Lecture #2

OUTLINE

- Energy-band model
- Doping

Read: Chapter 2

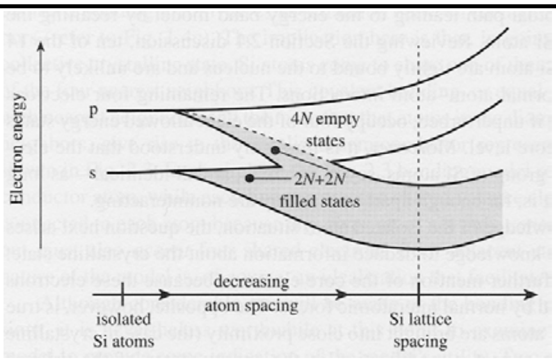
Definition of Terms

n = number of electrons/cm^3
p = number of holes/cm^3
n_i = intrinsic carrier concentration

In a pure semiconductor,

$$n = p = n_i$$

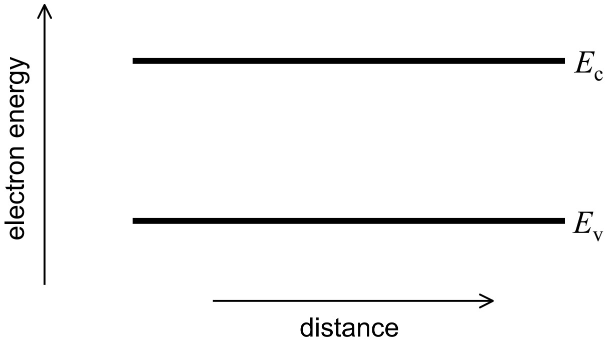
Si: From Atom to Crystal



Energy states in Si atom → energy bands in Si crystal

- The highest nearly-filled band is the ***valence band***
- The lowest nearly-empty band is the ***conduction band***

Energy Band Diagram

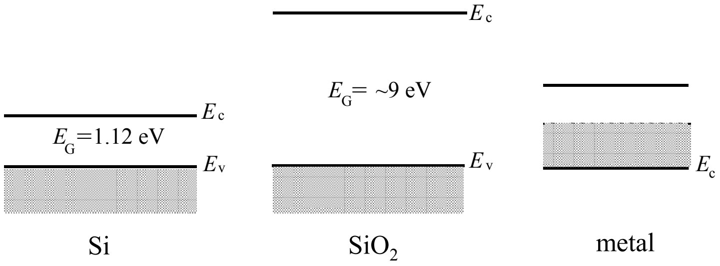


Simplified version of energy band model, indicating

- bottom edge of the conduction band ($\boldsymbol{E_c}$)
- top edge of the valence band ($\boldsymbol{E_v}$)

➢ E_c and E_v are separated by the **band gap energy $\boldsymbol{E_G}$**

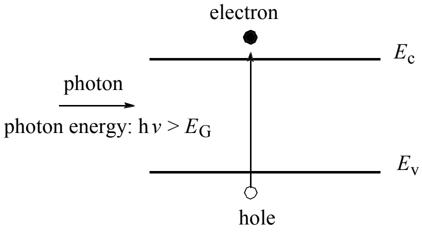
Band Gap and Material Classification



- Filled bands and empty bands do not allow current flow
- Insulators have large E_G
- Semiconductors have small E_G
- Metals have no band gap
  - conduction band is partially filled

Measuring Band Gap Energy

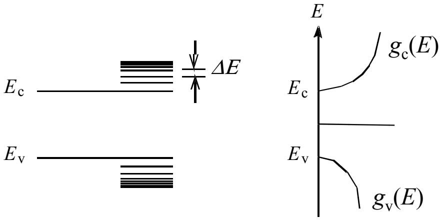
- E_G can be determined from the minimum energy ($h\nu$) of photons that are absorbed by the semiconductor.



Band gap energies of selected semiconductors

Semiconductor	**Ge**	**Si**	**GaAs**
Band gap (eV)	0.67	1.12	1.42

Density of States



$g(E)dE$ = number of states per cm^3 in the energy range between E and $E+dE$

Near the band edges:

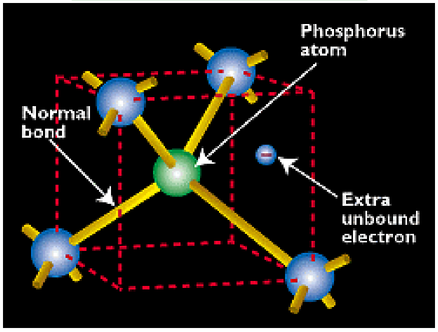
$$g_c(E) = \frac{m_n^* \sqrt{2m_n^*(E-E_c)}}{\pi^2 \hbar^3} \qquad E \geq E_c$$

$$g_v(E) = \frac{m_p^* \sqrt{2m_p^*(E_v-E)}}{\pi^2 \hbar^3} \qquad E \leq E_v$$

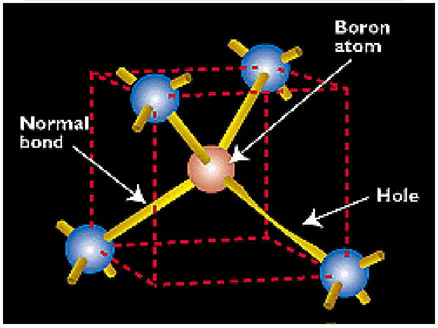
Doping

By substituting a Si atom with a special impurity atom (Column V or Column III element), a conduction electron or hole is created.

Donors: P, As, Sb



Acceptors: B, Al, Ga, In



Doping Silicon with Donors

Example: Add arsenic (As) atom to the Si crystal

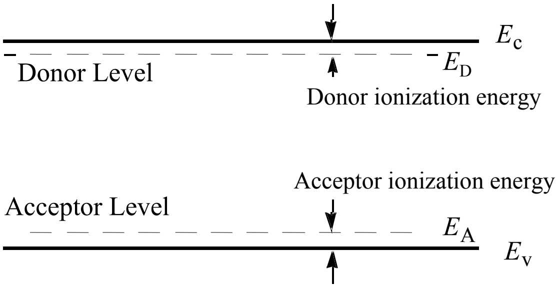
The loosely bound 5th valence electron of the As atom "breaks free" and becomes a mobile electron for current conduction.

Doping Silicon with Acceptors

Example: Add boron (B) atom to the Si crystal

The B atom accepts an electron from a neighboring Si atom, resulting in a missing bonding electron, or "hole". The hole is free to roam around the Si lattice, carrying current as a positive charge.

Donor / Acceptor Levels (Band Model)



Ionization energy of selected donors and acceptors in silicon

	Donors			Acceptors		
Dopant	Sb	P	As	B	Al	In
Ionization energy, E_c-E_d or E_a-E_v (meV)	39	45	54	45	67	160

Charge-Carrier Concentrations

N_D: ionized donor concentration (cm^{-3})
N_A: ionized acceptor concentration (cm^{-3})

Charge neutrality condition: $N_D + p = N_A + n$

At thermal equilibrium, $np = n_i^2$ ("Law of Mass Action")

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

Note: Carrier concentrations depend on *net* dopant concentration (N_D - N_A) !

N-type Material

N_D >> **N_A**

($N_D - N_A >> n_i$)**:**

P-type Material

N_A >> **N_D**

($N_A - N_D >> n_i$)**:**

Terminology

donor: impurity atom that increases n

acceptor: impurity atom that increases p

n-type material: contains more electrons than holes

p-type material: contains more holes than electrons

majority carrier: the most abundant carrier

minority carrier: the least abundant carrier

intrinsic semiconductor: $n = p = n_i$

extrinsic semiconductor: doped semiconductor

Summary: Band Model

- Splitting of allowed atomic energy levels occurs in a crystal
  - Separation between energy levels is small, so we can consider them as bands of continuous energy levels
    - Highest nearly-filled band is the ***valence band***
    - Lowest nearly-empty band is the ***conduction band***

- Energy-band diagram:
  - Shows only bottom edge of conduction band E_c and top edge of valence band E_v
  - E_c and E_v are separated by the band-gap energy E_G
  - Dopants introduce localized energy levels within the band gap:
    - donor level: slightly below E_c
    - acceptor level: slightly above E_v

Summary: Doping

- **Dopants in Si:**
  - Reside on lattice sites (substituting for Si)
  - Group V elements contribute conduction electrons, and are called ***donors***
  - Group III elements contribute holes, and are called ***acceptors***
  - Very low ionization energies (<50 meV)
    → ionized at room temperature

Dopant concentrations typically range from 10^{14} cm^{-3} to 10^{20} cm^{-3}