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Semiconductor Doping

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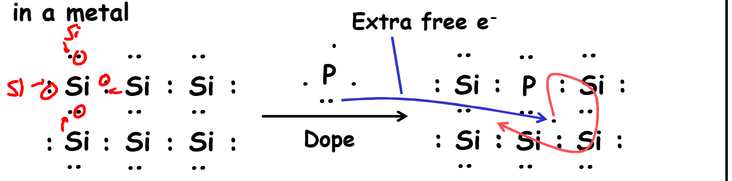
Doping of Semiconductors

- 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



  - ⇨ 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**:

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

conductivity

electron mobility

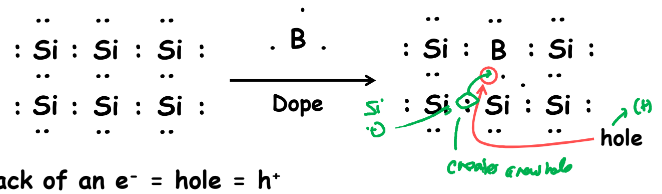
electron density

charge magnitude on an electron

hole mobility

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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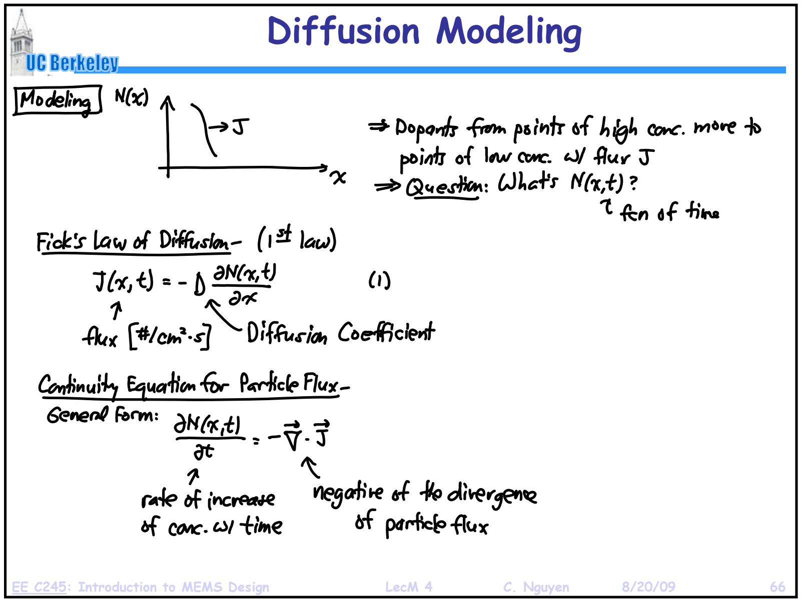
General Comments on Predeposition

- 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

EE247B/ME218: Introduction to MEMS Design
Lecture 6m1: Lithography, Etching, & Doping



Diffusion Modeling

Modeling

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

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

Fick's Law of Diffusion – (1st law)

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

flux [#/cm²·s]

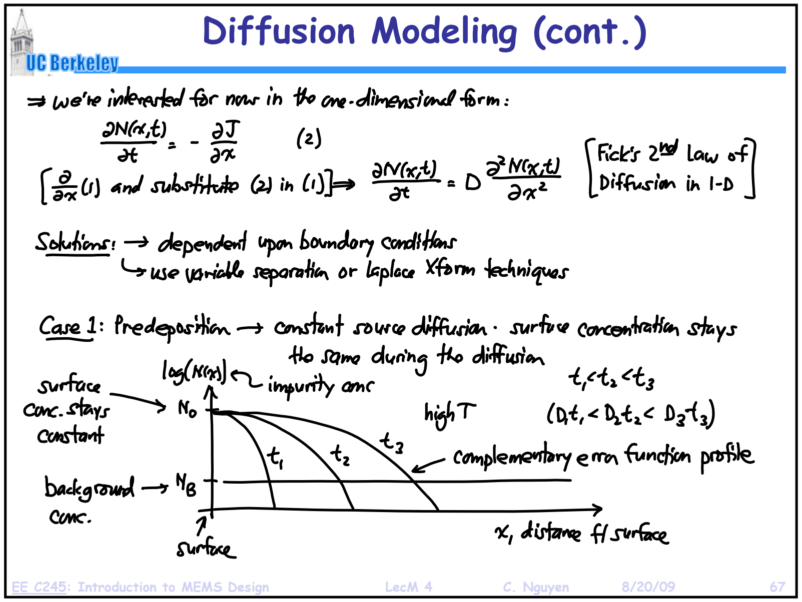
Diffusion Coefficient

Continuity Equation for Particle Flux –

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

rate of increase of conc. w/ time

negative of the divergence of particle flux



Diffusion Modeling (cont.)

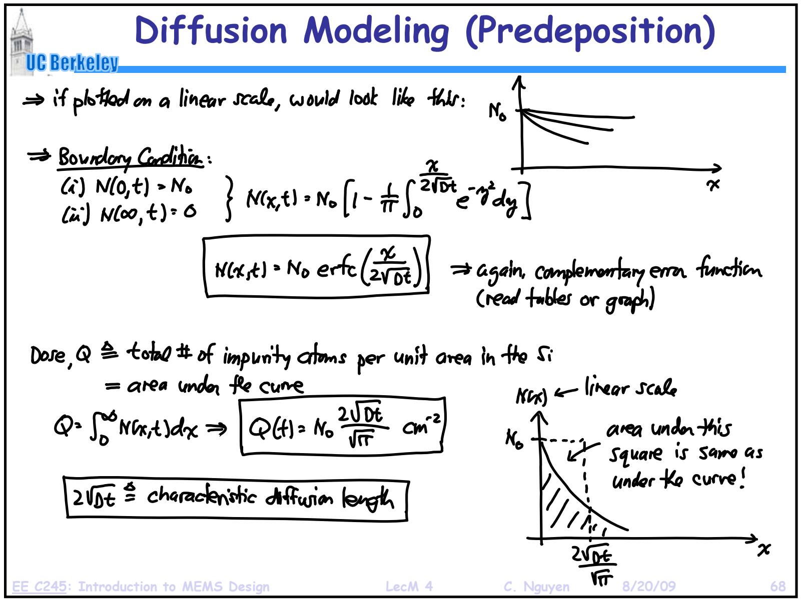
⇒ we're interested for now in the one-dimensional form:

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

$\left[\frac{\partial}{\partial x}(1) \text{ and substitute (2) in (1)}\right] \Rightarrow$ $$\frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2}$$ [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 Condition:

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

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

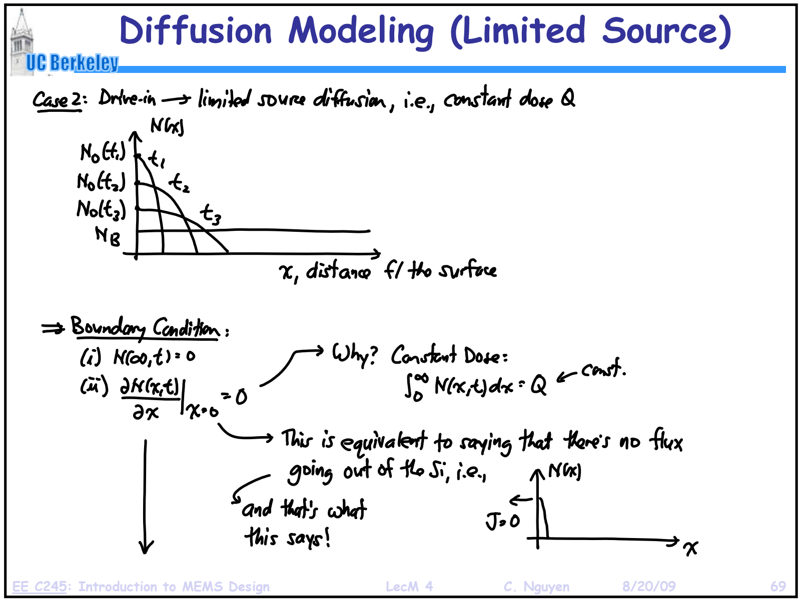
$$\boxed{N(x,t) = N_o\,\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)}$$

⇒ 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

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

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



Diffusion Modeling (Limited Source)

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

⇒ Boundary Condition:

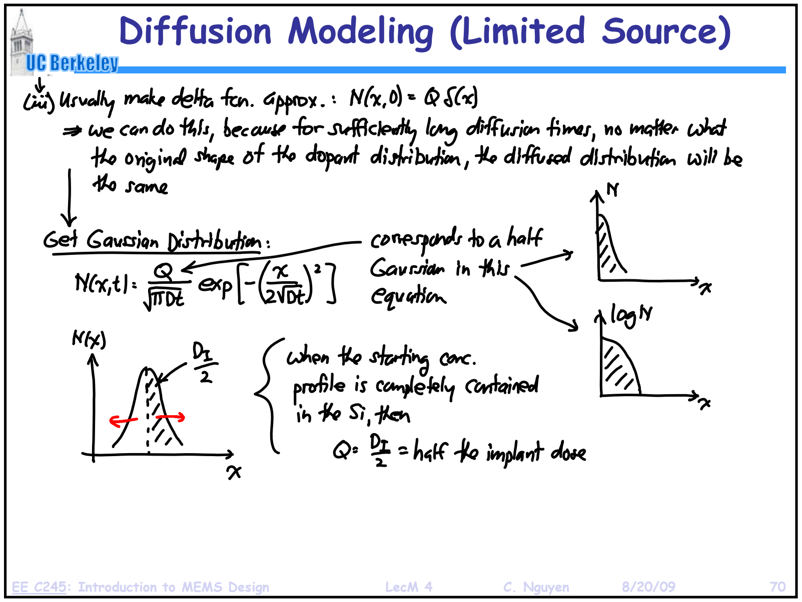
(i) $N(\infty,t) = 0$

(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)

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(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

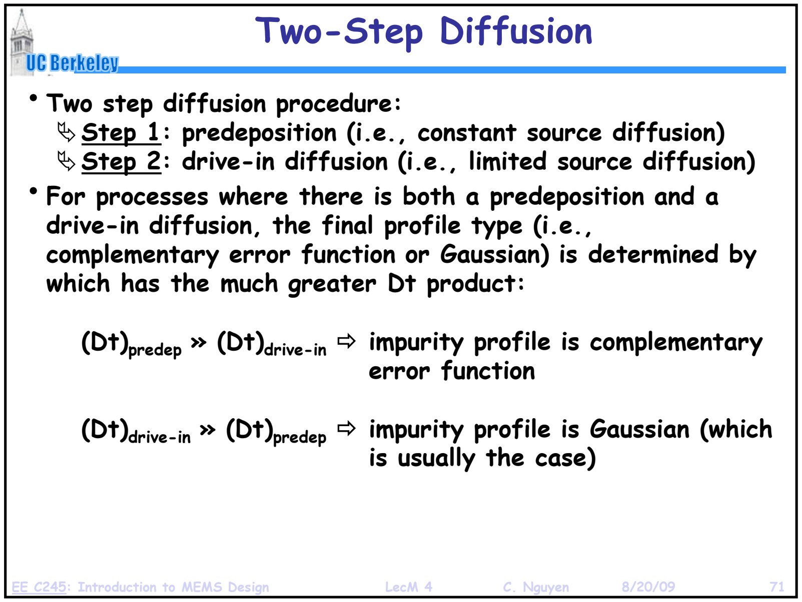
Get Gaussian Distribution:

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

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

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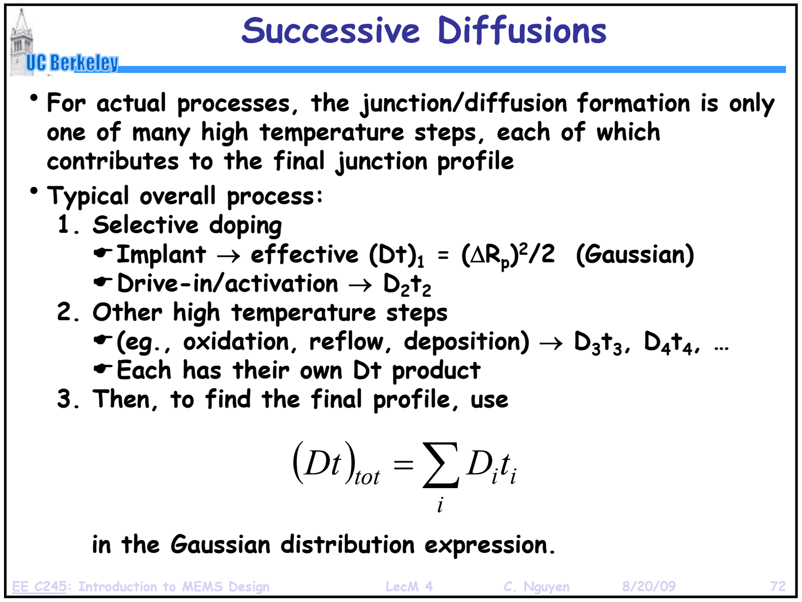
- Two step diffusion procedure:
  - **Step 1**: predeposition (i.e., constant source diffusion)
  - **Step 2**: drive-in diffusion (i.e., limited source diffusion)
- For processes where there is both a predeposition and a drive-in diffusion, the final profile type (i.e., complementary error function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

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

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



Successive Diffusions

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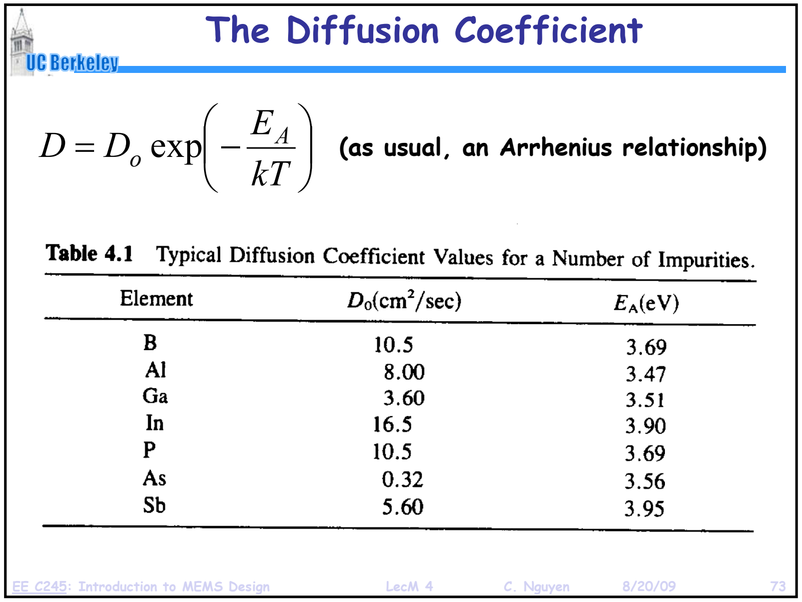
- For actual processes, the junction/diffusion formation is only one of many high temperature steps, each of which contributes to the final junction profile
- Typical overall process:
  1. Selective doping
     - Implant → effective $(Dt)_1 = (\Delta R_p)^2/2$ (Gaussian)
     - Drive-in/activation → 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

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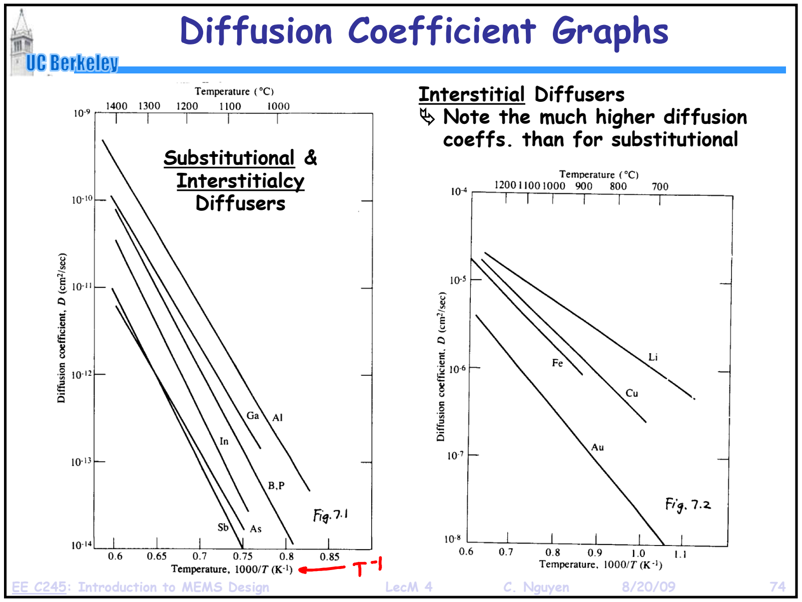
$$D = D_o \exp\left(-\frac{E_A}{kT}\right)$$ (as usual, an Arrhenius relationship)

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

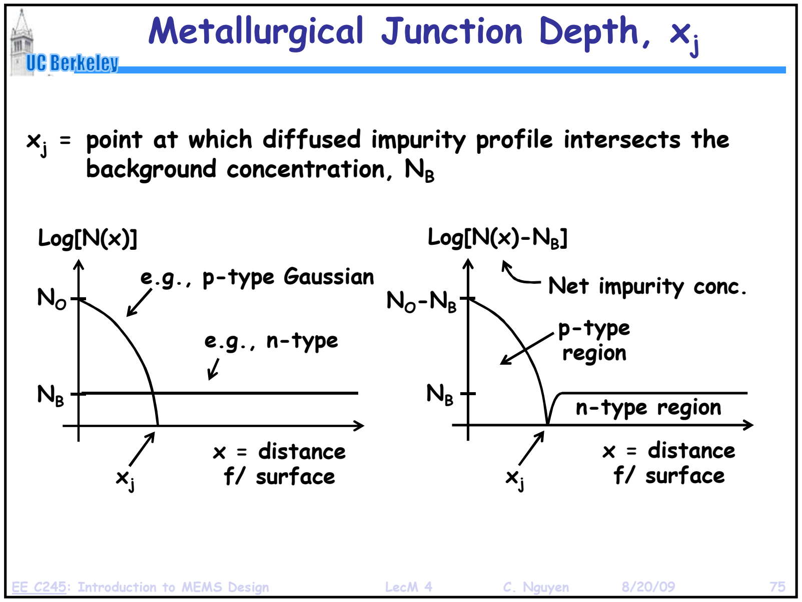


Diffusion Coefficient Graphs

Substitutional & Interstitialcy Diffusers

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

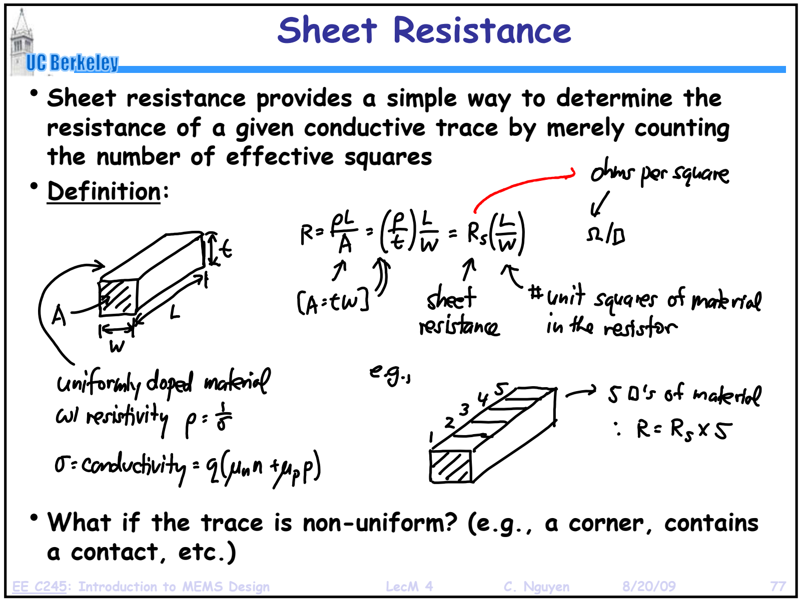
Expressions for x_j

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

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

- For a complementary error function profile:

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



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
- **Definition**:

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

ohms per square

Ω/□

[A=tW]

sheet resistance

unit squares of material in the resistor

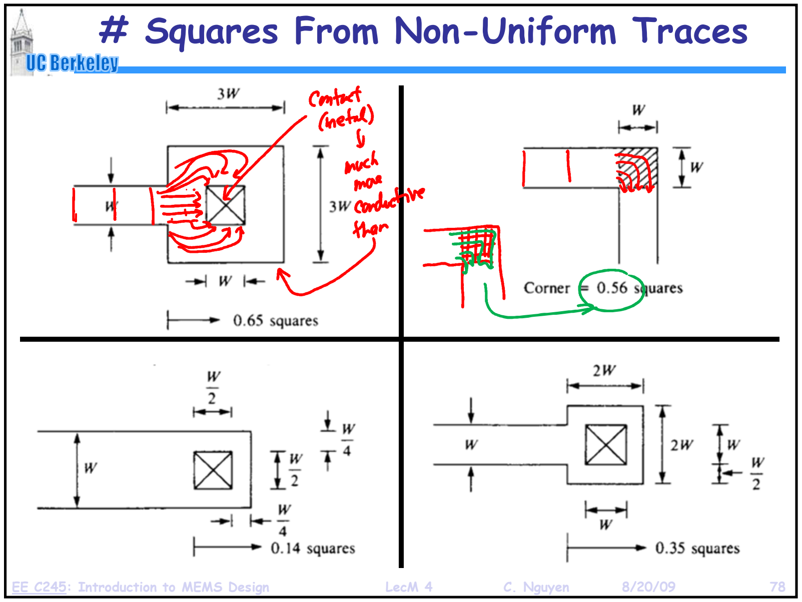
uniformly doped material w/ resistivity $\rho=\frac{1}{\sigma}$

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

e.g.,

→ 5 □'s of material ∴ $R=R_s\times 5$

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



Squares From Non-Uniform Traces

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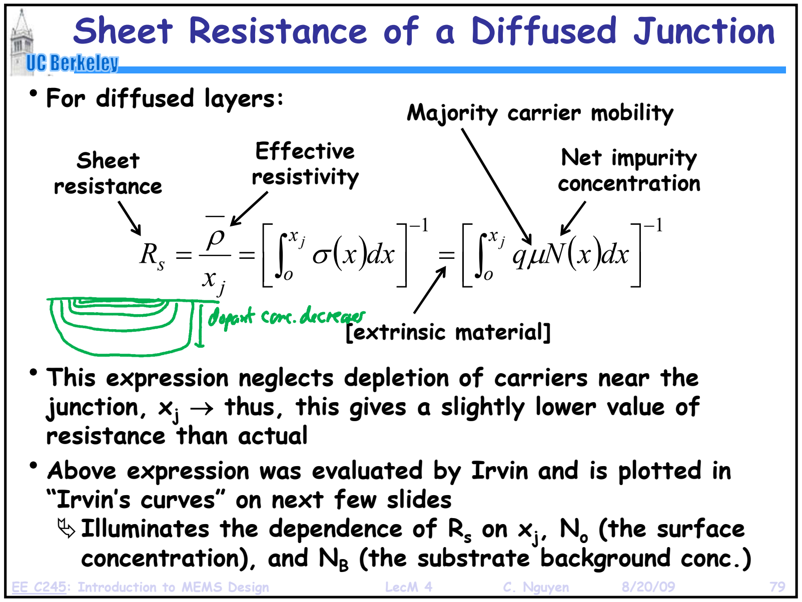

Sheet Resistance of a Diffused Junction

- For diffused layers:

Sheet resistance
Effective resistivity
Majority carrier mobility
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]

dopant conc. decreases

- This expression neglects depletion of carriers near the junction, x_j → 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.)

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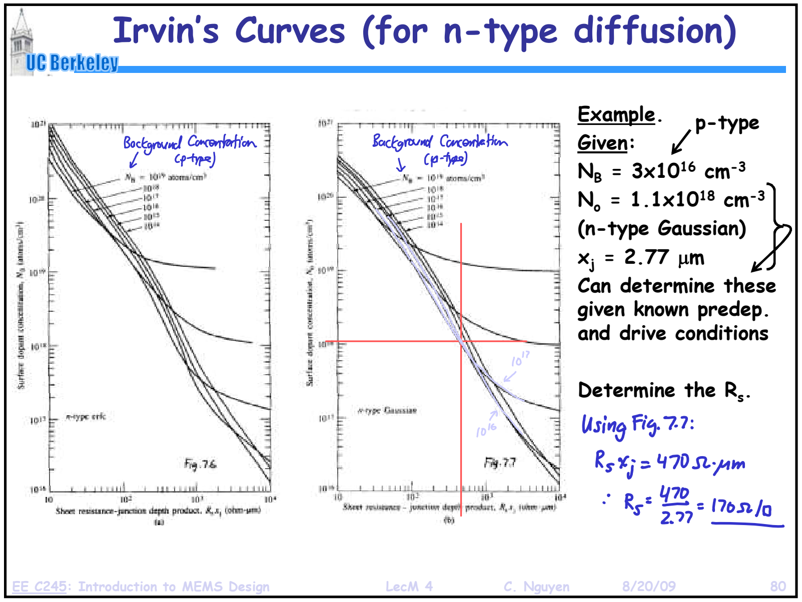

Irvin's Curves (for n-type diffusion)

Example.
Given: p-type
N_B = 3x10^{16} cm^{-3}
N_o = 1.1x10^{18} cm^{-3}
(n-type Gaussian)
x_j = 2.77 μm
Can determine these given known predep. and drive conditions

Determine the R_s.

Using Fig. 7.7:

$R_s x_j = 470\,\Omega\cdot\mu m$

$\therefore R_s = \frac{470}{2.77} = 170\,\Omega/\square$

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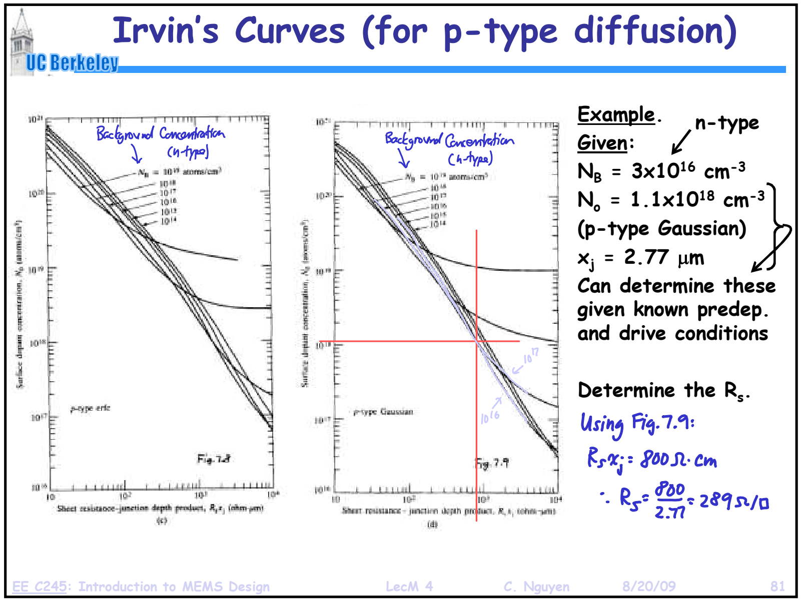

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Given: n-type
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(p-type Gaussian)
x_j = 2.77 μm
Can determine these given known predep. and drive conditions

Determine the R_s.

Using Fig. 7.9:

$R_s x_j = 800\,\Omega\cdot cm$

$\therefore R_s = \frac{800}{2.77} = 289\,\Omega/\square$

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