EE C245 – ME C218
Introduction to MEMS Design
Fall 2007

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Lecture 7: I/I, Diffusion

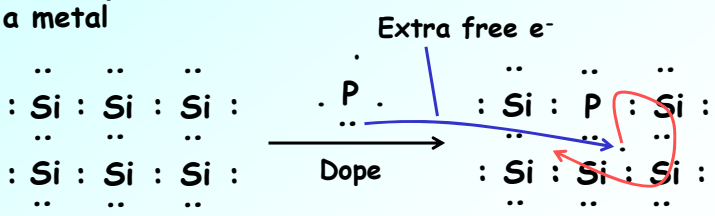
Lecture Outline

- Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 4, 5
- Lecture Topics:
  - Ion Implantation
  - Diffusion

Semiconductor Doping

Doping of Semiconductors

- Semiconductors are not intrinsically conductive
- To make them conductive, replace silicon atoms in the lattice with dopant atoms that have valence bands with fewer or more e^-'s than the 4 of Si
- If more e^-'s, then the dopant is a donor: P, As
  - The extra e^- is effectively released from the bonded atoms to join a cloud of free e^-'s, free to move like e^-'s in a metal



  - The larger the # of donor atoms, the larger the # of free e^-'s → the higher the conductivity

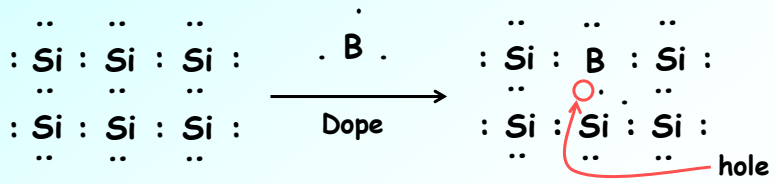
Doping of Semiconductors (cont.)

- **Conductivity Equation**:

$$\sigma = q\mu_n n + q\mu_p p$$

conductivity; electron mobility; electron density; hole mobility; hole density; charge magnitude on an electron

- If fewer e^-'s, then the dopant is an acceptor: B



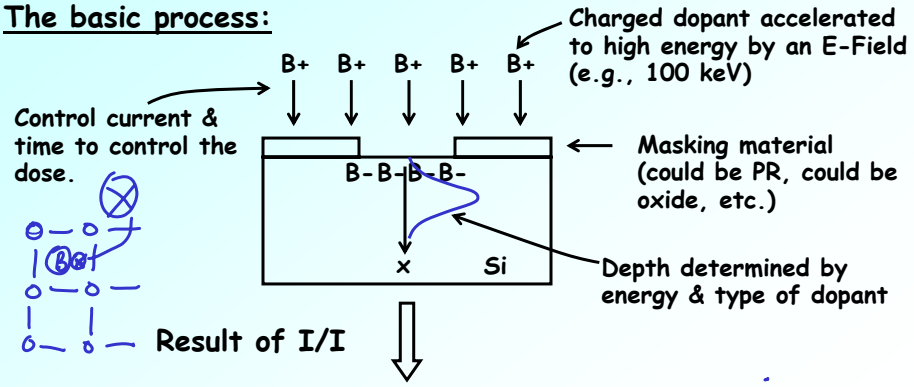
- Lack of an e^- = hole = h^+
- When e^-'s move into h^+'s, the h^+'s effectively move in the opposite direction → a h^+ is a mobile (+) charge carrier

Ion Implantation

Ion Implantation

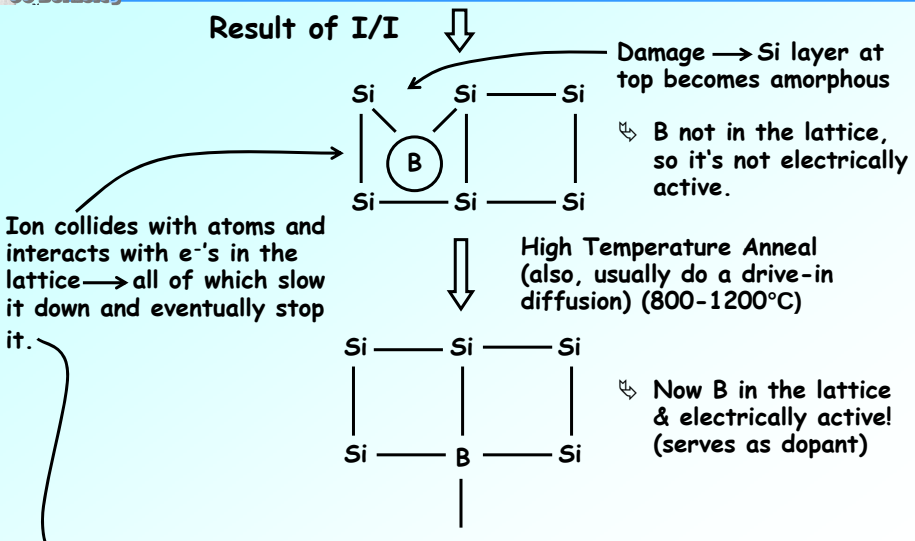
- Method by which dopants can be introduced in silicon to make the silicon conductive, and for transistor devices, to form, e.g., pn-junctions, source/drain junctions, …

The basic process:



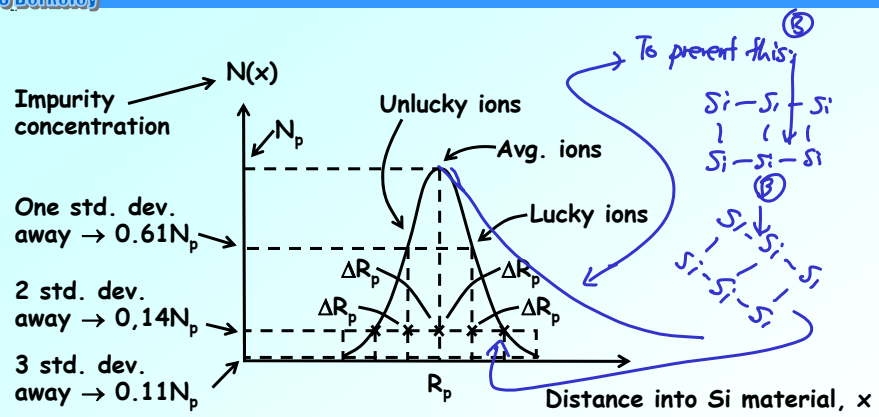
Ion Implantation (cont.)

Result of I/I



This is a statistical process → implanted impurity profile can be approximated by a Gaussian distribution.

Statistical Modeling of I/I



$R_p \triangleq$ Projected range = avg. distance on ion trends before stopping

$\Delta R_p \triangleq$ Straggle = std. deviation characterizing the spread of the distribution.

Analytical Modeling for I/I

Mathematically:

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

Area under the impurity distribution curve } Implanted Dose = $Q = \int_0^\infty N(x)dx \ \left[ions/cm^2\right]$

For an implant completely contained within the Si:

$$Q = \sqrt{2\pi} N_p \Delta R_p$$

Assuming the peak is in the silicon: (putting it in one-sided diffusion form)

$D_I = Q$ → So we can track the dopant front during a subsequent diffusion step.

$$N(x) = \frac{D_I/2}{\sqrt{\pi (Dt)_{eff}}} \exp\left[-\frac{(x-R_p)^2}{2(\Delta R_p)^2}\right], \text{ where } (Dt)_{eff} = \frac{(\Delta R_p)^2}{2}$$

I/I Range Graphs

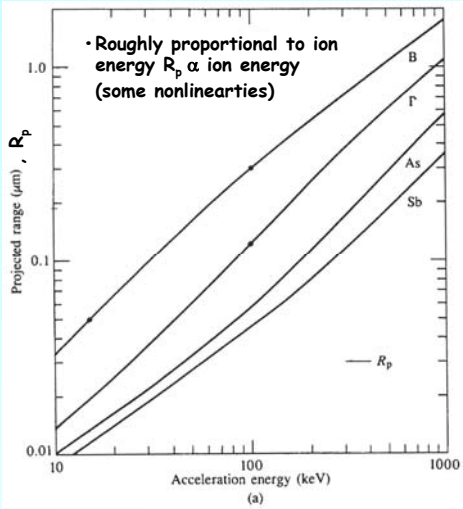


Figure 6.1

- R_p is a function of the energy of the ion and atomic number of the ion and target material

<u>Lindhand, Scharff and Schiott (LSS) Theory</u>:

- Assumes implantation into amorphous material, i.e, atoms of the target material are randomly positioned
- Yields the curves of Fig. 6.1 and 6.2
- For a given energy, lighter elements strike Si with higher velocity and penetrate more deeply

I/I Straggle Graphs

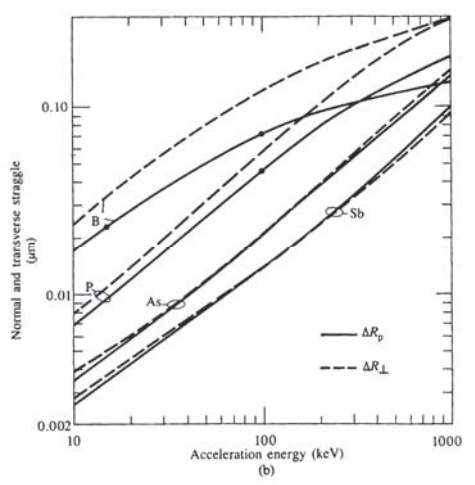


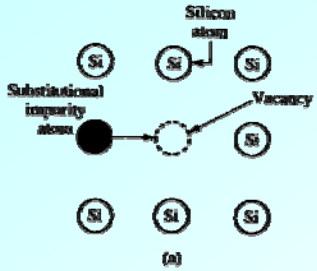
Figure 6.2

- Results for Si and SiO_2 surfaces are virtually identical → so we can use these curves for both

Diffusion

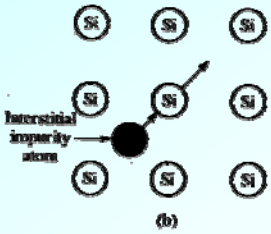
Diffusion in Silicon

- Movement of dopants within the silicon at high temperatures
- Three mechanisms: (in Si)



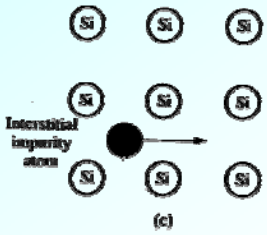
Substitutional Diffusion

- Impurity moves along vacancies in the lattice
- Substitutes for a Si-atom in the lattice



Interstitialcy Diffusion

- Impurity atom replaces a Si atom in the lattice
- Si atom displaced to an interstitial site

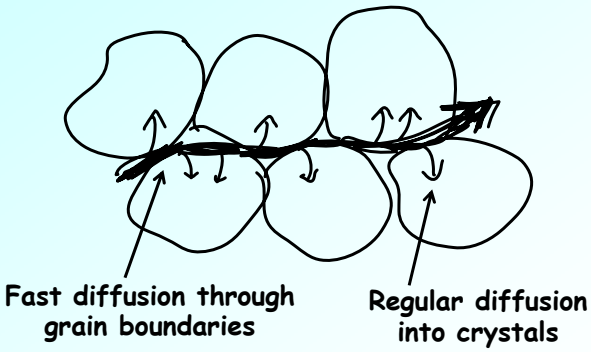


Interstitial Diffusion

- Impurity atoms jump from one interstitial site to another
- Get rapid diffusion
  - Hard to control
  - Impurity not in lattice so not electrically active

Diffusion in Polysilicon

- In polysilicon, still get diffusion into the crystals, but get more and faster diffusion through grain boundaries
- Result: overall faster diffusion than in silicon

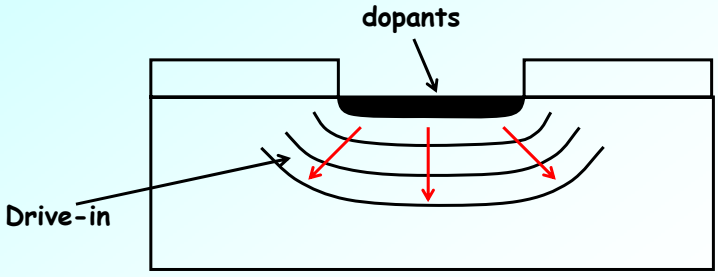


- In effect, larger surface area allows much faster volumetric diffusion

Basic Process for Selective Doping

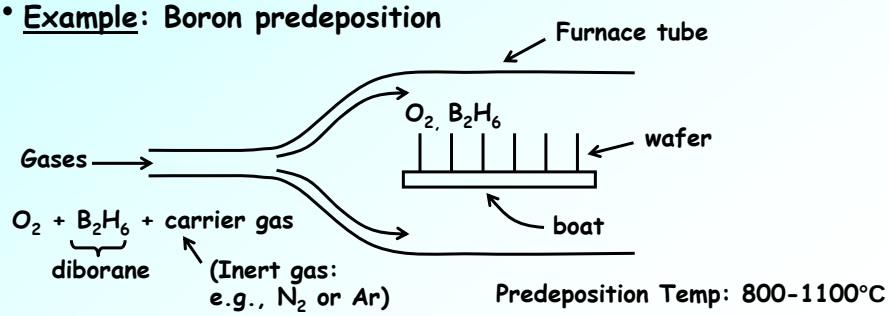
1. Introduce dopants (introduce a fixed dose Q of dopants)
   (i) Ion implantation
   (ii) Predeposition
2. Drive in dopants to the desired depth
   ↳ High temperature > 900°C in N_2 or N_2/O_2

- Result:



Predeposition

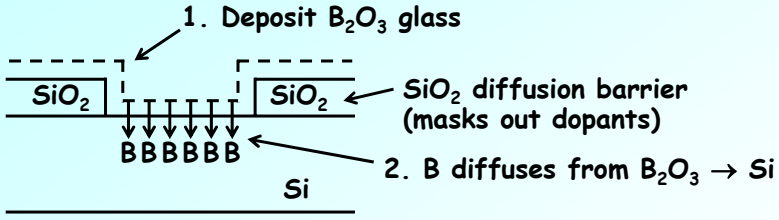
- Furnace-tube system using solid, liquid, or gaseous dopant sources
- Used to introduced a controlled amount of dopants
  - Unfortunately, not very well controlled
  - Dose (Q) range: 10^{13} – 10^{16} ± 20%
  - For ref: w/ ion implantation: 10^{11} – 10^{16} ± 1% (larger range & more accurate)
- Example: Boron predeposition



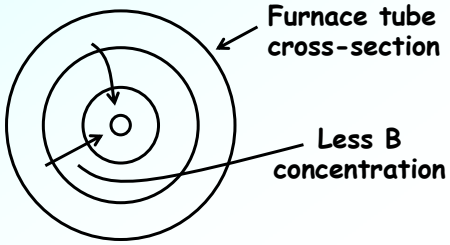
Predeposition Temp: 800-1100°C

Ex: Boron Predeposition

- Basic Procedure:

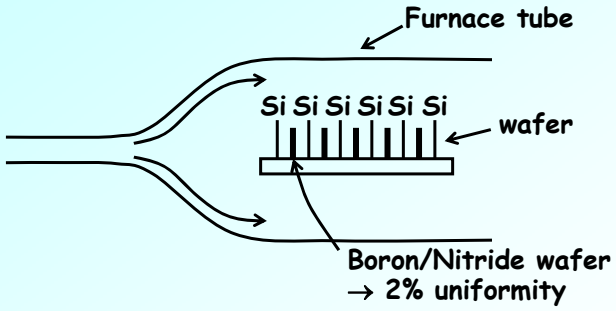


- Difficult to control dose Q, because it's heavily dependent on partial pressure of B_2H_6 gas flow
  - this is difficult to control itself
  - get only 10% uniformity



Ex: Boron Predeposition (cont.)

For better uniformity, use solid source:



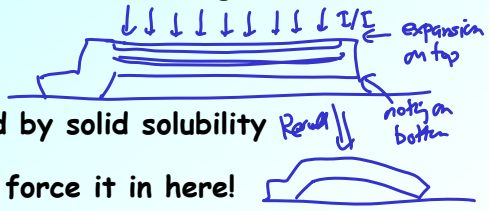
Reactions:

$B_2H_6 + 3O_2 \rightarrow 3H_2O + B_2O_3$

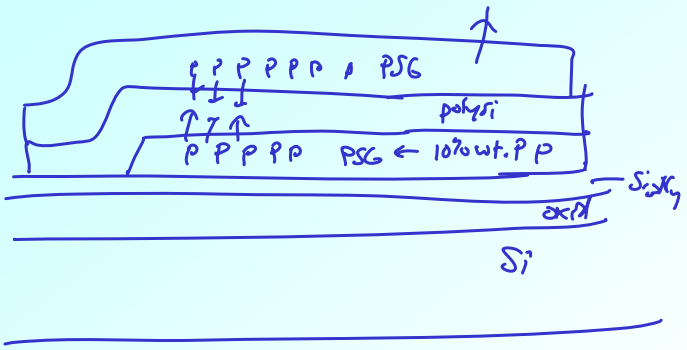
$Si + O_2 \rightarrow SiO_2$

General Comments on Predeposition

- Higher doses only: Q = 10^{13} – 10^{16} cm^{-2} (I/I is 10^{11} – 10^{16})
- Dose not well controlled: ± 20% (I/I can get ± 1%)
- Uniformity is not good
  - ± 10% w/ gas source
  - ± 2% w/ solid source

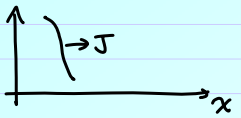


- Max. conc. possible limited by solid solubility
  - Limited to ~10^{20} cm^{-3}
  - No limit for I/I → you force it in here!
- For these reasons, I/I is usually the preferred method for introduction of dopants in transistor devices
- But I/I is not necessarily the best choice for MEMS
  - I/I cannot dope the underside of a suspended beam
  - I/I yields one-sided doping → introduces unbalanced stress → warping of structures
  - I/I can do physical damage → problem if annealing is not permitted
- Thus, predeposition is often preferred when doping MEMS



Diffusion Modeling

Modeling N(x)



⇒ Dopants from points of high conc. move to points of low conc. w/ flux J

⇒ Question: What's N(x,t)? ↑ fcn of time

Fick's Law of Diffusion – (1st law)

$$J(x,t) = -D\frac{\partial N(x,t)}{\partial x} \quad (1)$$

J(x,t): flux [#/cm²·s]; D: Diffusion Coefficient

Continuity Equation for Particle Flux –

General form:

$$\frac{\partial N(x,t)}{\partial t} = -\vec{\nabla}\cdot\vec{J}$$

$\frac{\partial N(x,t)}{\partial t}$: rate of increase of conc. w/ time

$-\vec{\nabla}\cdot\vec{J}$: negative of the divergence of particle flux

Diffusion Modeling (cont.)

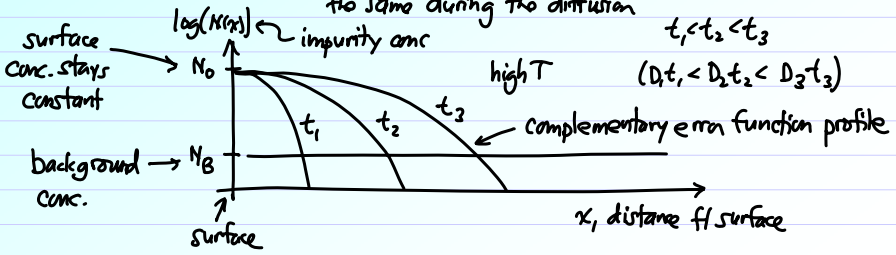
⇒ we've integrated for now in the one-dimensional form:

$$\frac{\partial N(x,t)}{\partial t} = -\frac{\partial J}{\partial x} \qquad (2)$$

$\left[\frac{\partial}{\partial x}(1)\text{ and substitute (2) in (1)}\right] \Rightarrow \frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2}$ [Fick's 2nd Law of Diffusion in 1-D]

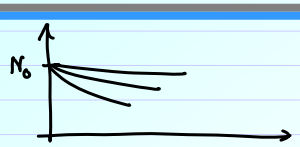
Solutions: → dependent upon boundary conditions
↳ use variable separation or Laplace Xform techniques

Case 1: Predeposition → constant source diffusion: surface concentration stays the same during the diffusion



Diffusion Modeling (Predeposition)

⇒ if plotted on a linear scale, would look like this:



⇒ Boundary Conditions:
(i) $N(0,t) = N_0$
(ii) $N(\infty,t) = 0$

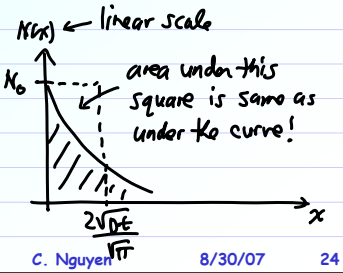
$$N(x,t) = N_0\left[1 - \frac{1}{\sqrt{\pi}}\int_0^{\frac{x}{2\sqrt{Dt}}} e^{-y^2}dy\right]$$

$$N(x,t) = N_0\,\text{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$$ ⇒ again, complementary error function (read tables or graph)

Dose, Q ≜ total # of impurity atoms per unit area in the Si
= area under the curve

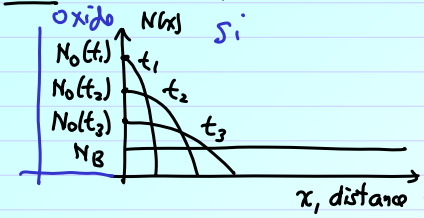
$$Q = \int_0^\infty N(x,t)dx \Rightarrow Q(t) = N_0\frac{2\sqrt{Dt}}{\sqrt{\pi}}\ \text{cm}^{-2}$$

$2\sqrt{Dt}$ ≜ characteristic diffusion length



Diffusion Modeling (Limited Source)

Case 2: Drive-in → limited source diffusion, i.e., constant dose Q



⇒ Boundary Condition:

(i) $N(\infty, t) = 0$

(ii) $\left.\frac{\partial N(x,t)}{\partial x}\right|_{x=0} = 0$ → Why? Constant Dose: $\int_0^\infty N(x,t)\,dx = Q$ ← const.

→ This is equivalent to saying that there's no flux going out of the Si, i.e., and that's what this says!

Diffusion Modeling (Limited Source)

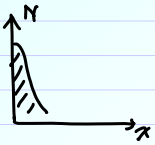
(iii) Usually make delta fcn. approx.: $N(x,0) = Q\,\delta(x)$

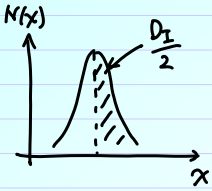
⇒ we can do this, because for sufficiently long diffusion times, no matter what the original shape of the dopant distribution, the diffused distribution will be the same

Get Gaussian Distribution:

$$N(x,t) = \frac{Q}{\sqrt{\pi D t}} \exp\left[-\left(\frac{x}{2\sqrt{Dt}}\right)^2\right]$$

corresponds to a half Gaussian in this equation





when the starting conc. profile is completely contained in the Si, then

$Q = \frac{D_I}{2}$ = half the implant dose

Two-Step Diffusion

- Two step diffusion procedure:
  - Step 1: predeposition (i.e., constant source diffusion)
  - Step 2: drive-in diffusion (i.e., limited source diffusion)
- For processes where there is both a predeposition and a drive-in diffusion, the final profile type (i.e., complementary error function or Gaussian) is determined by which has the much greater Dt product:

$(Dt)_{predep} \gg (Dt)_{drive\text{-}in}$ ⇨ impurity profile is complementary error function

$(Dt)_{drive\text{-}in} \gg (Dt)_{predep}$ ⇨ impurity profile is Gaussian (which is usually the case)

Successive Diffusions

- For actual processes, the junction/diffusion formation is only one of many high temperature steps, each of which contributes to the final junction profile
- Typical overall process:
  1. Selective doping
     - Implant → effective $(Dt)_1 = (\Delta R_p)^2/2$ (Gaussian)
     - Drive-in/activation → D_2t_2
  2. Other high temperature steps
     - (eg., oxidation, reflow, deposition) → D_3t_3, D_4t_4, …
     - Each has their own Dt product
  3. Then, to find the final profile, use

$$(Dt)_{tot} = \sum_i D_i t_i$$

in the Gaussian distribution expression.

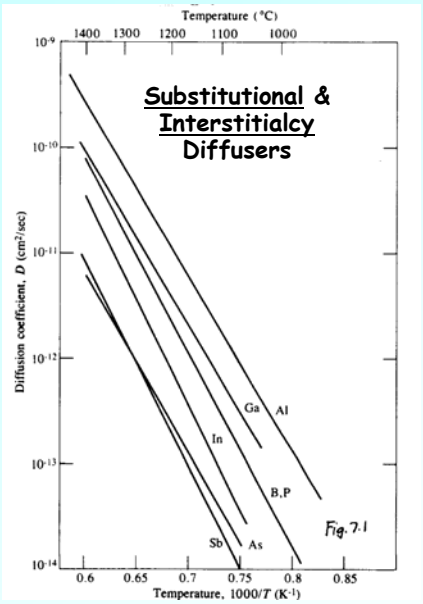
The Diffusion Coefficient

$$D = D_o \exp\left(-\frac{E_A}{kT}\right)$$ (as usual, an Arrhenius relationship)

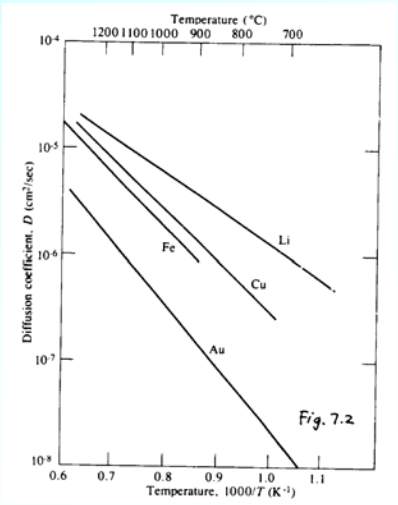
Table 4.1 Typical Diffusion Coefficient Values for a Number of Impurities.

Element	$D_0(cm^2/sec)$	$E_A(eV)$
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

Diffusion Coefficient Graphs

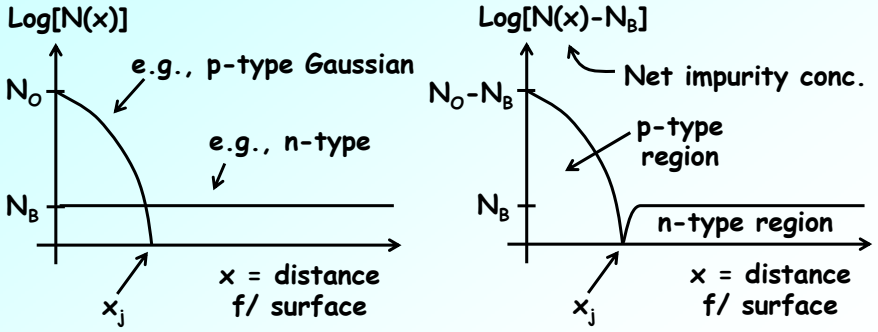


Interstitial Diffusers
↳ Note the much higher diffusion coeffs. than for substitutional



Metallurgical Junction Depth, x_j

x_j = point at which diffused impurity profile intersects the background concentration, N_B



Expressions for x_j

- Assuming a Gaussian dopant profile: (the most common case)

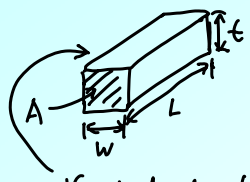
$$N(x_j,t) = N_o \exp\left[-\left(\frac{x_j}{2\sqrt{Dt}}\right)^2\right] = N_B \quad \rightarrow \quad x_j = 2\sqrt{Dt \ln\left(\frac{N_o}{N_B}\right)}$$

- For a complementary error function profile:

$$N(x_j,t) = N_o \text{erfc}\left(\frac{x_j}{2\sqrt{Dt}}\right) = N_B \quad \rightarrow \quad x_j = 2\sqrt{Dt}\,\text{erfc}^{-1}\left(\frac{N_B}{N_o}\right)$$

Sheet Resistance

- Sheet resistance provides a simple way to determine the resistance of a given conductive trace by merely counting the number of effective squares
- <u>Definition</u>:



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

ohms per square

$\Omega/\square$

$[A = tW]$

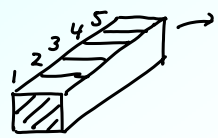
sheet resistance

unit squares of material in the resistor

uniformly doped material w/ resistivity $\rho = \frac{1}{\sigma}$

σ = conductivity $= q(\mu_n n + \mu_p p)$

e.g.,

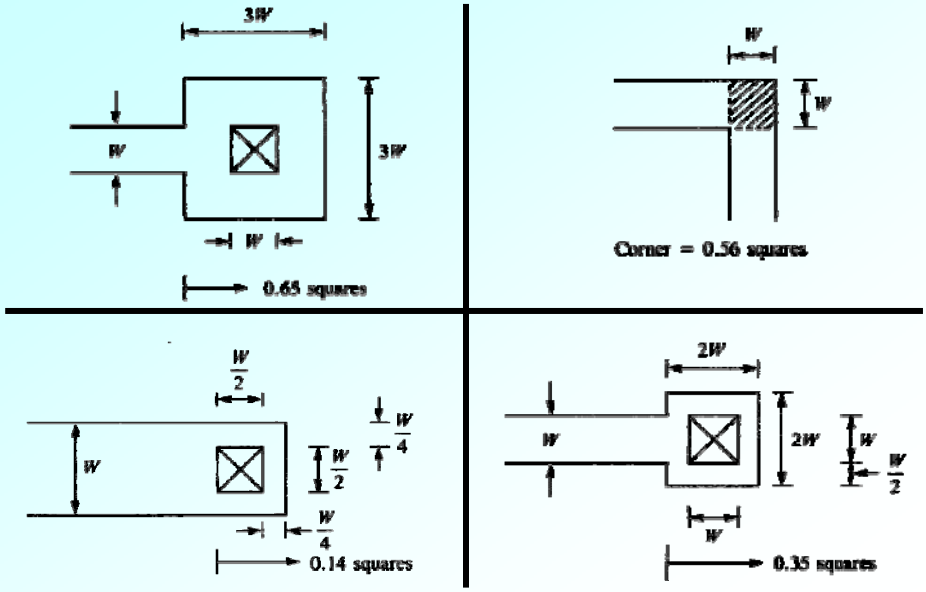


5 □'s of material

$\therefore R = R_s \times 5$

- What if the trace is non-uniform? (e.g., a corner, contains a contact, etc.)

Squares From Non-Uniform Traces



Sheet Resistance of a Diffused Junction

- For diffused layers:

Majority carrier mobility

Sheet resistance

Effective resistivity

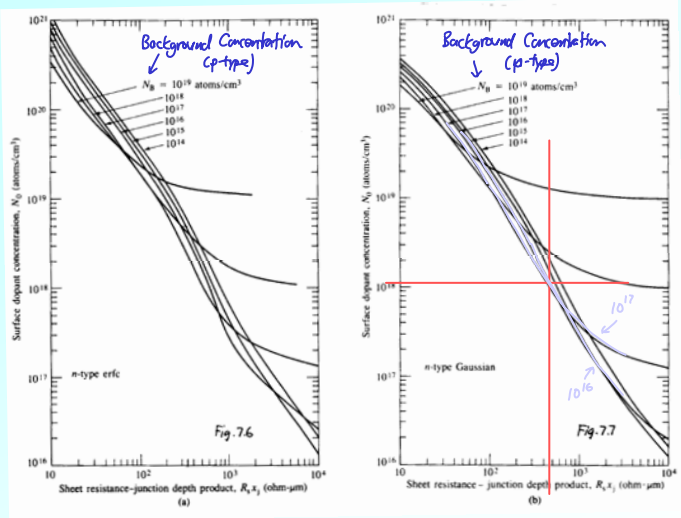
Net impurity concentration

$$R_s = \frac{\bar{\rho}}{x_j} = \left[\int_o^{x_j} \sigma(x)dx\right]^{-1} = \left[\int_o^{x_j} q\mu N(x)dx\right]^{-1}$$

[extrinsic material]

- This expression neglects depletion of carriers near the junction, $x_j \rightarrow$ thus, this gives a slightly lower value of resistance than actual
- Above expression was evaluated by Irvin and is plotted in "Irvin's curves" on next few slides
  - Illuminates the dependence of R_s on x_j, N_o (the surface concentration), and N_B (the substrate background conc.)

Irvin's Curves (for n-type diffusion)



Example.

Given: p-type

$N_B = 3 \times 10^{16}$ cm^{-3}

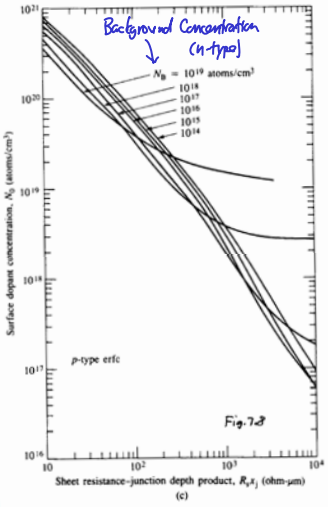
$N_o = 1.1 \times 10^{18}$ cm^{-3} (n-type Gaussian)

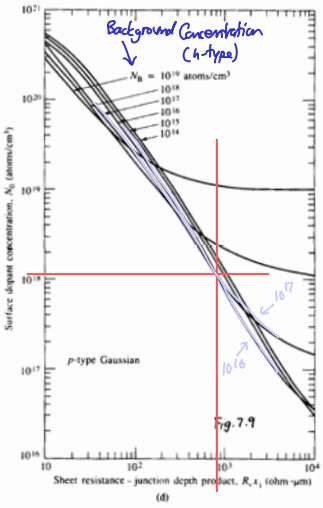
$x_j = 2.77$ μm

Can determine these given known predep. and drive conditions

Determine the R_s.

Irvin's Curves (for p-type diffusion)





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