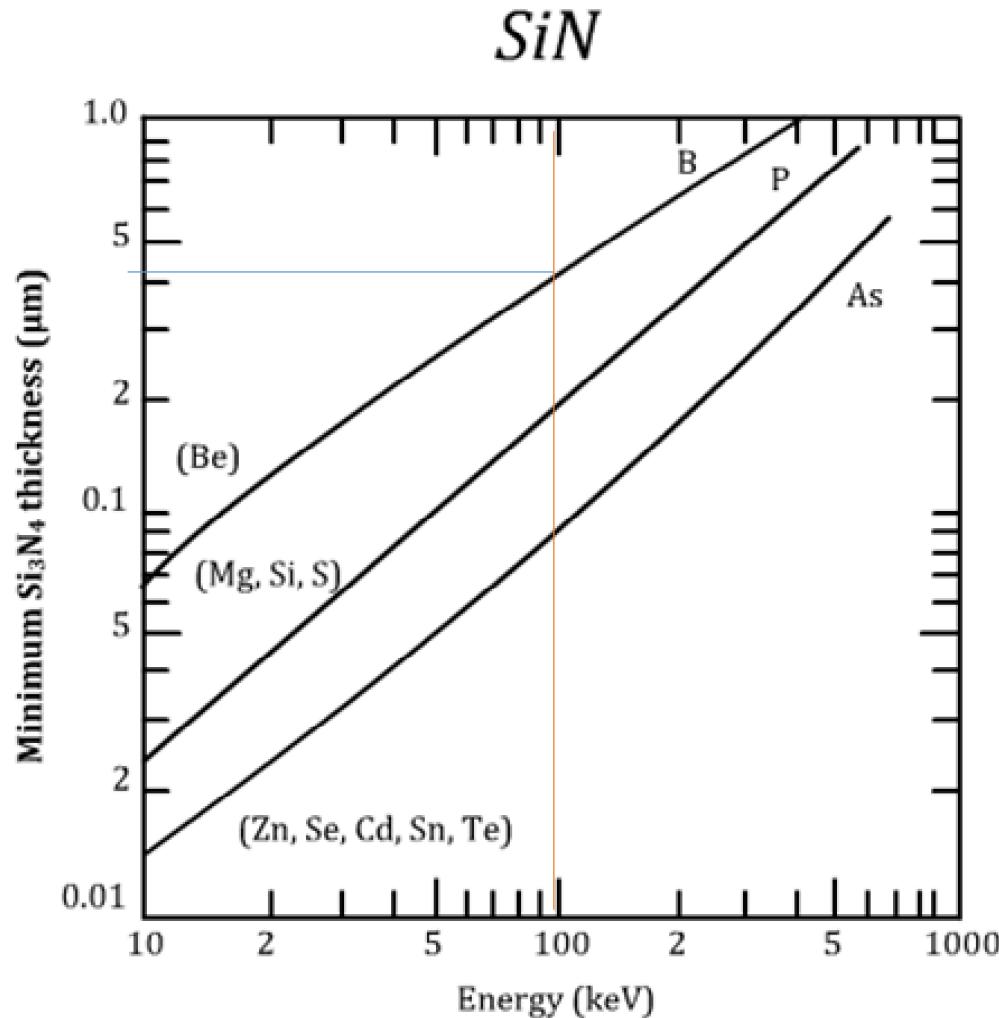
Figure 6.25

Silicon Nitride for Masking



Minimum SiO_2 thickness for a masking effectiveness of 99.99%.

Figure 6.26



Minimum Si_3N_4 thickness for a masking effectiveness of 99.99%.

Figure 6.27

Example

Question:

A boron implantation is to be performed through a **50nm** gate oxide so that the **peak** of the distribution is at the ***Si – SiO₂* interface**.

- a) What are the energy of the implantation and the peak concentration at the interface?
- b) What is the peak concentration at the interface if the dose of the implant in silicon is to be $1.0 \times 10^{13} \text{ cm}^{-2}$?
- c) How thick should the SiO_2 layer be in areas that are not to be implanted, if the background concentration is $1 \times 10^{16}/\text{cm}^2$?

Example (Cont'd.)

Solution:

a) From Figure 6.14 in slide 16, the projected range needs to be **$0.05 \mu m$** (*) and the required energy is **15 keV**. From fig 6.15 in slide 17, the straggle is **$0.023 \mu m$** .

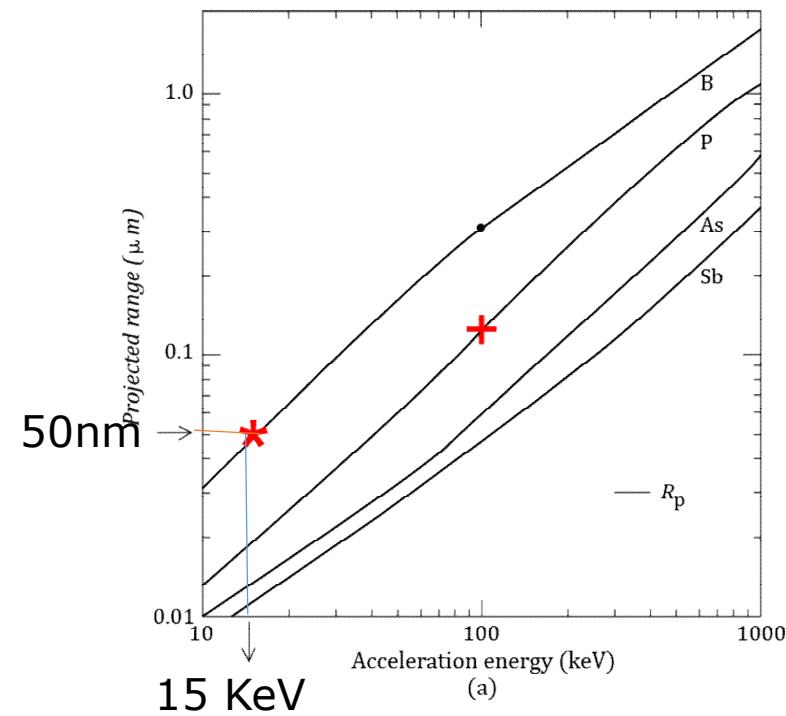


Figure 6.14

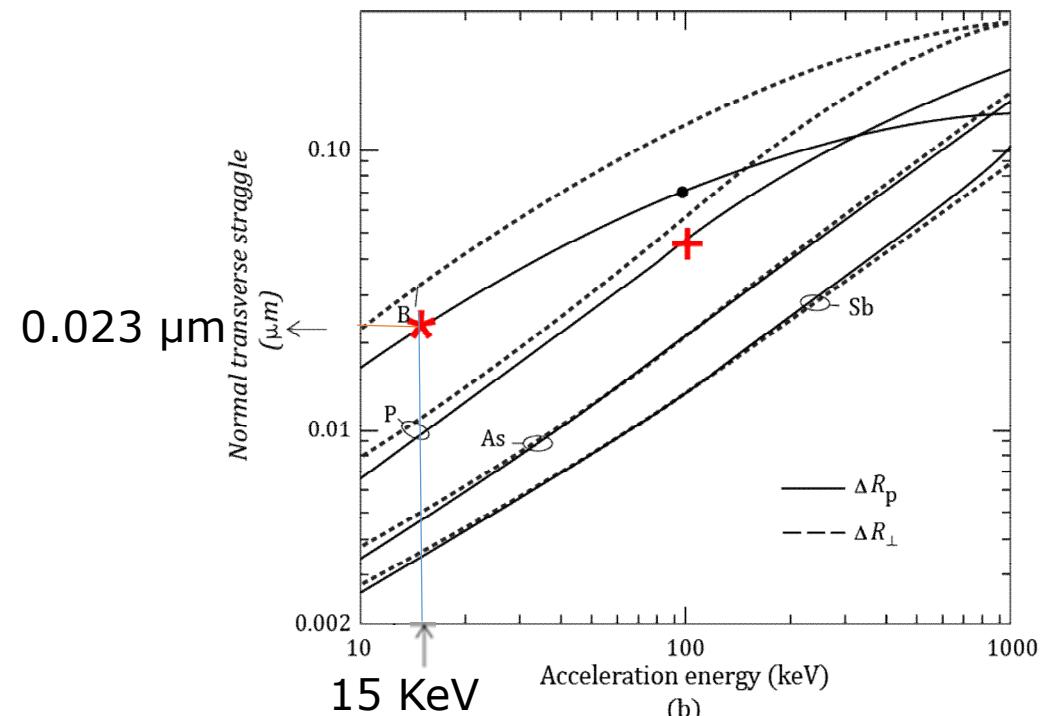


Figure 6.15

Example (Cont'd.)

- (b) Since the peak of the implant is at the interface, the total dose will be **twice** the dose needed in silicon (i.e. $Q = 2.0 \times 10^{13} \text{ cm}^{-2}$).

Using:

$$N_p = Q / \Delta R_p \sqrt{2\pi} = 2 \times 10^{13} / (2.3 \times 10^{-6} \sqrt{2\pi}) = 3.5 \times 10^{18} / \text{cm}^3$$

Example (Cont'd.)

Solution:

b) To completely mask the implantation, the tail of the distribution must be less than 1/10 of the background concentration at the interface. The minimum oxide thickness is:

$$t_{ox} \geq R_p + \Delta R_p \sqrt{2 \ln \left(\frac{10N_p}{N_B} \right)} \quad (\text{Equation 6.14})$$

$$= 0.05 + 0.023 \sqrt{2 \ln(10 \times 3.5 \times 10^{18} / 10^{16})} \mu\text{m} = 0.14 \mu\text{m}$$

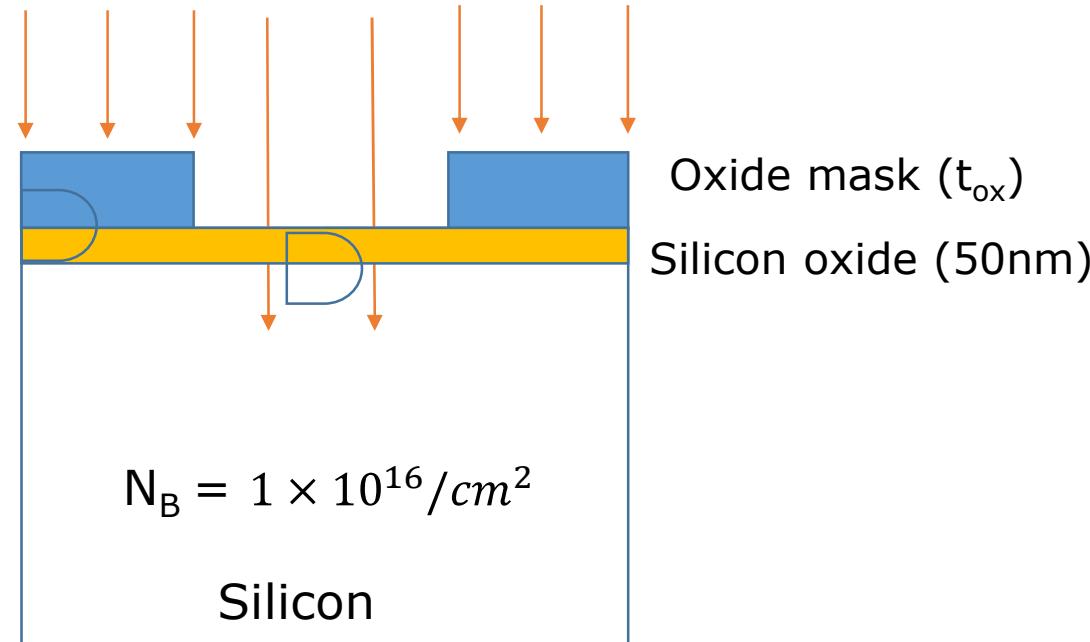


Figure 6.28. Boron Implantation

Junction Depth

- Shallow p-n junctions can be formed by implanting p-type dopants into n-Si substrate.
- Junction depth x_j can be found by equating the implanted concentration to the background concentration N_B .

$$N(x_j) = N_B$$

(Equation 6.6)

$$N_p \exp \left[-\frac{(x_j - R_p)^2}{2\Delta R_p^2} \right] = N_B$$

$$x_j = R_p \pm \Delta R_p \sqrt{2 \ln \left(\frac{N_p}{N_B} \right)}$$

(Equation 6.15)

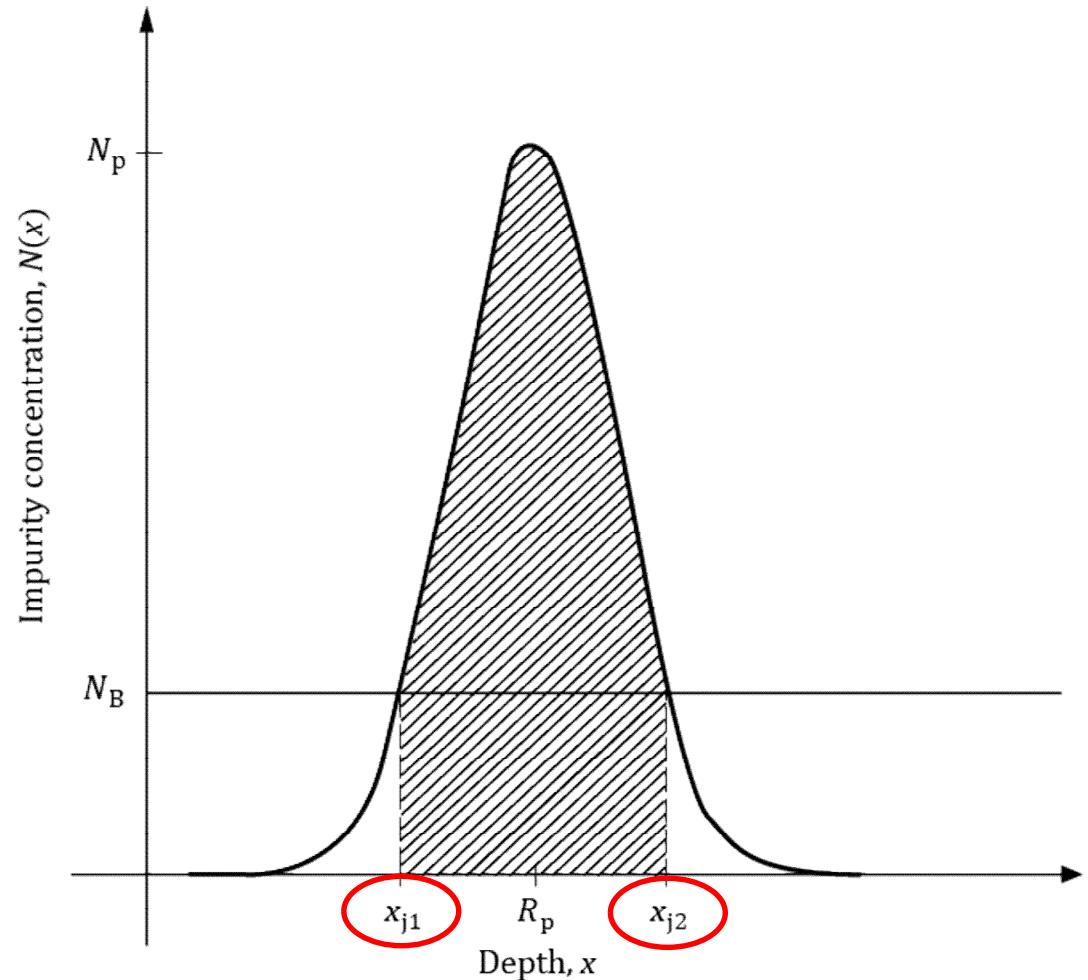


Figure 6.29

Annealing

- Implantation creates disorder leading to degradation of parameters such as mobility and lifetime.
- Semiconductor is annealed for electrical activation, and to restore single crystal phase.

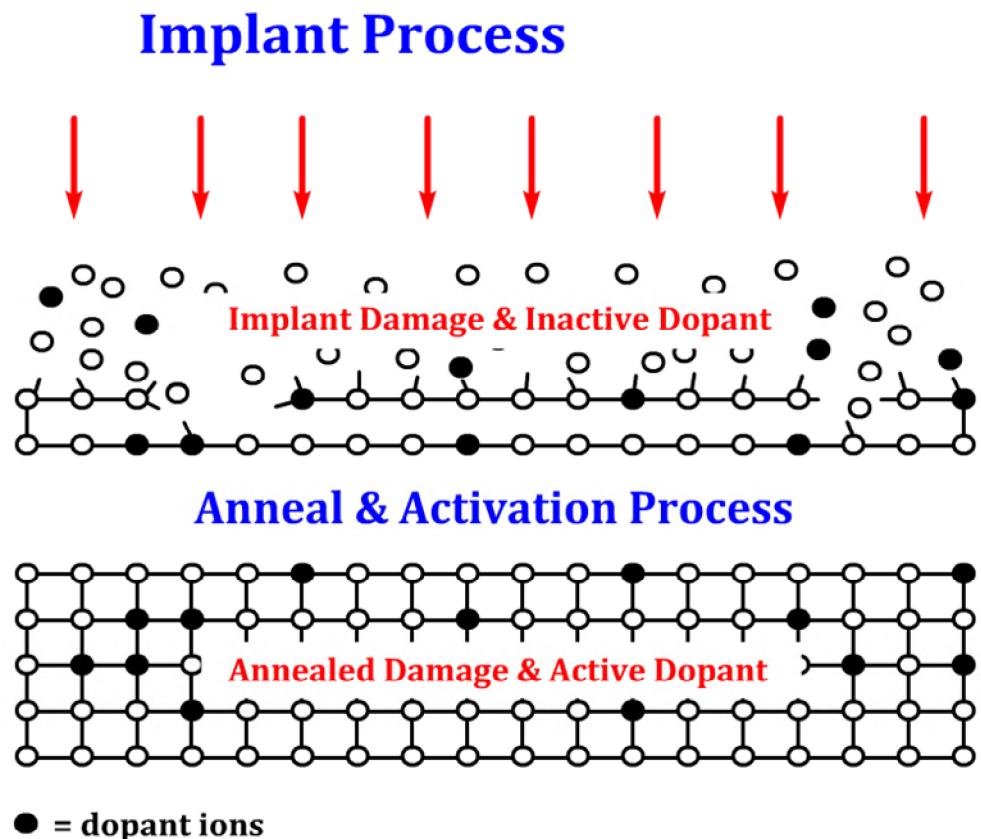


Figure 6.30 (a)

Figure 6.30 (b)

Annealing (Cont'd.)

- However, annealing leads to diffusion of dopants and the implanted doping profile will be broadened.

- R_p remains the same (at 0.7 μm), but

ΔR_p alters to $(\Delta R_p^2 + 2Dt)^{1/2}$. *(Equation 6.16)*

- Hence,

$$N(x) = \frac{Q}{\sqrt{2\pi}(\Delta R_p^2 + 2Dt)^{1/2}} \exp \left[-\frac{(x - R_p)^2}{2(\Delta R_p^2 + 2Dt)} \right]$$

(Equation 6.17)

- Short time annealing is preferred.

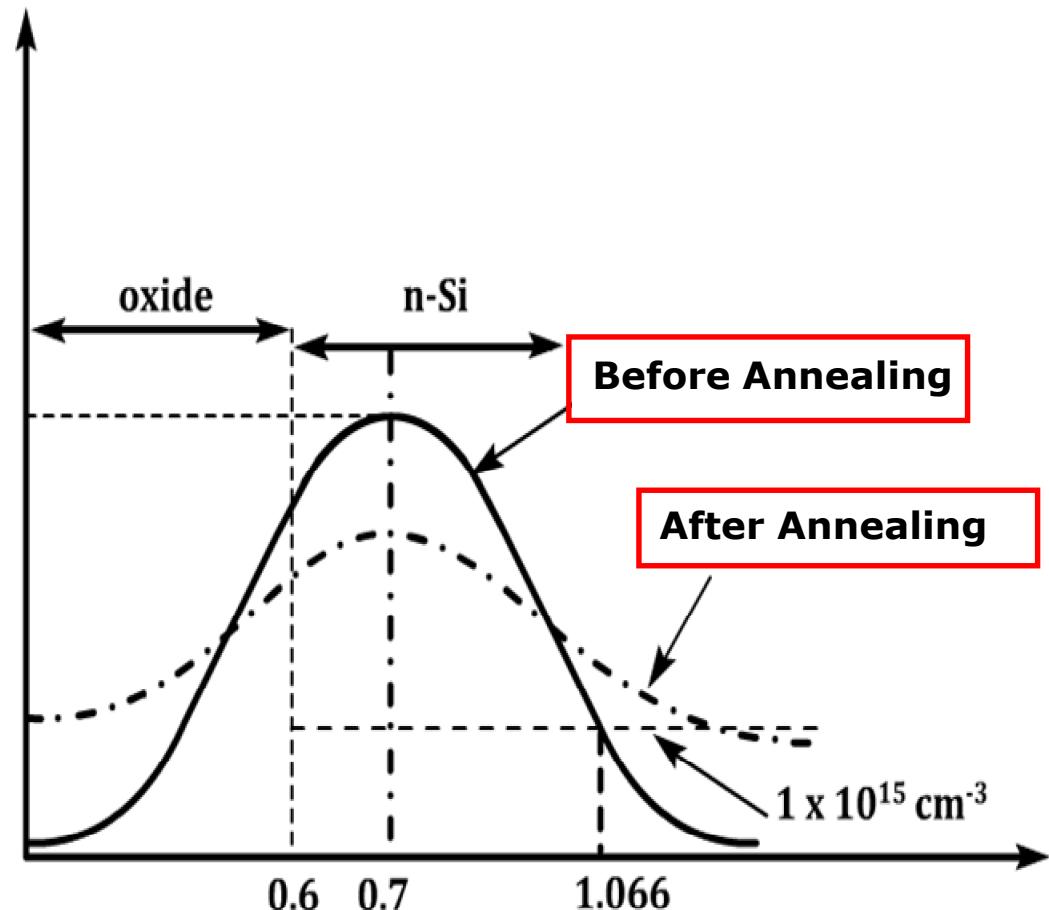
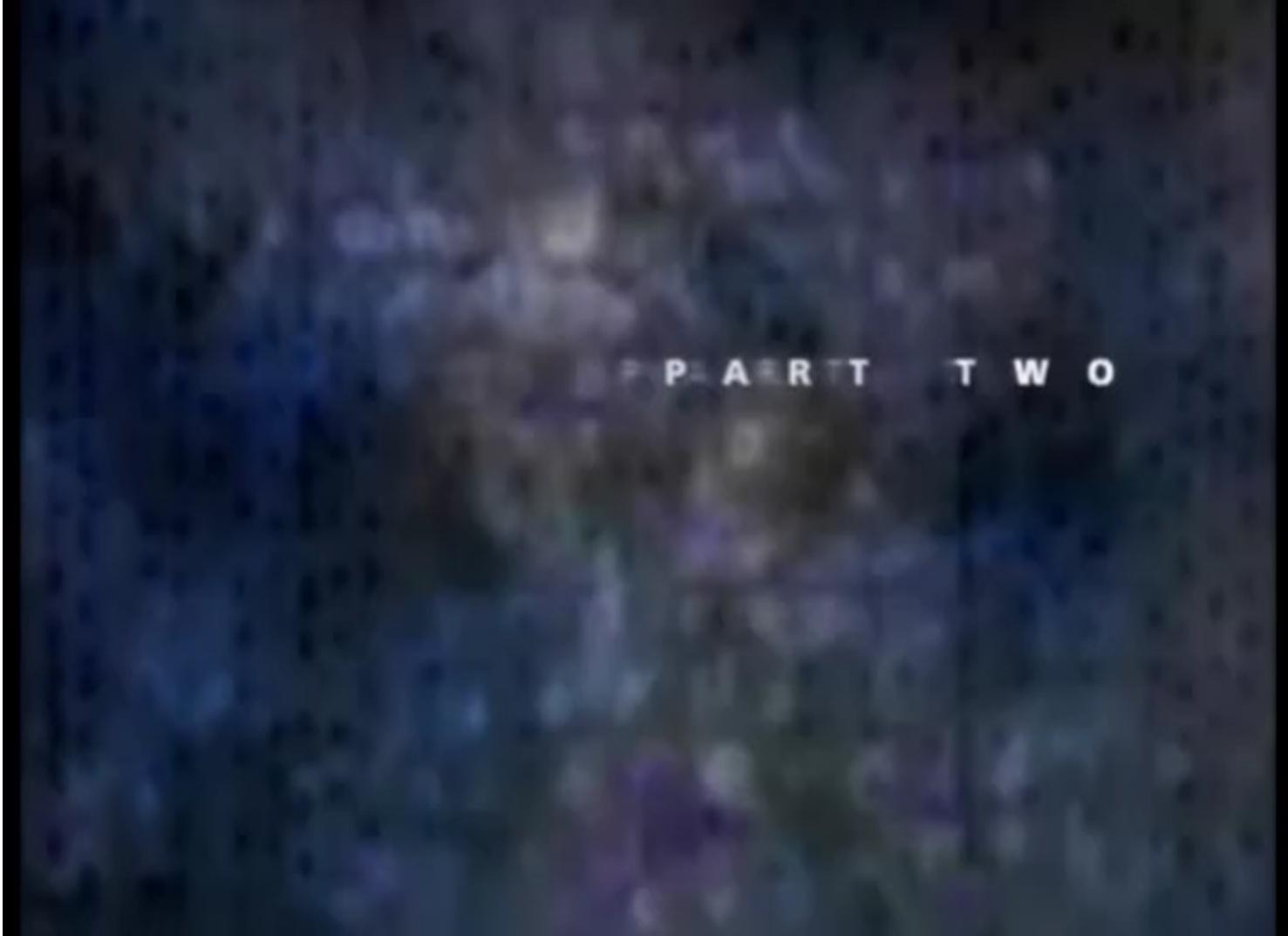


Figure 6.31

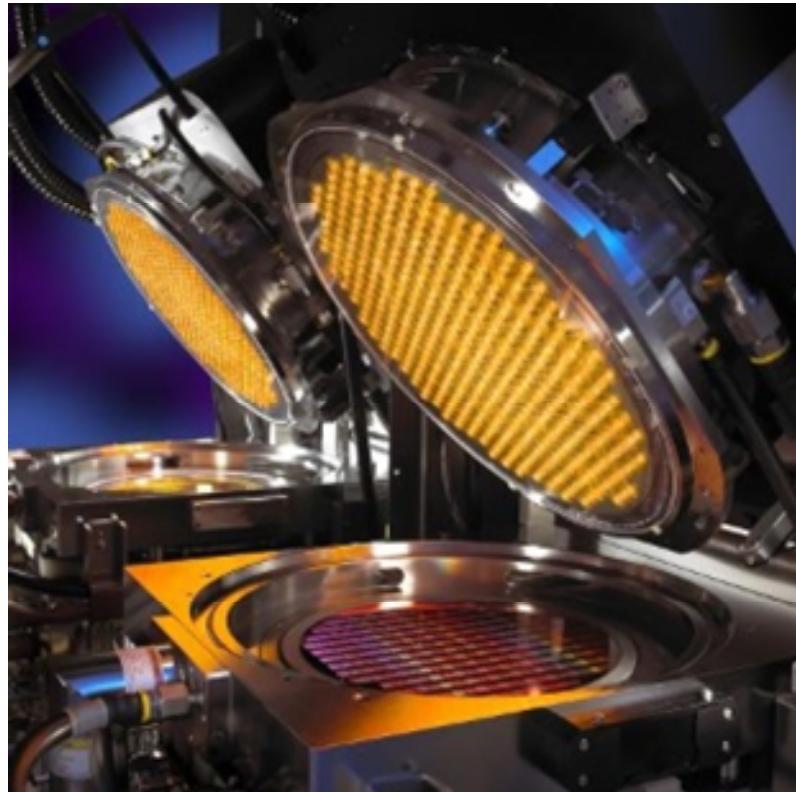
Making the Microchip



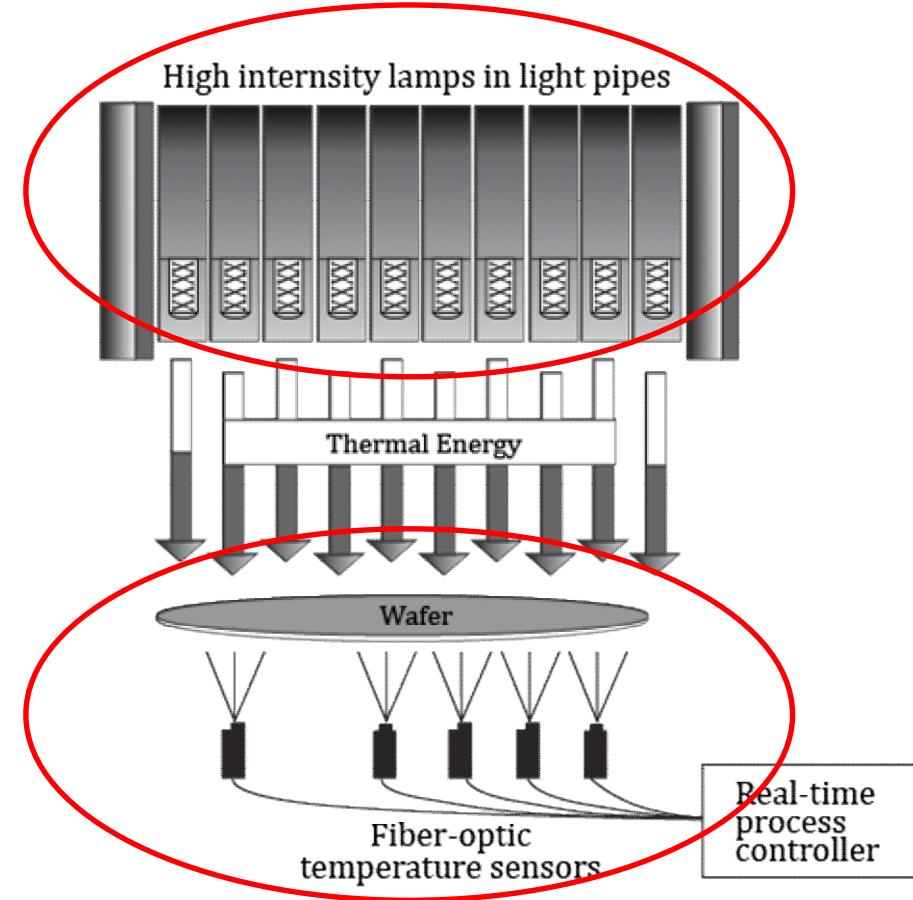
Making the Microchip



Rapid Thermal Annealing



- Rapid Heating
- $950 - 1050^{\circ}C$
- $50^{\circ}C/\text{sec}$
- Very Low Dt product



**Figure 6.32(a). Applied Materials
300 mm RTP System**

**Figure 6.32 (b) Schematic diagram
of rapid thermal annealing system**

Multi-Implantations for Widening Doping Region

- In many application doping profiles other than the simple Gaussian are required.
- Implantation profile can be simulated using commercial software such as SRIM (The **S**topping and **R**ange of **I**ons in **Matters).**

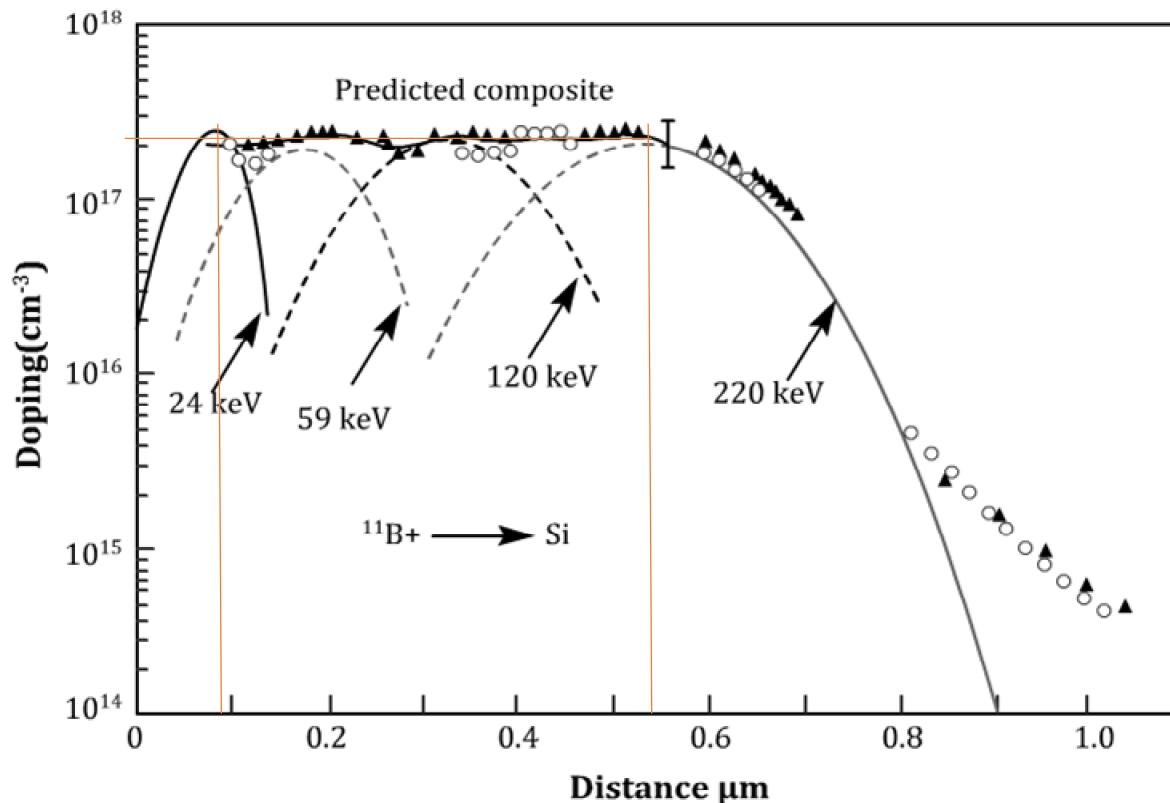


Figure 6.33

Lesson Summary

1. Implantation is a common technique in wafer processing and it can be used to create the doping regions as well as isolation regions.
2. **Advantage:** Low-temperature process, wide selection of masking materials, less sensitive to surface cleaning procedures, very fast and complex profiles can be achieved by multi-energy implants. **Disadvantage:** Very expensive equipment, low throughput at high dose values, ions damage the semiconductor lattice, Not all the damage can be corrected by annealing is needed to repair crystal damage and active dopants, very shallow and very deep doping are difficult or impossible.
3. An ion implanter typically consists of five main parts. These are (1) ion source, (2) mass spectrometer, (3) high voltage accelerator, (4) scanning system, and (5) target chamber.
4. Implantation profile is approximated by Gaussian distribution function: $N(x) = N_p \exp\left[-\frac{(x-R_p)^2}{2\Delta R_p^2}\right]$.
5. R_p is the project range and ΔR_p is the straggle and can be found graphically from fig 6.14 and 6.15.
6. Implant dose Q is given by: $Q = \int_0^\infty N(x) dx = \sqrt{2\pi} N_p \Delta R_p$.

Lesson Summary

7. There are two types of stopping mechanisms namely nuclear stopping and electronic stopping.
8. Ion channeling can occur in certain directions in single crystals which no nuclei will be encountered and the only stopping mechanism is due to electrons. Thus, the project range will be considerably increased.
9. To avoid channeling: tilt or surface amorphise.
10. To achieve masking effectiveness of 99.99%, Masking thickness $d = (3.72\Delta R_p + Rp)$.
11. For effective oxide masking $\rightarrow N(t_{ox}) = N_p \exp \left[-\frac{(t_{ox} - R_p)^2}{2\Delta R_p^2} \right] < \frac{N_B}{10}$ **or** $t_{ox} \geq R_p + \Delta R_p \sqrt{2 \ln \left(\frac{10N_p}{N_B} \right)}$.
12. Photoresist, silicon oxide and silicon nitride can be used as implant mask. But silicon nitride needs the least thickness.

Lesson Summary

13. To find junction depth, set $N(x_j) = N_B \rightarrow x_j = R_p \pm \Delta R_p \sqrt{2 \ln\left(\frac{N_p}{N_B}\right)}$
14. Annealing is required for implantation to repair lattice damage and to activate dopants.
15. Annealing leads to diffusion of dopants and broadening of the implanted doping profile:
- $N(x) = \frac{Q}{\sqrt{2\pi}(\Delta R_p^2 + 2Dt)^{1/2}} \exp\left[-\frac{(x-R_p)^2}{2(\Delta R_p^2 + 2Dt)}\right]$
 - R_p remains the same, but ΔR_p alters to $(\Delta R_p^2 + 2Dt)^{1/2}$.
16. Rapid thermal annealing system is used to achieve short annealing time thus reduces broadening of the implant profile.