EE C245 – ME C218
Introduction to MEMS Design
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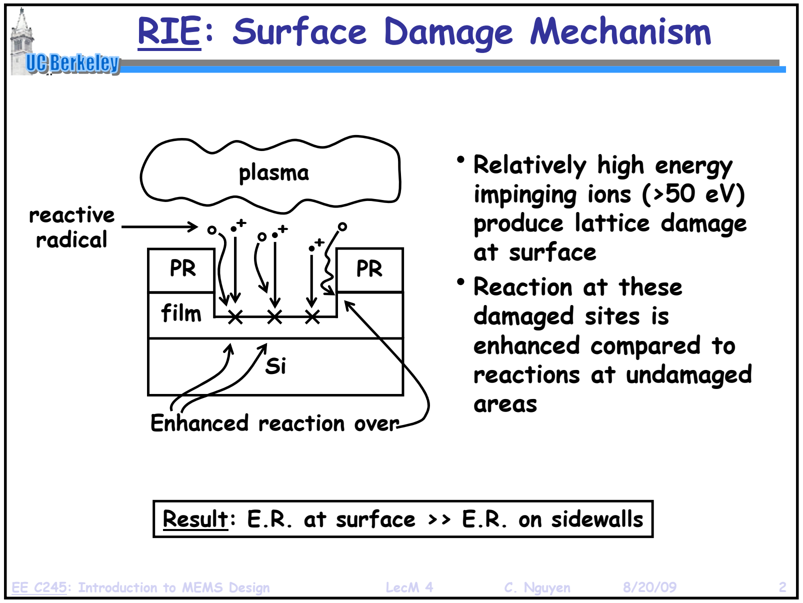
Lecture Module 4: Lithography, Etching, & Doping

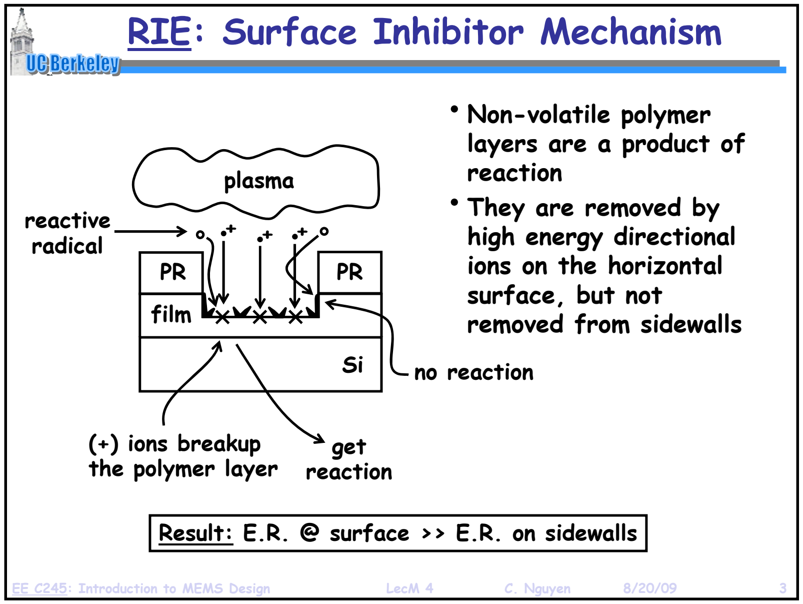
RIE: Surface Damage Mechanism



- Relatively high energy impinging ions (>50 eV) produce lattice damage at surface
- Reaction at these damaged sites is enhanced compared to reactions at undamaged areas

Result: E.R. at surface >> E.R. on sidewalls

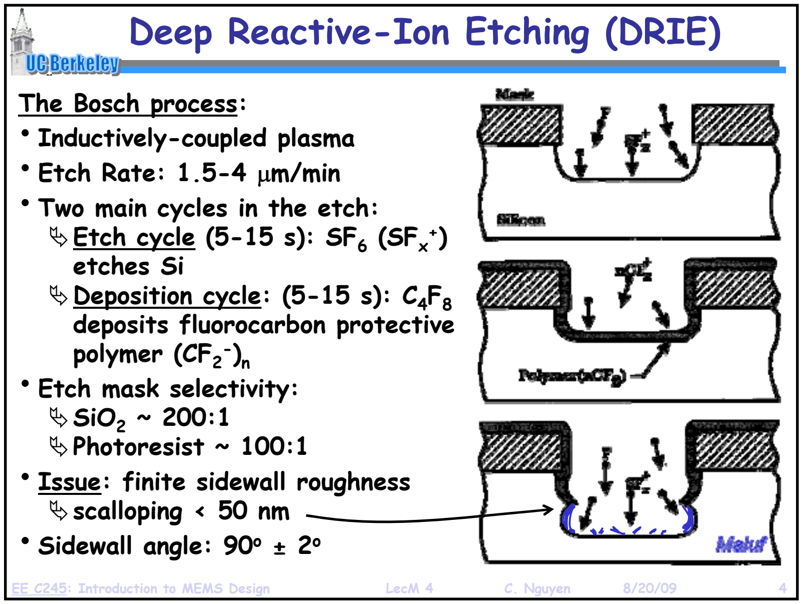
RIE: Surface Inhibitor Mechanism



- Non-volatile polymer layers are a product of reaction
- They are removed by high energy directional ions on the horizontal surface, but not removed from sidewalls

Result: E.R. @ surface >> E.R. on sidewalls

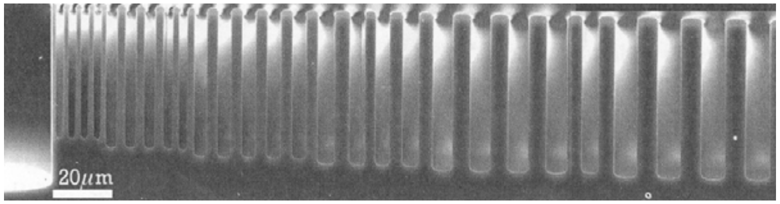
Deep Reactive-Ion Etching (DRIE)



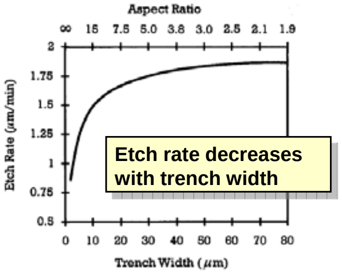
The Bosch process:

- Inductively-coupled plasma
- Etch Rate: 1.5-4 μm/min
- Two main cycles in the etch:
  - Etch cycle (5-15 s): SF_6 (SF_x^+) etches Si
  - Deposition cycle: (5-15 s): C_4F_8 deposits fluorocarbon protective polymer $(CF_2^-)_n$
- Etch mask selectivity:
  - SiO_2 ~ 200:1
  - Photoresist ~ 100:1
- Issue: finite sidewall roughness
  - scalloping < 50 nm
- Sidewall angle: 90° ± 2°

DRIE Issues: Etch Rate Variance



- Etch rate is diffusion-limited and drops for narrow trenches
  - Adjust mask layout to eliminate large disparities
  - Adjust process parameters (slow down the etch rate to that governed by the slowest feature)

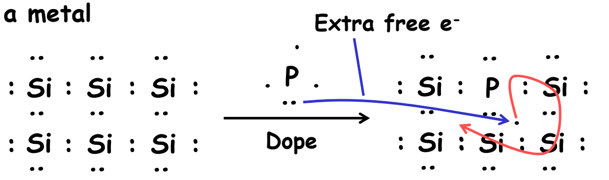


Etch rate decreases with trench width

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

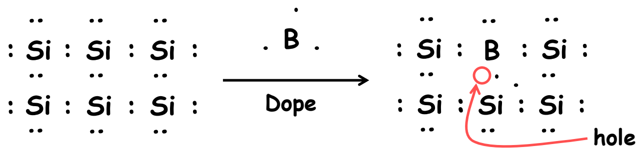
Doping of Semiconductors (cont.)

- **Conductivity Equation**:

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

charge magnitude on an electron
conductivity
electron mobility
electron density
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

Dopant Redistribution During Oxidation

Dopant Redistribution During Oxidation

- This must be considered and designed for when generating any process flow, especially for transistor circuits, e.g., CMOS
- During oxidation, the impurity concentration at the Si-SiO_2. interface can increase (pile-up) or deplete, depending upon the dopant type
- Whether a particular impurity depletes or piles up @ the interface depends on:

1. Diffusion coefficient, D (of the impurity in SiO_2)
2. Segregation coefficient, m:

$$m = \frac{\text{impurity equil. conc. in Si}}{\text{impurity equil. conc. in } \mathrm{SiO_2}}$$

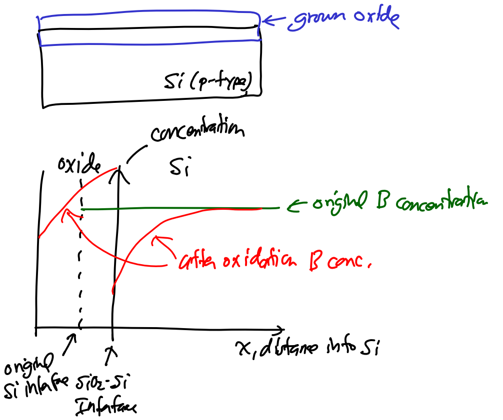
Dopant Behavior During Oxidation

- Segregation coefficient (m) and diffusion constant (D) combine to determine dopant behavior during oxidation:

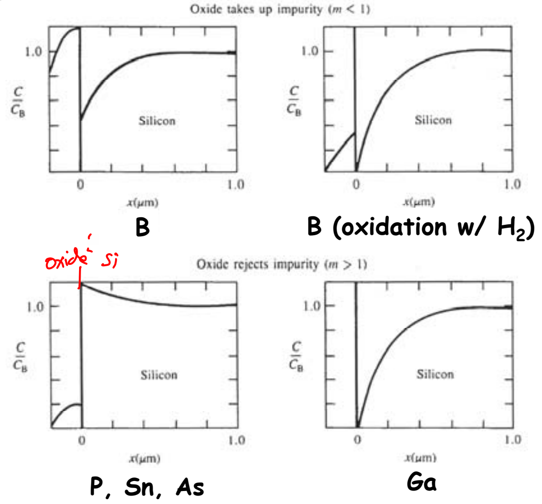
Impurity	m	D in SiO_2	Dopant Behavior During Oxidation
B	<0.3 (small)	Small	depl. f/Si surface, pile up in oxide
B (oxidation w/H_2)	<0.3 (small)	Large	depl. f/Si surface, depl. from oxide
P, Sn, As	~10 (large)	Small	pile up in Si, very little diff. into SiO_2
Ga	20 (large)	Large	depl. f/Si, depl. from oxide

e.g., wet oxidation where H_2 is present as a by-product.

So large that it depletes the dopant @ the Si surface despite



Dopant Redistribution During Oxidation

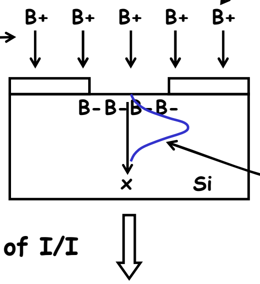


Ion Implantation

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:



Control current & time to control the dose.

Charged dopant accelerated to high energy by an E-Field (e.g., 100 keV)

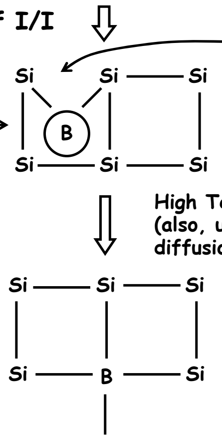
Masking material (could be PR, could be oxide, etc.)

Depth determined by energy & type of dopant

Result of I/I

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.

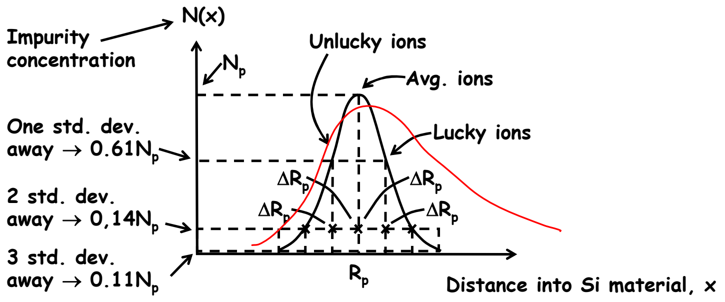
Ion collides with atoms and interacts with e-'s in the lattice → all of which slow it down and eventually stop it.

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.

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 = $Q = \int_0^\infty N(x)dx \; [ions/cm^2]$

For an implant completely contained within the Si:

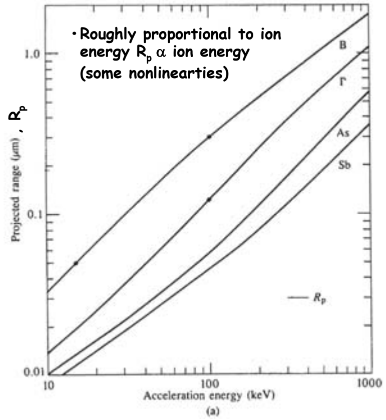
$$Q = \sqrt{2\pi} N_p \Delta R_p$$

Assuming the peak is in the silicon: (putting it in one-sided diffusion form) → So we can track the dopant front during a subsequent diffusion step.

$D_I = Q$

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

I/I Range Graphs



- Roughly proportional to ion energy $R_p \propto$ ion energy (some nonlinearties)

Figure 6.1

- R$_p$ is a function of the energy of the ion and atomic number of the ion and target material
- Lindhand, Scharff and Schiott (LSS) Theory:
- 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

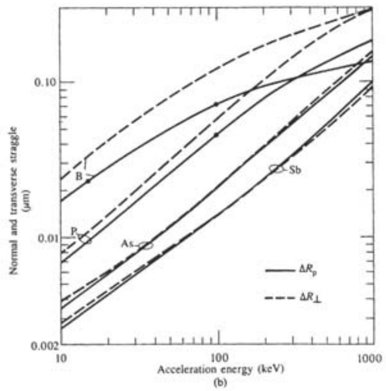


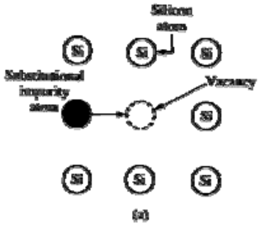
Figure 6.2

- Results for Si and SiO$_2$ surfaces are virtually identical → so we can use these curves for both

Diffusion

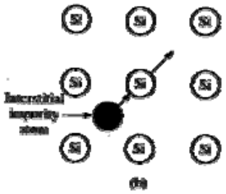
Diffusion in Silicon

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



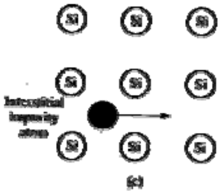
Substitutional Diffusion

- 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

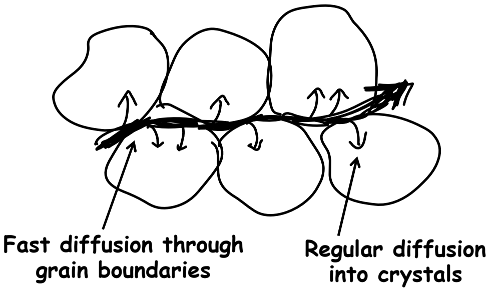


Interstitial Diffusion

- 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

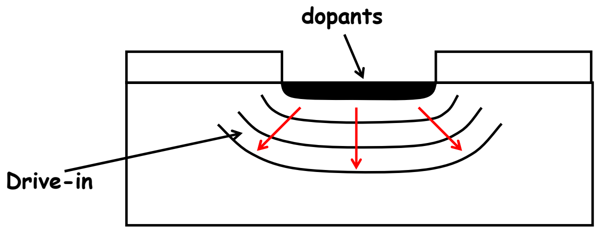


- In effect, larger surface area allows much faster volumetric diffusion

Basic Process for Selective Doping

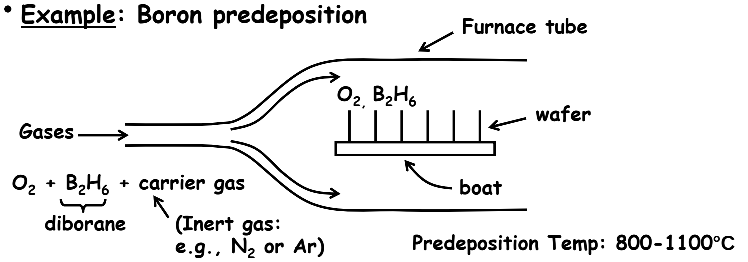
1. Introduce dopants (introduce a fixed dose Q of dopants)
   (i) Ion implantation
   (ii) Predeposition
2. Drive in dopants to the desired depth
   ↳ High temperature > 900°C in N_2 or N_2/O_2

- Result:



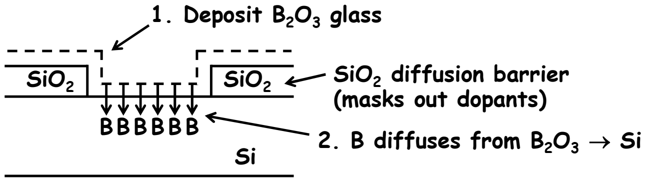
Predeposition

- 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% cm^{-2}
  - For ref: w/ ion implantation: 10^{11} – 10^{16} ± 1% (larger range & more accurate) cm^{-2}
- Example: Boron predeposition

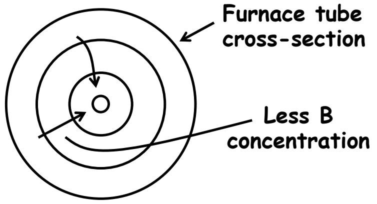

Furnace tube
O_2, B_2H_6
wafer
Gases
boat
O_2 + B_2H_6 + carrier gas
$\underbrace{B_2H_6}_{\text{diborane}}$
(Inert gas: e.g., N_2 or Ar)
Predeposition Temp: 800-1100°C

Ex: Boron Predeposition

- Basic Procedure:

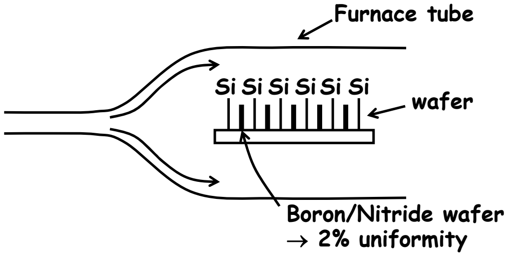

1. Deposit B_2O_3 glass
SiO_2
SiO_2
SiO_2 diffusion barrier (masks out dopants)
B B B B B B
2. B diffuses from B_2O_3 → Si
Si

- 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


Furnace tube cross-section
Less B concentration

Ex: Boron Predeposition (cont.)

For better uniformity, use solid source:


Furnace tube
Si Si Si Si Si Si
wafer
Boron/Nitride wafer
→ 2% uniformity

Reactions:

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

$Si + O_2 \rightarrow SiO_2$

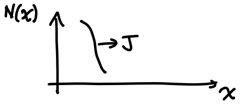
General Comments on Predeposition

- 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



⇒ 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)

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

↑ 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.)

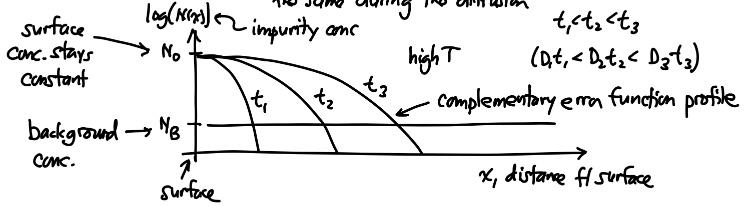
⇒ we're interested for now in the one-dimensional form:

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

$\left[\frac{\partial}{\partial x}(1) \text{ and substitute (2) in (1)}\right] \Rightarrow \frac{\partial N(x,t)}{\partial t} = D\frac{\partial^2 N(x,t)}{\partial x^2}$ [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) $N(0,t) = N_0$
(ii) $N(\infty,t) = 0$

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

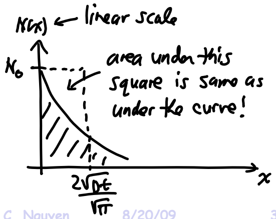
$$\boxed{N(x,t) = N_0\,\mathrm{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)}$$

⇒ 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

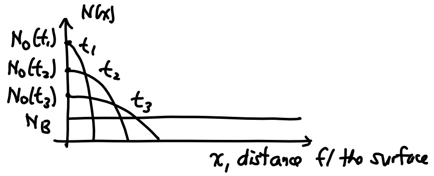
$$Q = \int_0^\infty N(x,t)dx \Rightarrow \boxed{Q(t) = N_0\frac{2\sqrt{Dt}}{\sqrt{\pi}}\ \mathrm{cm}^{-2}}$$

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



Diffusion Modeling (Limited Source)

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



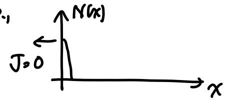
⇒ Boundary Condition:

(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)

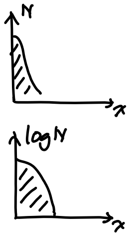
(iii) Usually make delta fcn. approx.: $N(x,0) = Q\,\delta(x)$

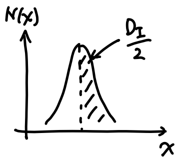
⇒ we can do this, because for sufficiently long diffusion times, no matter what the original shape of the dopant distribution, the diffused distribution will be the same

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 function of temperature, T
  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

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

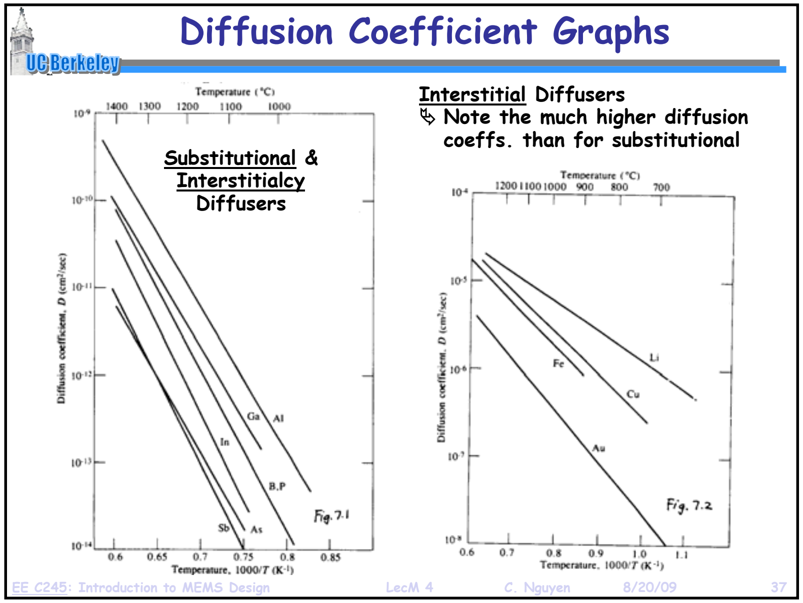
in the Gaussian distribution expression.

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.

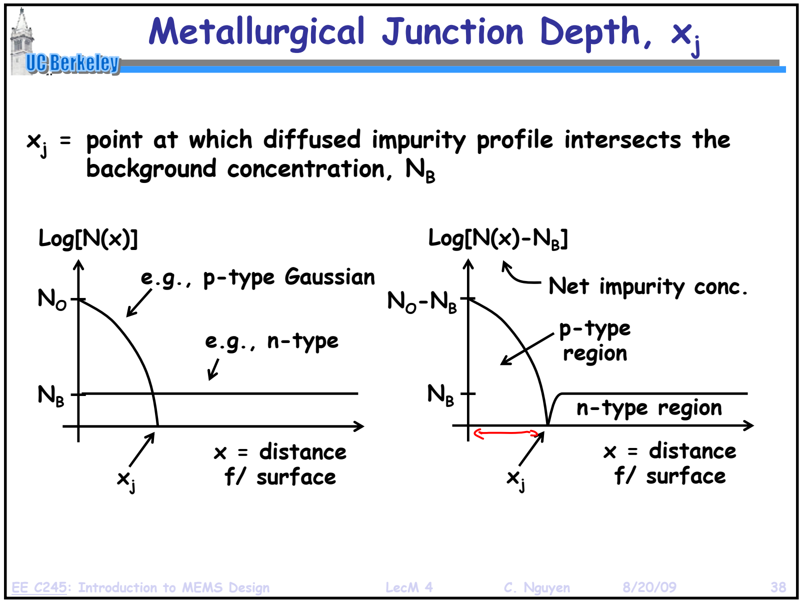
Element	D_o(cm²/sec)	E_A(eV)
B	10.5	3.69
Al	8.00	3.47
Ga	3.60	3.51
In	16.5	3.90
P	10.5	3.69
As	0.32	3.56
Sb	5.60	3.95



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

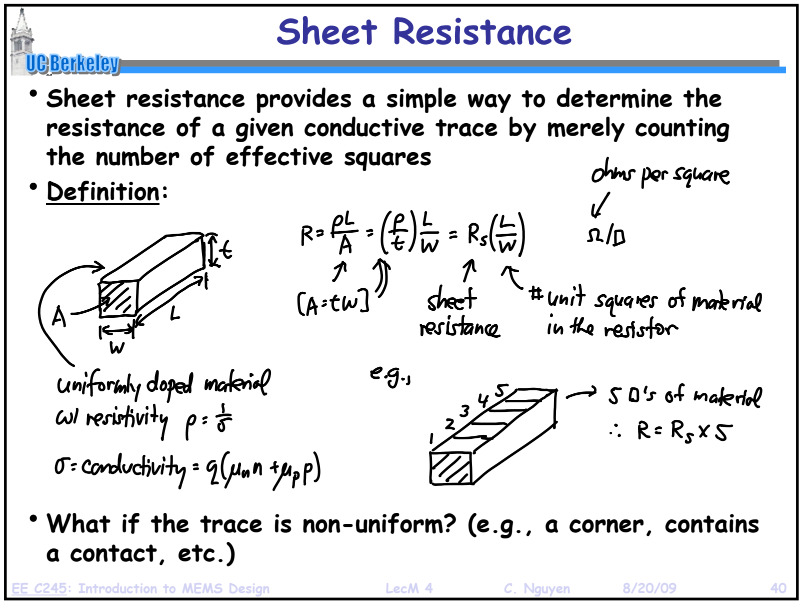
Expressions for x_j

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

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

- For a complementary error function profile:

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



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

$\Omega/\square$

[$A = tW$]

sheet resistance

unit squares of material in the resistor

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

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

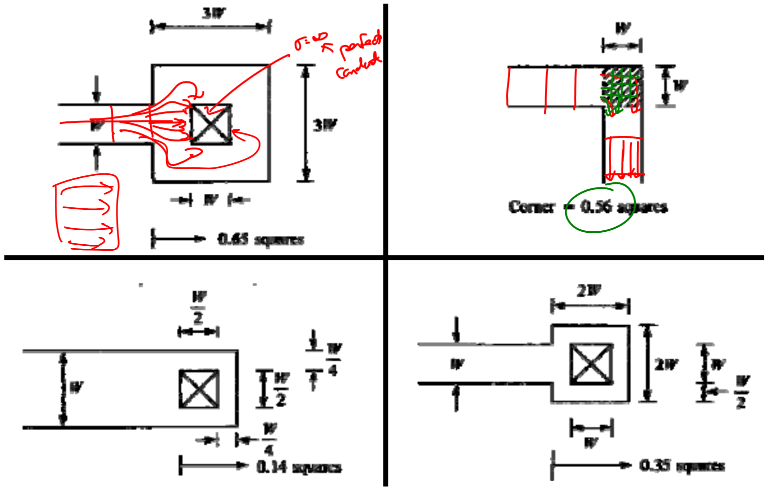
e.g.,

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



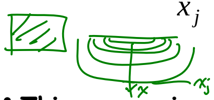
Sheet Resistance of a Diffused Junction

- For diffused layers:

Sheet resistance
Effective resistivity
Majority carrier mobility
Net impurity concentration

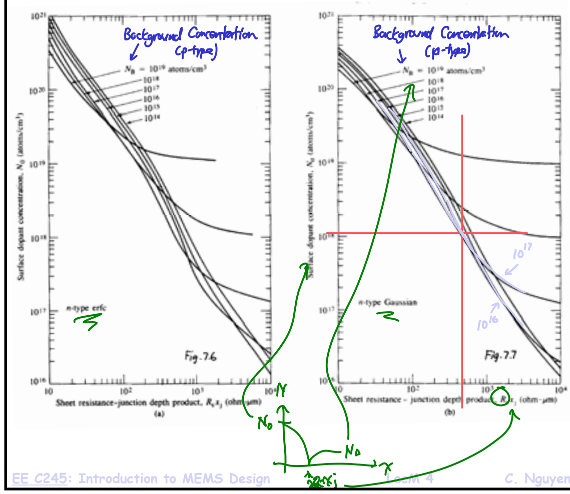
$$R_s = \frac{\bar{\rho}}{x_j} = \left[\int_o^{x_j} \sigma(x)dx\right]^{-1} = \left[\int_o^{x_j} q\mu N(x)dx\right]^{-1}$$

[extrinsic material]



- 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.)

Irvin's Curves (for n-type diffusion)



Example.
Given:
p-type
N_B = 3x10

$N_B = 3\text{x}10^{16}$ cm^{-3}
$N_o = 1.1\text{x}10^{18}$ cm^{-3}
(n-type Gaussian)
$x_j = 2.77$ μm
Can determine these given known predep. and drive conditions

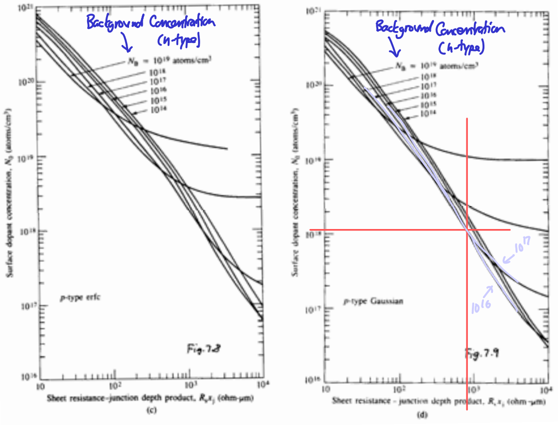
Determine the R_s.

Using Fig. 7.7:

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

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

Irvin's Curves (for p-type diffusion)



Example.
Given:
n-type

$N_B = 3\text{x}10^{16}$ cm^{-3}
$N_o = 1.1\text{x}10^{18}$ cm^{-3}
(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:

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

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