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EE C245 - ME C218 Introduction to MEMS Design Fall 2010

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Lecture Module 4: Lithography, Etching, & Doping

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Lecture Outline

- Reading: Senturia, Chpt. 3; Jaeger, Chpt. 2, 4, 5
- ↳ Lithography
- ↳ Etching
 - ↳ Wet etching
 - ↳ Dry etching
- ↳ Semiconductor Doping
 - ↳ Ion implantation
 - ↳ Diffusion

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Semiconductor Doping

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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

Extra free e^-

Dope

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

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Doping of Semiconductors (cont.)

Conductivity Equation:

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

Labels for the equation:
 - σ : conductivity
 - q : charge magnitude on an electron
 - μ_n : electron mobility
 - n : electron density
 - μ_p : hole mobility
 - p : hole density

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

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Ion Implantation

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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:

Control current & time to control the dose.
 Charged dopant accelerated to high energy by an E-Field (e.g., 100 keV)
 Masking material (could be PR, could be oxide, etc.)
 Depth determined by energy & type of dopant

Result of I/I

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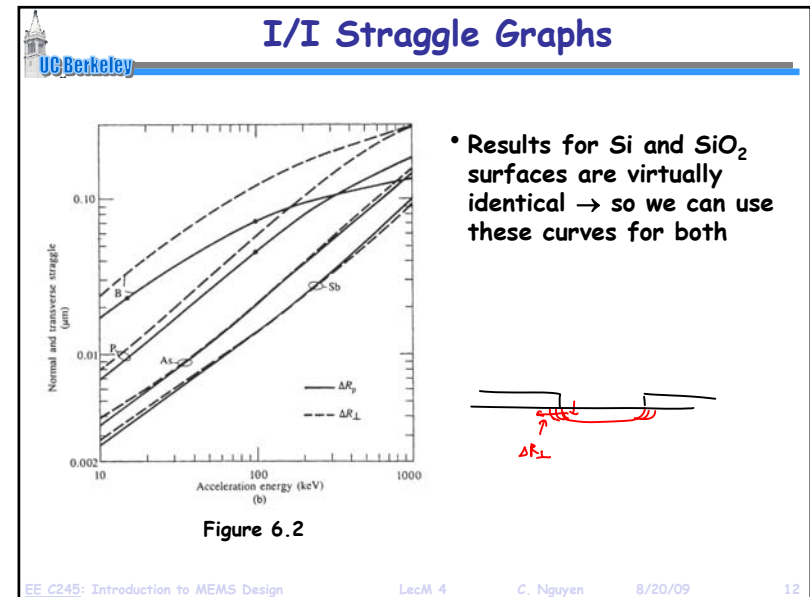
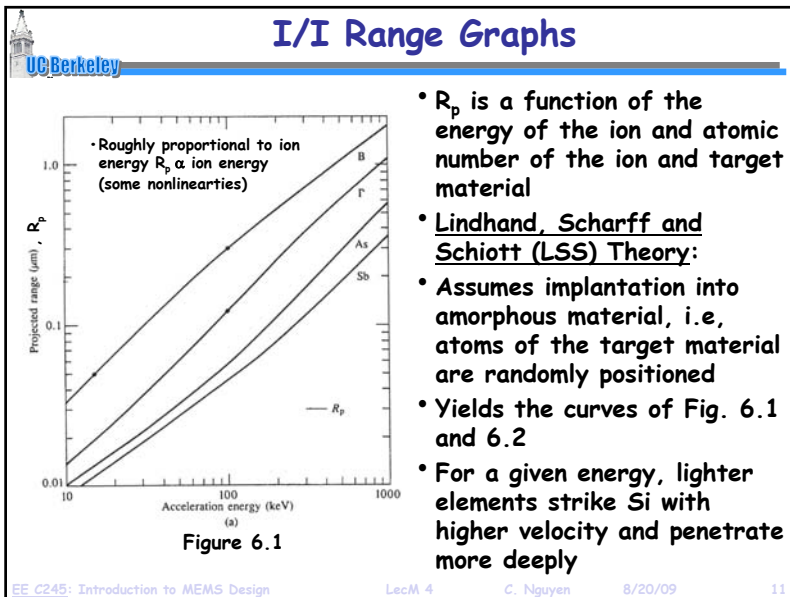
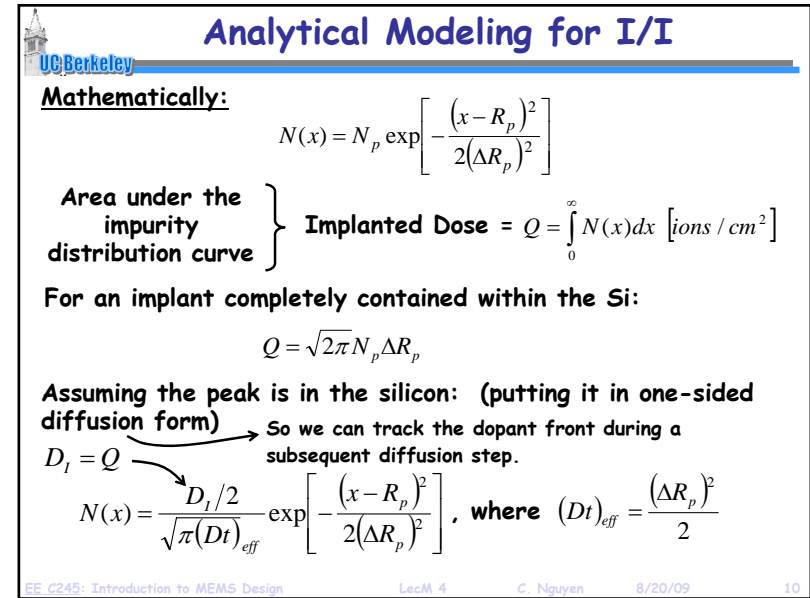
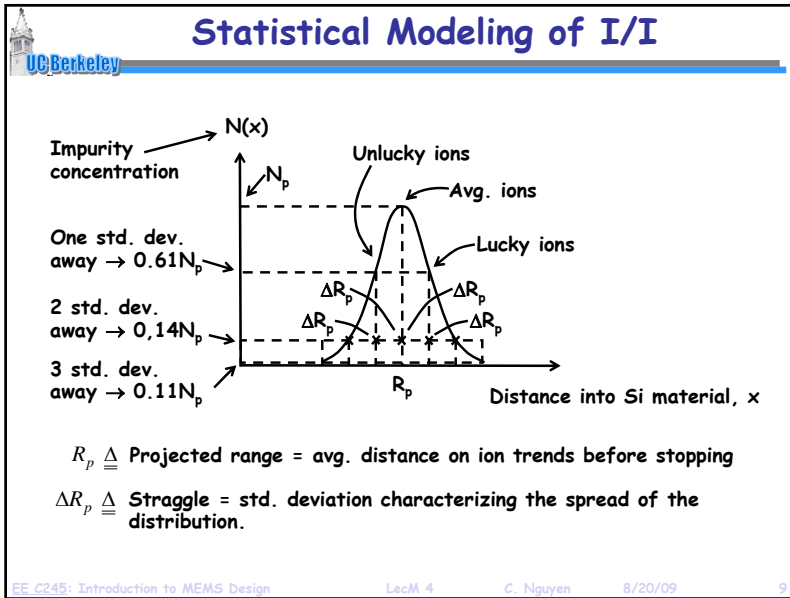
Ion Implantation (cont.)

Result of I/I

Damage → Si layer at top becomes amorphous
 ☞ B not in the lattice, so it's not electrically active.
 High Temperature Anneal (also, usually do a drive-in diffusion) (800-1200°C)
 ☞ Now B in the lattice & electrically active! (serves as dopant)

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

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Diffusion

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Diffusion in Silicon

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

(a)

(b)

(c)

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

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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

Fast diffusion through grain boundaries Regular diffusion into crystals

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

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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 $> 900^\circ\text{C}$ in N_2 or N_2/O_2

• **Result:**

dopants

Drive-in

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Predeposition

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

Predeposition Temp: 800-1100°C

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Ex: Boron Predeposition

- Basic Procedure:**
 - Deposit B_2O_3 glass
 - B diffuses from $B_2O_3 \rightarrow Si$
- 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

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Ex: Boron Predeposition (cont.)

For better uniformity, use solid source:

Boron/Nitride wafer
→ 2% uniformity

Reactions:
 $B_2H_6 + 3O_2 \rightarrow 3H_2O + B_2O_3$
 $Si + O_2 \rightarrow SiO_2$

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General Comments on Predeposition

- Higher doses only: $Q = 10^{13} - 10^{16} \text{ cm}^{-2}$ (I/I is $10^{11} - 10^{16}$)
- Dose not well controlled: $\pm 20\%$ (I/I can get $\pm 1\%$)
- Uniformity is not good
 - $\pm 10\%$ w/ gas source
 - $\pm 2\%$ w/ solid source
- Max. conc. possible limited by solid solubility
 - Limited to $\sim 10^{20} \text{ cm}^{-3}$
 - 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

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Diffusion Modeling

Modeling $N(x)$ $\rightarrow J$

\Rightarrow Dopants from points of high conc. move to points of low conc. w/ flux J
 \Rightarrow Question: What's $N(x,t)$?
 ? fn of time

Fick's Law of Diffusion - (1st law)
 $J(x,t) = -D \frac{\partial N(x,t)}{\partial x}$ (1)
 Flux [$\#/cm^2 \cdot s$] \leftarrow Diffusion Coefficient

Continuity Equation for Particle Flux -
 General Form: $\frac{\partial N(x,t)}{\partial t} = -\nabla \cdot \vec{J}$
 rate of increase of conc. w/ time \leftarrow negative of the divergence of particle flux

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Diffusion Modeling (cont.)

\Rightarrow We're interested for now in the one-dimensional form:

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

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

Solutions: \rightarrow dependent upon boundary conditions
 \rightarrow use variable separation or Laplace Xform techniques

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

surface conc. stays constant $\rightarrow N_0$ impurity conc
 high T $(D_1 < D_2 < D_3, t_1 < t_2 < t_3)$
 complementary error function profile
 background conc. $\rightarrow N_B$
 x , distance f/ surface

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Diffusion Modeling (Predeposition)

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

\Rightarrow Boundary Condition:
 (i) $N(0,t) = N_0$
 (ii) $N(\infty,t) = 0$

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

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

Dose, $Q \triangleq$ total # of impurity atoms per unit area in the Si
 = area under the curve
 $Q = \int_0^{\infty} N(x,t) dx \Rightarrow Q(t) = N_0 \frac{2\sqrt{Dt}}{\sqrt{\pi}} \text{ cm}^{-2}$

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

$N(x)$ \leftarrow linear scale
 area under this square is same as under the curve!
 N_0
 $2\sqrt{Dt}$

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Diffusion Modeling (Limited Source)

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

$N(x)$
 $N_0(t_1)$
 $N_0(t_2)$
 $N_0(t_3)$
 N_B
 x , distance f/ the surface

\Rightarrow Boundary Condition:
 (i) $N(\infty,t) = 0$
 (ii) $\frac{\partial N(x,t)}{\partial x} \Big|_{x=0} = 0$

Why? Constant Dose: $\int_0^{\infty} N(x,t) dx = Q \leftarrow \text{const.}$

This is equivalent to saying that there's no flux going out of the Si, i.e., $J=0$ and that's what this says!

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Diffusion Modeling (Limited Source)

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(i) Usually make delta fun. approx.: $N(x, 0) = Q \delta(x)$
 \Rightarrow 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: $N(x, t) = \frac{Q}{\sqrt{\pi Dt}} \exp\left[-\frac{x^2}{2Dt}\right]$ corresponds to a half Gaussian in this Equation

When the starting conc. profile is completely contained in the Si, then $Q = \frac{D_1}{2} = \text{half the implant dose}$

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Two-Step Diffusion

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- 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:
 - $(Dt)_{\text{predep}} \gg (Dt)_{\text{drive-in}} \Rightarrow$ impurity profile is complementary error function
 - $(Dt)_{\text{drive-in}} \gg (Dt)_{\text{predep}} \Rightarrow$ impurity profile is Gaussian (which is usually the case)

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Successive Diffusions

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- 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:
 - Selective doping
 - Implant \rightarrow effective $(Dt)_1 = (\Delta R_p)^2/2$ (Gaussian)
 - Drive-in/activation $\rightarrow D_2 t_2$
 - Other high temperature steps
 - (eg., oxidation, reflow, deposition) $\rightarrow D_3 t_3, D_4 t_4, \dots$
 - Each has their own Dt product
 - Then, to find the final profile, use

$$(Dt)_{\text{tot}} = \sum_i D_i t_i$$
 in the Gaussian distribution expression.

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The Diffusion Coefficient

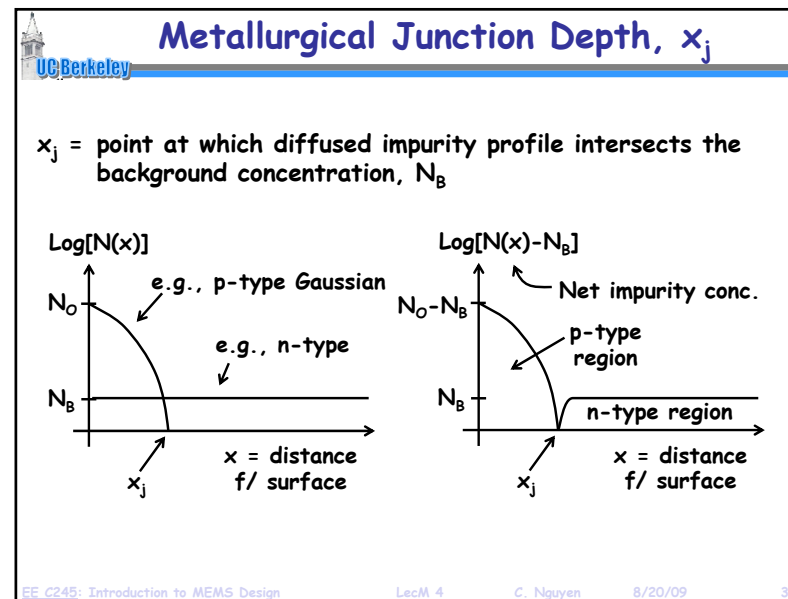
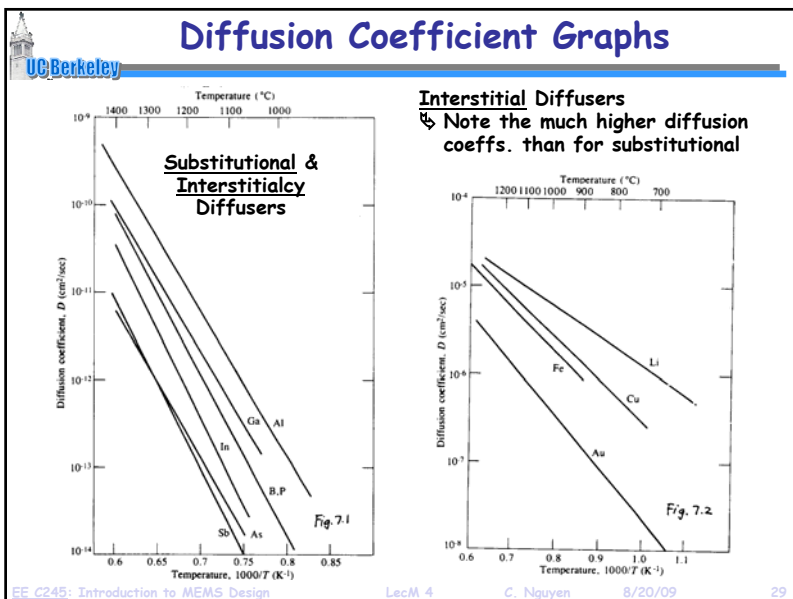
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$$D = D_0 \exp\left(-\frac{E_A}{kT}\right) \quad (\text{as usual, an Arrhenius relationship})$$

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

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

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Expressions for x_j

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

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

- For a complementary error function profile:

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

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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
- Definition:**

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

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Squares From Non-Uniform Traces

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Sheet Resistance of a Diffused Junction

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- For diffused layers:
 - Majority carrier mobility
 - Net impurity concentration
 - Effective resistivity
 - Sheet resistance

$$R_s = \frac{\rho}{x_j} = \left[\int_0^{x_j} \sigma(x) dx \right]^{-1} = \left[\int_0^{x_j} q\mu N(x) dx \right]^{-1}$$

[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
 - Illustrates the dependence of R_s on x_j , N_0 (the surface concentration), and N_B (the substrate background conc.)

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Irvin's Curves (for n-type diffusion)

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Example. \leftarrow p-type
Given:
 $N_B = 3 \times 10^{16} \text{ cm}^{-3}$
 $N_0 = 1.1 \times 10^{18} \text{ cm}^{-3}$
 (n-type Gaussian)
 $x_j = 2.77 \text{ } \mu\text{m}$
 Can determine these given known predep. and drive conditions

Determine the R_s .
 Using Fig. 7.7:
 $R_s x_j = 470 \text{ } \Omega \cdot \mu\text{m}$
 $\therefore R_s = \frac{470}{2.77} = 170 \text{ } \Omega / \mu\text{m}$

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Irvin's Curves (for p-type diffusion)

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Example. \leftarrow n-type
Given:
 $N_B = 3 \times 10^{16} \text{ cm}^{-3}$
 $N_0 = 1.1 \times 10^{18} \text{ cm}^{-3}$
 (p-type Gaussian)
 $x_j = 2.77 \text{ } \mu\text{m}$
 Can determine these given known predep. and drive conditions

Determine the R_s .
 Using Fig. 7.9:
 $R_s x_j = 800 \text{ } \Omega \cdot \text{cm}$
 $\therefore R_s = \frac{800}{2.77} = 289 \text{ } \Omega / \mu\text{m}$

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