CHE323/CHE384
Chemical Processes for Micro- and Nanofabrication

Lecture 5
Doping

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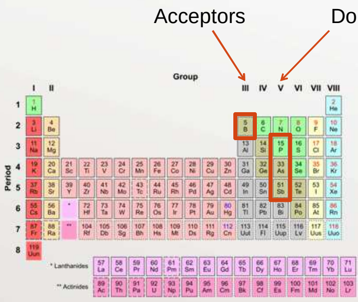
Doping

- Doping: intentionally adding impurities into the crystal structure to change n (mobile electron concentration) and p (mobile hole concentration) to be different from n_i
  - Intrinsic material: undoped, pure
  - Extrinsic material: doped semiconductor

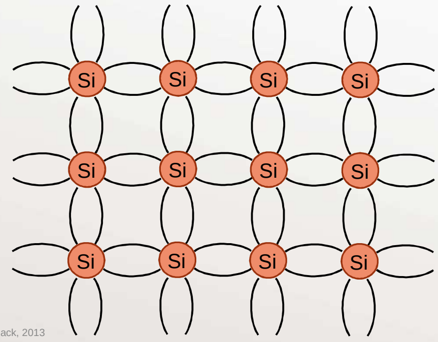
Two Types of Dopants



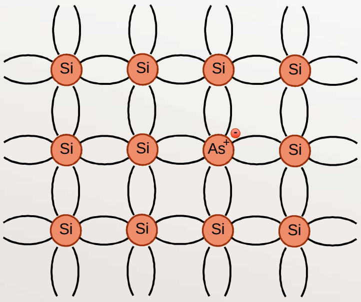
Acceptors

Donors

Intrinsic Silicon

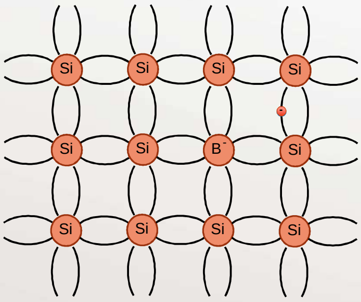


Donor (Group V) Impurity



- Donors have five electrons in their outer shell
- When the impurity is activated (incorporated into the crystal lattice), it has one unbonded electron
- This electron is easily removed at room temperature, resulting in an ionized dopant atom and a free electron

Acceptor (Group III) Impurity



- Acceptors have three electrons in their outer shell
- When the impurity is activated (incorporated into the crystal lattice), it needs one more electron to complete its bonds
- This electron is easily supplied by a nearby bond at room temperature, resulting in an ionized dopant atom and a mobile hole

Doping - The Math

- Charge balance: $N_D^+ + p = N_A^- + n$
- Mass action equation: $np = n_i^2$

$N_A = acceptor\ concetration$
$N_D = donor\ concetration$
$N_A^- = ionized\ acceptor\ conc.$
$N_D^+ = ionized\ donor\ conc.$

$n = mobile\ electron\ concetration$
$p = mobile\ hole\ concetration$

- At room temperature, $N_A^- \approx N_A, \quad N_D^+ \approx N_D$

The Math – an example

- Consider a wafer that is doped p-type, with $N_A = 2 \times 10^{16}\ cm^{-3}$.
- Now, add n-type dopant with $N_D = 1 \times 10^{18}\ cm^{-3}$. What are *n* and *p* (at room temp.)?
- Assume complete ionization: $N_A \approx N_A^-, \quad N_D \approx N_D^+$
- Solve simultaneous equations:

$$np = n_i^2 \qquad N_D^+ + p = N_A^- + n$$

The Math – an example (2)

- Simplification: since $N_D >> N_A$, we will have lots of mobile electrons (majority carrier) and not many holes (minority carrier)

$$N_D^+ + \underset{\substack{\uparrow \\ \text{small}}}{p} = N_A^- + n \quad \rightarrow \quad n \approx N_D - N_A = 9.8 \times 10^{17}\ cm^{-3}$$

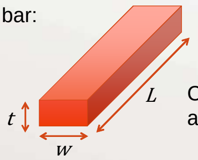
$$p = \frac{n_i^2}{n} = \frac{(1.5 \times 10^{10} cm^{-3})^2}{9.8 \times 10^{17}\ cm^{-3}} = 2.3 \times 10^2 cm^{-3}$$

Metal/Insulator Resistor

- Conductivity (σ) and resistivity (ρ = 1/σ) are material properties

Resistance of the bar:

$$R = \rho \frac{L}{A}$$



Cross-sectional area $A = wt$

Semiconductor Resistor

- Conductivity of a semiconductor can be varied by doping

$$\sigma = q\left(n\mu_n + p\mu_p\right)$$

q = charge on electron = 1.6×10^{-19} C
μ_n = electron mobility = 1500 cm^2/Vs for Si at 300K
μ_p = hole mobility = 450 cm^2/Vs for Si at 300K

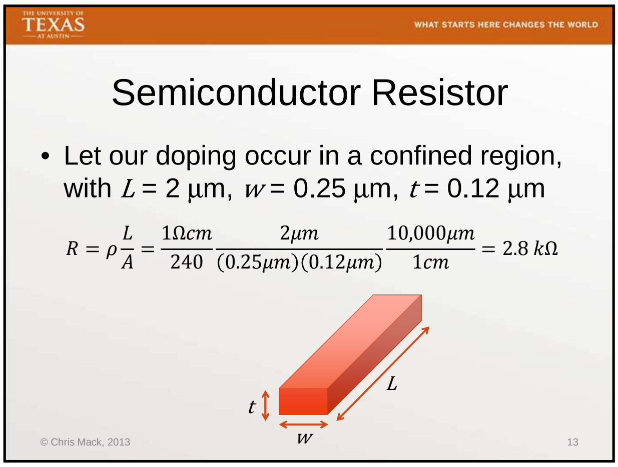
Semiconductor Resistor

- A wafer that is doped p-type, with $N_A = 2 \times 10^{16}\ cm^{-3}$. Now, add n-type dopant with $N_D = 1 \times 10^{18}\ cm^{-3}$ in the region where we want our resistor.

$$\sigma_{wafer} = q\left(n\mu_n + p\mu_p\right) \approx qN_A\mu_p = 1.44\ (\Omega cm)^{-1}$$

[Units: 1 C/s = 1 A (amperes), 1 V/A = 1 Ω (ohm)]

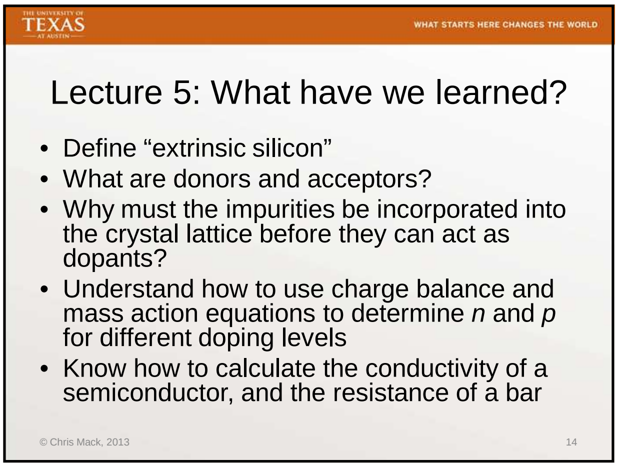
$$\sigma_{resistor} = q\left(n\mu_n + p\mu_p\right) \approx qN_D\mu_n = 240\ (\Omega cm)^{-1}$$



Semiconductor Resistor

- Let our doping occur in a confined region, with L = 2 µm, w = 0.25 µm, t = 0.12 µm

$$R = \rho\frac{L}{A} = \frac{1\Omega cm}{240}\frac{2\mu m}{(0.25\mu m)(0.12\mu m)}\frac{10{,}000\mu m}{1cm} = 2.8\ k\Omega$$



Lecture 5: What have we learned?

- Define “extrinsic silicon”
- What are donors and acceptors?
- Why must the impurities be incorporated into the crystal lattice before they can act as dopants?
- Understand how to use charge balance and mass action equations to determine *n* and *p* for different doping levels
- Know how to calculate the conductivity of a semiconductor, and the resistance of a bar