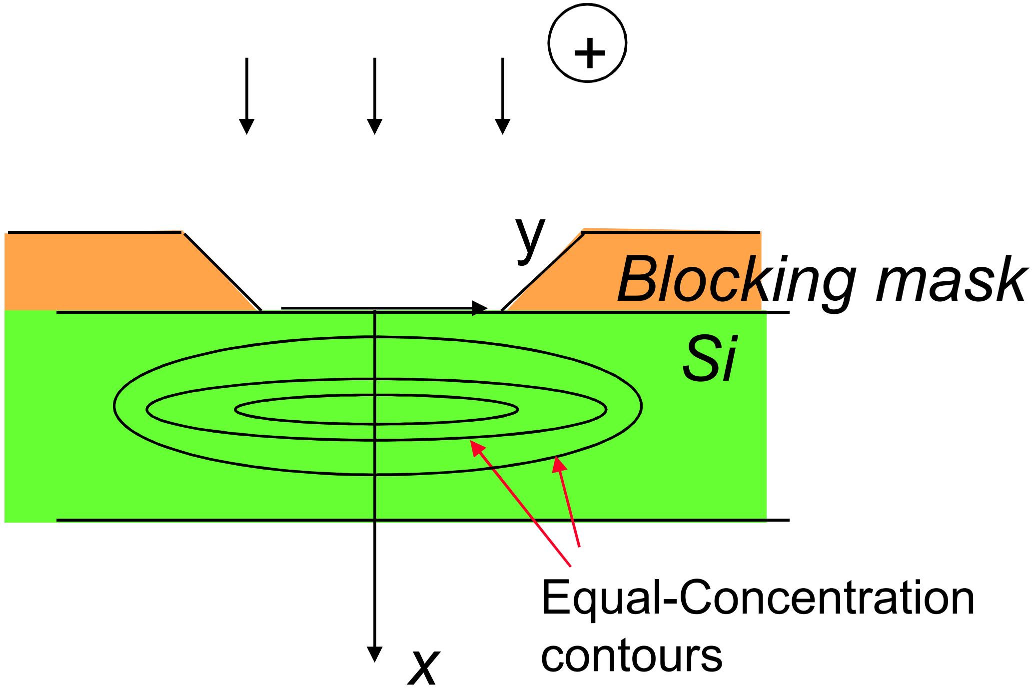
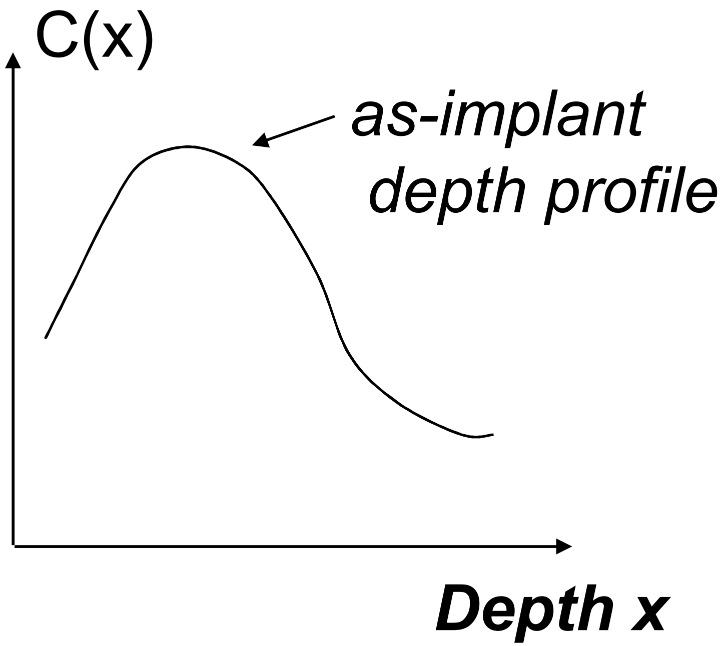
Ion Implantation





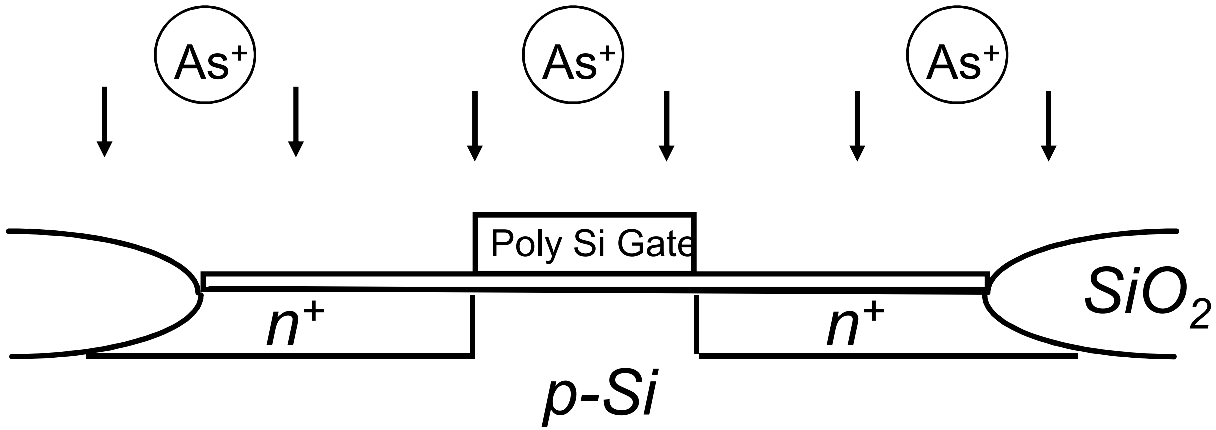
Concentration Profile versus Depth is a single-peak function

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

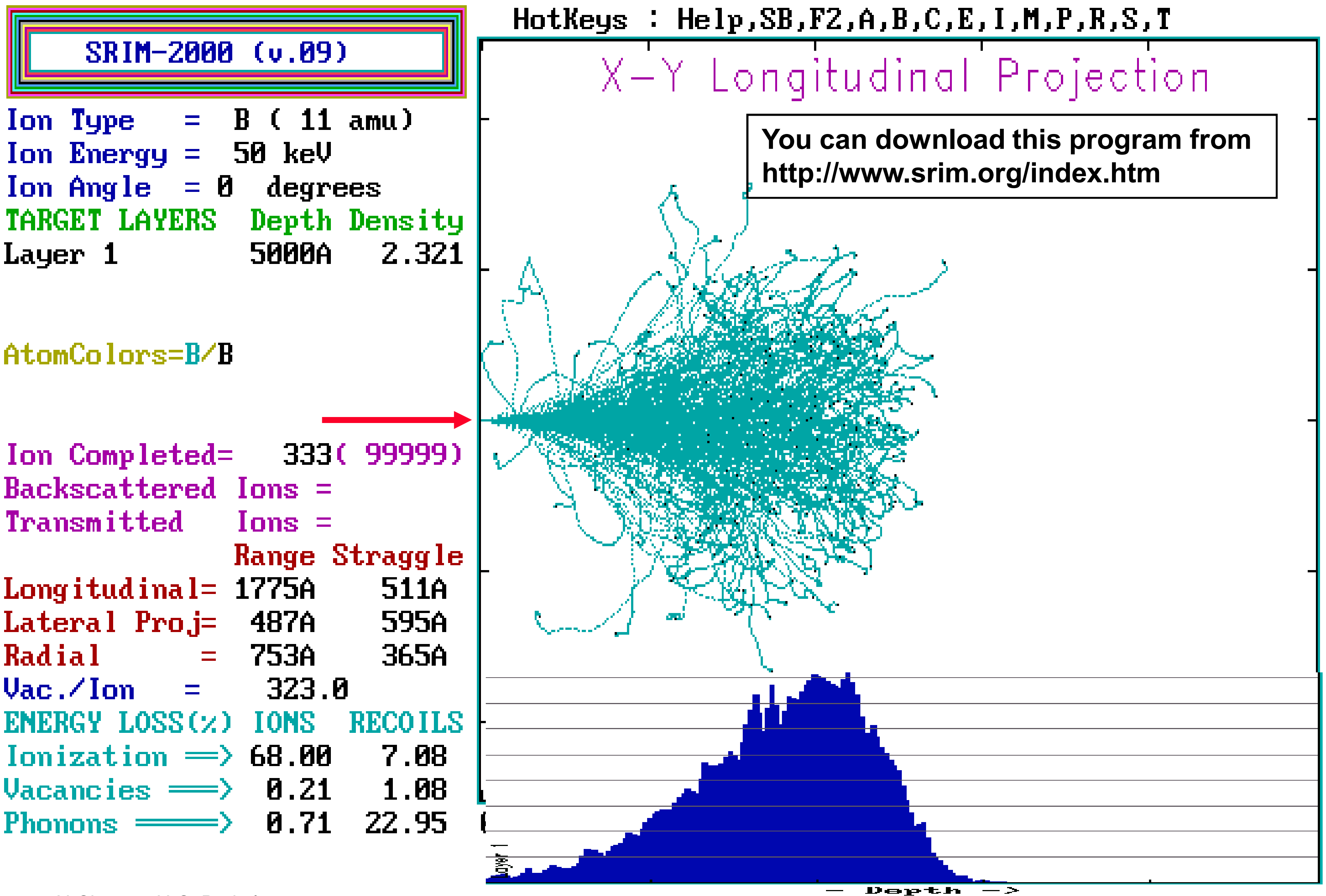
Advantages of Ion Implantation

- Precise control of <u>dose</u> and <u>depth</u> 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)

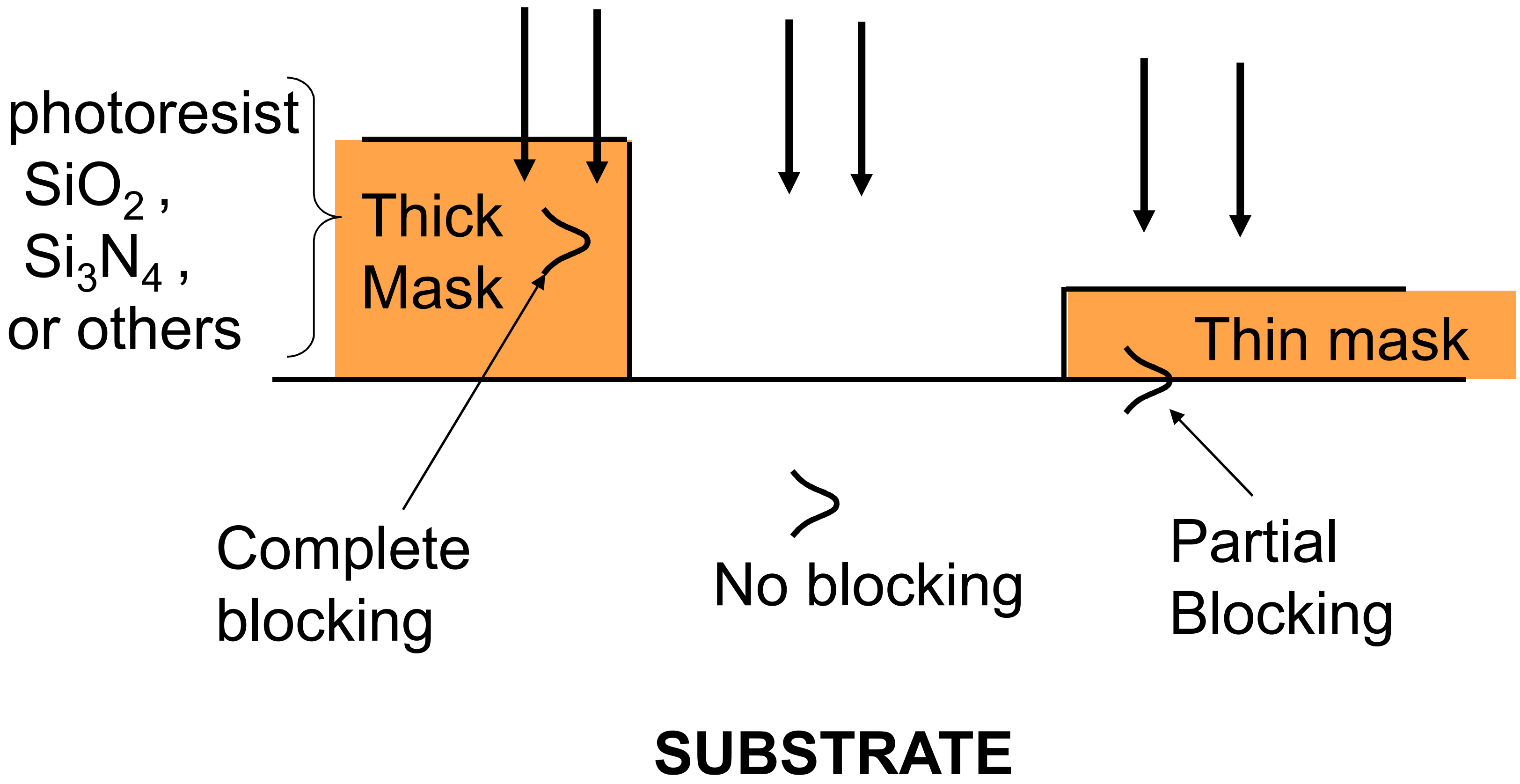
<u>Application example</u>: self-aligned MOSFET source/drain regions



Monte Carlo Simulation of 50keV Boron implanted into Si



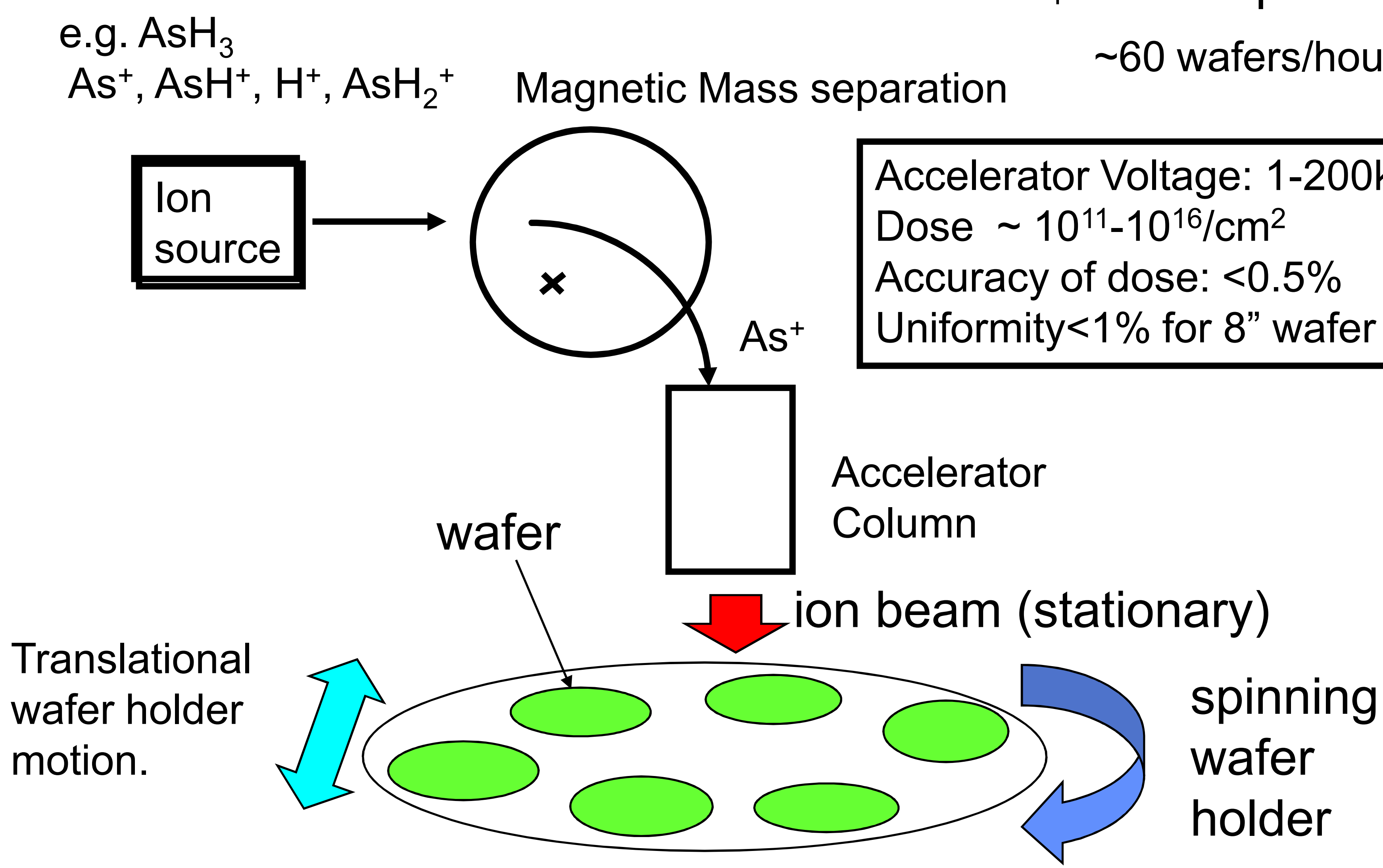
Mask layer thickness can block ion penetration



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

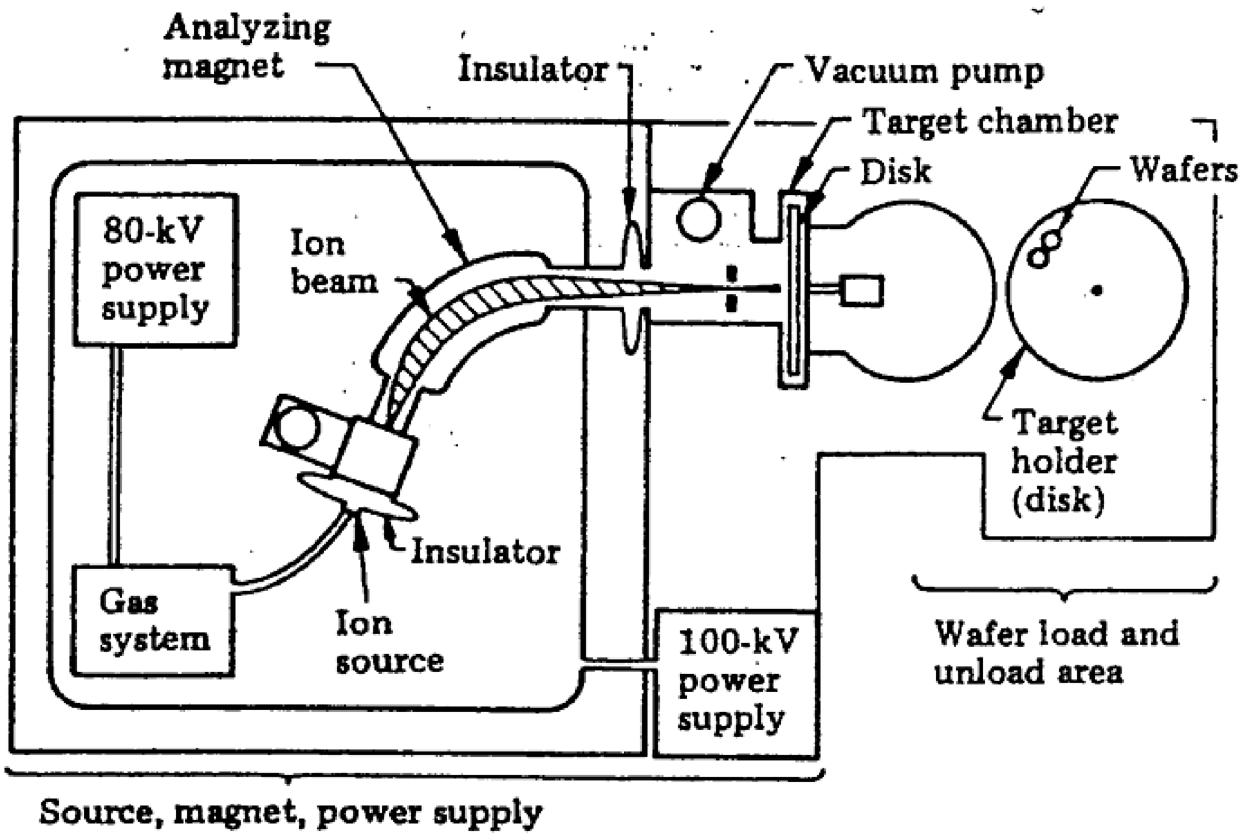
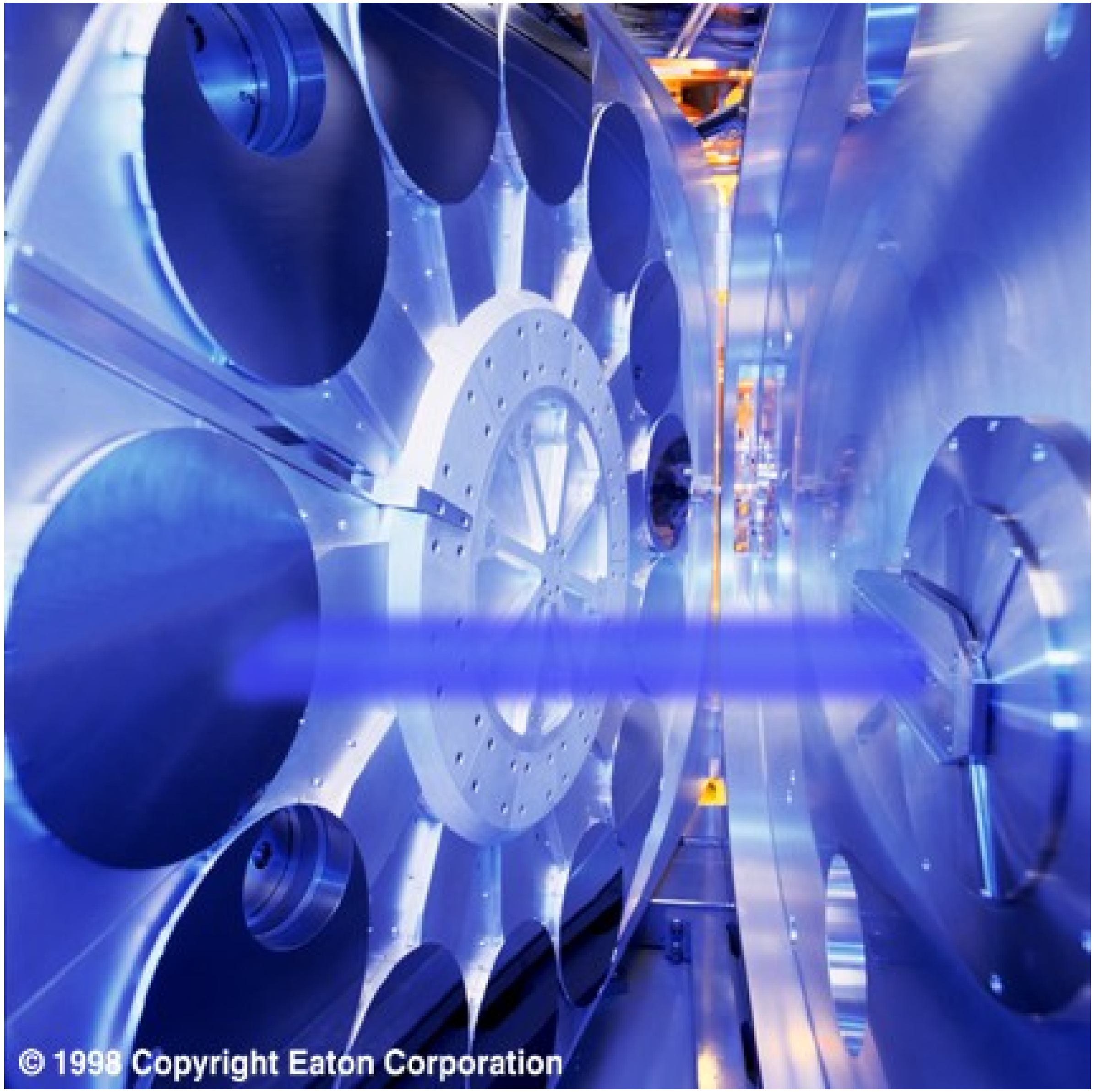


FIGURE 8.4 Schematic of a commercial ion-implantation system, the Nova-10-160, 10 mA at 160 keV.

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

Eaton HE3 High Energy Implanter, showing the ion beam hitting the 300mm wafer end-station.



Implantation Dose

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

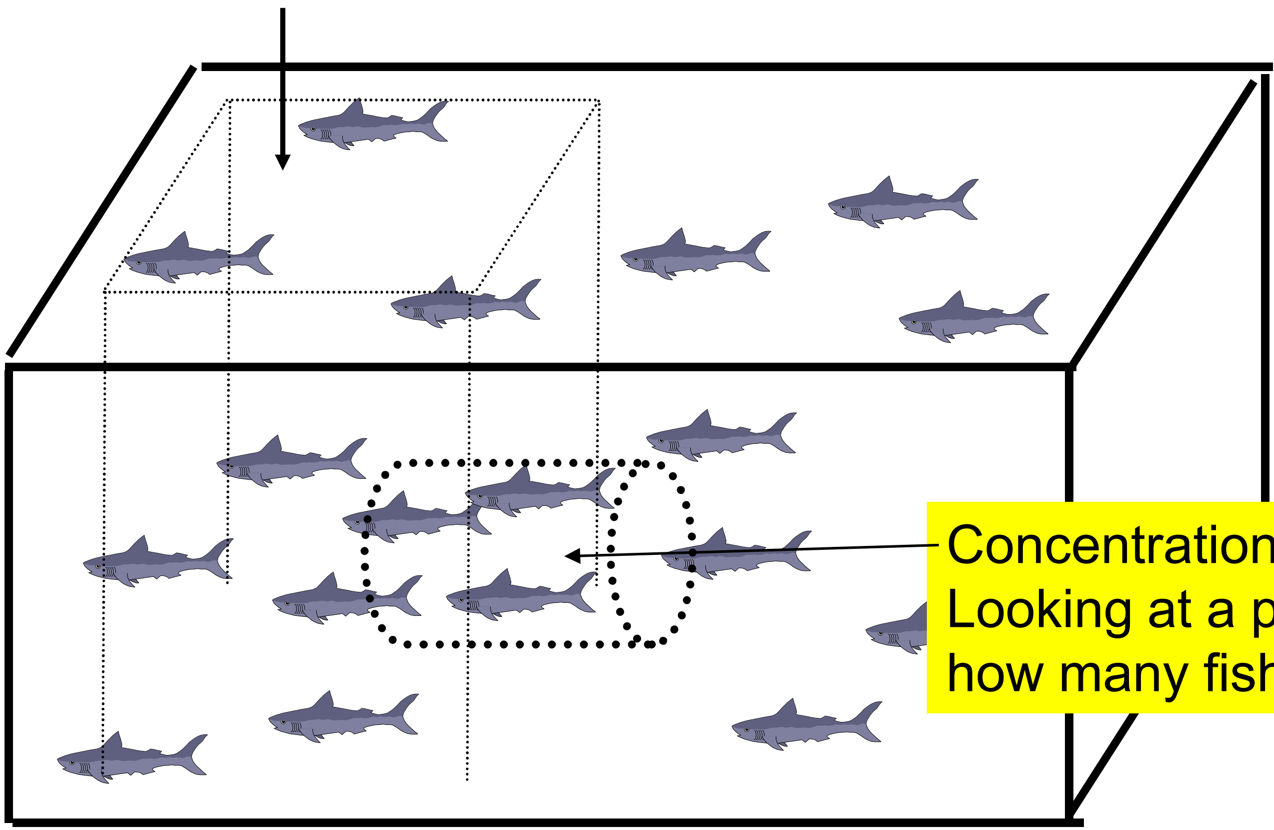
$$\text{Dose } \Phi = \frac{\left(\frac{\text{Ion Beam Current in amps}}{q}\right) \times \left(\text{Implant time}\right)}{\left[\text{Ion Beam Scanning Area}\right]}$$

$$= \#/\text{cm}^2$$

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

Meaning of Dose and Concentration

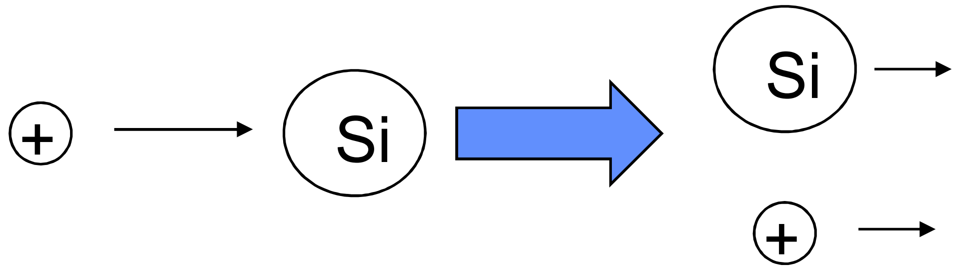
Dose [#/area] : looking downward, how many fish per unit area for ALL depths ?



Concentration [#/volume] : Looking at a particular location, how many fish per unit volume ?

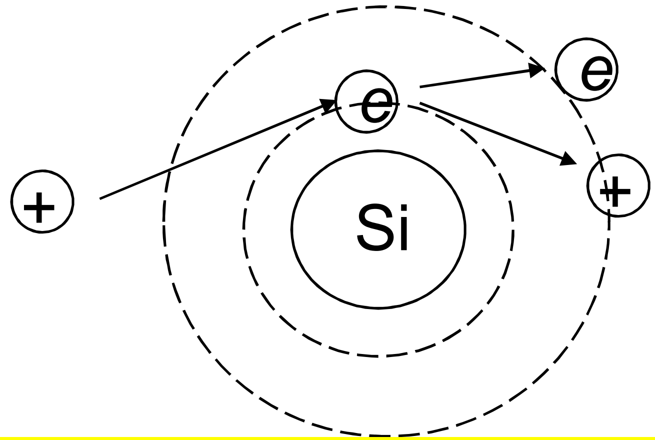
Ion Implantation Energy Loss Mechanisms

Nuclear stopping



Crystalline Si substrate damaged by collision

Electronic stopping



Electronic excitation creates heat

Ion Energy Loss Characteristics

Light ions/at higher energy → more electronic stopping

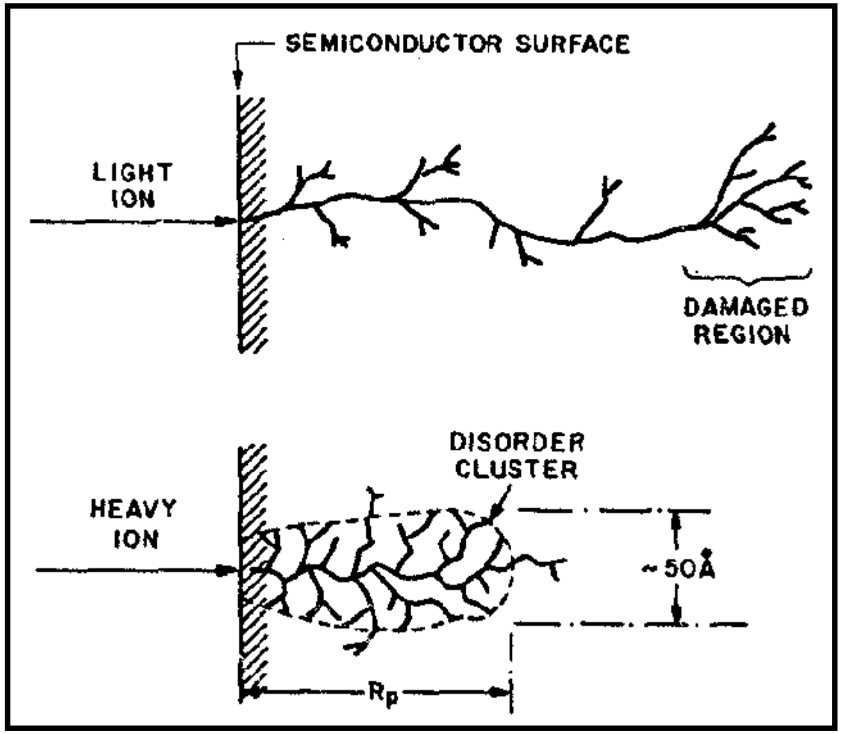
Heavier ions/at lower energy → more nuclear stopping

EXAMPLES
Implanting into Si:

H^+ ⇨ Electronic stopping dominates

B^+ ⇨ Electronic stopping dominates

As^+ ⇨ Nuclear stopping dominates



Stopping Mechanisms

- Electronic collisions dominate at high energies.
- Nuclear collisions dominate at low energies.

	E1(keV)	E2(keV)
B into Si	3	17
P into Si	17	140
As into Si	73	800

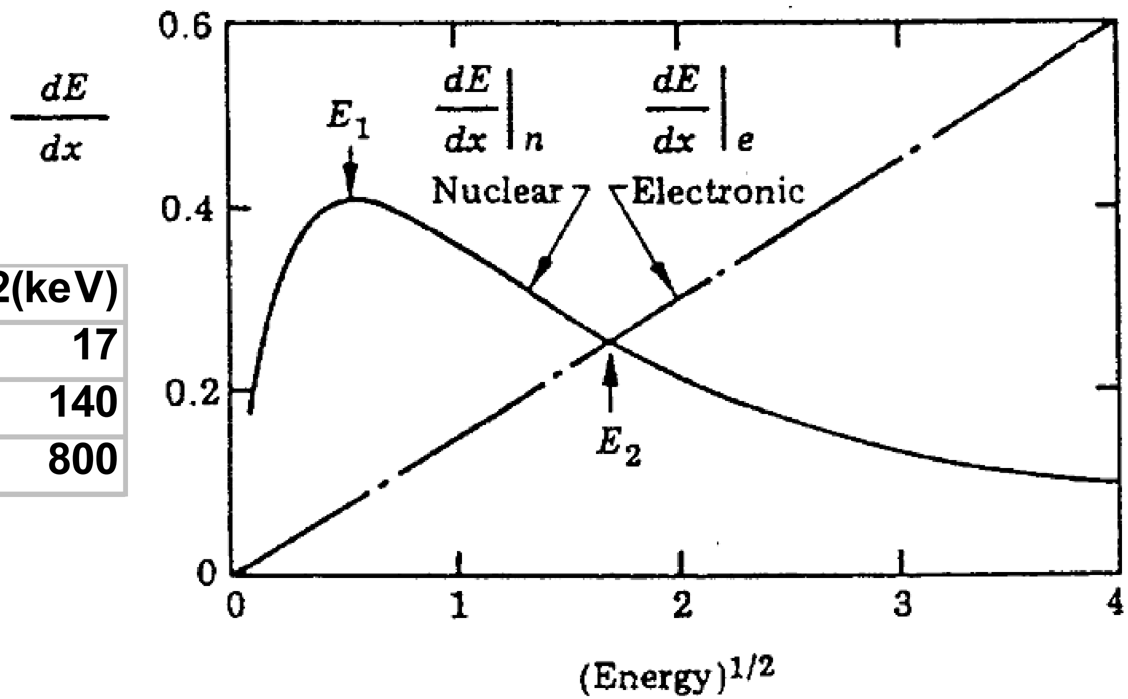
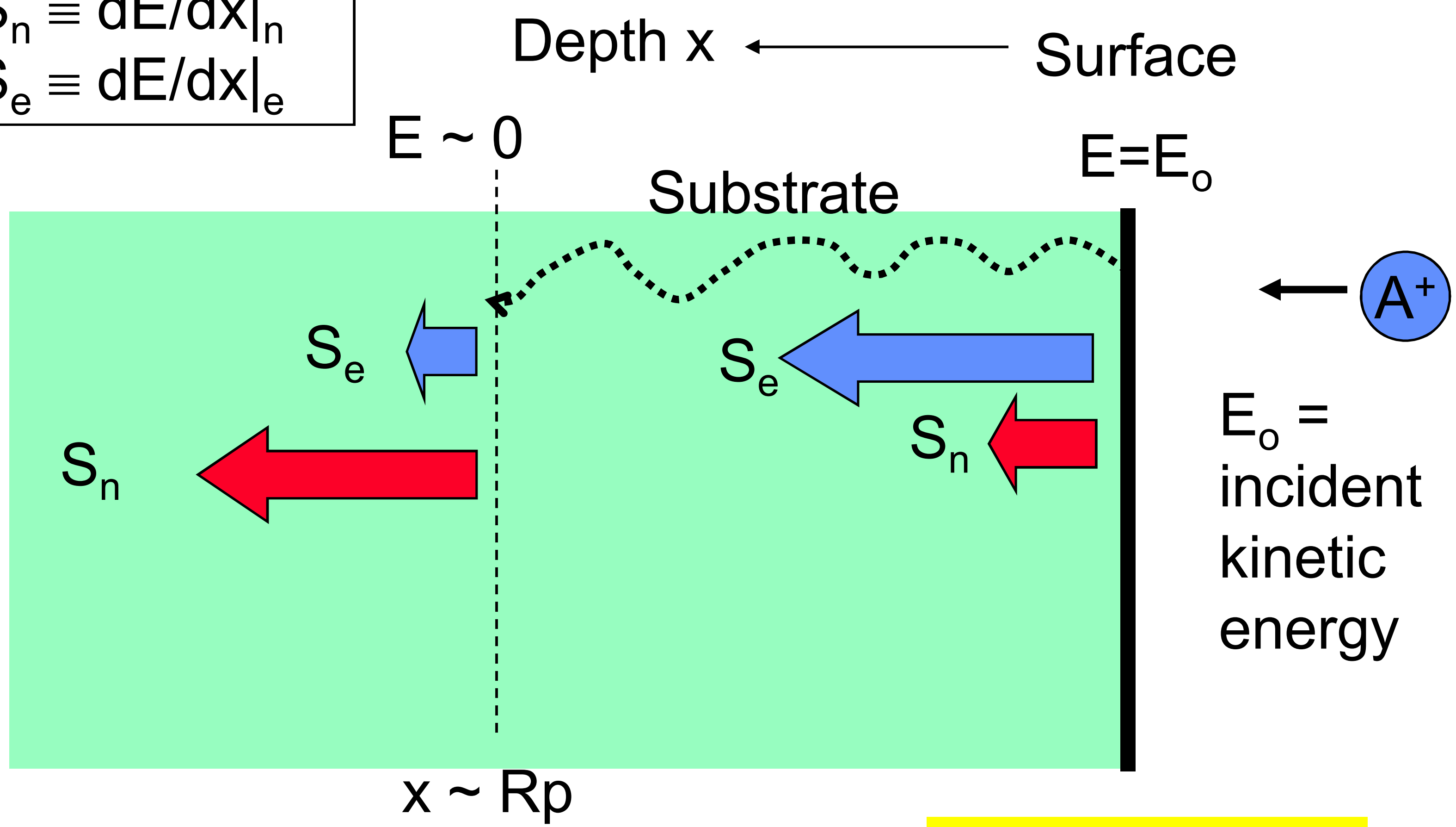


FIGURE 8.12 Rate of energy loss dE/dx versus (energy)$^{1/2}$, showing nuclear and electronic loss contributions.

$S_n \equiv dE/dx|_n$
$S_e \equiv dE/dx|_e$



More crystalline damage at end of range $S_n > S_e$

Less crystalline damage $S_e > S_n$

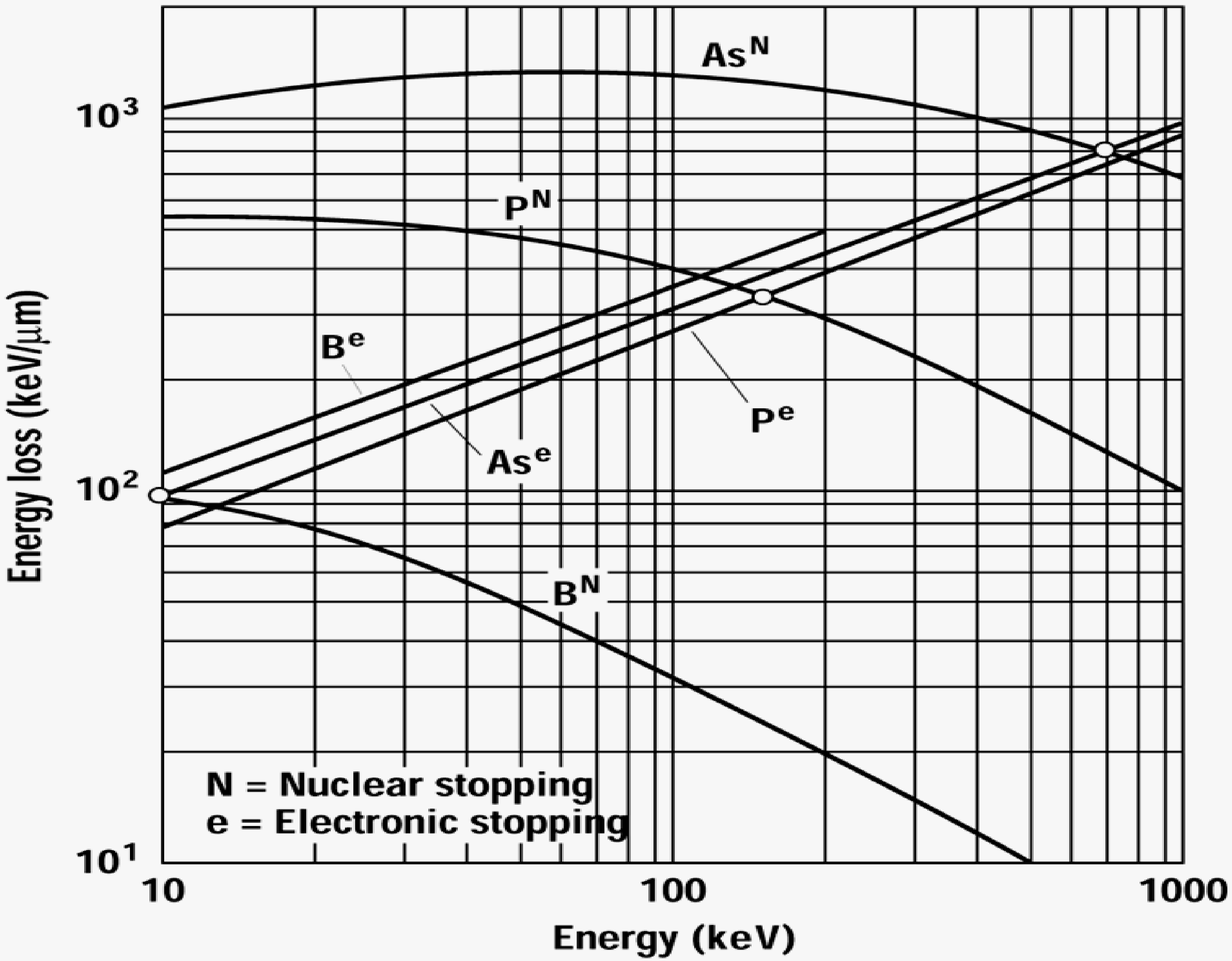
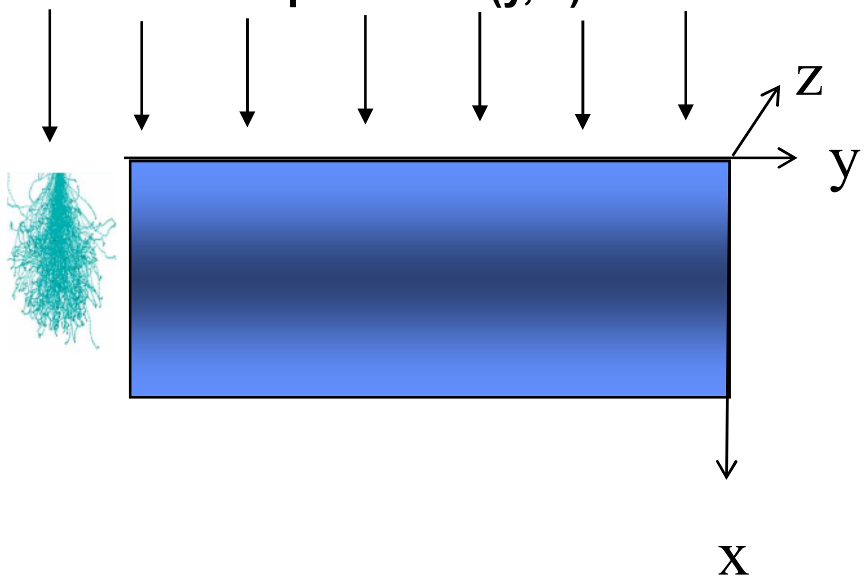
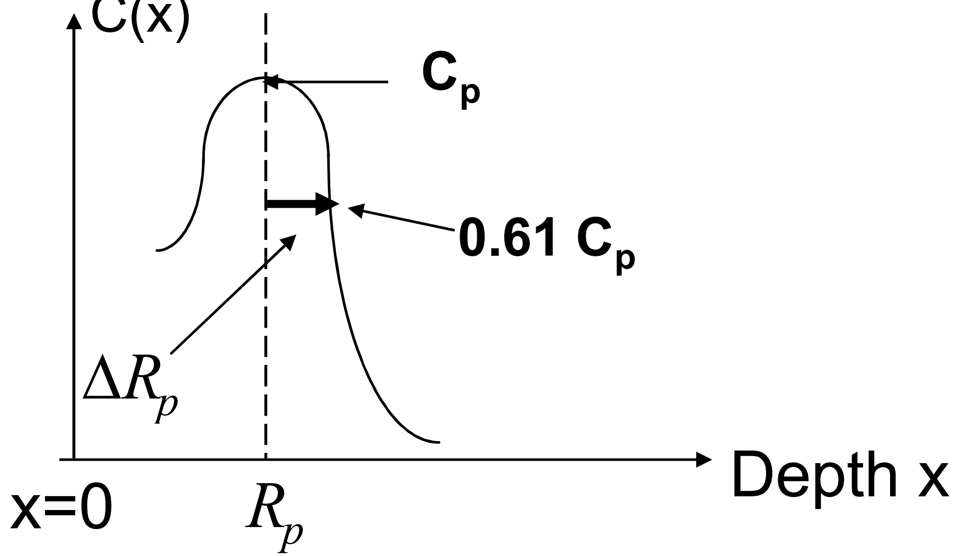


Figure 5.8 Nuclear and electronic components of $S(E)$ for several common silicon dopants as a function of energy *(after Smith as redrawn by Seidel, "Ion Implantation," reproduced by permission, McGraw-Hill, 1983).*

Gaussian Approximation of One-Dimensional Depth Profile

Superposition of implantation at all lateral positions (y, z)





Concentration $C(x,y,z) = C(x)$ and is independent of lateral position (y,z)

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

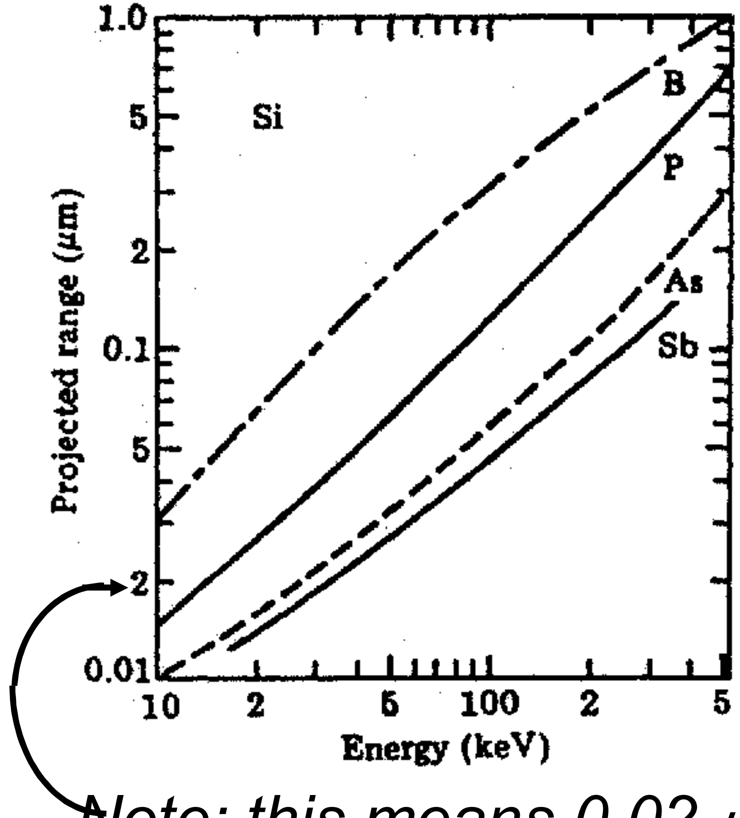
R_p = projected range

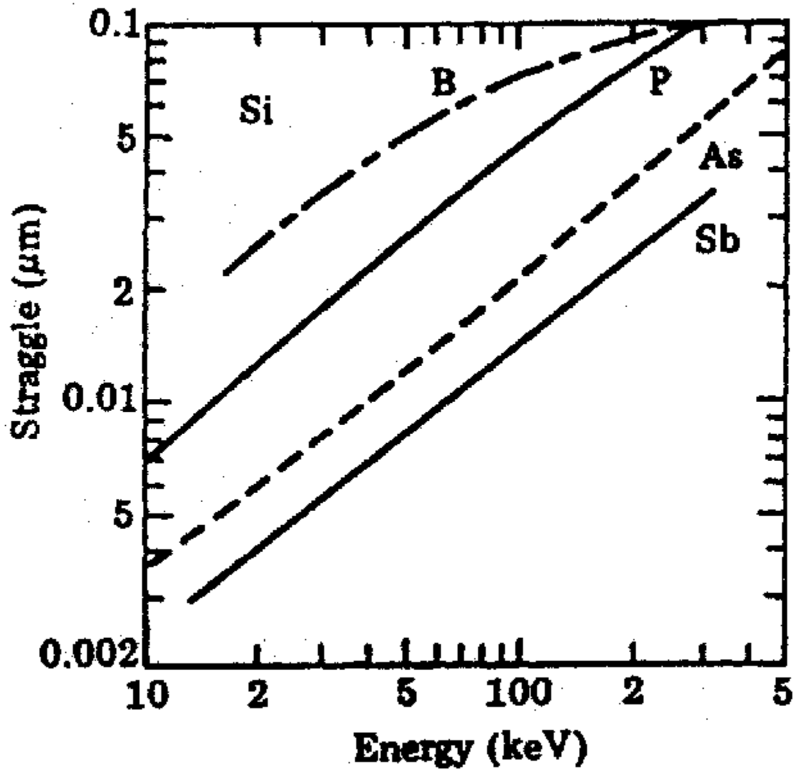
ΔR_p = longitudinal straggle

Projected Range and Straggle

Rp and ΔRp values are given in tables or charts

e.g. see pp. 113 of Jaeger





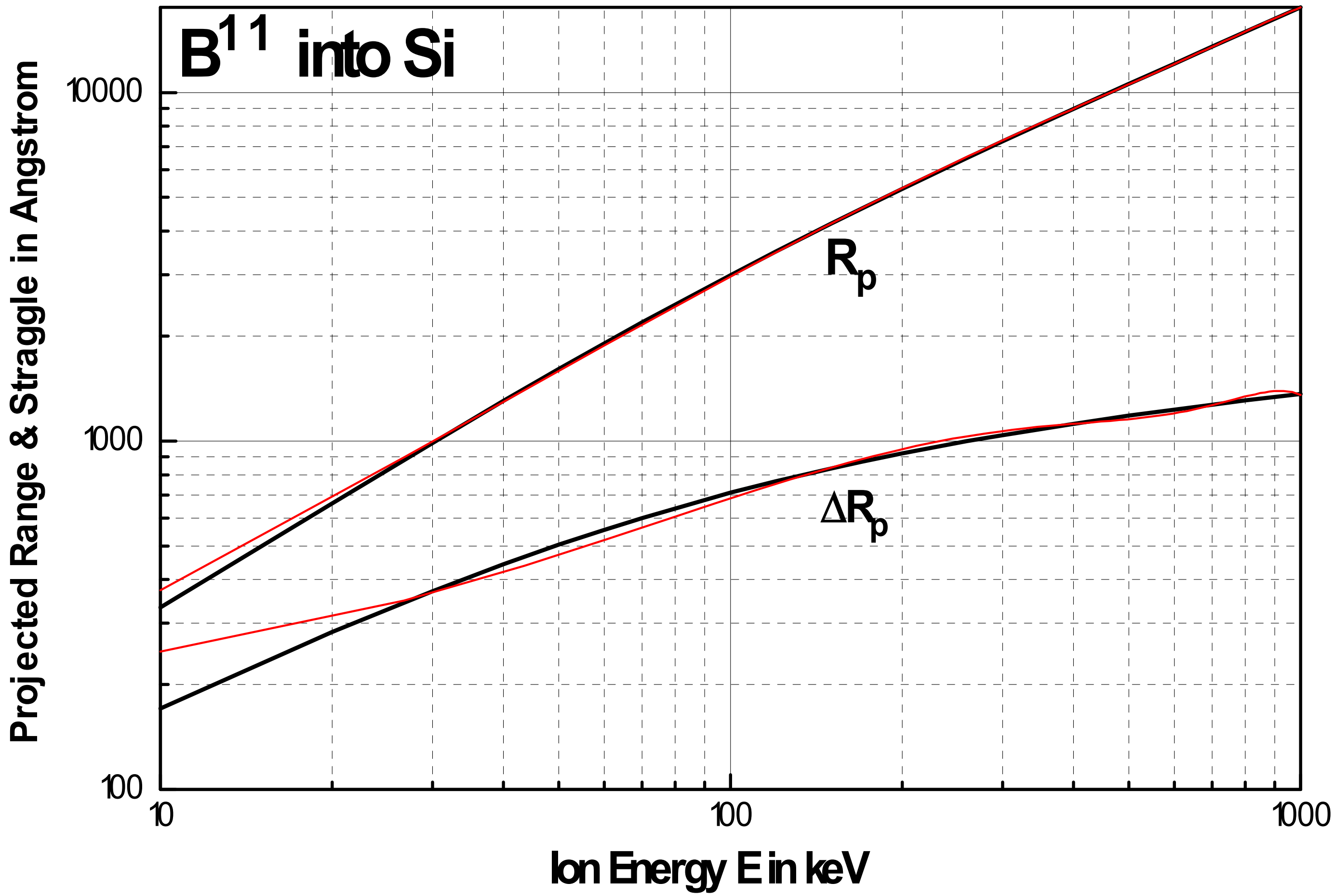
Note: this means 0.02 μm.

Rp and ΔRp values from Monte Carlo simulation

[see 143 Reader for other ions]

$$R_p = 51.051 + 32.60883\,E - 0.03837\,E^2 + 3.758e\text{-}5\,E^3 - 1.433e\text{-}8\,E^4$$

$$\Delta R_p = 185.34201 + 6.5308\,E - 0.01745\,E^2 + 2.098e\text{-}5\,E^3 - 8.884e\text{-}9\,E^4$$



(both theoretical & expt values are well known for Si substrate)

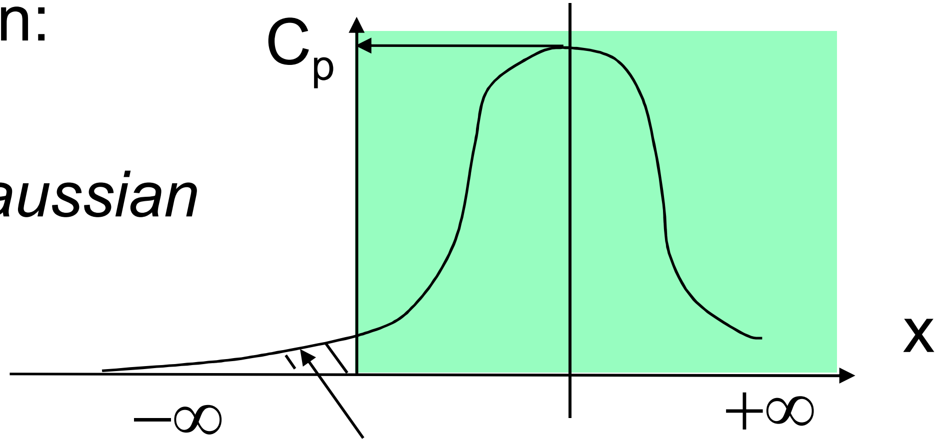
Dose-Concentration Relationship

Using Gaussian Approximation:

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

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

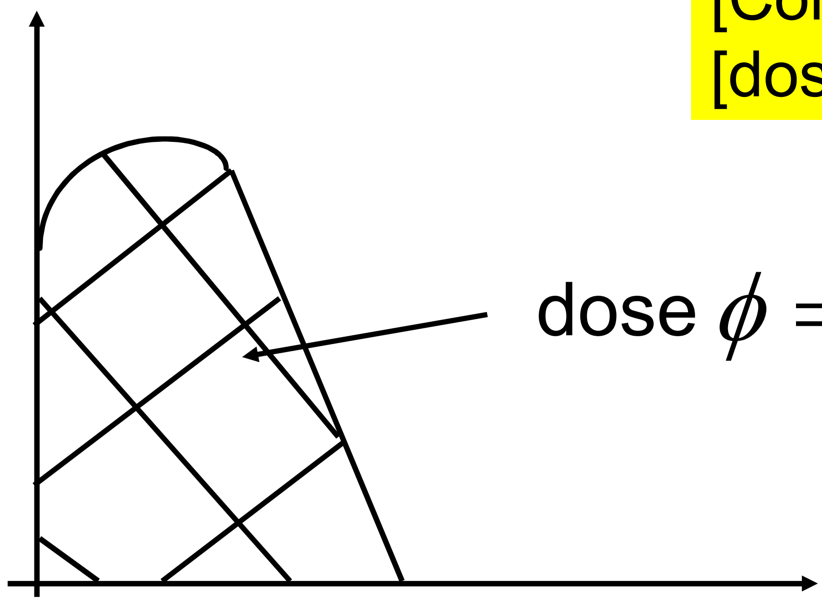
$$= C_p \cdot \left[\sqrt{2\pi} \cdot \Delta R_p\right]$$



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

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

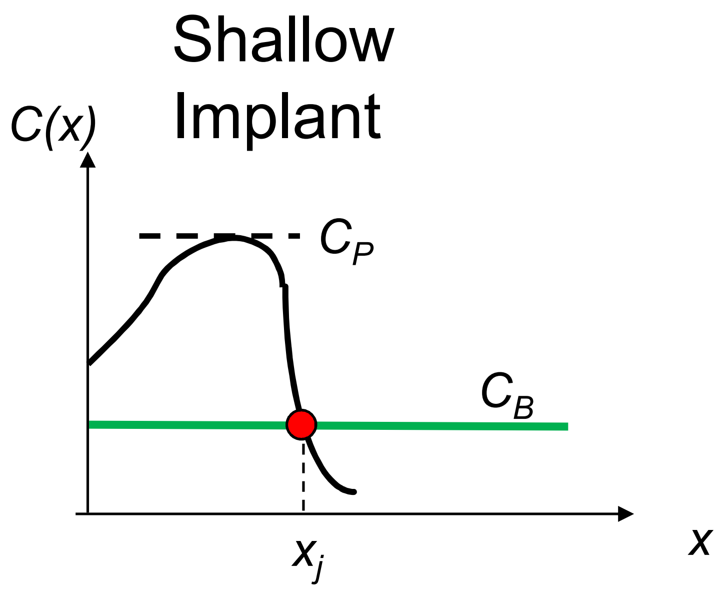
(2) Height (i.e. Concentration) of profile depends on the implantation dose

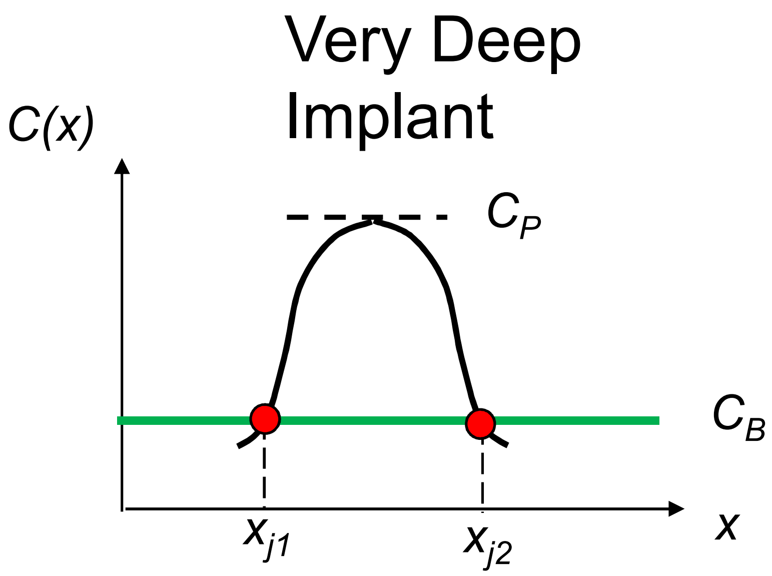


[Conc] = # of atoms/**cm^3**
[dose] = # of atoms/**cm^2**

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

Junction Depth, x_j





$C(x = x_j) = C_B$ = *Substrate Bulk Concentration*

If Gaussian approx for C(x) is used :

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

We can solve for x_j .

Definitions of Profile Parameters

For reference only

(1) **Dose** $\phi = \int_0^\infty C(x)dx$

(2) **Projected Range**: $R_p \equiv \frac{1}{\phi}\int_0^\infty x \cdot C(x)dx$

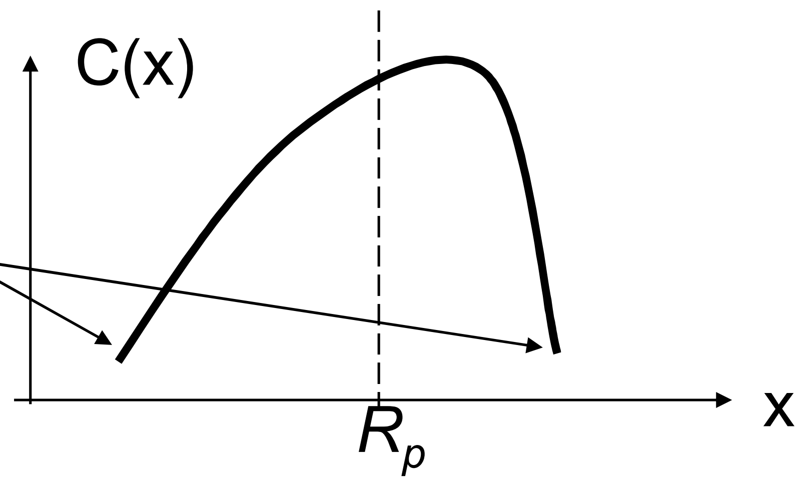
(3) **Longitudinal Straggle**: $(\Delta R_p)^2 \equiv \frac{1}{\phi}\int_0^\infty (x - R_p)^2 \cdot C(x)dx$

(4) **Skewness**: $M_3 \equiv \frac{1}{\phi}\int_0^\infty (x - R_p)^3 C(x)dx$ $\quad M_3 > 0$ *or* < 0

-describes asymmetry between left side and right side of C(x)

(5) **Kurtosis**: $\propto \int_0^\infty (x - R_p)^4 C(x)dx$

Kurtosis characterizes the contributions of the "tail" regions



Electrical Conductivity σ

When an electric field is applied, current flows due to drift of mobile electrons and holes:

electron current density: $$J_n = (-q)nv_n = qn\mu_n E$$

hole current density: $$J_p = (+q)pv_p = qp\mu_p E$$

total current density: $$J = J_n + J_p = (qn\mu_n + qp\mu_p)E$$

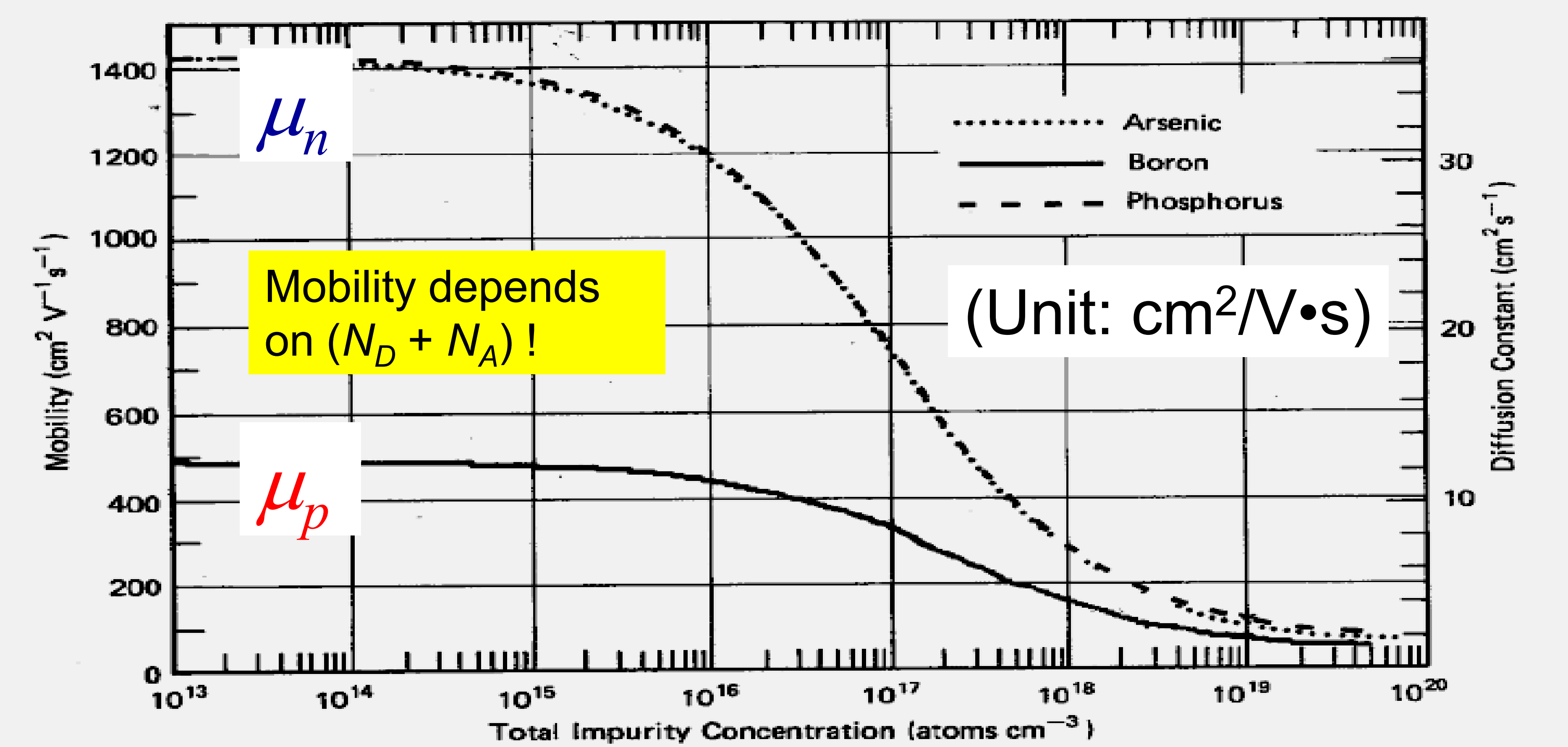
$$J = \sigma E$$

conductivity $$\boxed{\sigma \equiv qn\mu_n + qp\mu_p}$$

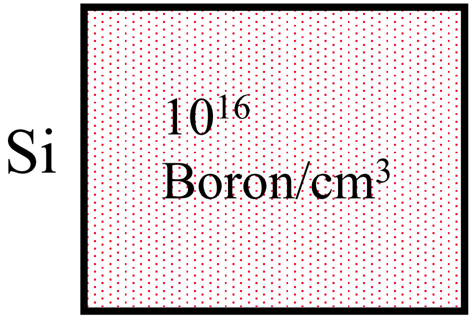
Carrier Mobility μ

Mobile charge-carrier drift velocity v is proportional to applied *E*-field:

$$|v| = \mu E$$



Example Calculation 1



What are n and p values?
What is its electrical resistivity ?

Answer:

Note: $n \bullet p = n_i^2 \sim 10^{20}/cm^3$ for Si at 300K

$N_A = 10^{16}/cm^3$, $N_D = 0$ ($N_A >> N_D$ → p-type)

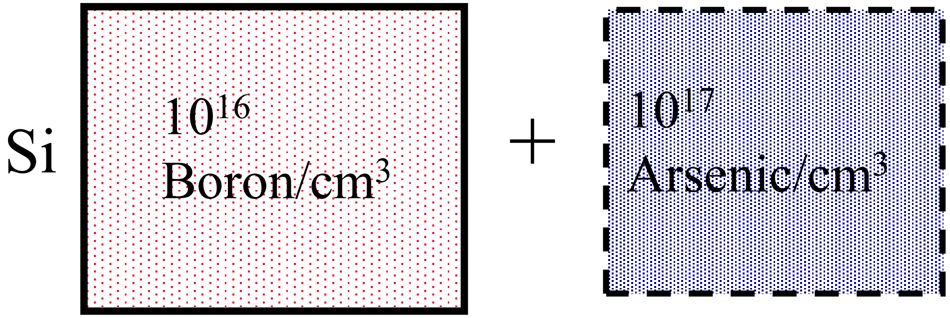
→ $p \approx 10^{16}/cm^3$ and $n \approx 10^4/cm^3$

$$\rho = \frac{1}{qn\mu_n + qp\mu_p} \cong \frac{1}{qp\mu_p}$$

$$= \left[(1.6\times10^{-19})(10^{16})(450)\right]^{-1} = 1.4\,\Omega - \mathrm{cm}$$

From μ_p vs. ($N_A + N_D$) plot

Example Calculation 2: Dopant Compensation



What are n and p values?
What is its electrical resistivity ?

Answer:

$N_A = 10^{16}/\text{cm}^3$, $N_D = 10^{17}/\text{cm}^3$ ($N_D >> N_A \rightarrow$ n-type)

$\rightarrow n \approx 9\text{x}10^{16}/\text{cm}^3$ and $p \approx 1.1\text{x}10^3/\text{cm}^3$

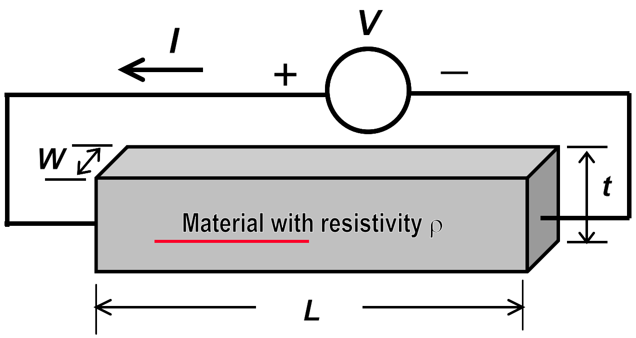
$$\rho = \frac{1}{qn\mu_n + qp\mu_p} \cong \frac{1}{qn\mu_n}$$

From μ_n vs. ($N_A + N_D$) plot

$$= \left[(1.6\times10^{-19})(9\times10^{16})(600)\right]^{-1} = 0.12\,\Omega-\text{cm}$$

* The p-type sample is converted to n-type material by adding more donors than acceptors, and is said to be “compensated”.

Sheet Resistance R_S



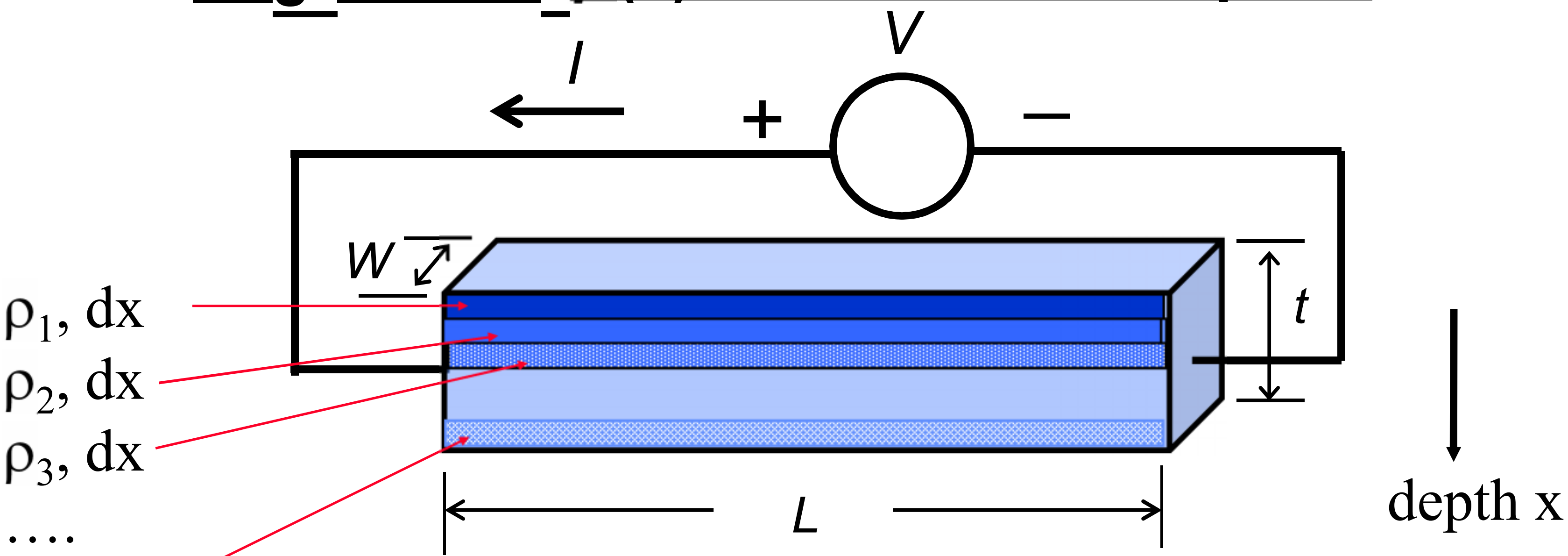
$$R = \rho \frac{L}{Wt} = R_s \frac{L}{W}$$

R_s is the resistance when W = L (unit of R_S in ohms/square)

$$\mathbf{R_s} \equiv \frac{\rho}{\mathbf{t}}$$ if ρ is independent of depth x

- *R_s* value for a given conductive layer (*e.g.* doped Si, metals) in IC or MEMS technology is used
  - for design and layout of resistors
  - for estimating values of parasitic resistance in a device or circuit

R_S when $\rho(x)$ is function of depth x



$$\frac{1}{R_S} = \frac{dx}{\rho_1} + \frac{dx}{\rho_2} + \frac{dx}{\rho_3} + \dots + \frac{dx}{\rho_n} = (\sigma_1 + \sigma_2 + ..\sigma_n)dx$$

For a continuous $\sigma(x)$ function:

$$R_S = \frac{1}{\int_0^t \sigma(x)dx}$$

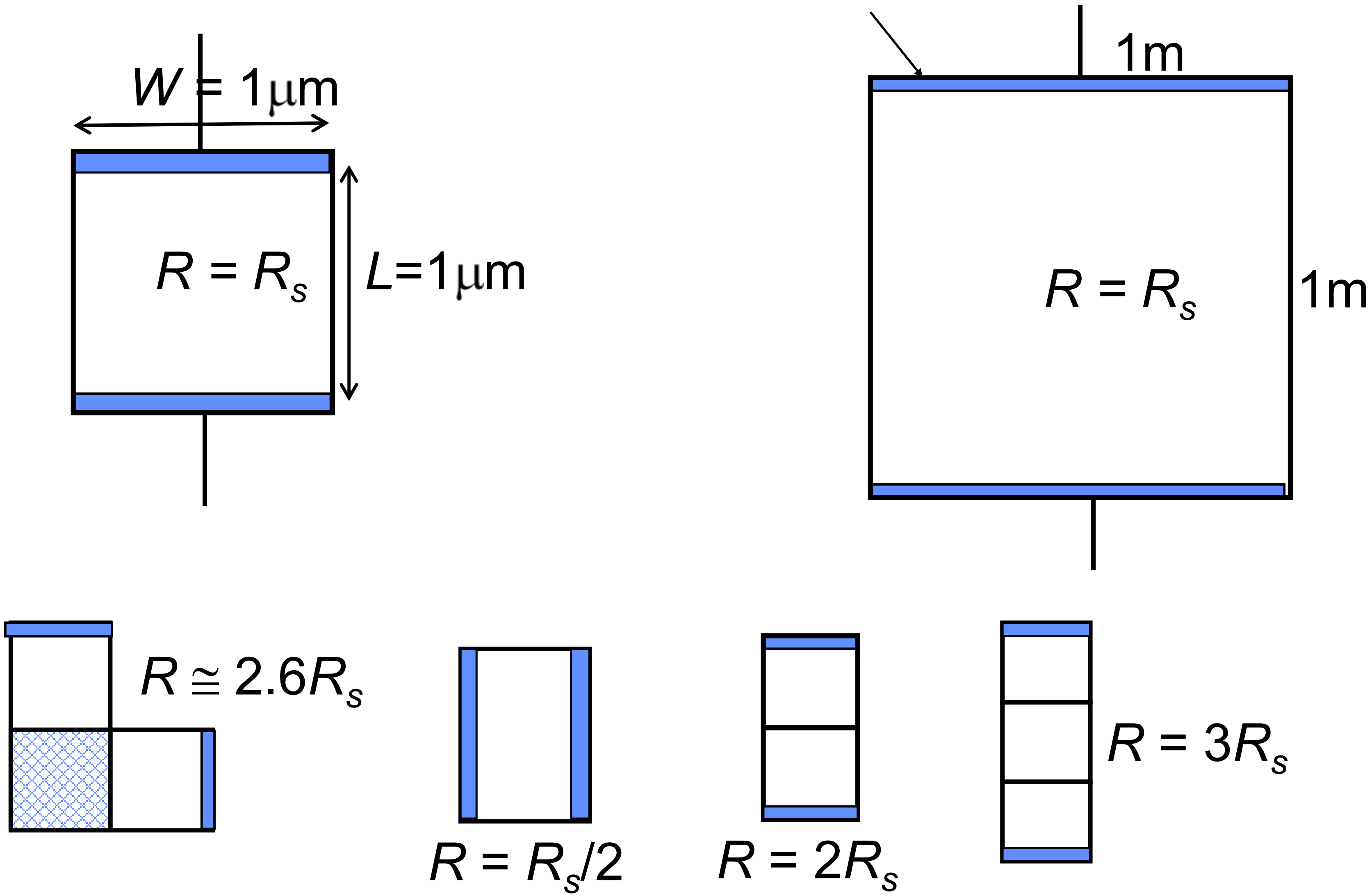
$$= \frac{1}{\int_0^t \left[q\mu_n(x)n(x) + q\mu_p(x)p(x)\right]dx}$$

Electrical Resistance of Layout Patterns

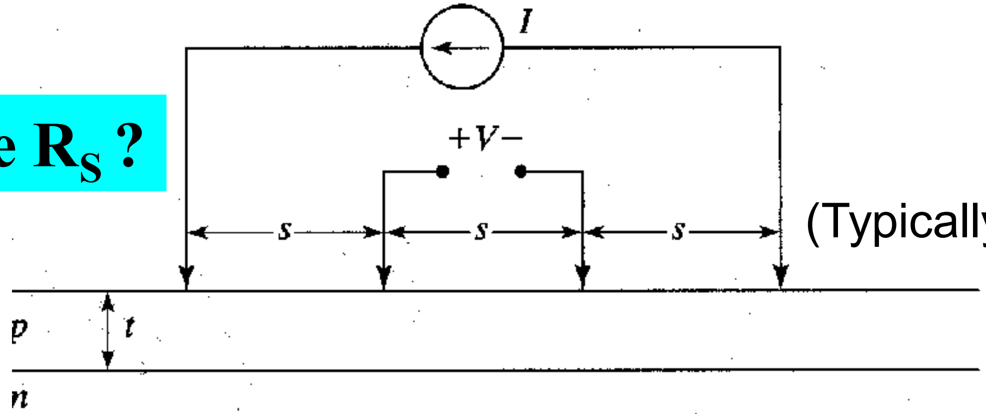
(Unit of R_S: ohms/square)

Metal contact

Top View



How to measure R_S ?



(Typically, $s \approx 1$ mm >>t)

- The ***Four-Point Probe*** is used to measure R_s
  - 4 probes are arranged in-line with equal spacing ***s***
  - 2 outer probes used to flow current ***I*** through the sample
  - 2 inner probes are used to sense the resultant voltage drop ***V*** with a voltmeter

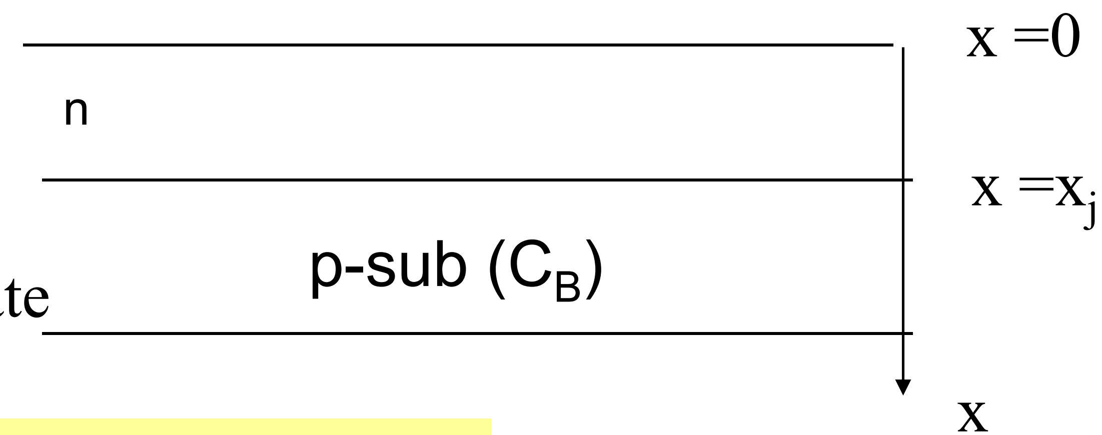
For a *thin* layer ($t \leq s/2$), $$R_s = \frac{4.532V}{I}$$

If ρ is known, then R_s measurement can be used to determine thickness t

For derivation of expression, see EE143 Lab Manual
http://www-inst.eecs.berkeley.edu/~ee143/fa10/lab/four_point_probe.pdf

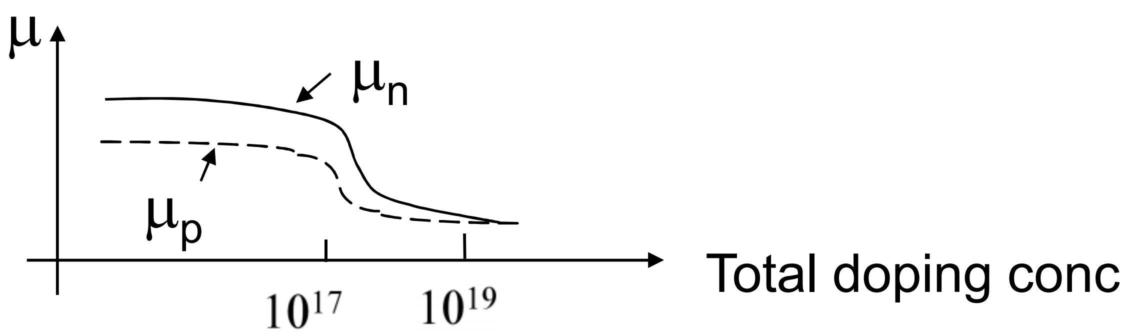
Sheet Resistance R_S of Implanted Layers

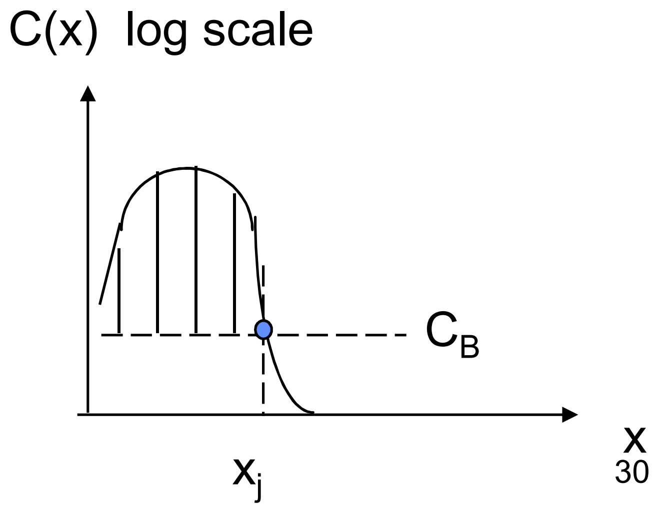
Example:
n-type dopants
implanted
into p-type substrate



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

•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: $\mu(x)$ ~ 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

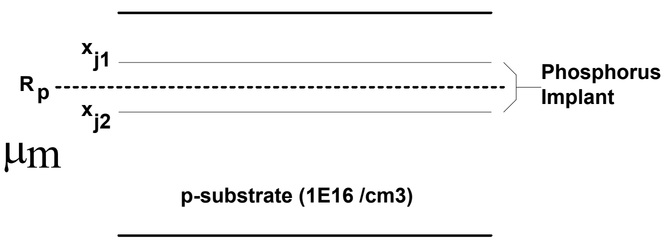
$Cp = (0.4 \times 10^{13})/(0.0775 \times 10^{-4}) = 5.2 \times 10^{17}/cm^3$

(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), μ_n= 350 cm^2 /V-sec

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