MSN 551 Notes

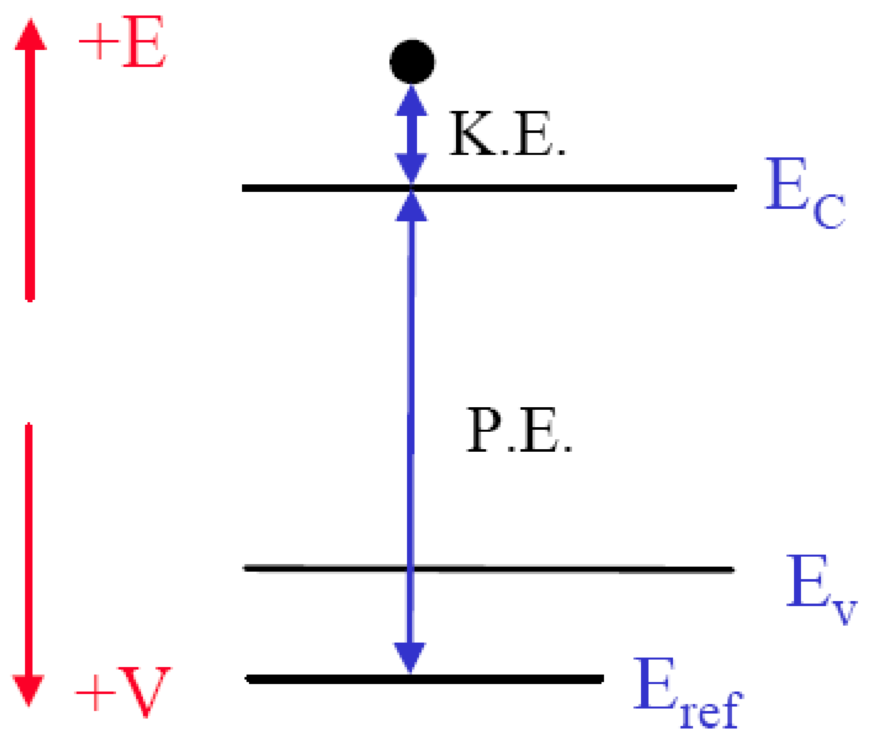
Ion Implantation and Diffusion

Overview

- Basic semiconductor physics: Most common application of ion implantation is doping silicon
- Ion implantation
- Dopant activation and Diffusion

Energy bands

Basic convention:



Kinetic energy:

$$K.E. = E - E_C$$

Potential Energy:

$$P.E. = -qV = E_C - E_{ref}$$

$$V = -\frac{1}{q}\left(E_C - E_{ref}\right)$$

Electric field: $\mathbf{e} = -\nabla V$, or in 1D $\mathbf{e} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_C}{dx}$

Basic semiconductor physics

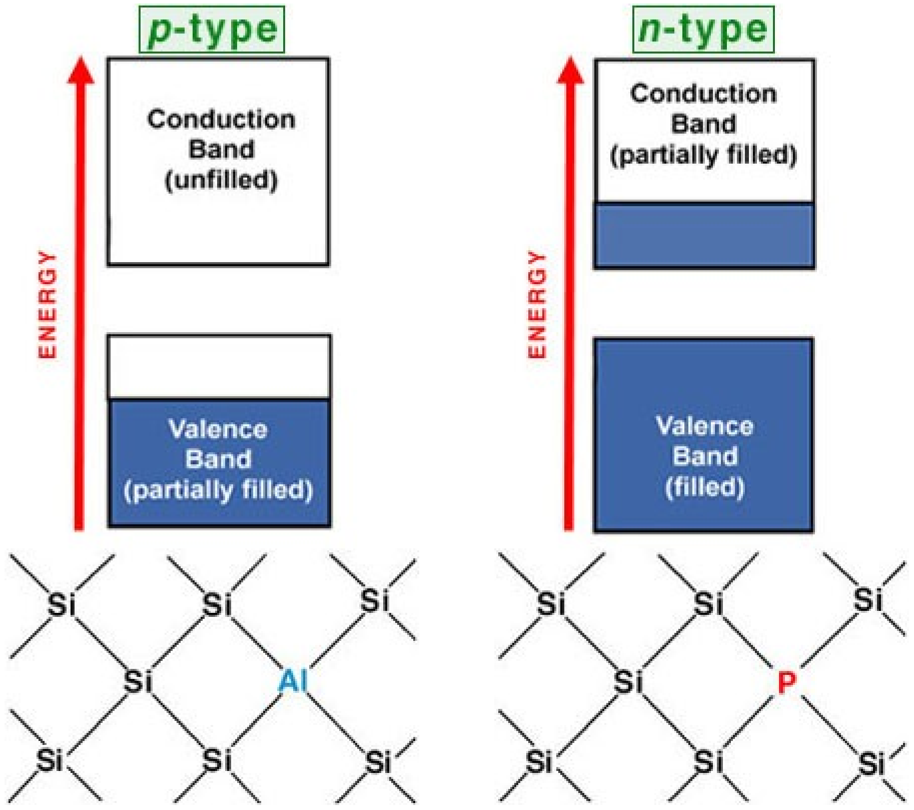
- Semiconductor bands

Current density

$$J_n = -qnv_e$$

$$J = J_n + J_p = q\mu_n n\mathcal{E} + q\mu_p p\mathcal{E}$$

mobility 1400 cm^2/V-s



Basic semiconductor physics

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mobility 1400 cm^2/V-s

$$\mathcal{E} = \frac{1}{q}\frac{dE_C}{dx}$$

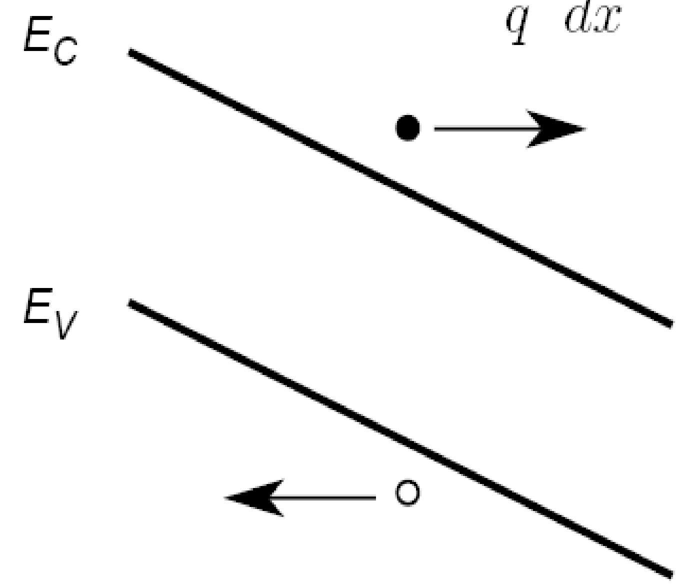
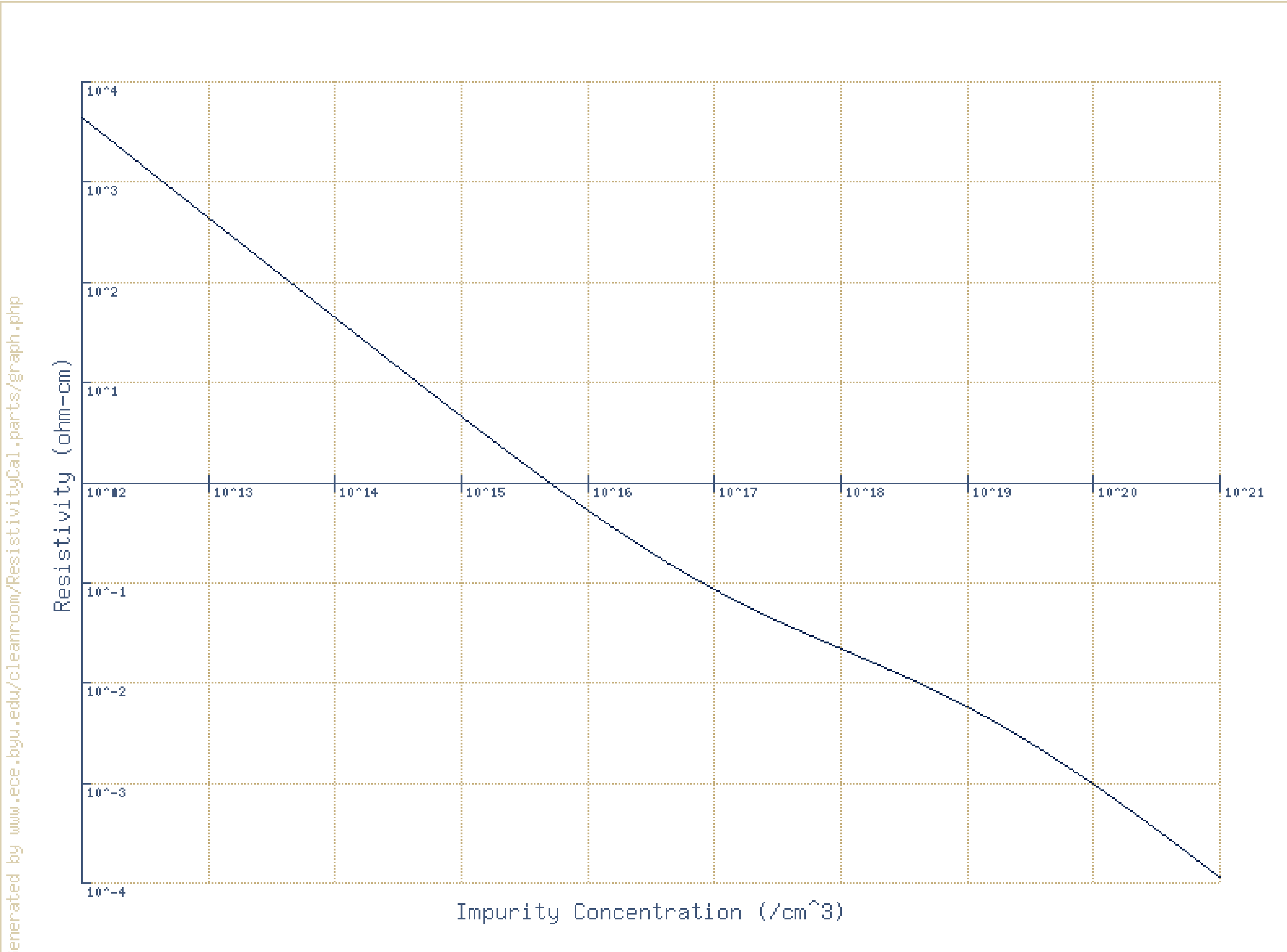


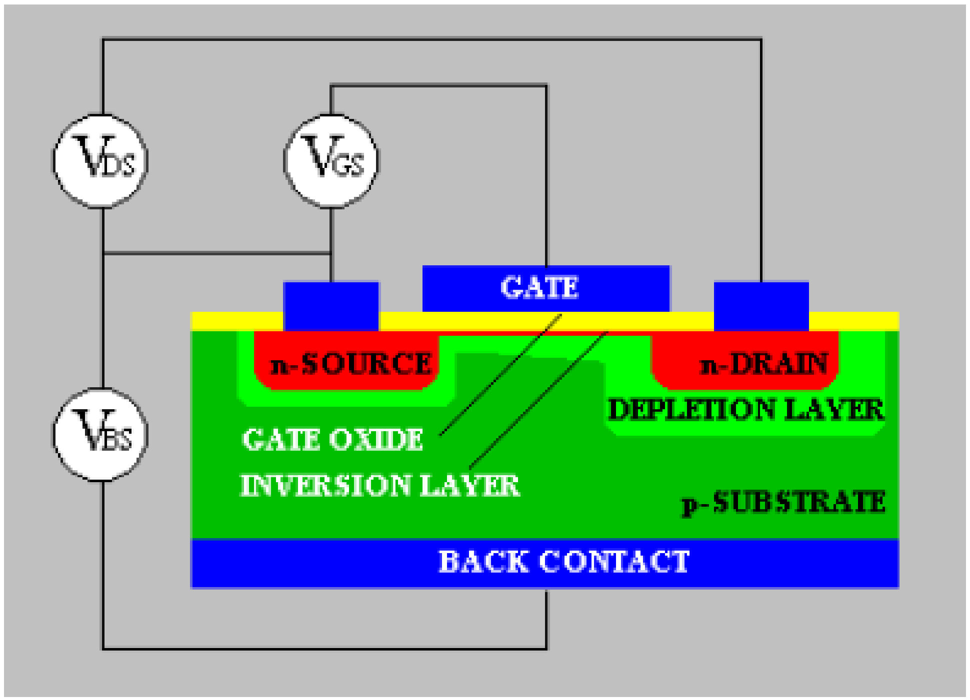
FIGURE 5: Band diagram with an electric field.

Doping and resistivity

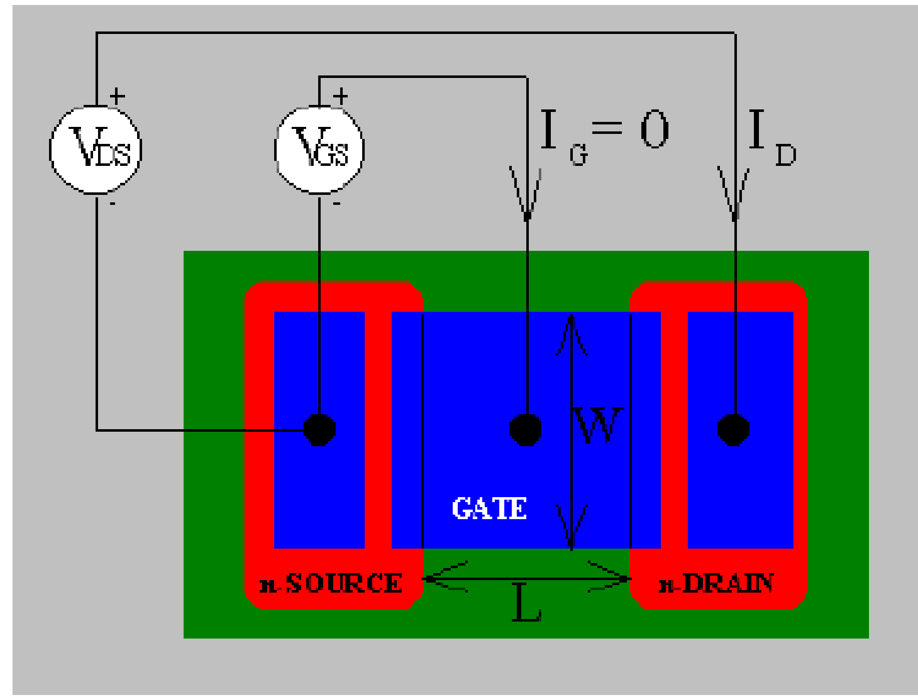


• MOSFET is a four-terminal device. Basic device configuration is illustrated on the figures below.

Side-view of the device



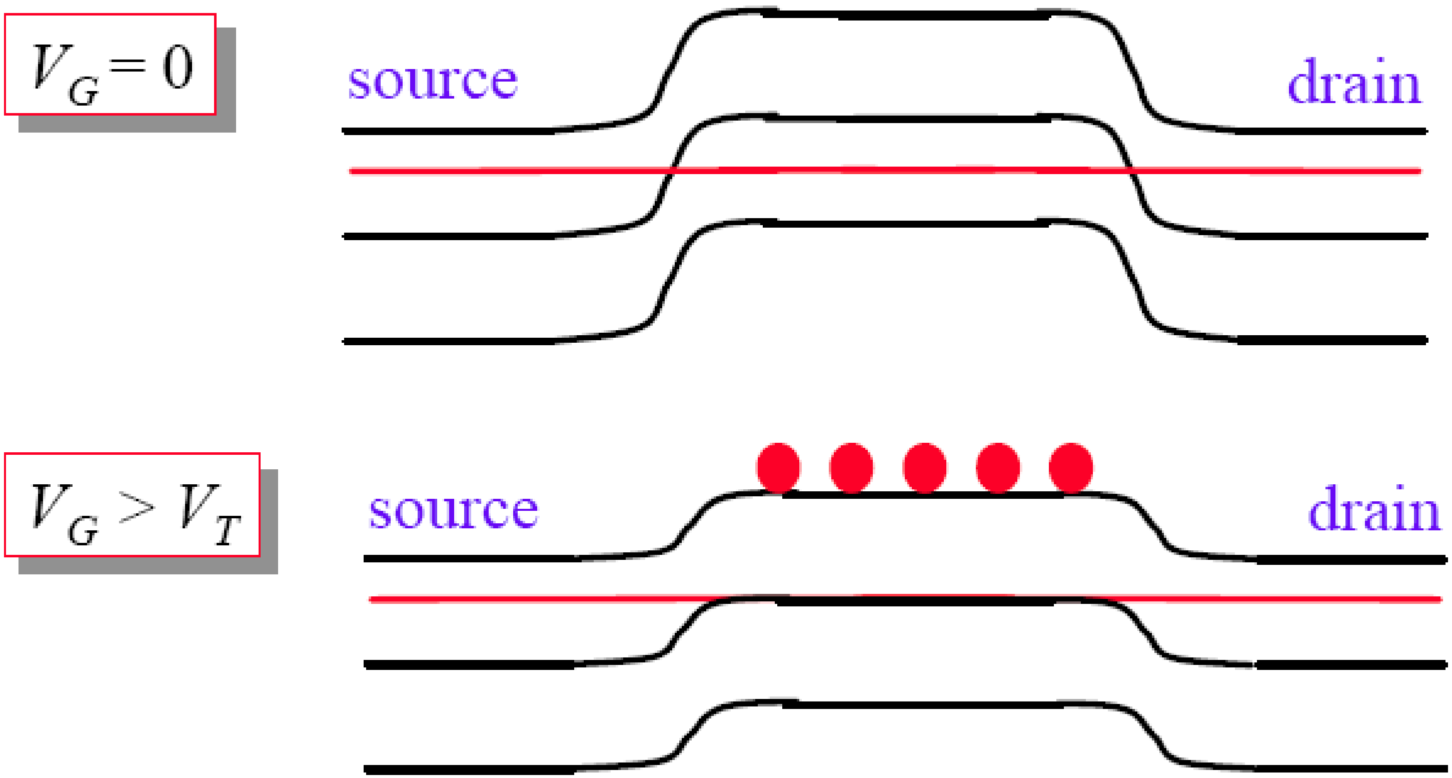
Top-view of the device



Basic device parameters:

channel length L
channel width W
oxide thickness d_{ox}
junction depth r_j
substrate doping N_A

- The role of the Gate electrode for *n*-channel MOSFET:



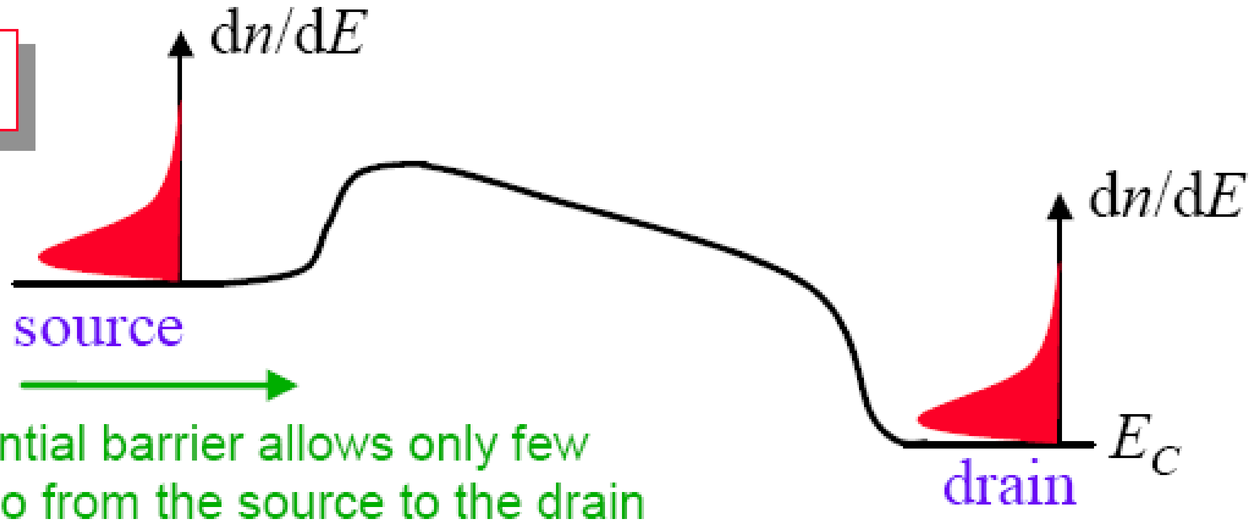
Positive gate voltage does two things:

(1) Reduces the potential energy barrier seen by the electrons from the source and the drain regions.

(2) Inverts the surface, and increases the conductivity of the channel.

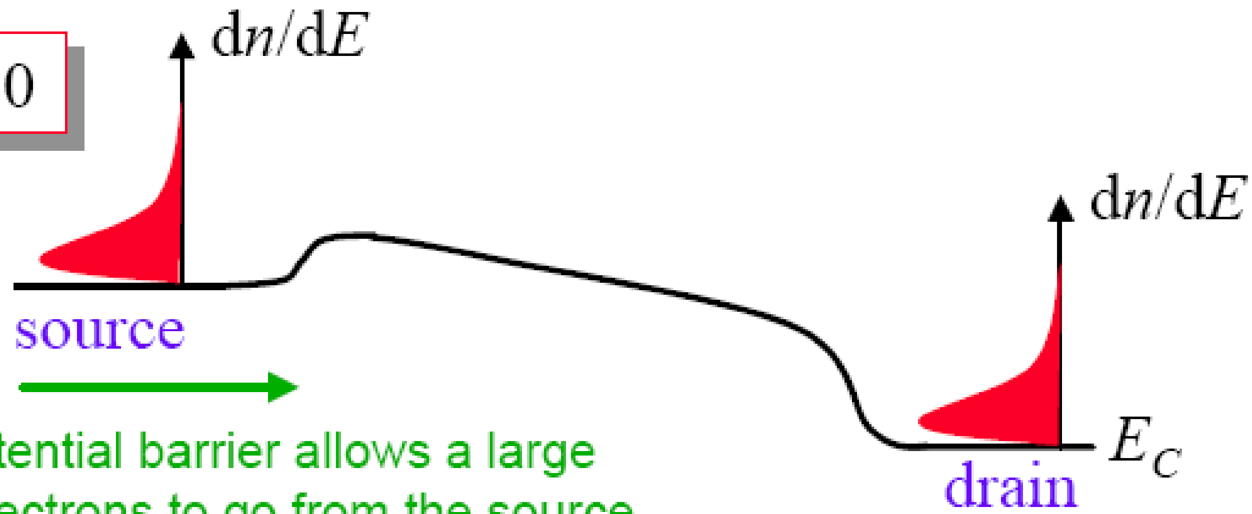
- The role of the Drain electrode for *n*-channel MOSFET:

$V_G = 0, V_D > 0$



Large potential barrier allows only few electrons to go from the source to the drain (subthreshold conduction)

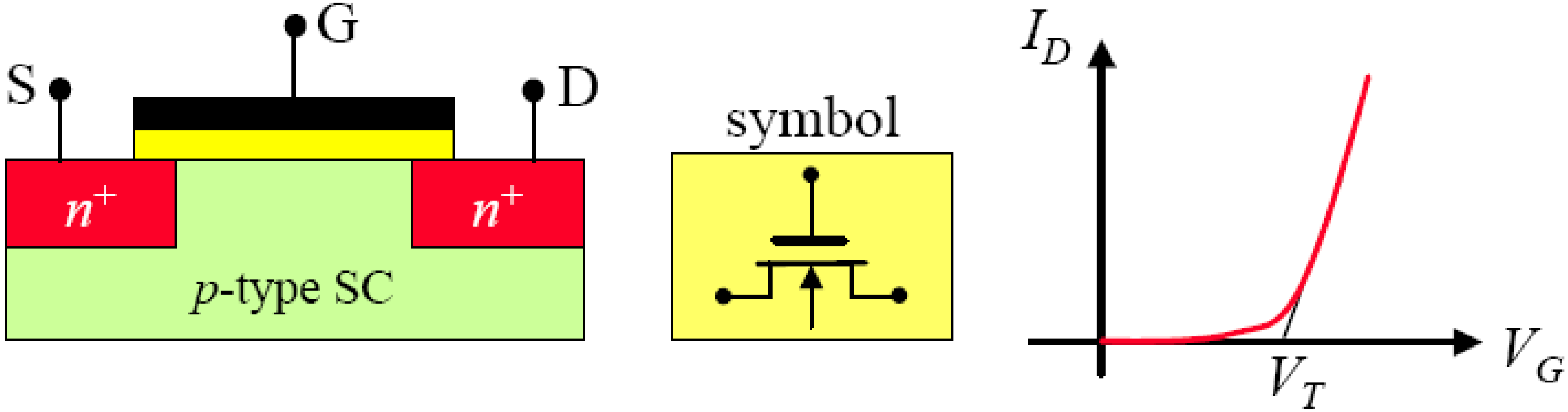
$V_G > V_T, V_D > 0$



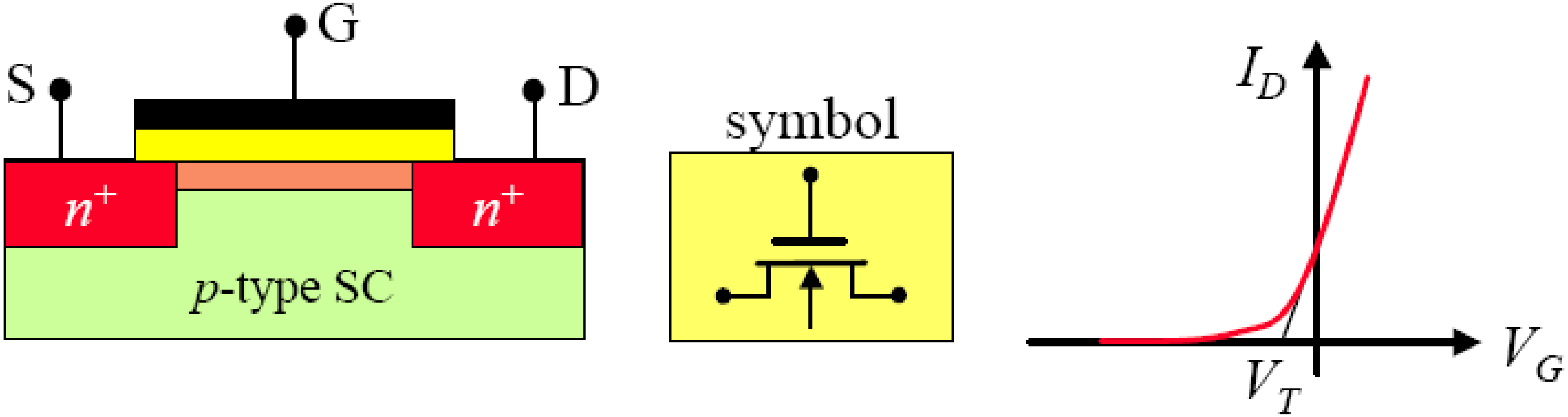
Smaller potential barrier allows a large number of electrons to go from the source to the drain

- There are basically four types of MOSFETs:

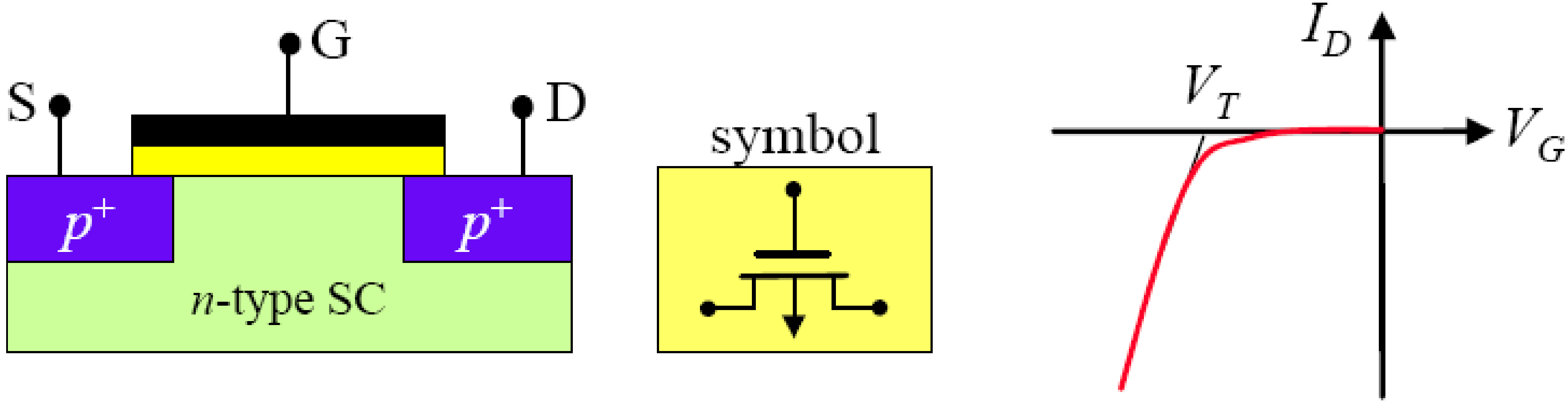
(a) *n*-cnannel, enhancement mode device



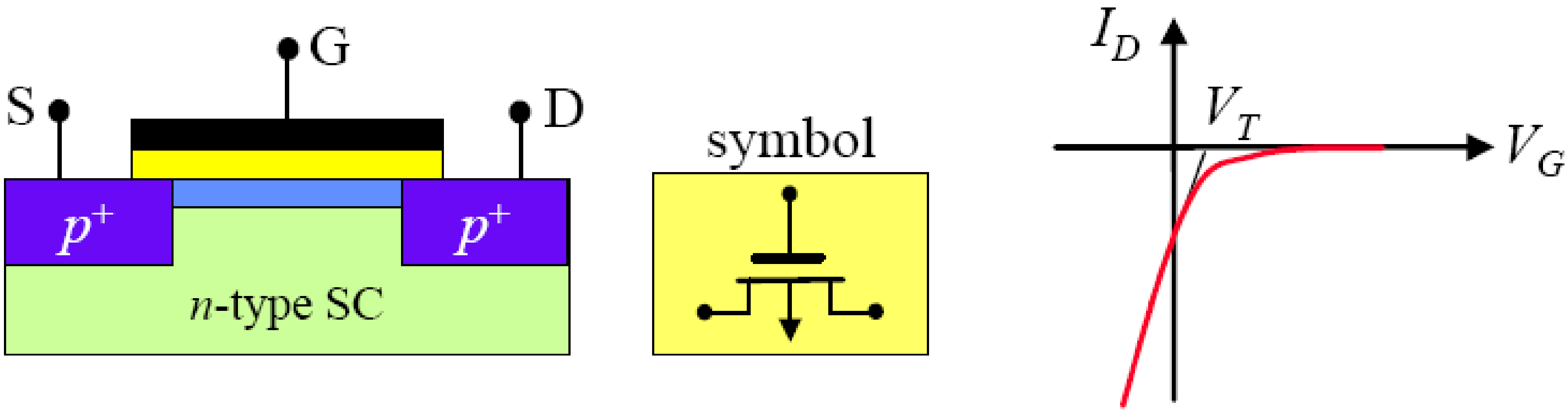
(b) *n*-cnannel, depletion mode device



(c) *p*-cnannel, enhancement mode device



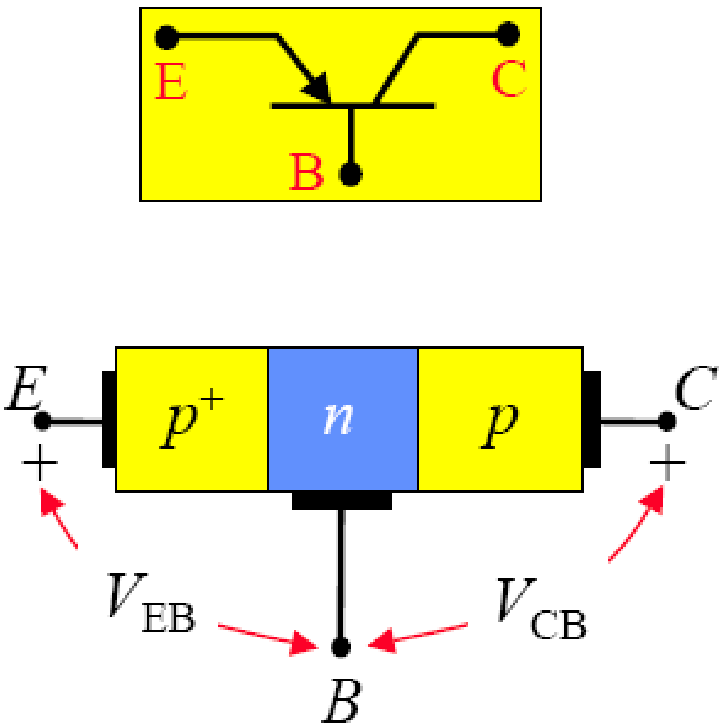
(b) *p*-cnannel, depletion mode device



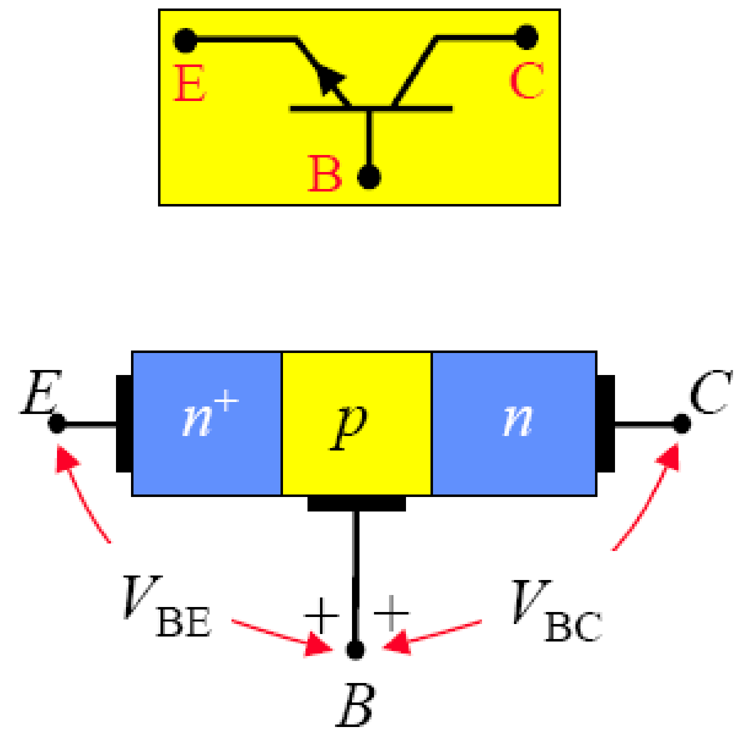
(A) Terminology and symbols

Bipolar Junction Transistor

PNP - transistor



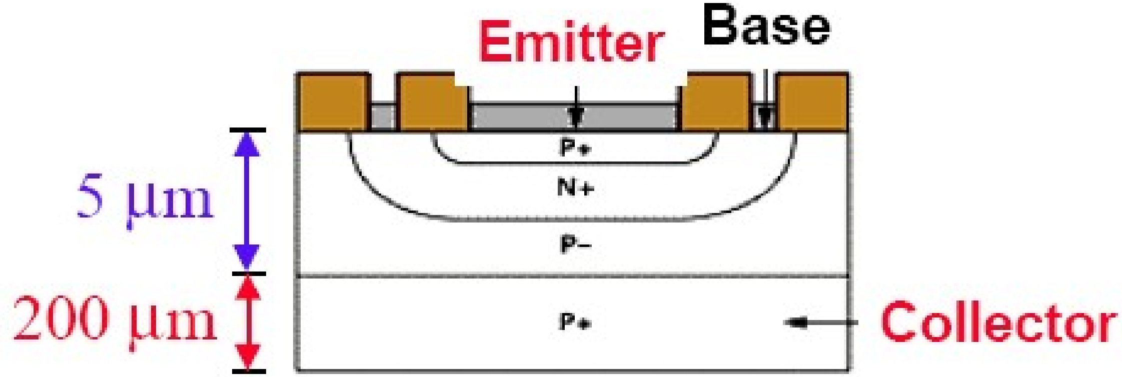
NPN - transistor



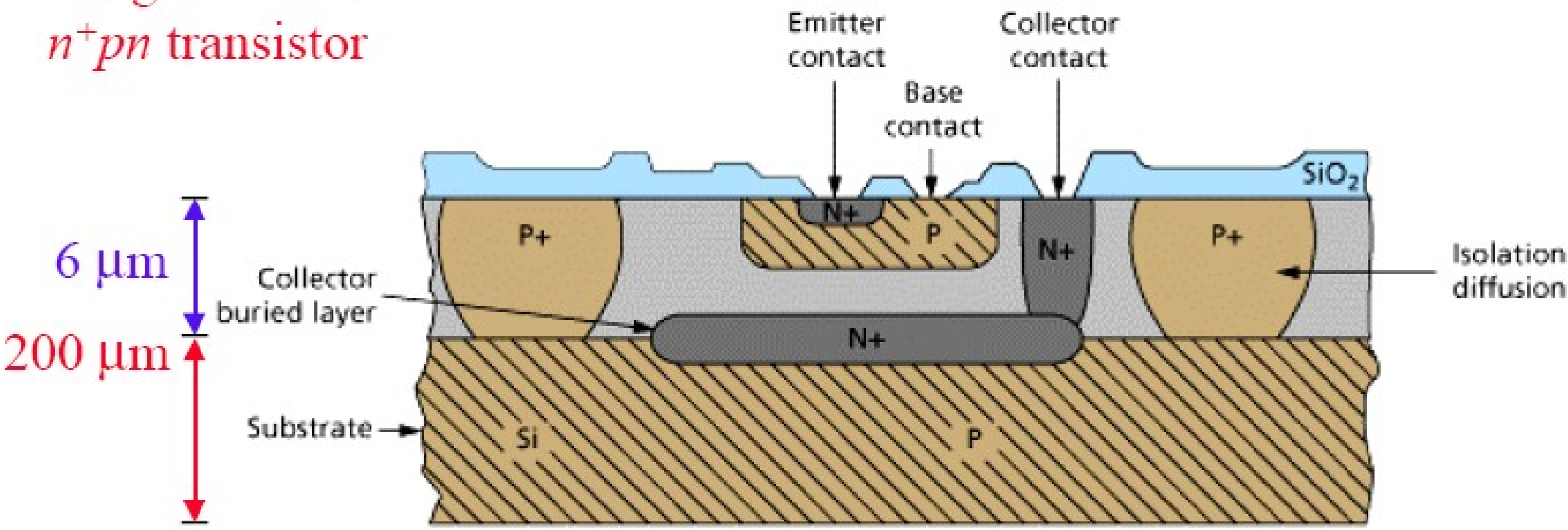
- Both, *pnp* and *npn* transistors can be thought as two very closely spaced *pn*-junctions.
- The base must be small to allow interaction between the two *pn*-junctions.

(D) Types of transistors

- Discrete (double-diffused) $p^{+}np$ transistor



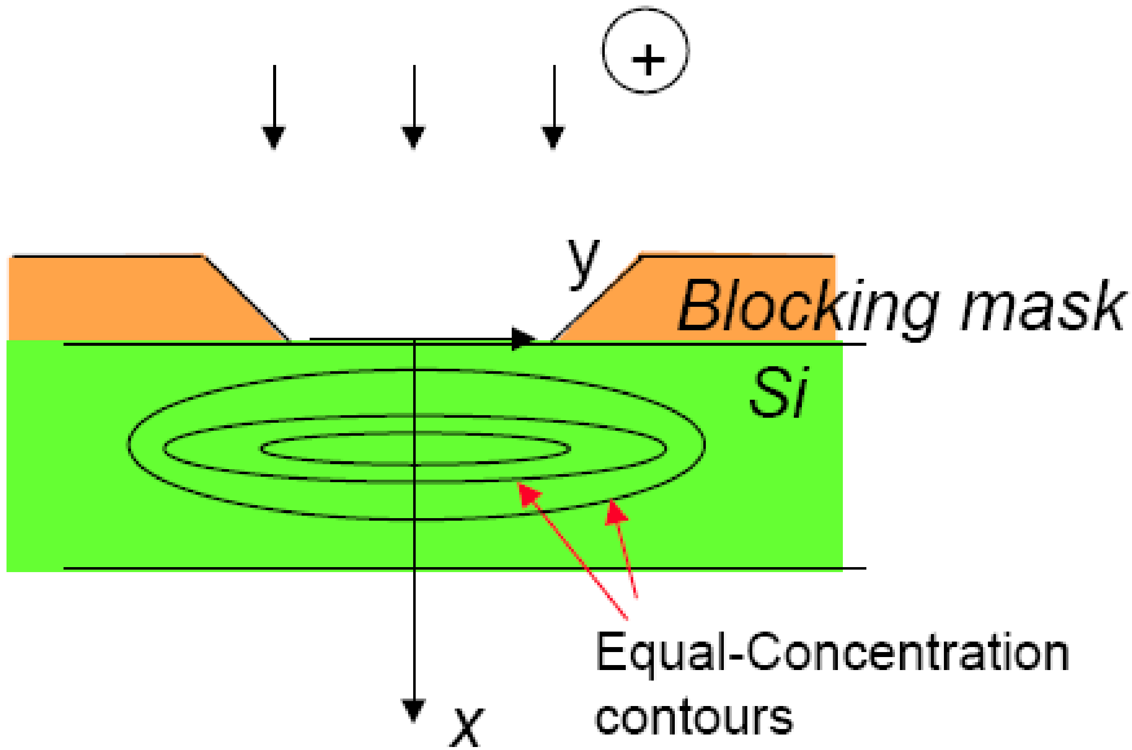
- Integrated-circuit $n^{+}pn$ transistor

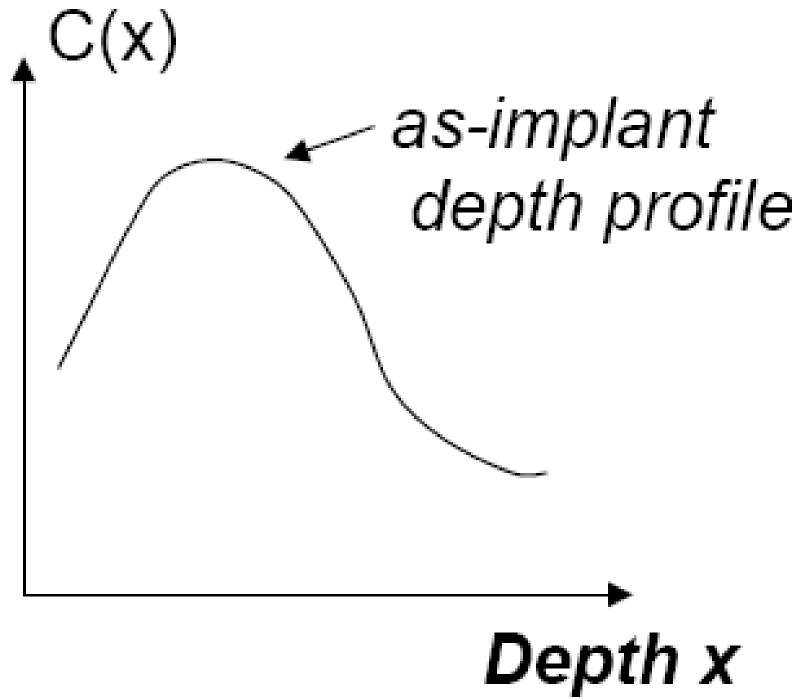


Summary

- We need to control doping in XY and Z, and also in density
- Ion Implantation and diffusion give us the freedom to do this

Ion Implantation





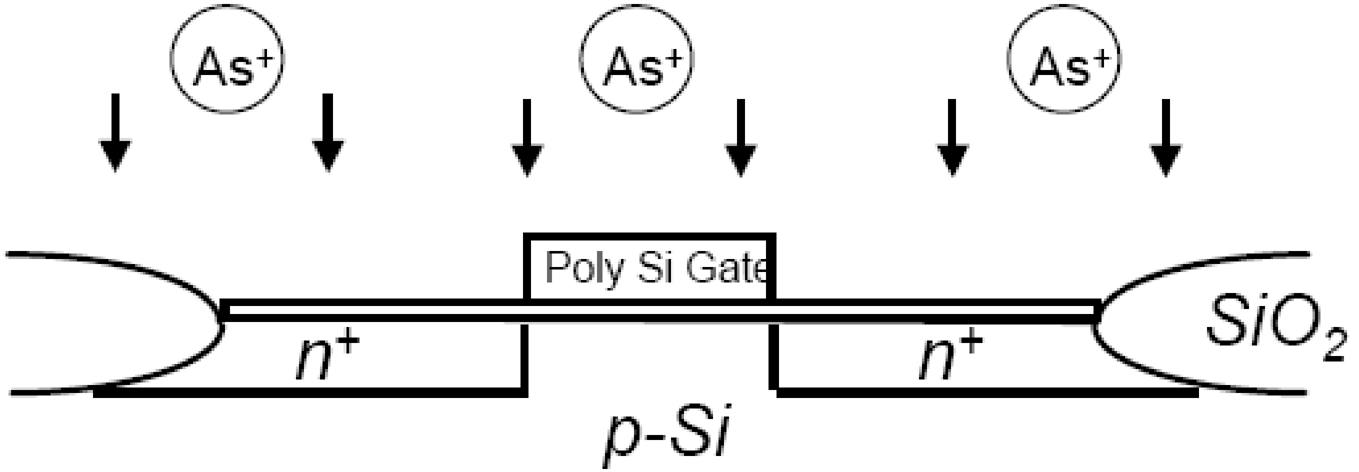
Concentration Profile versus Depth is a single-peak function

Reminder: During implantation, temperature is ambient. However, post-implant annealing step (>900°C) is required to anneal out defects.

Advantages of Ion Implantation

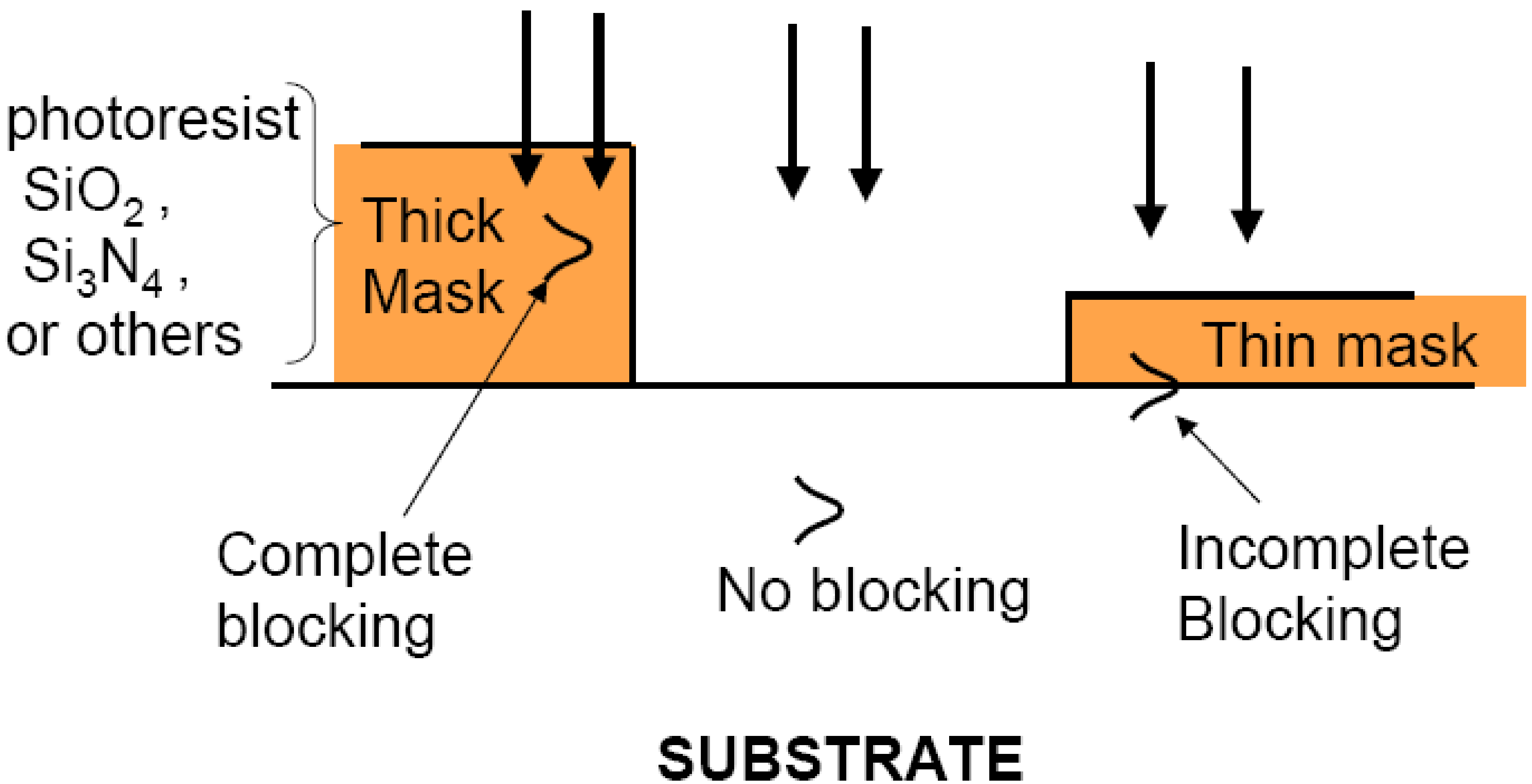
- Precise control of dose and depth profile
- Low-temp. process (can use photoresist as mask)
- Wide selection of masking materials
  e.g. photoresist, oxide, poly-Si, metal
- Less sensitive to surface cleaning procedures
- Excellent lateral dose uniformity (< 1% variation across 12" wafer)

Application example: self-aligned MOSFET source/drain regions



Masking

Mask layer thickness can block ion penetration

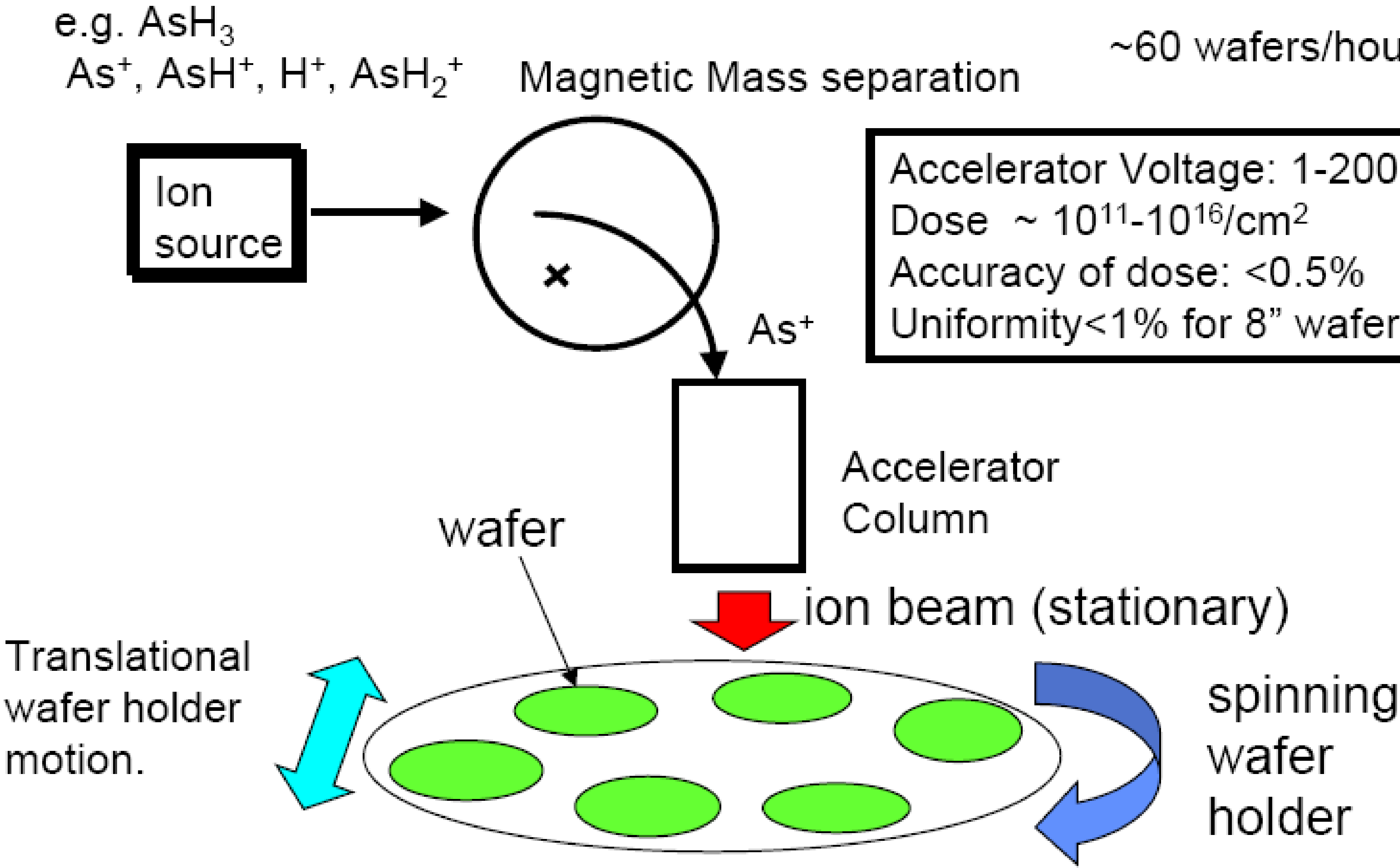


Ion Implanter

$3-4M/implanter

~60 wafers/hour

Accelerator Voltage: 1-200kV
Dose ~ 10^{11}-10^{16}/cm^2
Accuracy of dose: <0.5%
Uniformity<1% for 8" wafer



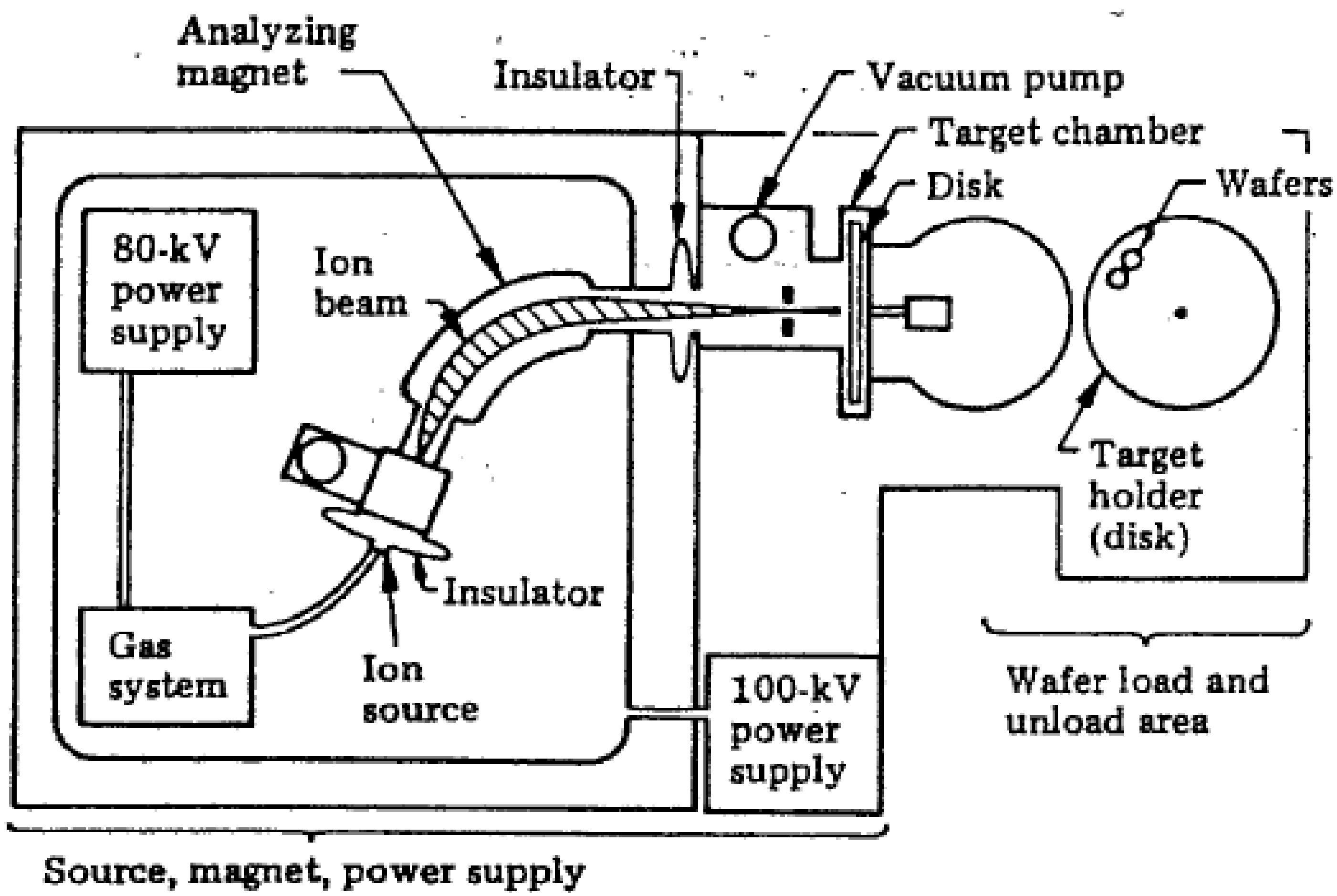


FIGURE 8.4 Schematic of a commercial ion-implantation system, the Nova-10-160, 10 mA at 160 keV.

Energetic ions penetrate the surface of the wafer and then undergo a series of collisions with the atoms and electrons in the target.

Monte Carlo Simulation of 50keV Boron implanted into Si

SRIM-2000 (v.09)

Ion Type = B (11 amu)
Ion Energy = 50 keV
Ion Angle = 0 degrees

TARGET LAYERS	Depth	Density
Layer 1	5000A	2.321

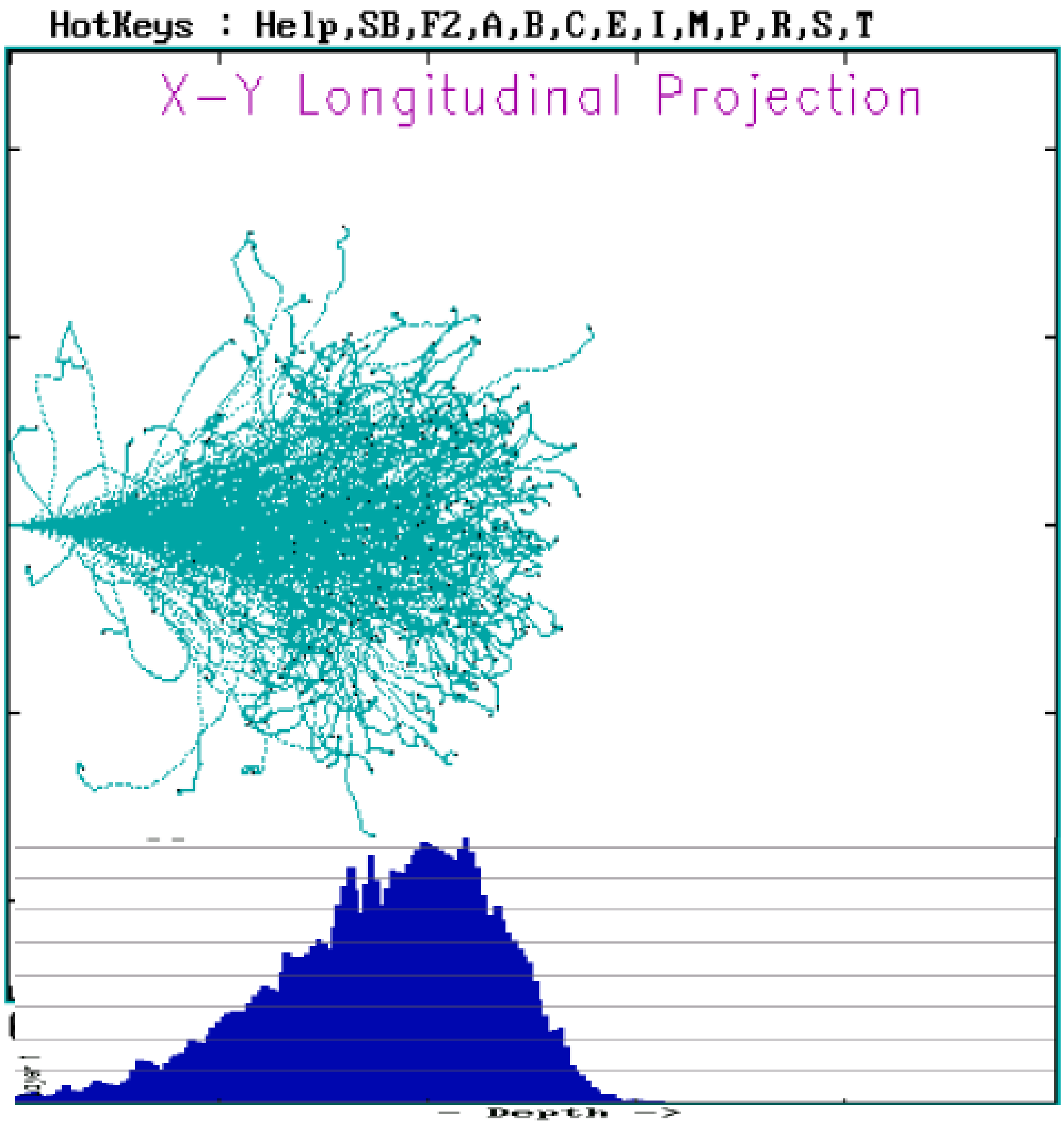
AtomColors=B/B

Ion Completed= 333(99999)
Backscattered Ions =
Transmitted Ions =

	Range	Straggle
Longitudinal=	1775A	511A
Lateral Proj=	487A	595A
Radial =	753A	365A

Vac./Ion = 323.0

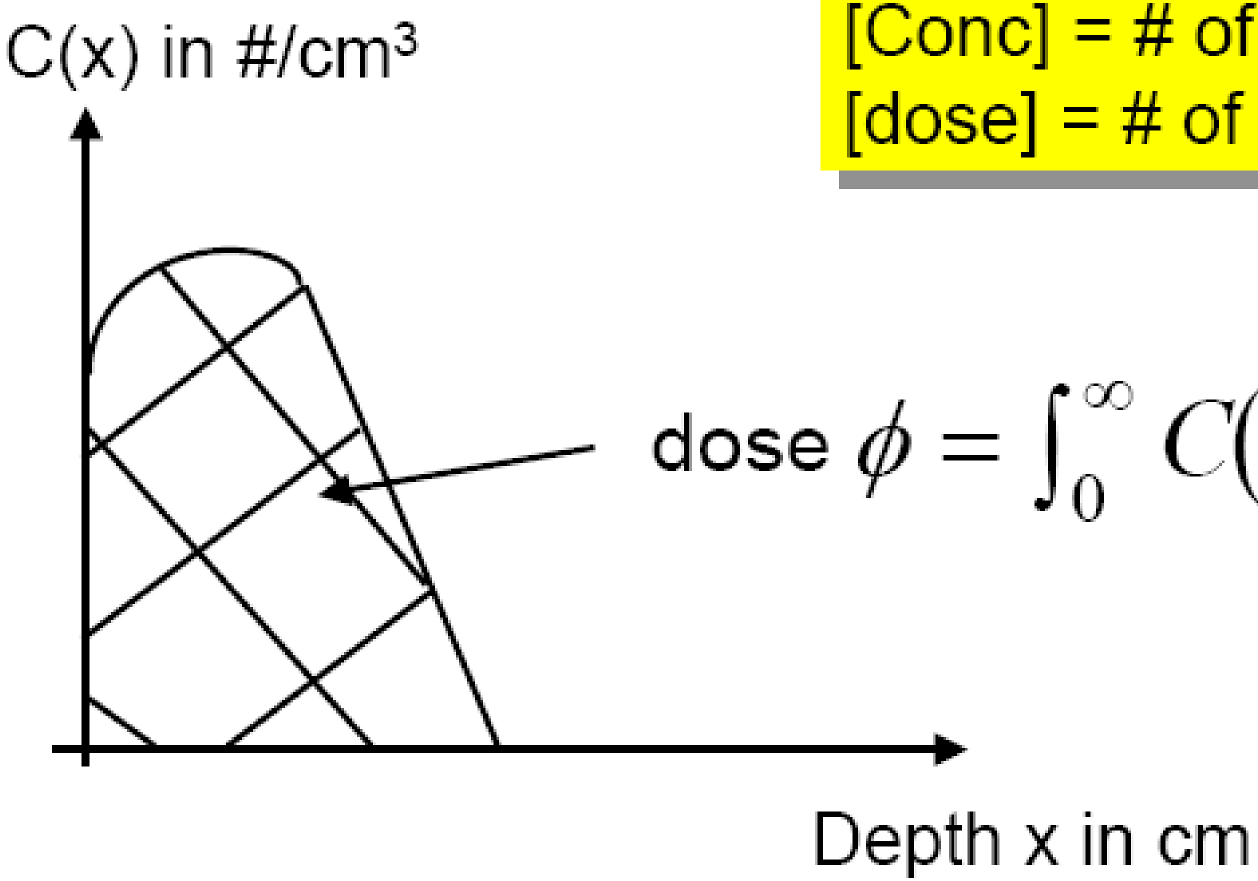
ENERGY LOSS(%)	IONS	RECOILS
Ionization ==>	68.00	7.08
Vacancies ===>	0.21	1.08
Phonons ====>	0.71	22.95



(1) Range and profile shape depends on the ion energy
(for a particular ion/substrate combination)

(2) Height (i.e. Concentration) of profile depends on the implantation dose

[Conc] = # of atoms/**cm^3**
[dose] = # of atoms/**cm^2**

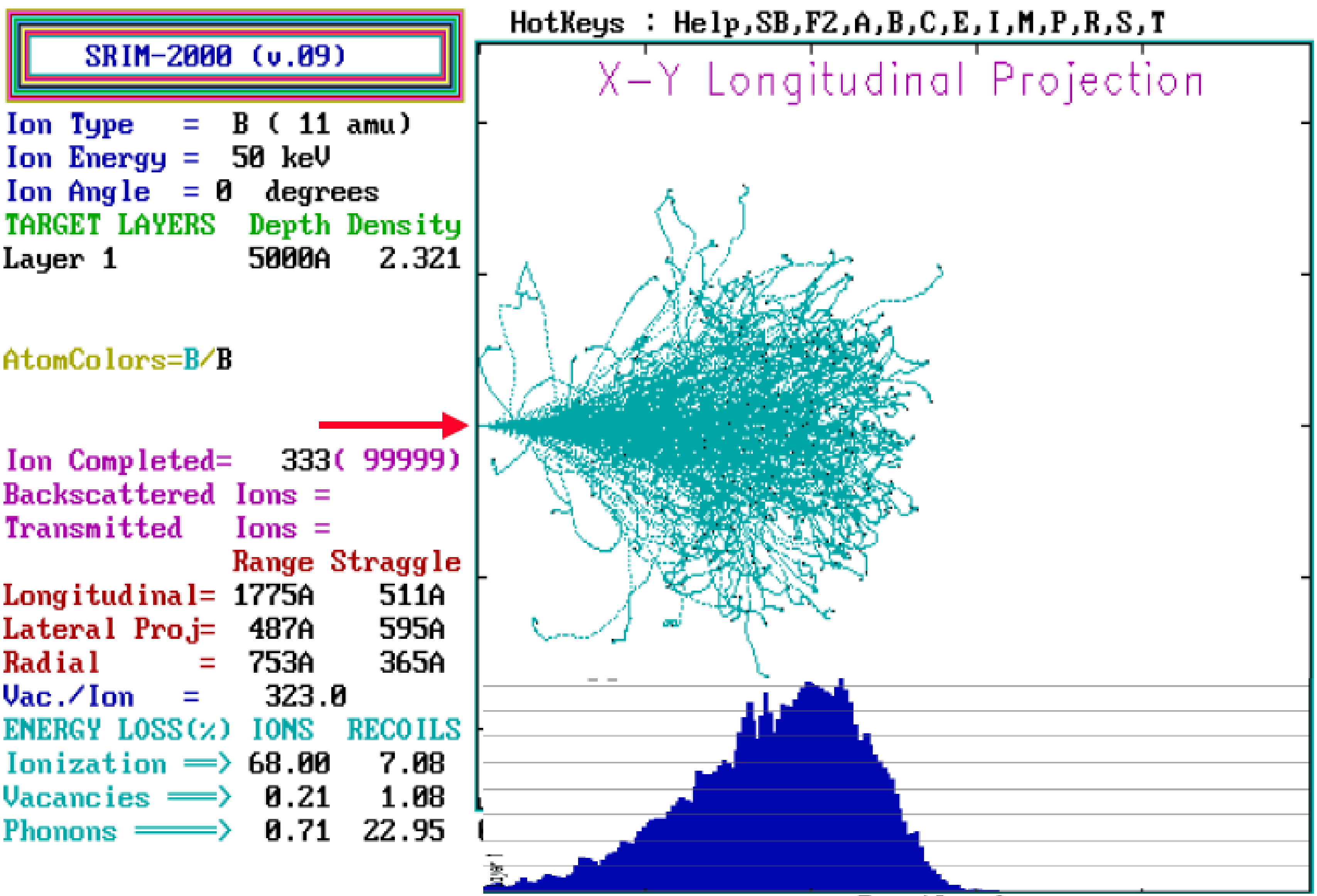


dose $\phi = \int_0^\infty C(x)dx$

Simulation: SRIM

http://www.srim.org/

Monte Carlo Simulation of 50keV Boron implanted into Si



Implantation Dose

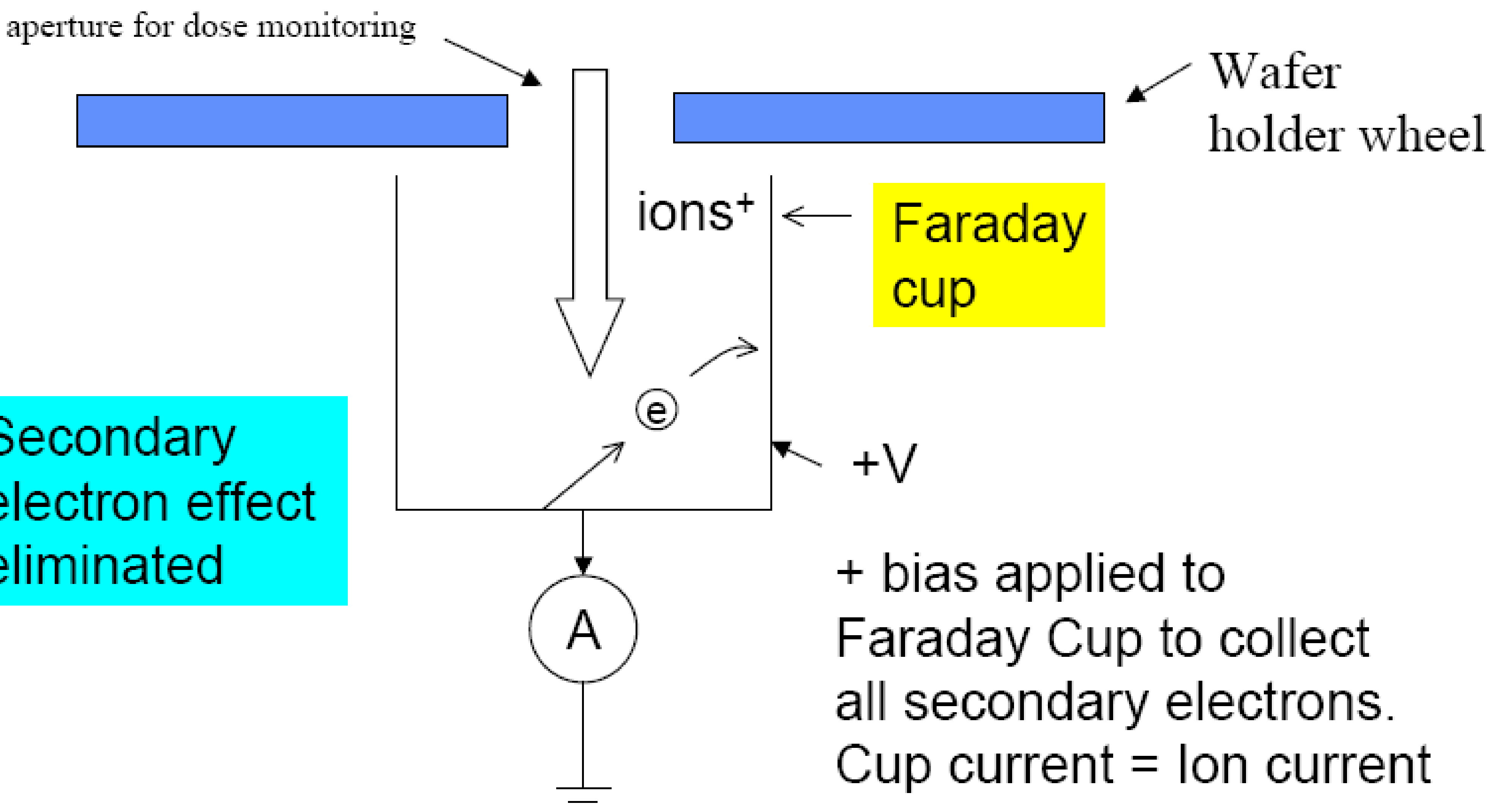
For *singly charged* ions (e.g. As^+)

$$\text{Dose}\quad \Phi = \frac{\left(\dfrac{Ion\ \ Beam\ \ Current\ \ in\ amps}{q}\right) \times \left(\begin{array}{l} Implant \\ time \end{array}\right)}{[Implant\ \ area\ ]}$$

$$= {}^{\#}\!\!\big/_{cm^2}$$

Over-scanning of beam across wafer is common.
In general , Implant area > Wafer area

Practical Implantation Dosimetry



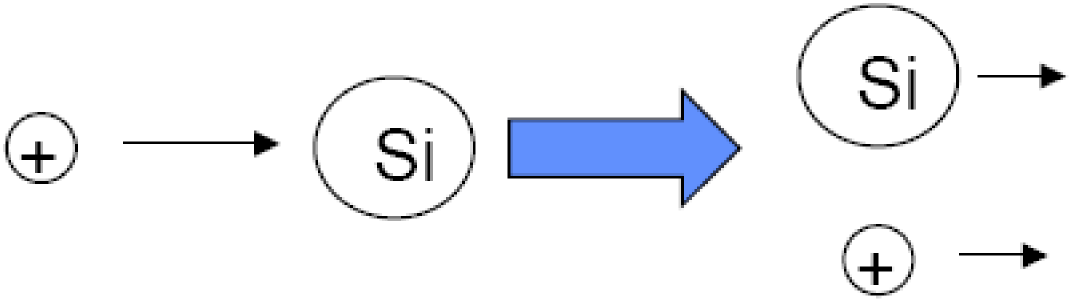
Secondary electron effect eliminated

+ bias applied to Faraday Cup to collect all secondary electrons.
Cup current = Ion current

* (Charge collected by integrating cup current) / (cup area) = dose

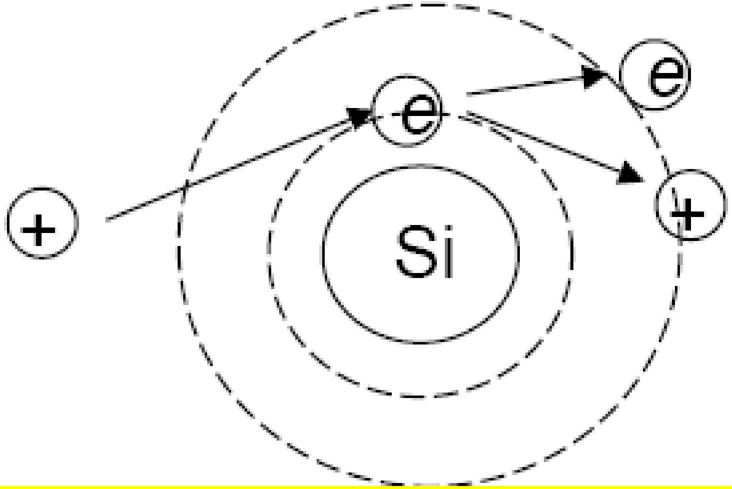
Ion Implantation Energy Loss Mechanisms

Nuclear stopping



Crystalline Si substrate damaged by collision

Electronic stopping



Electronic excitation creates heat

Energy Loss and Ion Properties

Light ions/at higher energy → more electronic stopping

Heavier ions/at lower energy → more nuclear stopping

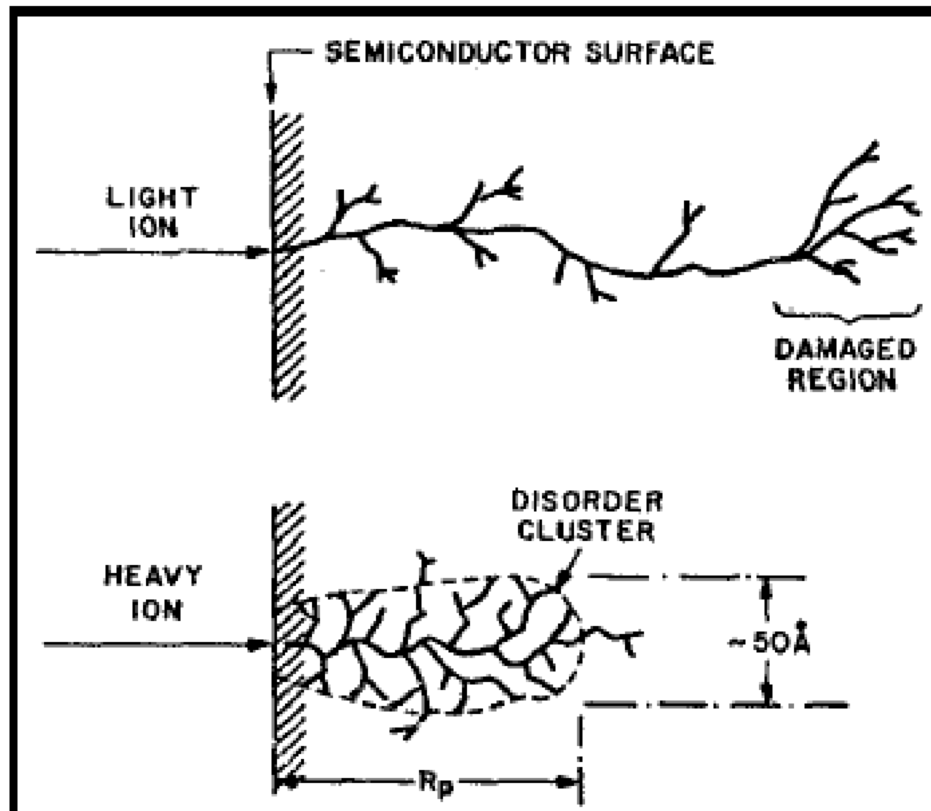
EXAMPLES

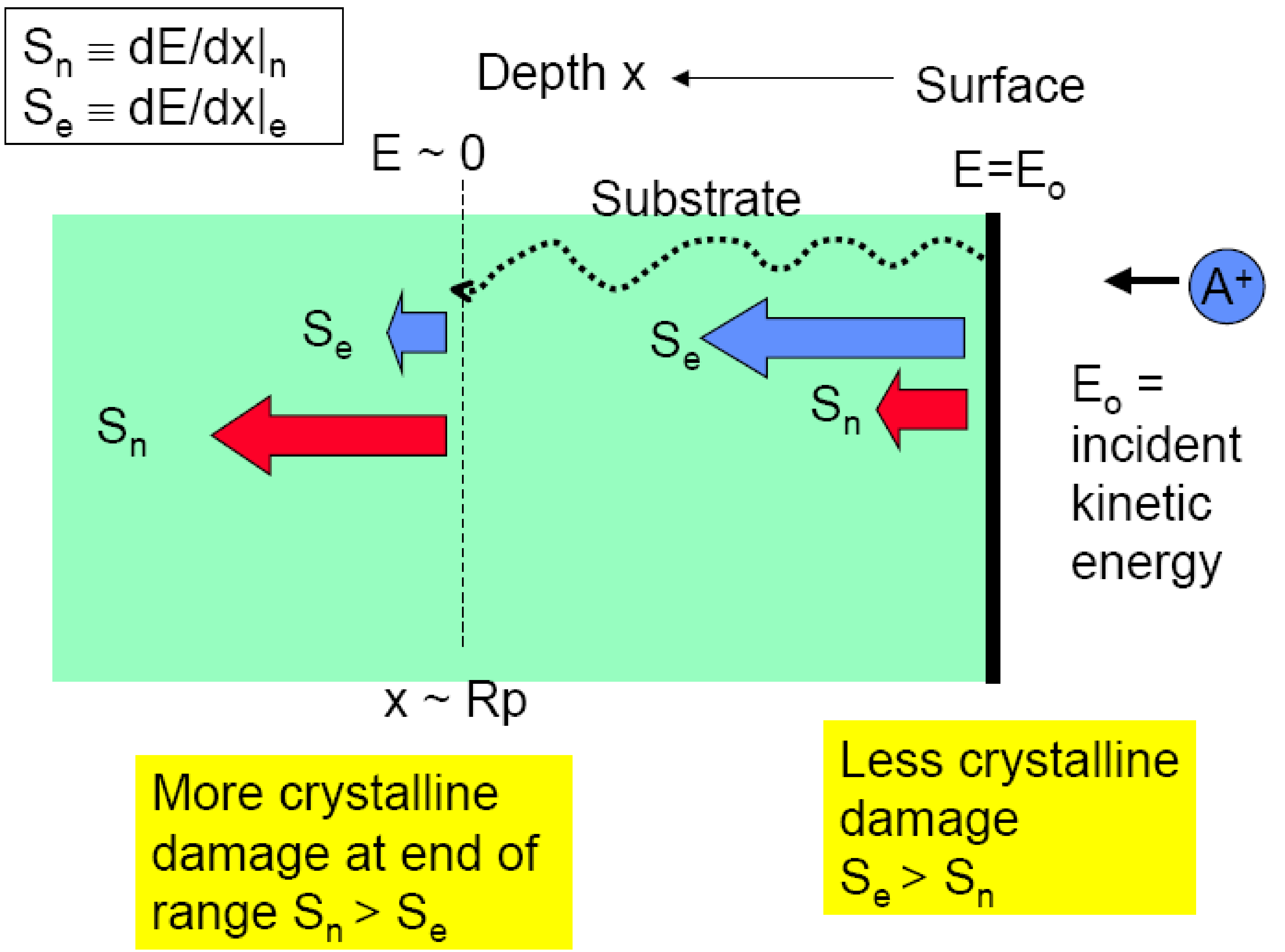
Implanting into Si:

H^+ ⇨ Electronic stopping dominates

B^+ ⇨ Electronic stopping dominates

As^+ ⇨ Nuclear stopping dominates





$S_n \equiv dE/dx|_n$
$S_e \equiv dE/dx|_e$
Depth x
Surface
E ~ 0
$E = E_o$
Substrate
A^+
S_e
S_n
S_e
S_n
E_o = incident kinetic energy
x ~ Rp
More crystalline damage at end of range $S_n > S_e$
Less crystalline damage $S_e > S_n$

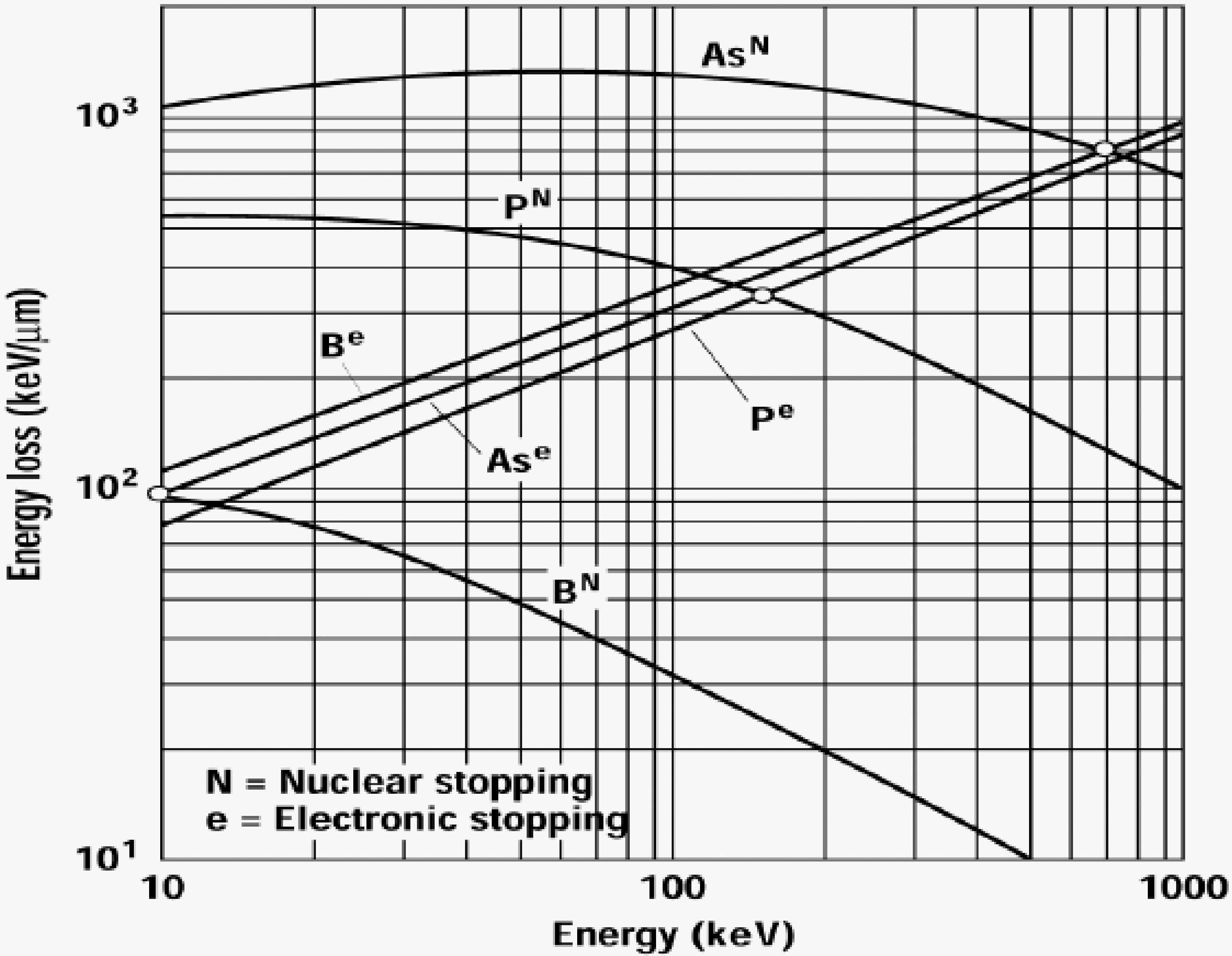
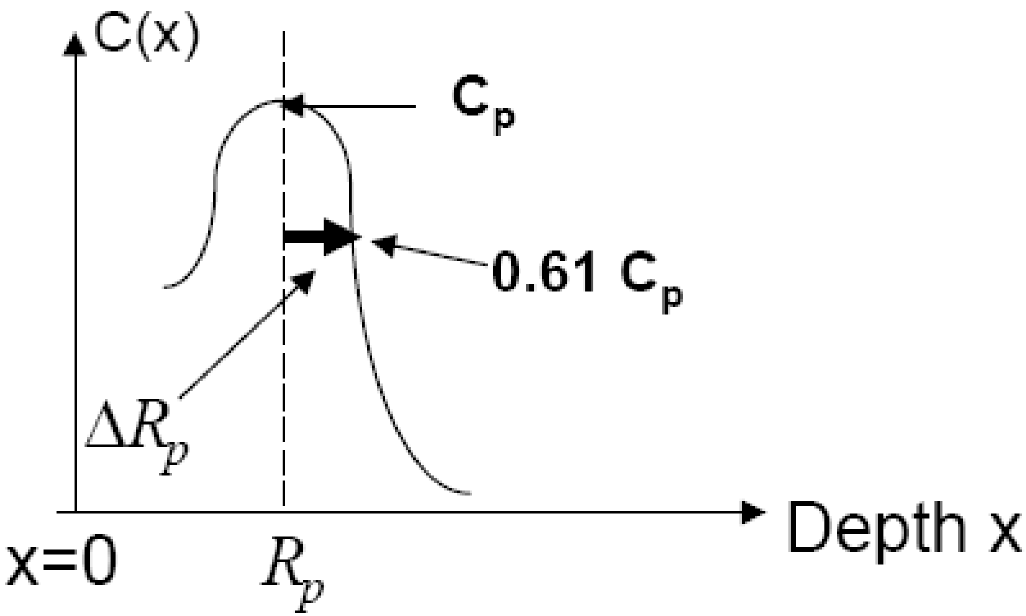
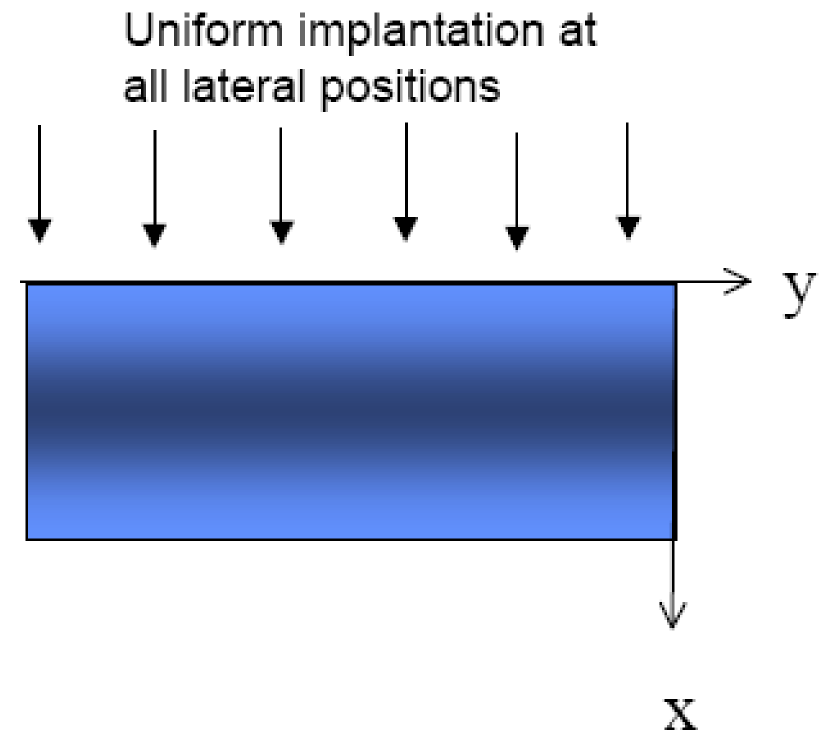


Figure 5.8 Nuclear and electronic components of $S(E)$ for several common silicon dopants as a function of energy (*after Smith as redrawn by Seidel, "Ion Implantation," reproduced by permission, McGraw-Hill, 1983*).

Gaussian Approximation of One-Dimensional Implant Depth Profile





$$C(x) = C_p \cdot e^{\frac{-(x-R_p)^2}{2(\Delta R_p)^2}}$$

R_p = projected range

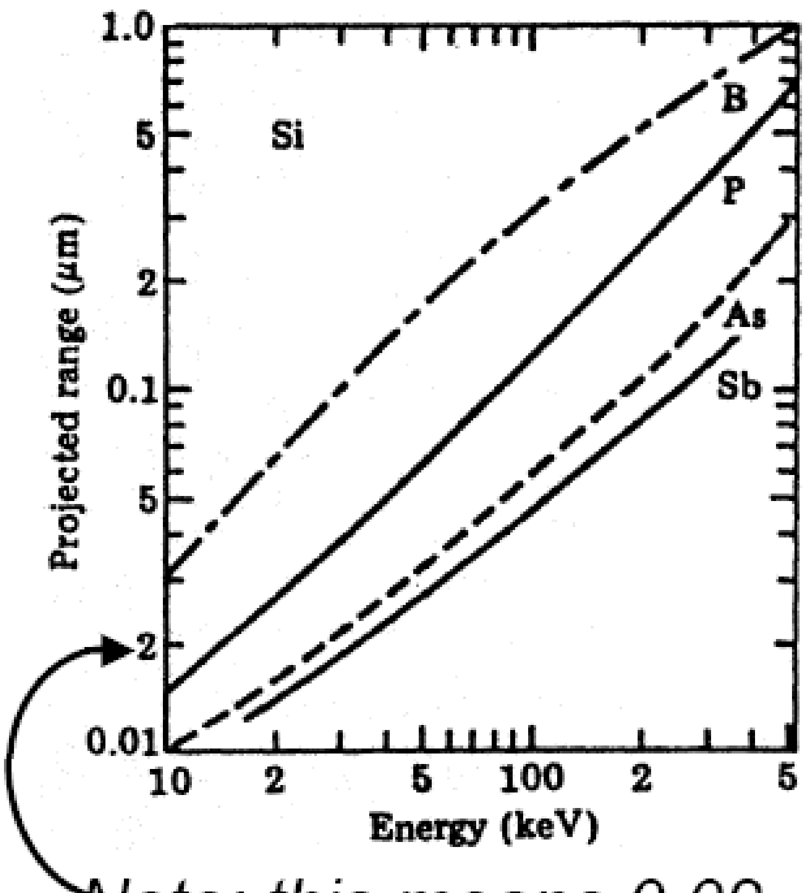
ΔR_p = longitudinal straggle

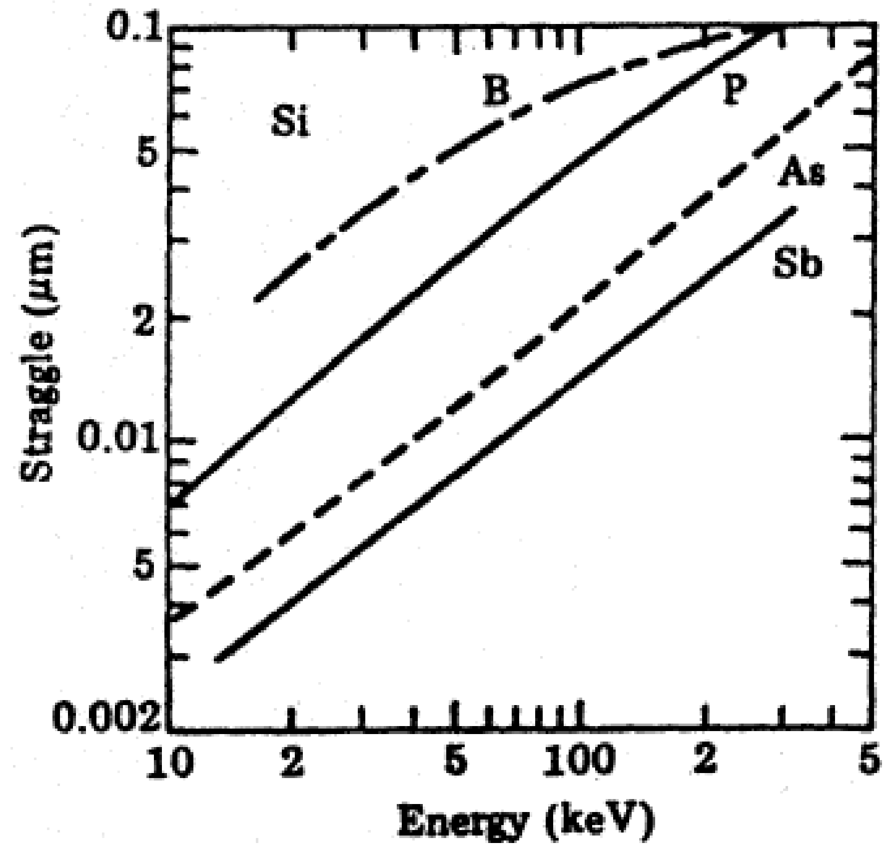
Note: For lateral positions far from masking boundaries, C(x) is independent of lateral position y

Projected Range and Straggle

Rp and ΔRp values are given in tables or charts

e.g. see pp. 113 of Jaeger





Note: this means 0.02 μm.

Dose-Concentration Relationship

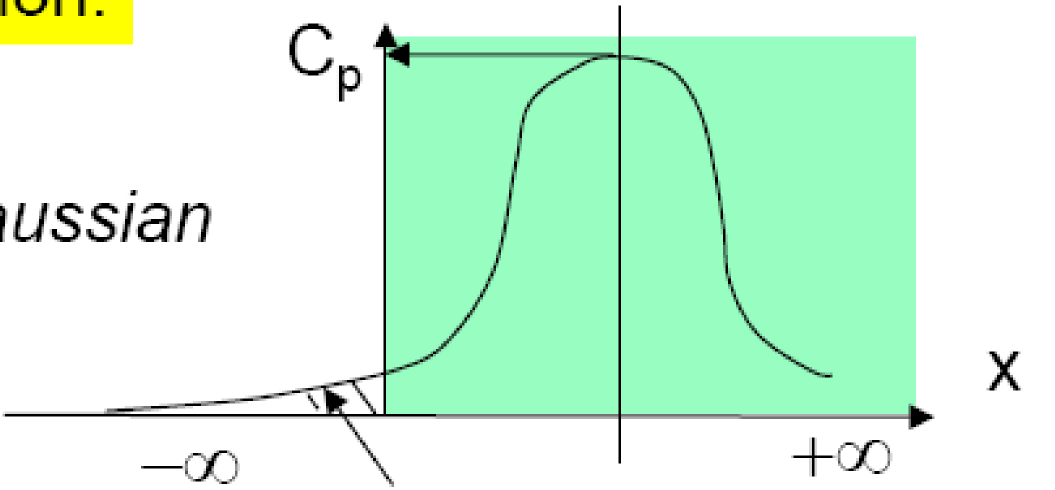
Using Gaussian Approximation:

$$\text{Dose} = \phi = \int_0^{\infty} C(x)dx$$

$$\approx \int_{-\infty}^{+\infty} C(x)dx$$

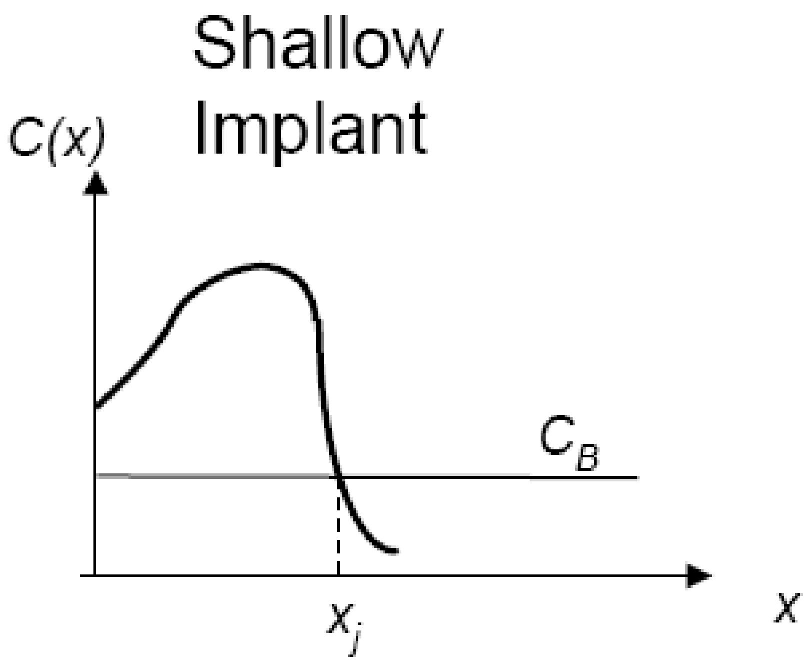
$$= C_p \cdot \left[\sqrt{2\pi} \cdot \Delta R_p\right]$$

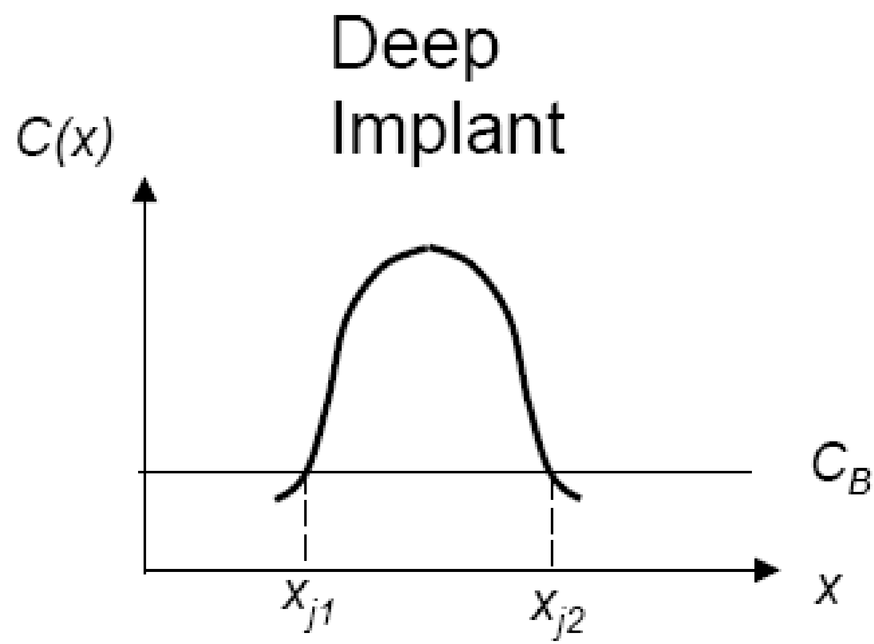
Gaussian



$$\therefore C_p = \frac{\phi}{\sqrt{2\pi} \cdot \Delta R_p} \cong \frac{0.4\phi}{\Delta R_p}$$

Junction Depth, x_j





$C(x = x_j) = N_B$ = *Bulk Conc.* $\Rightarrow$ *Solution for* x_j

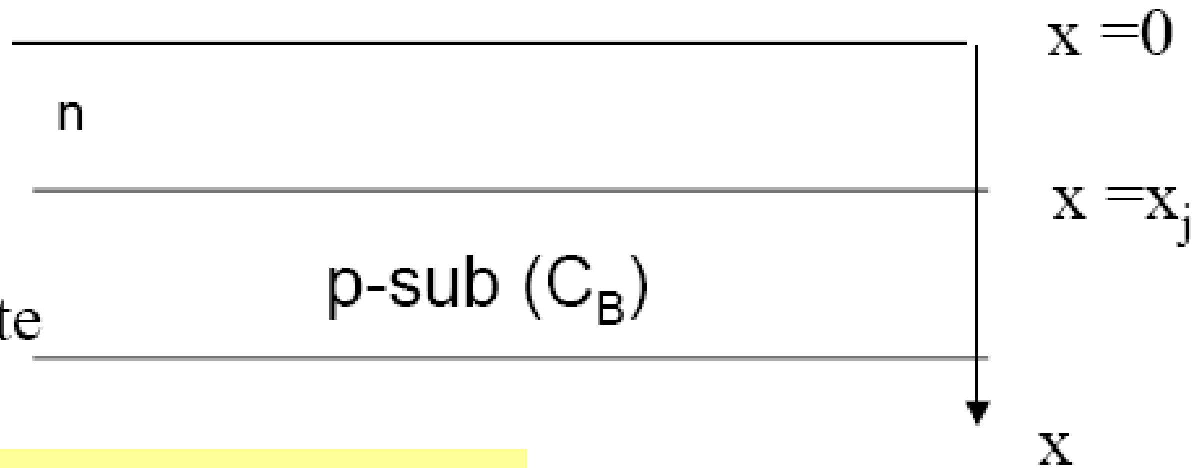
If Gaussian approx for C(x) is used , from

$$C_p \exp[-(x_j - R_p)^2 / 2(\Delta R_p)^2] = C_B$$

we can solve for x_j .

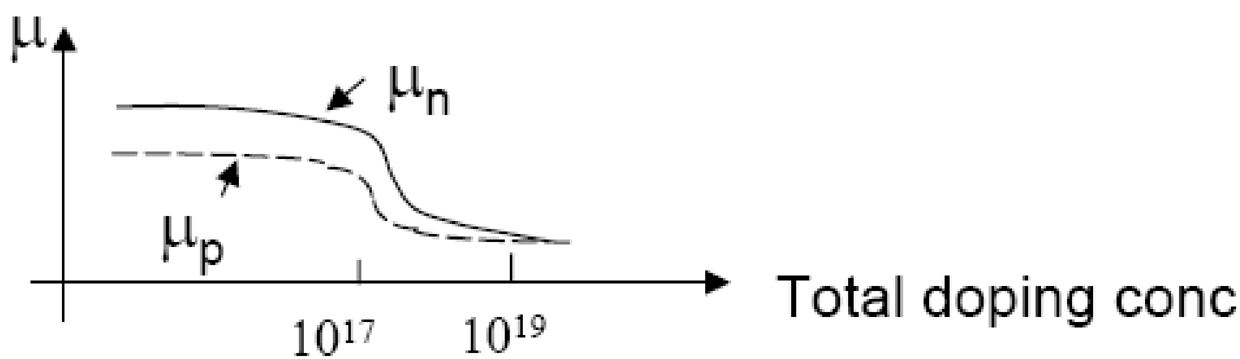
Sheet Resistance R_S of Implanted Layers

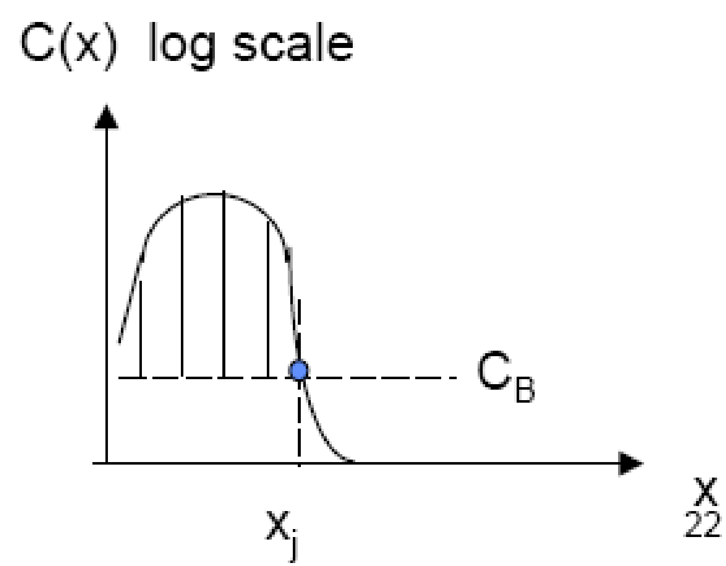
Example:
n-type dopants implanted into p-type substrate



$$\mathbf{R_S = \frac{1}{\int_0^{x_j} q \cdot \mu(x)\left[C(x) - C_B\right] dx}}$$

•Needs numerical integration to get Rs value





Approximate Value for R_S

If $C(x) >> C_B$ for most depth x of interest
and use approximation: $\mu(x) \sim$ constant

$$\Rightarrow R_s \rightarrow \frac{1}{q\mu\int_0^{x_j} C(x)dx} \cong \frac{1}{q\mu\phi}$$

This expression assumes ALL implanted dopants are 100% electrically activated

$$R_s \cong \frac{1}{q\mu\phi}$$

use the μ for the highest doping region which carries most of the current

$$[R_s] = ohm/\square$$

or ohm/square

Example Calculations

200 keV Phosphorus is implanted into a p-Si ($C_B = 10^{16}/cm^3$) with a dose of $10^{13}/cm^2$.

From graphs or tables , Rp =0.254 μm , ΔRp=0.0775μm

(a) Find peak concentration

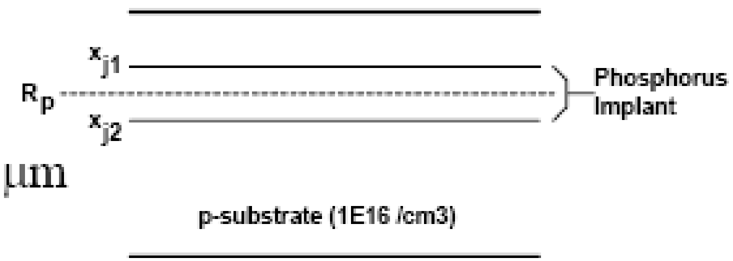
$Cp = (0.4 \times 10^{13})/(0.0775 \times 10^{-4}) = 5.2 \times 10^{17}/cm^3$

(b) Find junction depths

(b) $C_p \exp[-(x_j - 0.254)^2 / 2 \Delta R_p^2] = C_B$ with x_j in μm

$\therefore (x_j - 0.254)^2 = 2 \times (0.0775)^2 \ln [5.2 \times 10^{17}/10^{16}]$

or $x_j = 0.254 \pm 0.22$ μm ; $x_{j1} = 0.032$ μm and $x_{j2} = 0.474$ μm

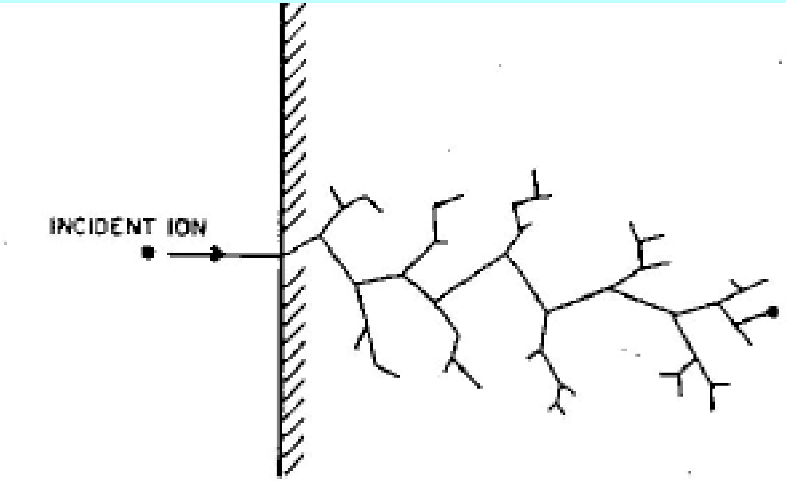


(c) Find sheet resistance

From the mobility curve for electrons (using peak conc as impurity conc), $\mu_n = 350\ cm^2$ /V-sec

$$R_s = \frac{1}{q\mu_n\phi} = \frac{1}{1.6\times10^{-19} \times 350 \times 10^{13}} \approx 1780\ \Omega/\text{square}.$$

Implantation Damage



After implantation, we need an annealing step. A typical ~900^{o}C, 30min will:

(1) Restore Si crystallinity.

(2) Put dopants into Si substitutional sites for electrical activation

Implantation Damage

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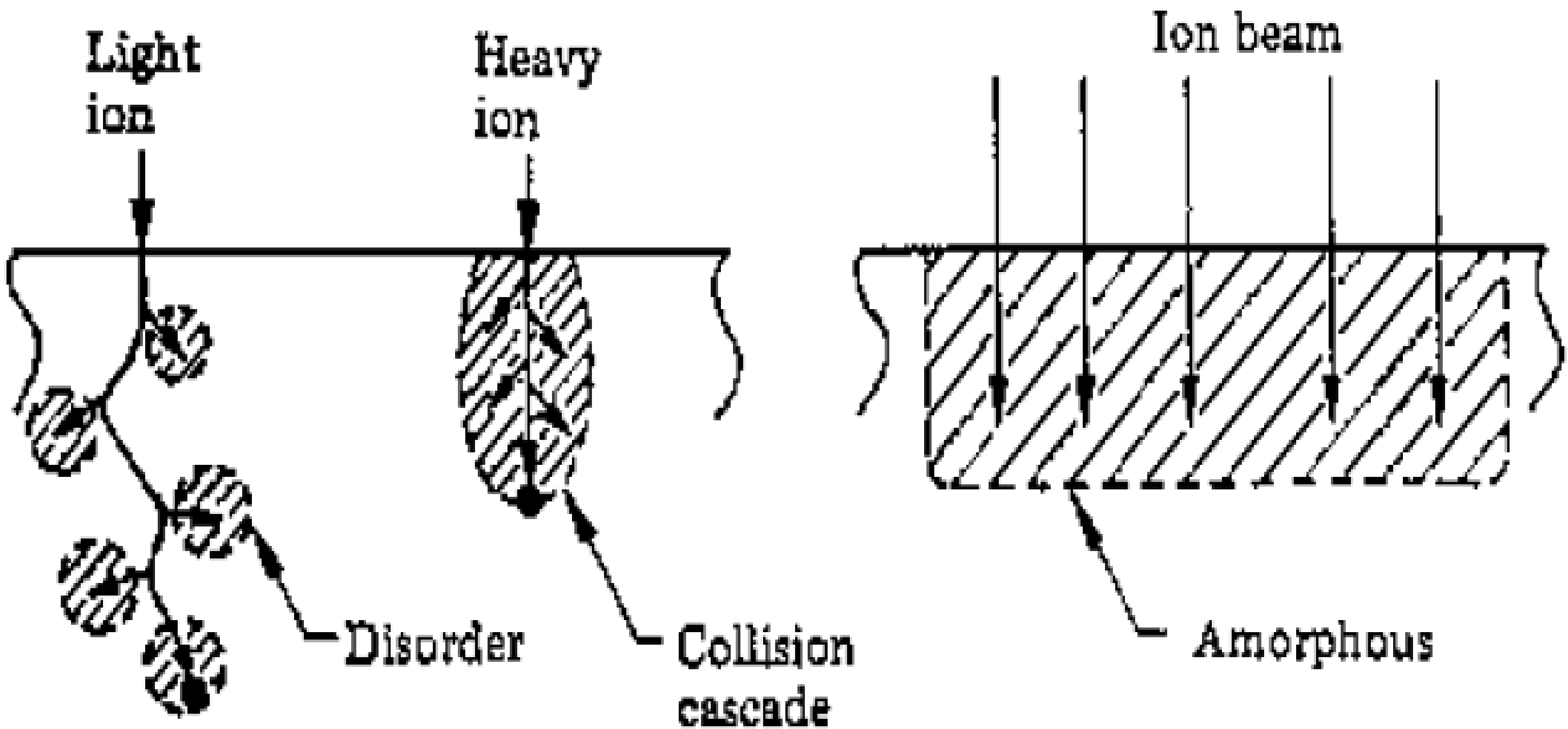
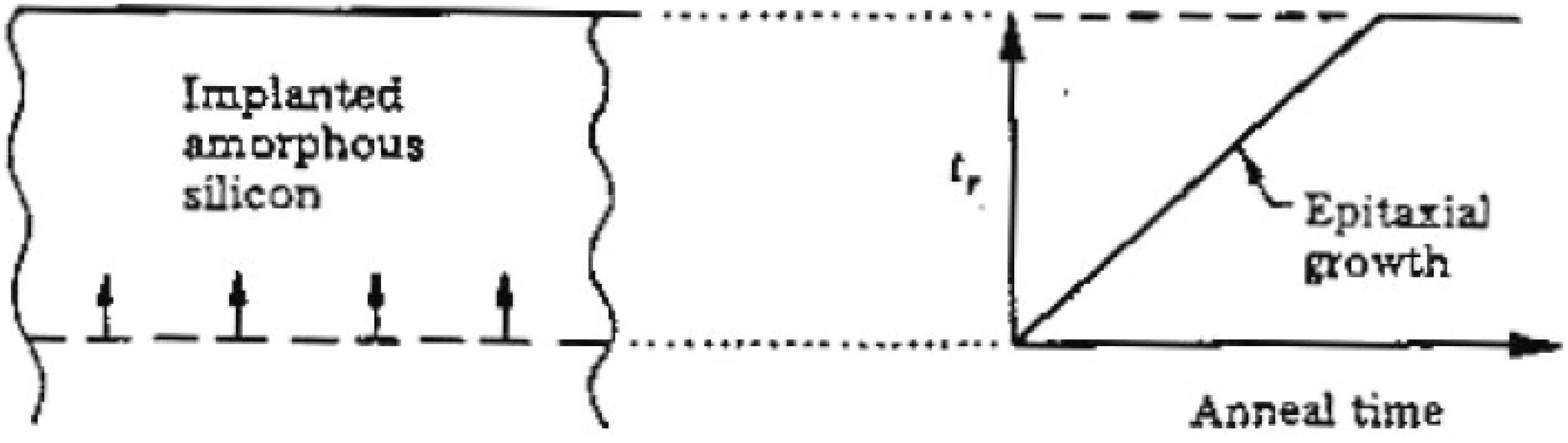


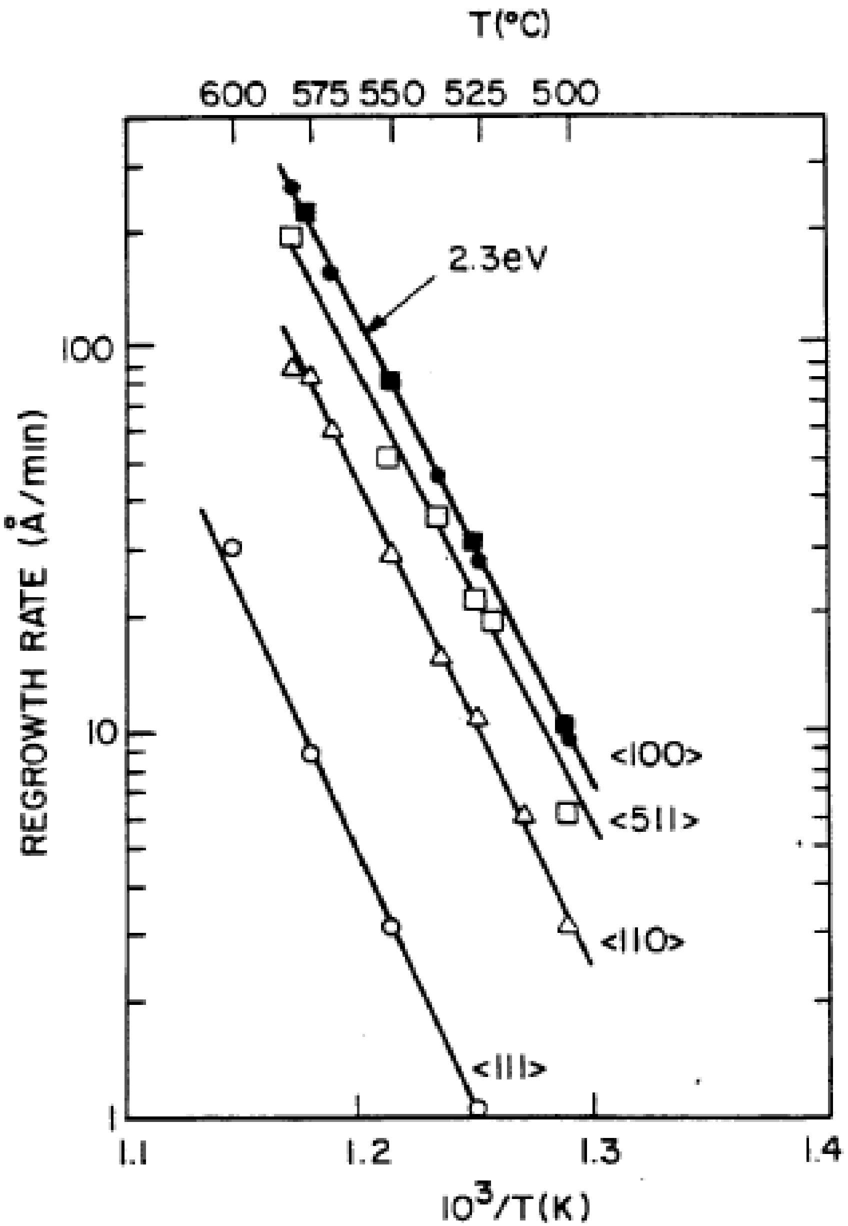
Schematic of the disorder produced along the individual paths of light and heavy ions and the formation of an amorphous region.

Solid Epitaxial "Growth" through the Implant Damaged Region



t_r = regrown layer thickness

Solid Epitaxial "Growth" through the Implant Damaged Region – cont.



(1) Regrow the amorphous region at T = 500-600°C into single crystal. The substrate acts as a seed. If higher temperatures are used then nucleation within the amorphous layer takes place making it polycrystalline and crystal structure can never be regained. This temperature range also recovers most of the electrical activity.

(2) A further anneal at T>900°C restores the crystal structure and electrical activity 100%.

Dopant Activation Versus Annealing Temp

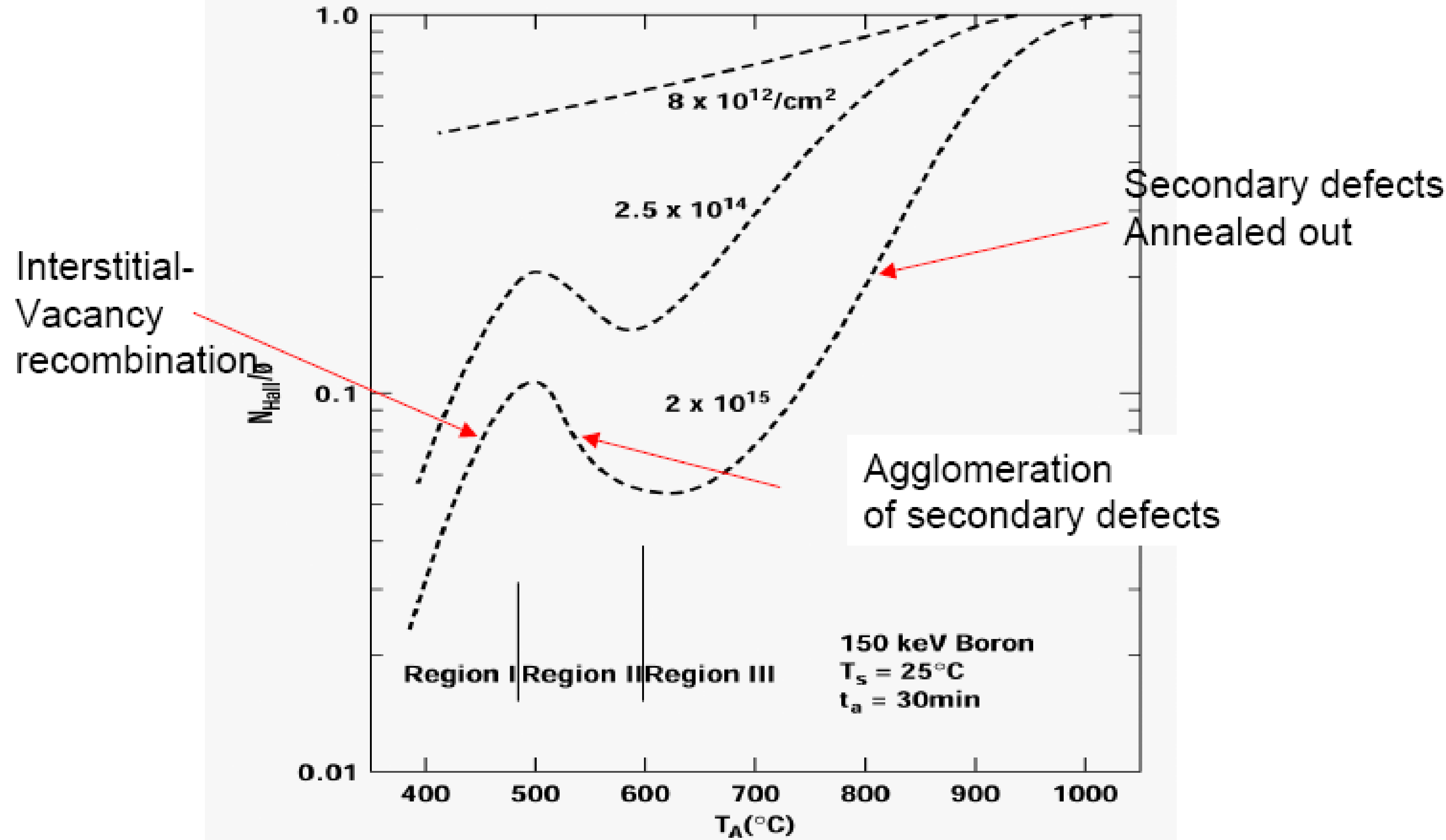
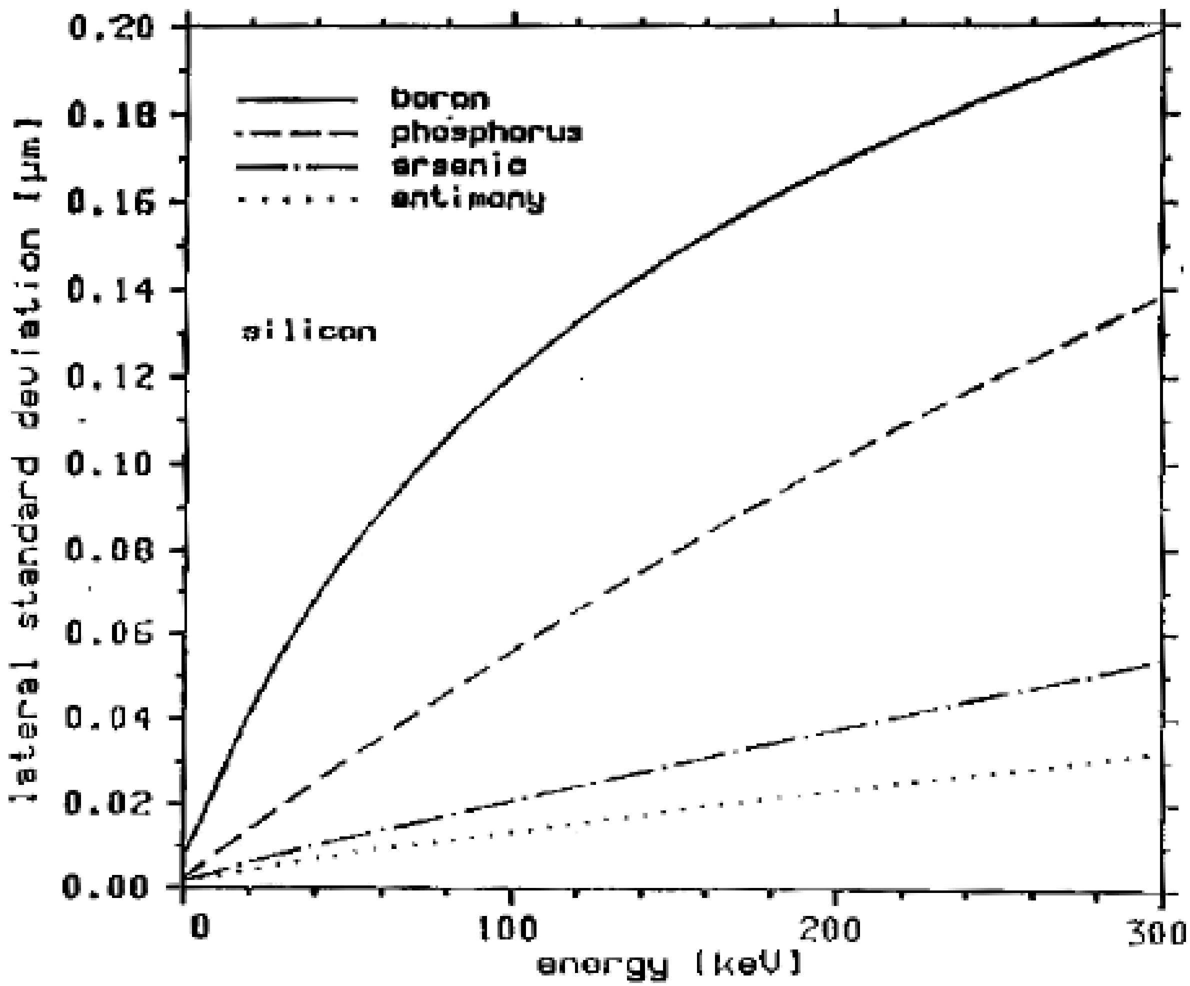


Figure 5.15 Fraction of implanted boron activated in silicon for several isochronal anneals *(after Seidel and MacRae, reprinted by permission, Elsevier Science).*

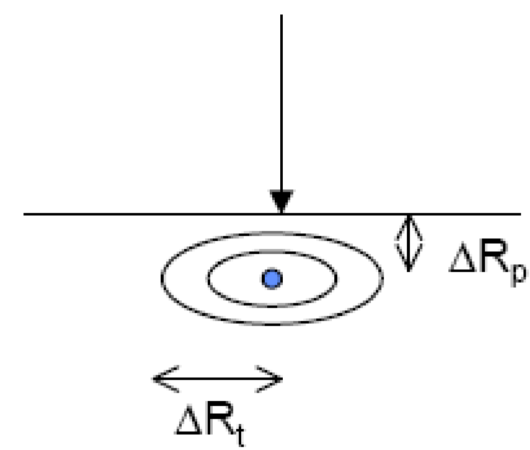
Transverse (or Lateral) Straggle (ΔR_t or $\Delta R_\perp$)

ΔR_t

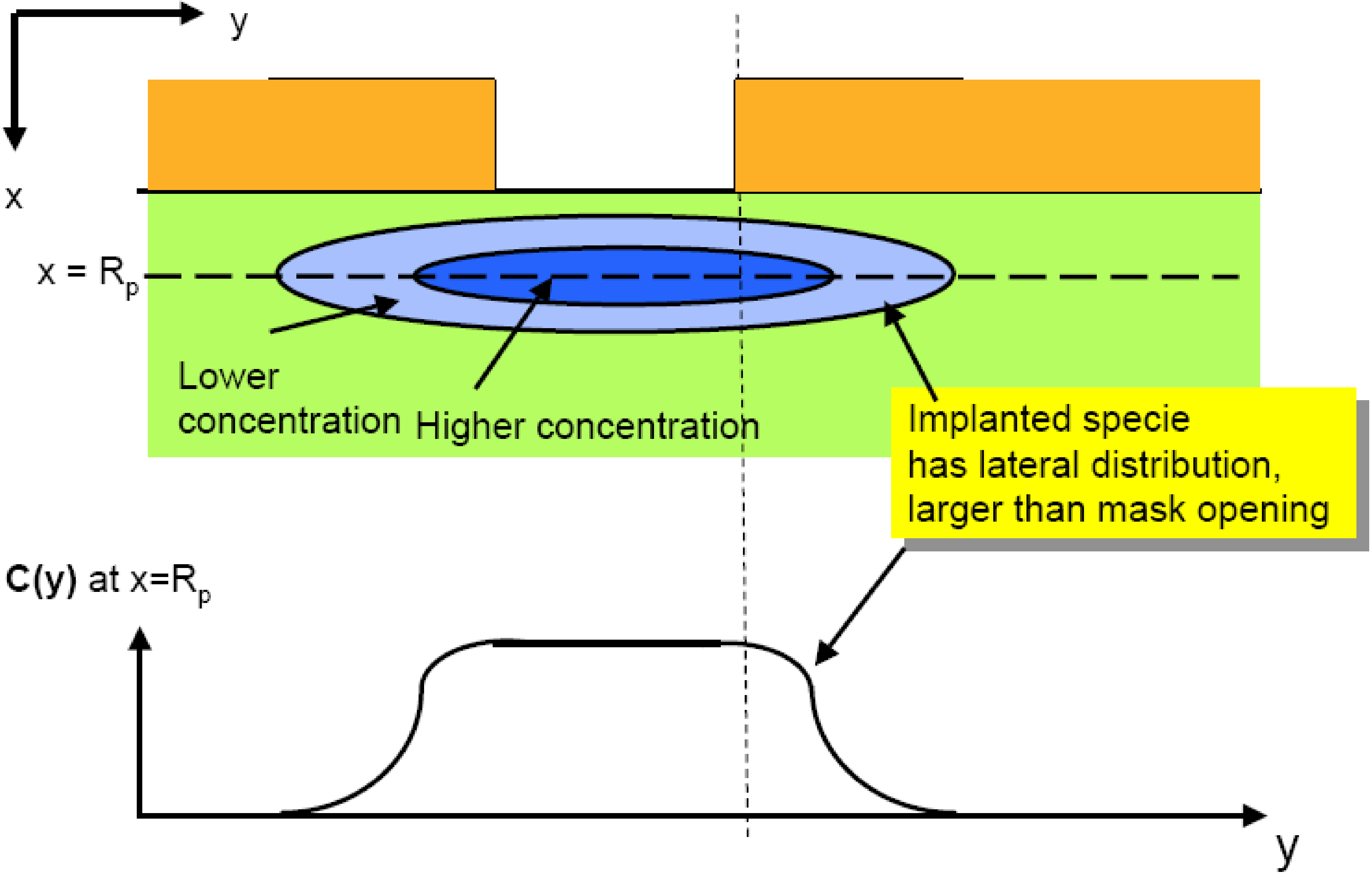


Lateral standard deviation of boron, phosphorus, arsenic and antimony in silicon

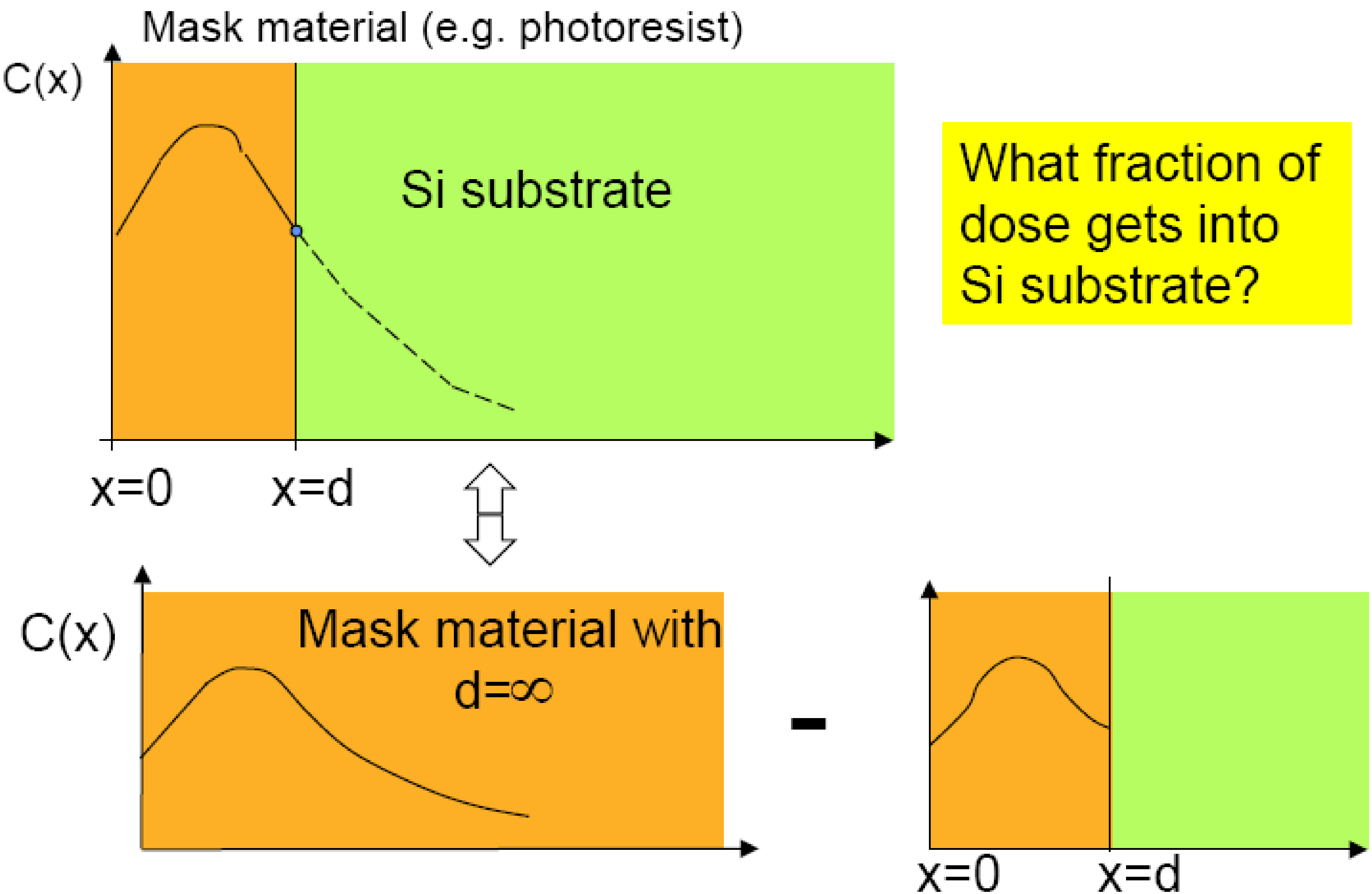
$$\frac{\Delta R_t}{\Delta R_p} > 1$$



Lateral Scattering Causes Feature Enlargement



Transmission Factor of Implantation Mask



What fraction of dose gets into Si substrate?

Transmitted Fraction

$$T = \int_0^\infty C(x)dx - \int_0^d C(x)dx$$

$$= \frac{1}{2} erfc\left\{\frac{d - R_p}{\sqrt{2}\Delta R_p}\right\}$$

$$erfc(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^x e^{-y^2} dy$$

R_p, ΔR_p are values of for ions into the **masking material**

Rule of thumb : Good masking thickness

$$d = R_p + 4.3\Delta R_p \qquad \frac{C(x=d)}{C(x=R_p)} \sim 10^{-4}$$

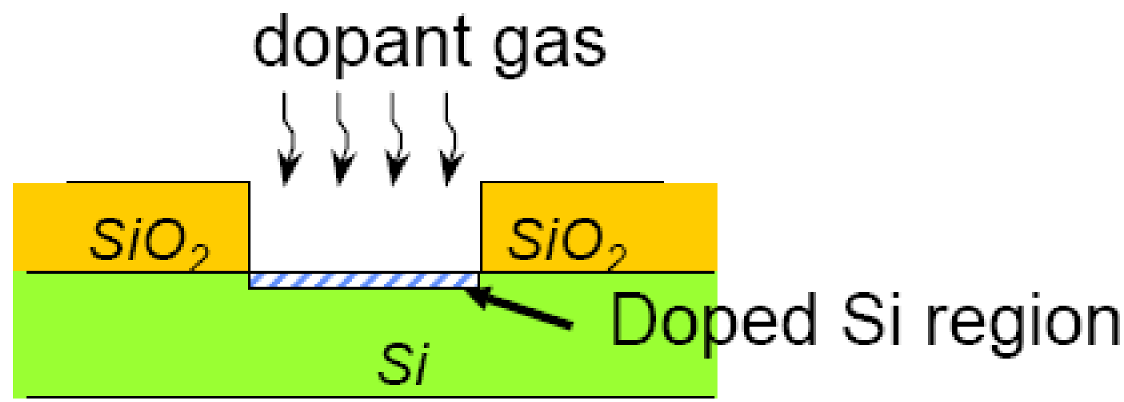
Diffusion

- Motion of impurities inside the crystal
- Sometimes intentional
- Sometimes unintentional, as a byproduct of a thermal process

Dopant Diffusion

(1) Predeposition

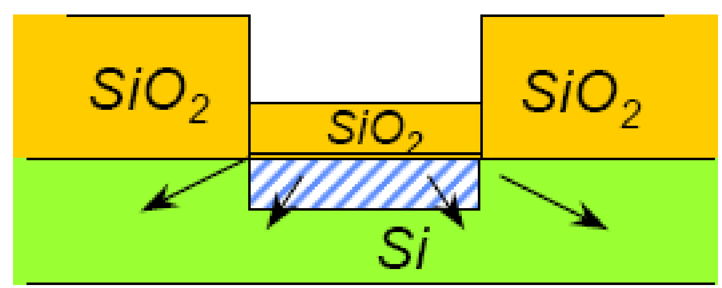
dose control



(2) Drive-in

Turn off dopant gas
or seal surface with oxide

profile control
(junction depth;
concentration)

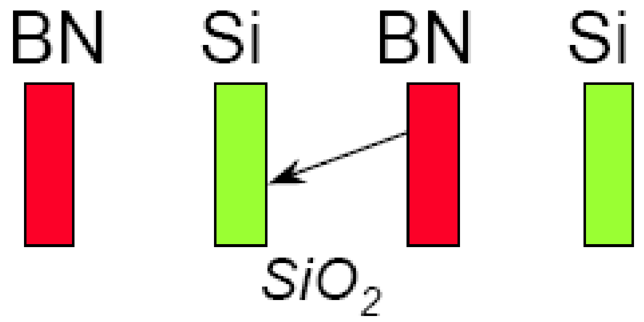


Note: Predeposition by diffusion can also be replaced by a shallow implantation step.

Dopant Diffusion Sources

(a) Gas Source: AsH_3, PH_3, B_2H_6

(b) Solid Source



(c) Spin-on-glass SiO_2+dopant oxide

(d) Liquid Source.

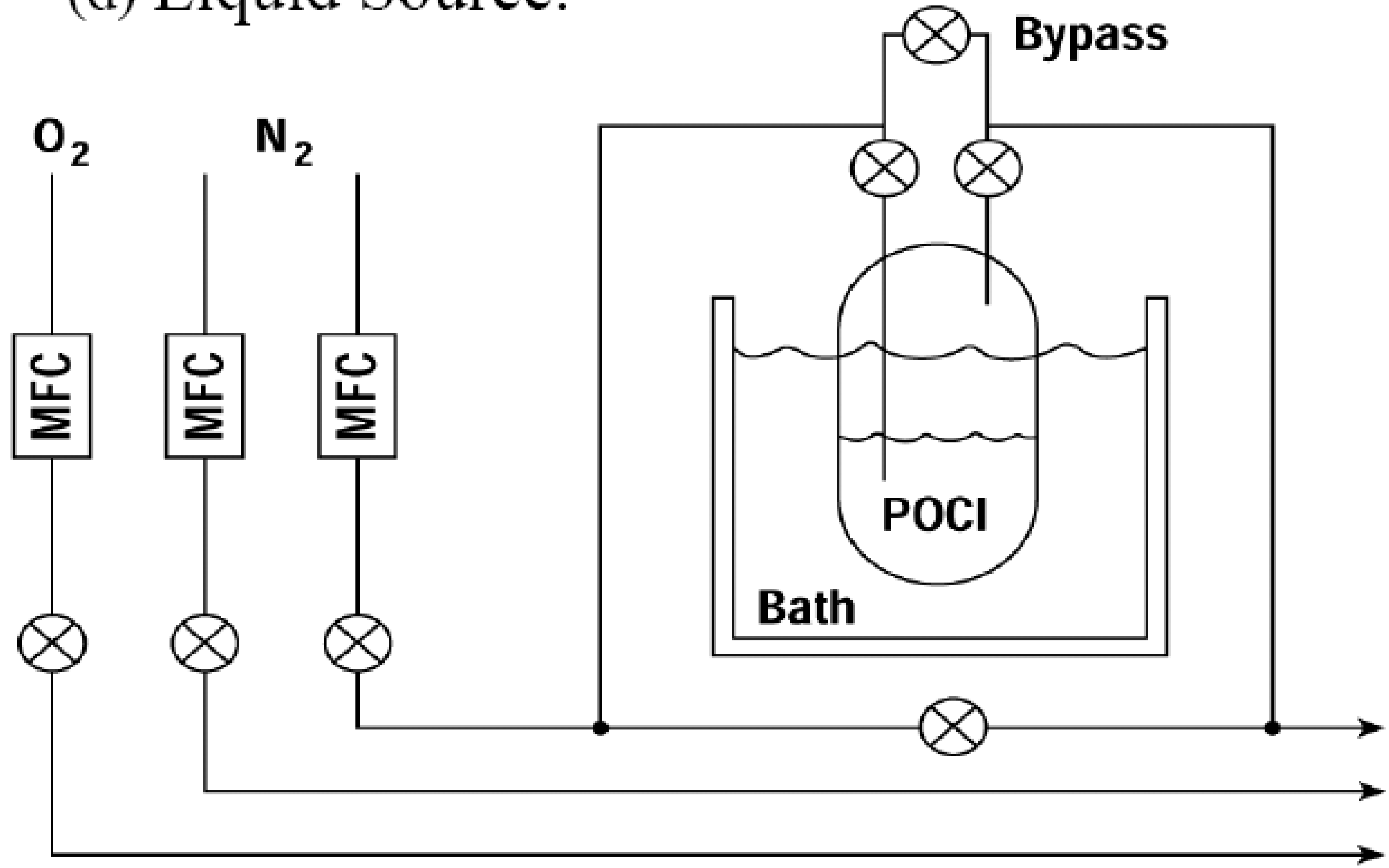
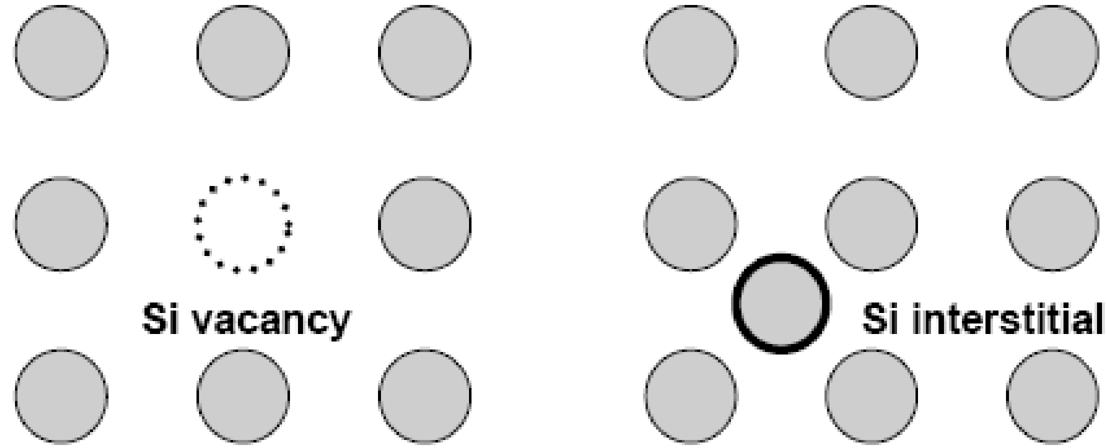


Figure 3.20 A typical bubbler arrangement for doping a silicon wafer using a POCl source. The gas flow is set using mass flow controllers (MFC).

Si Native Point Defects



For reference only

1) Thermal-equilibrium values of Si *neutral* interstitials and vacancies at diffusion temperatures
<< doping concentration of interest
($10^{15} - 10^{20}$ /cm^3)

$$C^*_{I^0} \cong 1 \times 10^{27} \exp\left(\frac{-3.8\ \text{eV}}{kT}\right)$$

$$C^*_{V^0} \cong 9 \times 10^{23} \exp\left(\frac{-2.6\ \text{eV}}{kT}\right)$$

At 1000°C, $C_{I_o}^* \sim 10^{12}$ /cm3
$C_{V_o}^* \sim 10^{13}$ /cm3

2) Diffusivity of Si interstitials and Si vacancies >>
diffusivity of dopants

$$d_I = 1.58 \times 10^{-1} \exp\left(-\frac{1.37}{kT}\right) \text{cm}^2 \sec^{-1}$$

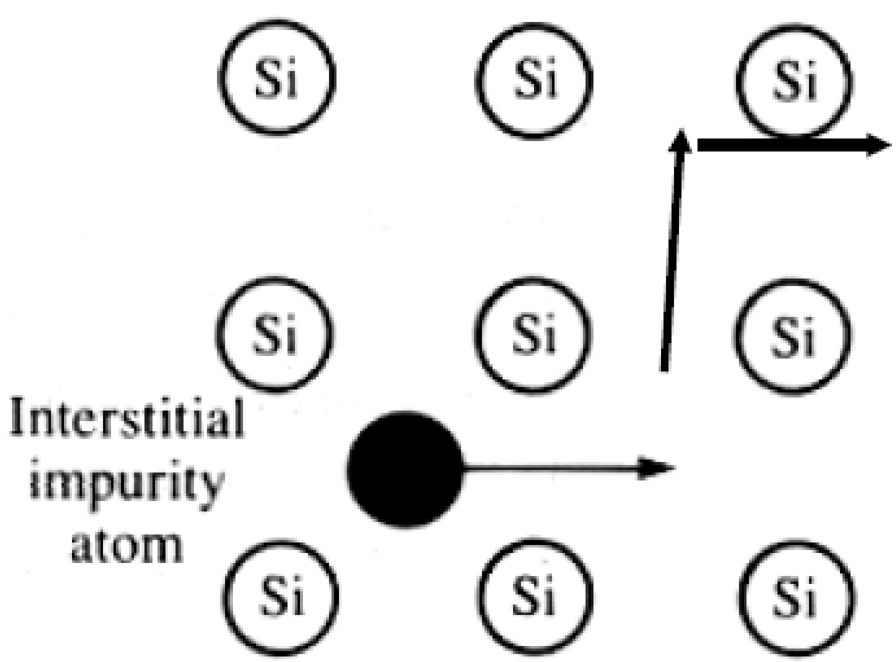
$$d_V = 1.18 \times 10^{-4} \exp\left(-\frac{0.1}{kT}\right) \text{cm}^2 \sec^{-1}$$

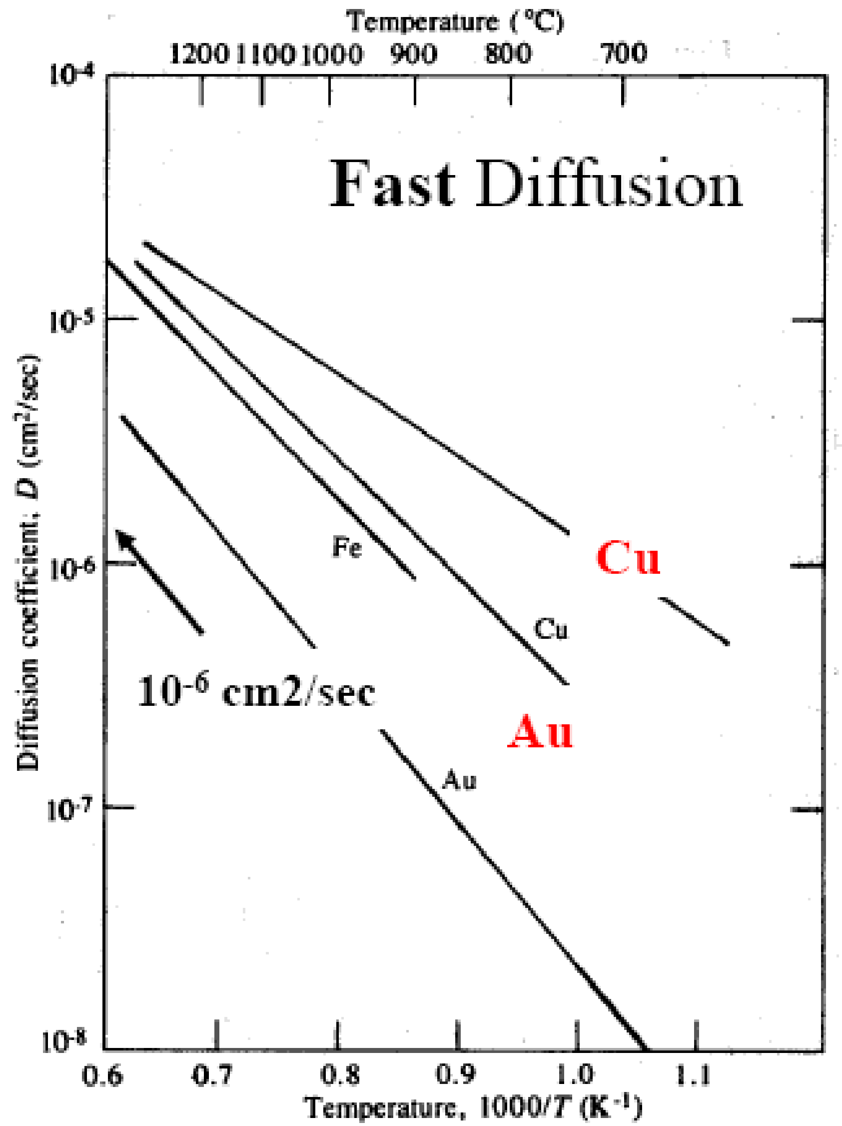
Diffusion Mechanisms in Si

(A) No Si Native Point Defect Required

Example: Cu, Fe, Li, H

(a) Interstitial Diffusion



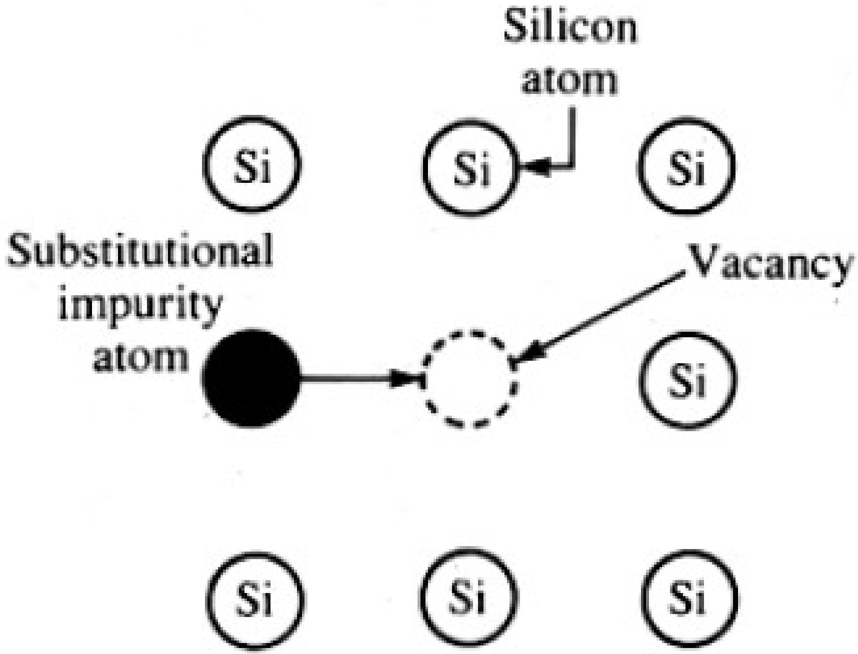


Diffusion Mechanisms in Si

(B) Si Native Point Defects Required (Si vacancy and Si interstitials)

Example: Dopants in Si (e.g. B, P,As,Sb)

(a) Substitutional Diffusion



(b) Interstitialcy Diffusion

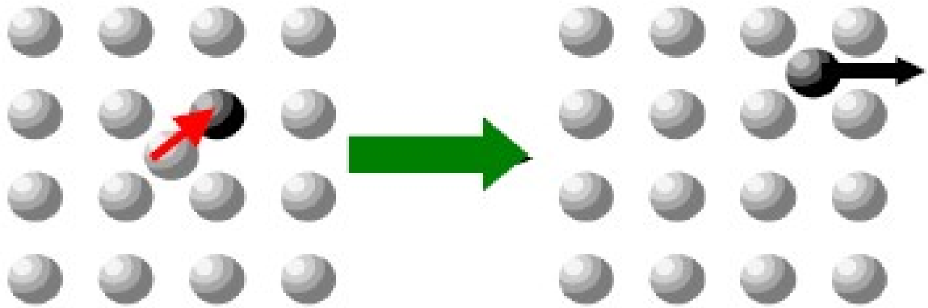


Figure 3.5 In interstitialcy diffusion an interstitial silicon atom displaces a substitutional impurity, driving it to an interstitial site where it diffuses some distance before it returns to a substitutional site.

(B) Si Native Point Defects Required (Si vacancy and Si interstitials) continued

(c) Kick-Out Diffusion
(d) Frank Turnbull Diffusion

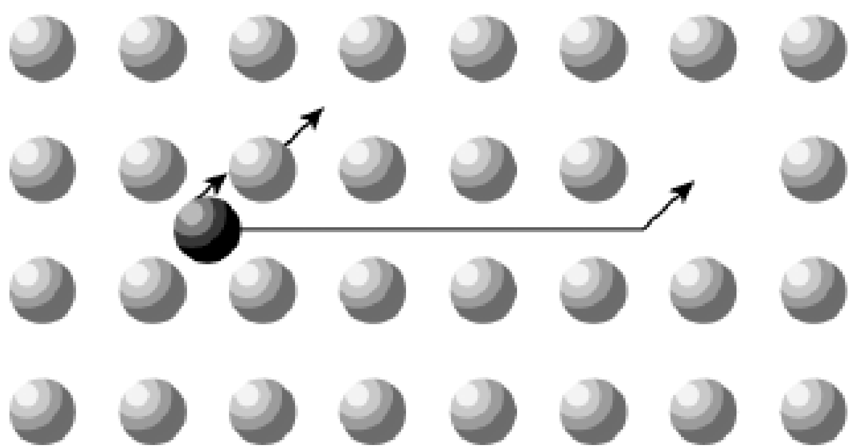
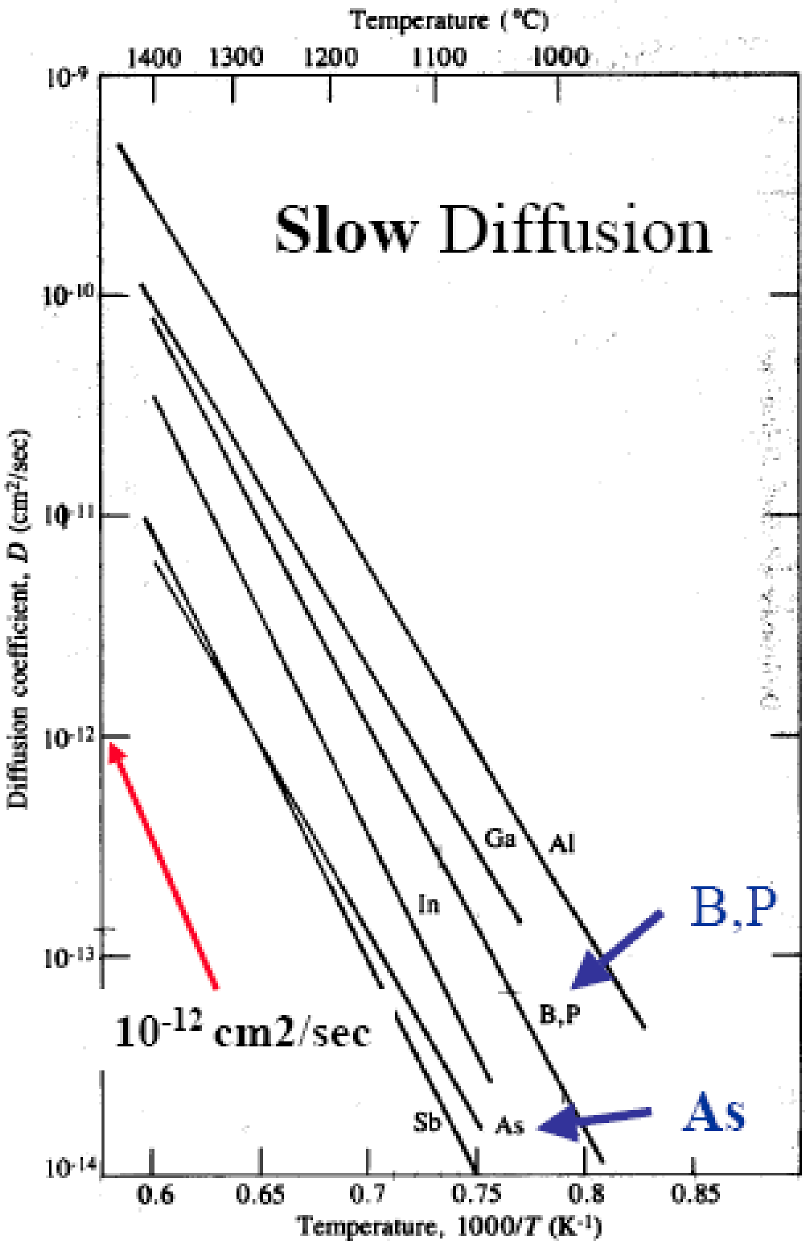
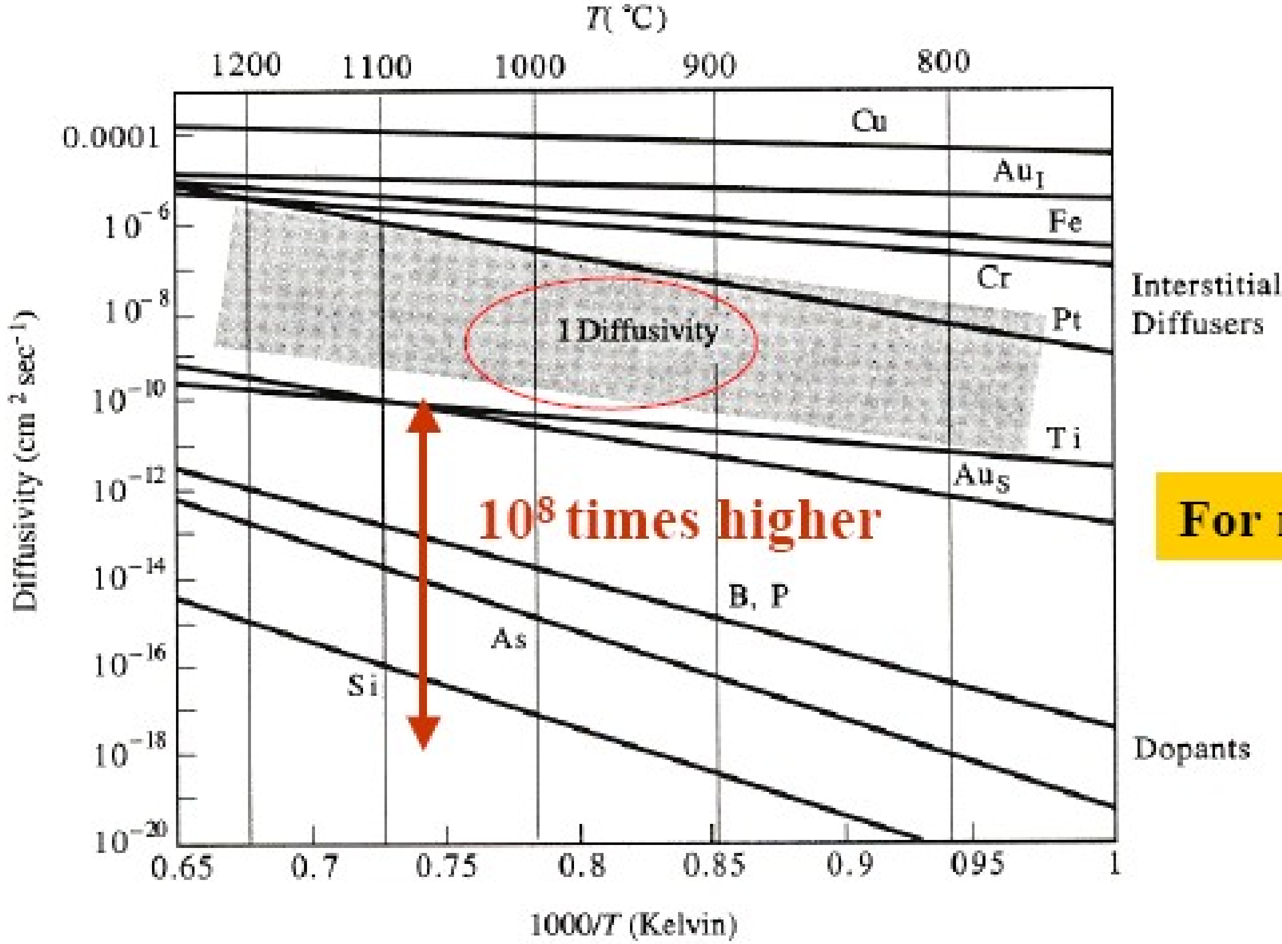


Figure 3.6 The kick-out (left) and Frank–Turnbull mechanisms (right).



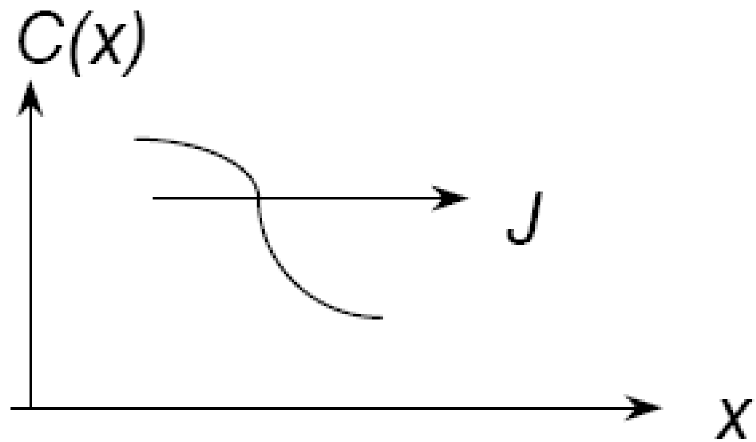
Diffusivity Comparison:
Dopants, Si interstitial, and interstitial diffusers



For reference only

Figure 4–8 Diffusivities of various species in silicon. Au_s refers to gold in substitutional form (on a lattice site); Au_I to gold in an interstitial site. The silicon interstitial (I) diffusivity is also shown and will be discussed later. The gray area representing the I diffusivity indicates the uncertainty in this parameter. (After [4.10, 4.11].)

Mathematics of Diffusion



Fick's First Law:

$$J(x,t) = -D \cdot \frac{\partial C(x,t)}{\partial x}$$

$$D : \textit{diffusion} \quad \textit{constant}$$

$$[D] = cm^2 / \sec$$

Concentration independence of D

If D is independent of C
(i.e., D is independent of x).

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2}$$

Concentration Independent Diffusion Equation

State of the art devices use fairly high concentrations, causing variable diffusivity and other significant side-effects (transient-enhanced diffusion, for example.)

Solid Solubility of Common Impurities in Si

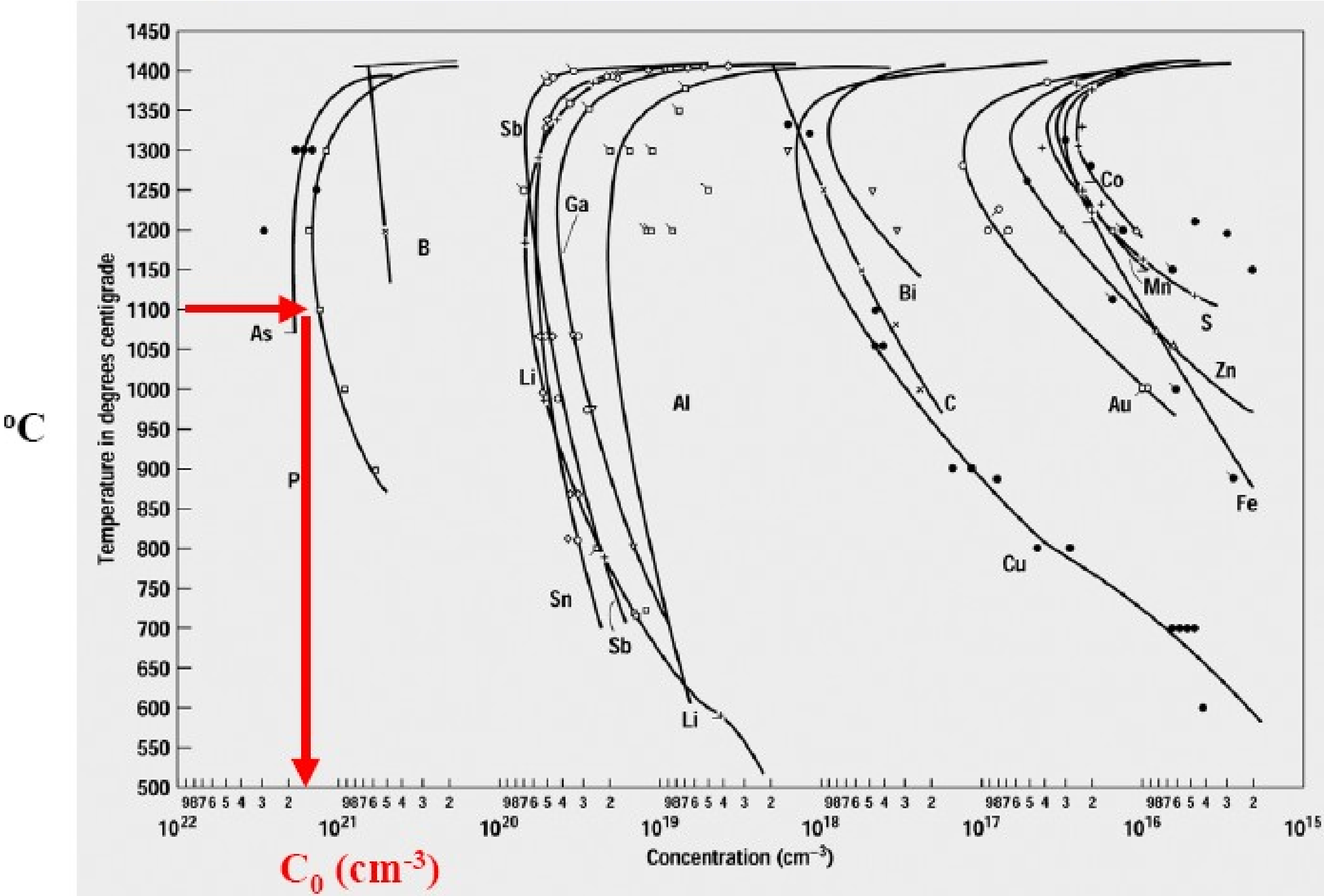


Figure 2.4 Solid solubility of common silicon impurities *(all rights reserved, reprinted with permission, © 1960 AT & T).*

A. Predeposition Diffusion Profile

- *Boundary Conditions:*

$$C(x=0,t) = C_0 = \textit{solid solubility of the dopant}$$

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

Justification:
Si wafers are ~500um thick, doping depths of interest are typically < several um

- *Initial Condition:*

$$C(x,t=0) = 0$$

At time =0, there is no diffused dopant in substrate

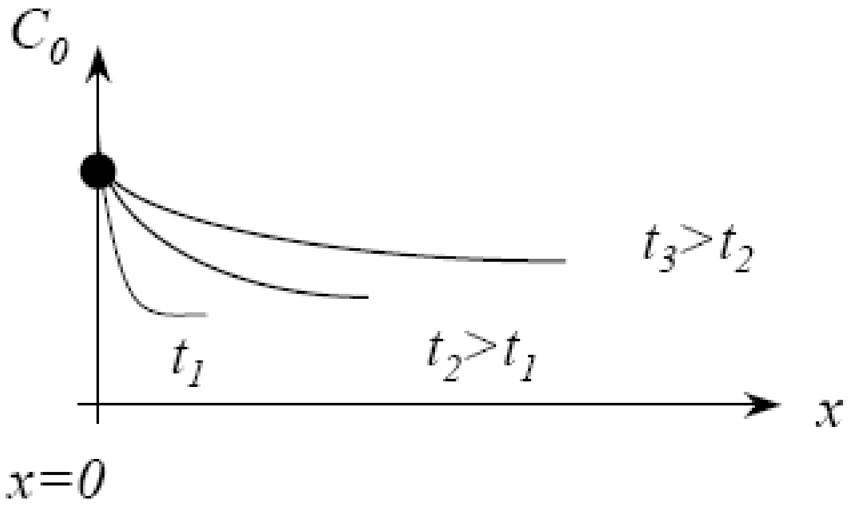
Diffusion under constant surface concentration

$$C(x,t) = C_0 \cdot \left[1 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{Dt}}} e^{-y^2} dy \right]$$

$$= C_0 \cdot erfc\left(\frac{x}{2\sqrt{Dt}} \right)$$

$2\sqrt{Dt}$ = Characteristic distance for diffusion.

$C_0 \equiv$ Surface Concentration (solid solubility limit)



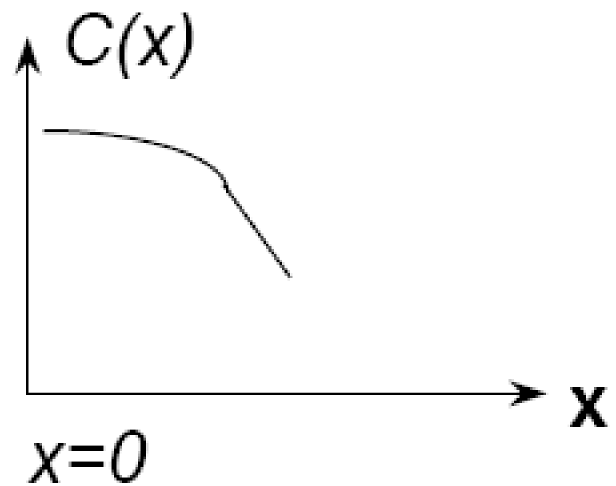
B. Drive-in Profile

- *Boundary Conditions* :

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

$$\left.\frac{\partial C}{\partial x}\right|_{x=0} = 0$$

Physical meaning of ∂C/∂t =0:
No diffusion flux in/out of the Si surface.Therefore, dopant dose is conserved



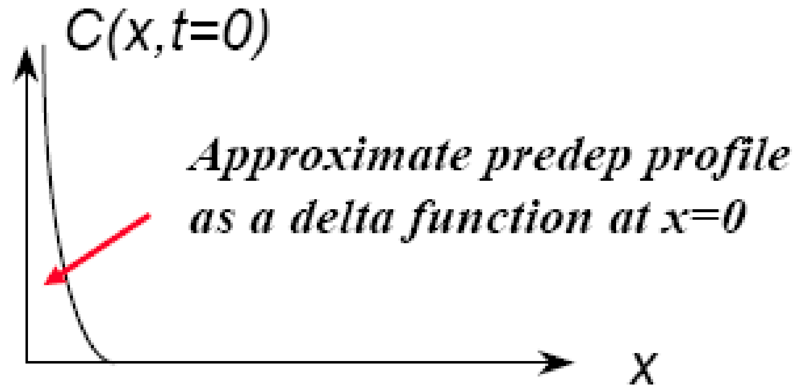
- *Initial Conditions* :

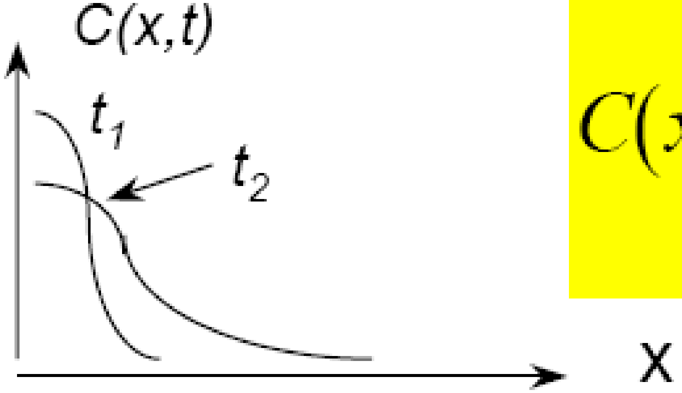
$$C(x, t=0) = Co \cdot erfc\left[\frac{x}{2\sqrt{(Dt)}}\right]$$

Predep's (Dt)

Solution of Drive-in Profile with **Shallow** Predeposition Approximation:

$$Q = \frac{C_0 \cdot 2\sqrt{(Dt)}_{predep}}{\sqrt{\pi}}$$





$$C(x,t) = \frac{Q}{\sqrt{\pi (Dt)_{drive-in}}} e^{-x^2 / 4(Dt)_{drive-in}}$$

Summary of Predeposition + Drive-in

$D_1 =$ Diffusivity at Predeposition temperature

$t_1 =$ Predeposition time

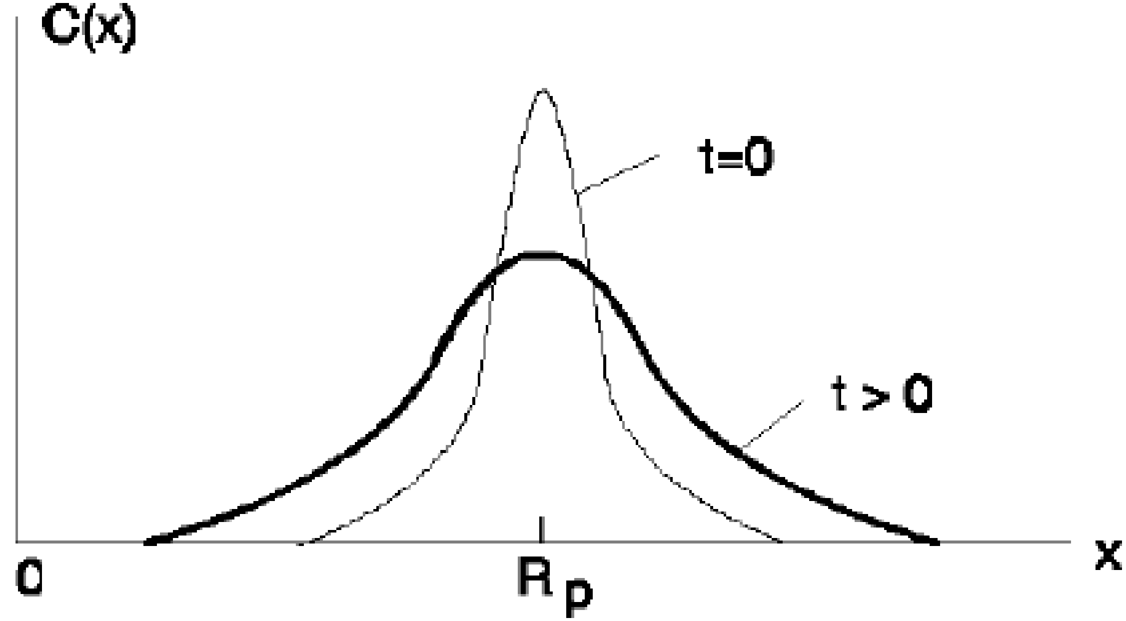
$D_2 =$ Diffusivity at Drive-in temperature

$t_2 =$ Drive-in time

$$C(x) = \left(\frac{2C_0}{\pi}\right)\left(\frac{D_1 t_1}{D_2 t_2}\right)^{1/2} e^{-x^2/4D_2 t_2}$$

*This will be the overall diffusion profile after a "shallow" predeposition diffusion step, followed by a drive-in diffusion step.

Diffusion of Gaussian Implantation Profile



$$C(x, t) = \frac{\phi}{\sqrt{2\pi}\,(\Delta R_p^2 + 2Dt)^{1/2}} \cdot e^{-\frac{(x - R_p)^2}{2\,(\Delta R_p^2 + 2Dt)}}$$

Note: ϕ is the implantation dose

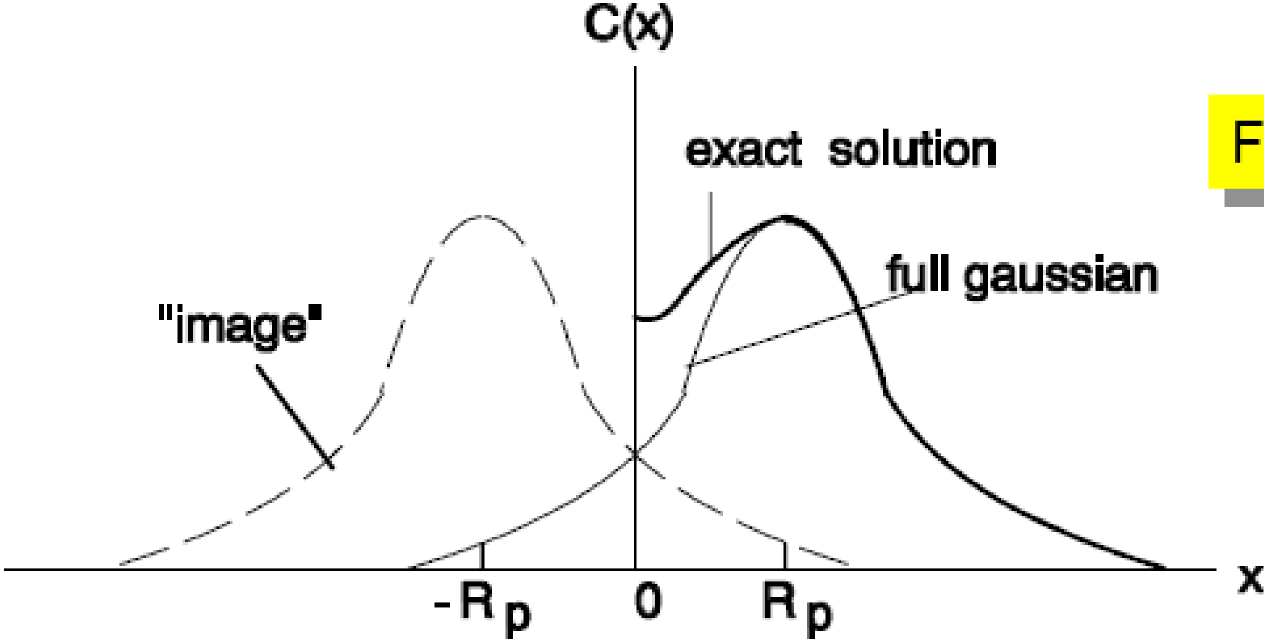
Diffusion of Gaussian Implantation Profile (arbitrary Rp)

The exact solutions with $\frac{\partial C}{\partial x} = 0$ at $x = 0$ (.i.e. no dopant loss through surface) can be constructed by adding another full gaussian placed at $-R_p$ [Method of Images].

$$C(x, t) = \frac{\phi}{\sqrt{2\pi}\,(\Delta R_p^2 + 2Dt)^{1/2}} \cdot \left[e^{-\frac{(x - R_p)^2}{2\,(\Delta R_p^2 + 2Dt)}} + e^{-\frac{(x + R_p)^2}{2\,(\Delta R_p^2 + 2Dt)}} \right]$$

We can see that in the limit $(Dt)^{1/2} \gg R_p$ and ΔR_p ,

$$C(x,t) \rightarrow \frac{\phi e^{-x^2/4Dt}}{(\pi Dt)^{1/2}}$$ (the half-gaussian drive-in solution)



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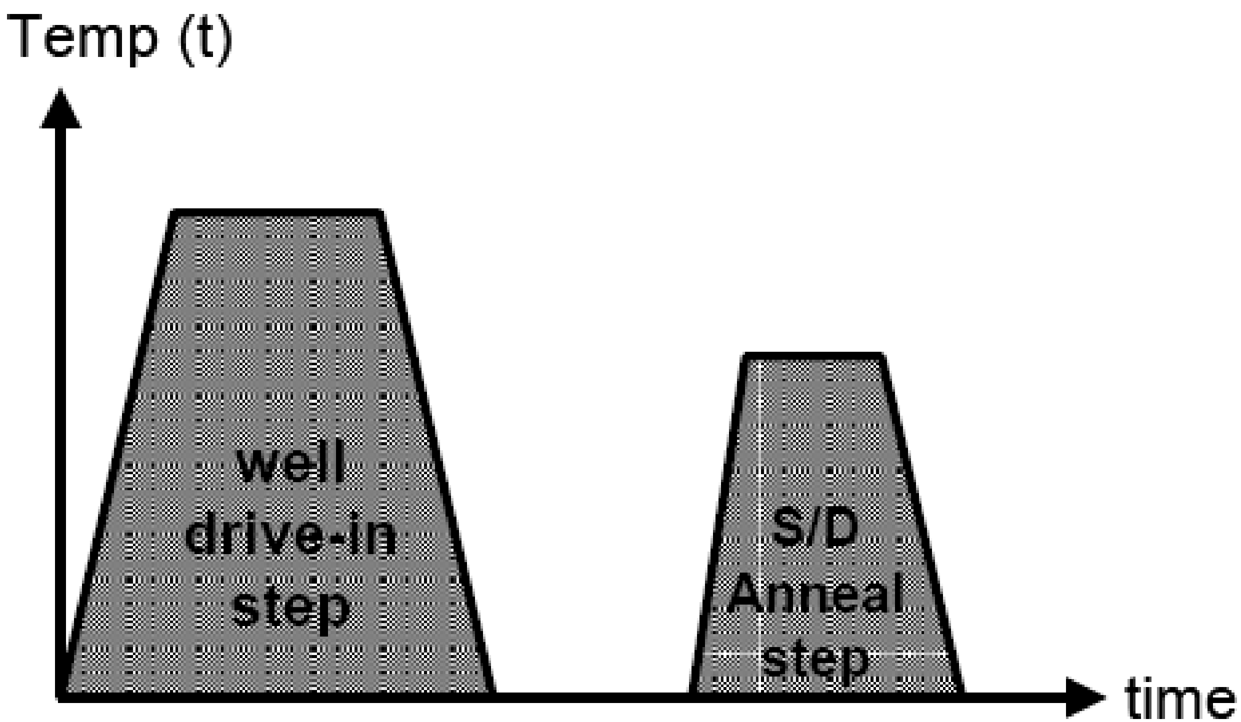
Thermal Budget

$$(Dt)_{effective} = \sum_{step\ i} (Dt)_i$$



Example

Dt_{total} of :

Well drive-in

and

S/D annealing

For a complete process flow, only those steps with high Dt values are important