Unit 1: Material Properties

Lecture 1.6: Doping

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Doping makes semiconductors useful

metal

semiconductor

insulator

gold (Au)

silicon (Si)

glass (SiO₂)

Lundstrom: 2018
Things have changed

“One shouldn’t work on semiconductors, that is a filthy mess; who knows whether any semiconductors exist.”

Wolfgang Pauli, 1931
Recall: Bonding cartoon of Si lattice

shared valence electron

atom plus core levels

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Doping a semiconductor

Phosphorus or Arsenic

"N-type" doping

Gallium or boron

"P-type doping"
Dopants in Si

P-type dopants come from column III

N-type dopants come from column V
N-type doping

$E_B \approx -0.1 \text{ eV}$

Weakly bound

Easily broken at room temperature

Produces an electron in the conduction band.
Concentration of dopants:

\[ N_D \text{ cm}^{-3} \]

Concentration of ionized donors:

\[ N_D^+ \text{ cm}^{-3} \]

Concentration of electrons in the conduction band:

\[ n \approx N_D^+ \text{ cm}^{-3} \]
Be careful about units!

\[ n \approx N^+ \text{ cm}^{-3} \]

We will be working in SI (MKS) units. The carrier concentration should be given per cubic meter, but semiconductor people like to mix their units.

It is safest to do the calculations in SI units, and then convert to cubic cm.

\[ n = 10^{26} \text{ m}^{-3} \rightarrow n = 10^{26} \frac{1}{m^3} \times \left( \frac{10^{-2} \text{ m}}{\text{cm}} \right)^3 \rightarrow n = 10^{20} \text{ cm}^{-3} \]
Binding energy of the donor

Hydrogen atom:

\[ E_B = -\frac{m_0 q^4}{2 \left(4\pi\epsilon_0 \hbar\right)^2} \text{ eV} \]

\[ E_B = -13.6 \text{ eV} \]

Donor in Si:

\[ \epsilon = K_S \epsilon_0 \]

\[ = 11.8 \times \left(8.854 \times 10^{-12} \text{ F/m}\right) \]

\[ m^*_n = 1.18 m_0 \]

\[ E_B \approx -0.1 \text{ eV} \]
Energy band view (n-type)

\[ E_G = 1.1 \text{ eV} \]

n-doped Si

\[ n \approx 10^{18} \text{ cm}^{-3} \]

\[ E_C \]

\[ E_V \]

\[ p = ? \text{ cm}^{-3} \]

neutral donor  ionized donor

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\[ N_D = 10^{18} \text{ cm}^{-3} \]

\[ N_D^+ = 10^{18} \text{ cm}^{-3} \]

\[ n \approx N_D^+ = 10^{18} \text{ cm}^{-3} \]

\[ p \approx ? \]

(T = 300 K)

\[ 10^{14} \leq N_D \leq 10^{20} \text{ cm}^{-3} \]

\[ N_{\text{atoms}} \approx 5 \times 10^{22} \text{ cm}^{-3} \]
P-type doping

Boron or gallium

Missing bond
Ionized acceptor

Concentration of dopants:
\[ N_A \text{ cm}^{-3} \]
Concentration of ionized acceptors:
\[ N_A^- \text{ cm}^{-3} \]
Concentration of “holes” in the valence band:
\[ p \approx N_A^- \text{ cm}^{-3} \]
Energy band view (p-type)

$p$-doped Si

neutral acceptor ions \\
ionized acceptor

\[ E_C \]
\[ n = ? \text{ cm}^{-3} \]

\[ E_G = 1.1 \text{ eV} \]

\[ E_{AV} \approx 0.05 \text{ eV} \]

\[ E_V \]
\[ p \approx 10^{18} \text{ cm}^{-3} \]

\[ N_A = 10^{18} \text{ cm}^{-3} \]
\[ N_A^- = 10^{18} \text{ cm}^{-3} \]
\[ p \approx N_A^- = 10^{18} \text{ cm}^{-3} \]
\[ n \approx ? \]

(T = 300 K)

\[ 10^{14} \leq N_A \leq 10^{20} \text{ cm}^{-3} \]
“Deep donors” and “deep acceptors”

If the donor or acceptor level is much larger than kT (at room temperature), we say that the level is “deep”). Donors and acceptors will be partially ionized at room temperature.

“Shallow” donors and acceptors are fully ionized at room temperature.
1) What type of dopant is Si in GaAs?

a) n-type
b) p-type
c) either n-type or p-type
d) neither n-type nor p-type
e) don’t know
Si vs. GaAs crystals

**Si**
- Diamond lattice

**GaAs**
- Zinc blende lattice
Every Ga atom has 4 NN As atoms.

Every As atom has 4 NN Ga atoms.
Si in GaAs: Two possibilities

Si on a Ga site is a donor.

Si on a As site is an acceptor.

Si is an “amphoteric” dopant in GaAs.

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How does the carrier concentration vary with $T$?

$T = 0 \text{ K}$

No extrinsic carriers due to doping, and no intrinsic carriers due to thermal excitation across the band gap.
Low temperature

$T > 0 \text{ K}$

$E_C \quad n = N_p^+ > 0 \text{ cm}^{-3}$

$k_B T < E_{CD}$

$k_B T \ll E_G = 1.1 \text{ eV}$

$E_V$

A few extrinsic carriers due to doping, but no intrinsic carriers due to thermal excitation across the band gap.
Room temperature (shallow dopants)

\[ T = 300 \text{ K} \]

\[ n = N_D^+ = N_D \text{ cm}^{-3} \]

\[ k_B T \approx E_{CD} \]

\[ k_B T \ll E_G = 1.1 \text{ eV} \]

Many extrinsic carriers due to doping, but very few intrinsic carriers due to thermal excitation across the band gap.
High temperature

\[ T >> 300 \text{ K} \]

Extrinsic carriers due to doping, but also many intrinsic carriers due to thermal excitation across the band gap. Also many holes in the valence band now.
At high temperatures, the intrinsic carriers produced by thermal excitation across the bandgap overwhelm the extrinsic carriers produced by doping.

Because semiconductor devices are produced by selective doping, the device ceases to operate.

Semiconductor devices for operation at high temperature should be made with materials with large band gaps, such as SiC and GaN.
Carrier concentration vs. temperature

\[
\frac{n}{N_D} = 1.0 \quad \frac{n}{N_D} = 0 \quad \frac{n}{N_D} = n_i
\]

freeze out \quad extrinsic \quad intrinsic

0 K \quad 300 K \quad 600 K

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Summary

To dope a semiconductor, we replace a few atoms with atoms from a different column of the periodic table.

Ionized dopants produce electrons in the conduction band or holes in the valence band.

Dopants can be energetically shallow or deep.

The carrier concentration vs. temperature characteristic has freeze out, extrinsic, and intrinsic regions.

A low temperatures, semiconductors become insulators.