ECC01: Basic Electronics

Course Outcomes:

CO1: Knowledge of Semiconductor Physics and Devices.

CO2: Have an in depth understanding of basic electronic circuit, construction and operation.

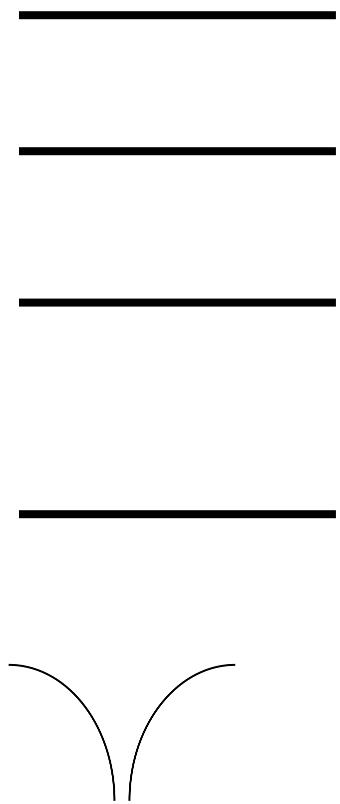
CO3: Ability to make proper designs using these circuit elements for different applications.

CO4: Learn to analyze the circuits and to find out relation between input and output.

Basics of Semiconductor

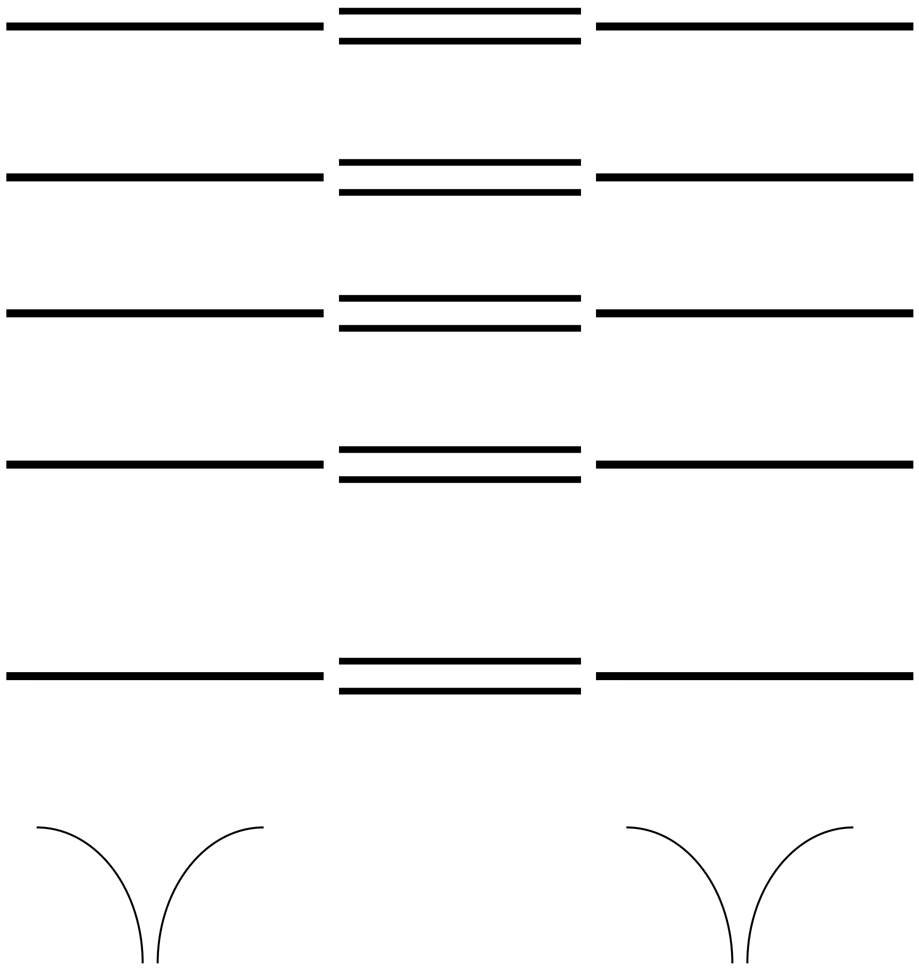
Classifications of Materials
I Metal
II Insulator
III Semiconductor

Band Gap



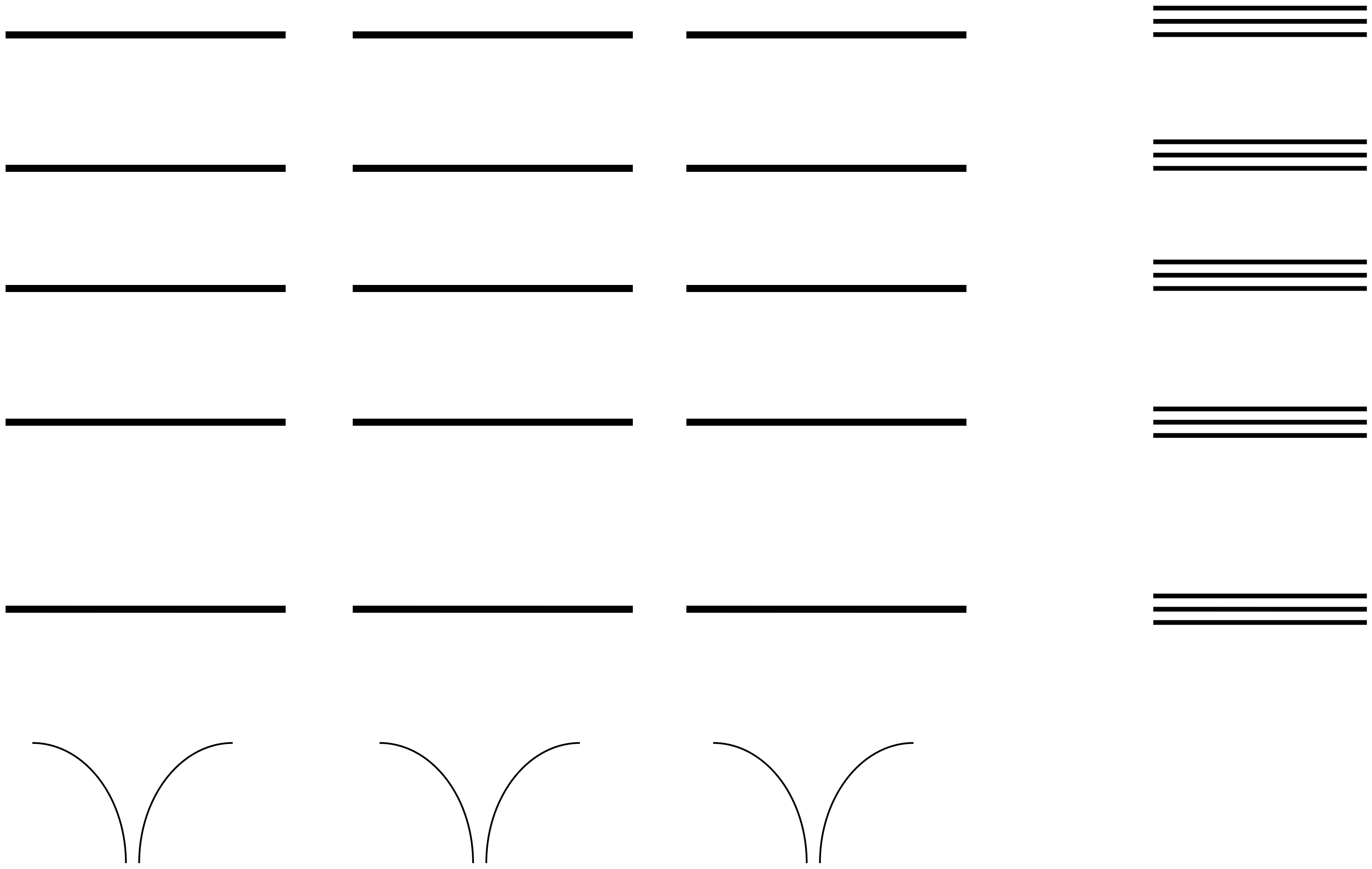
- atom has discrete energy levels

Energy Bands



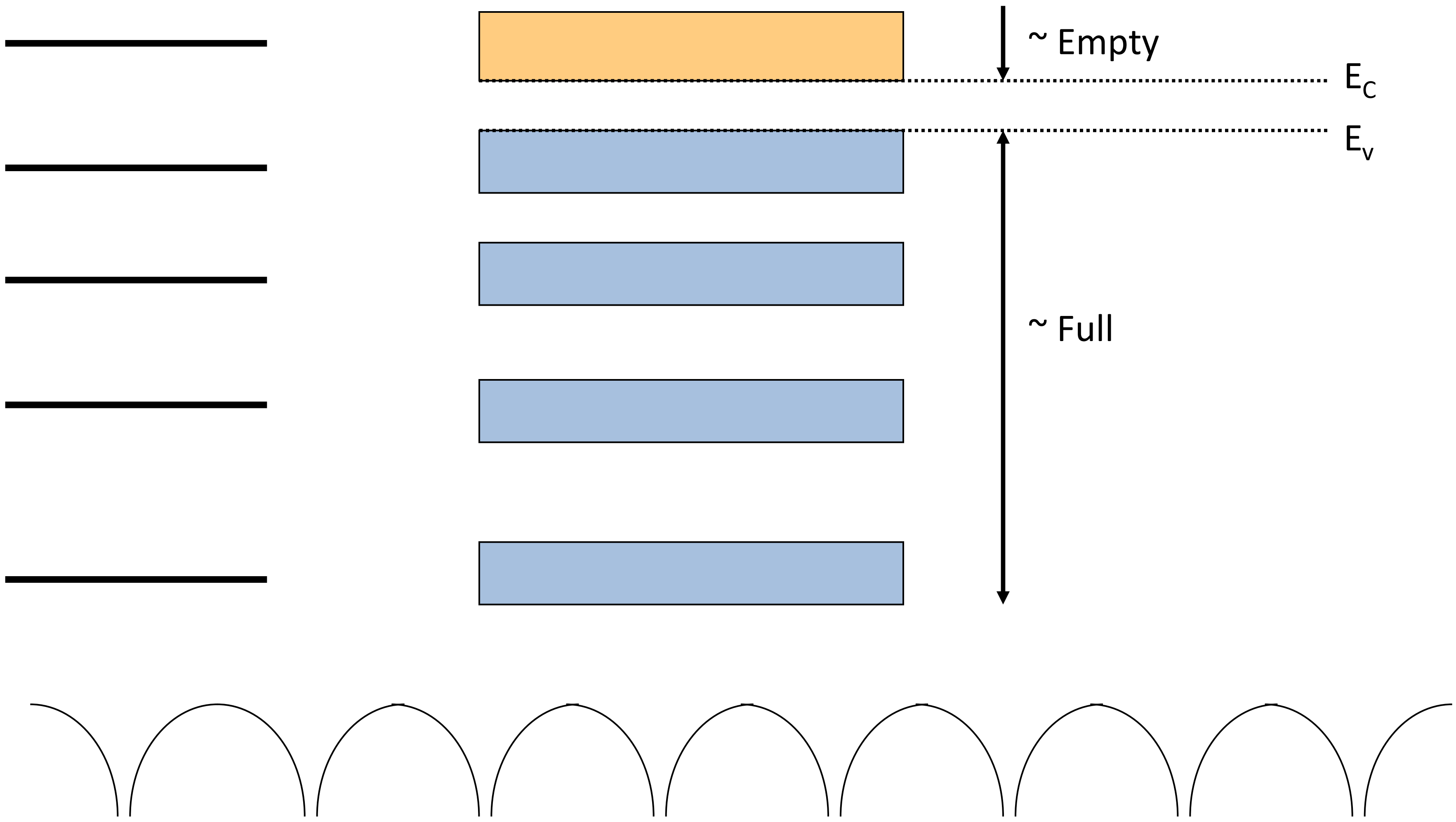
- 2 atoms have doublet energy levels

Energy Bands



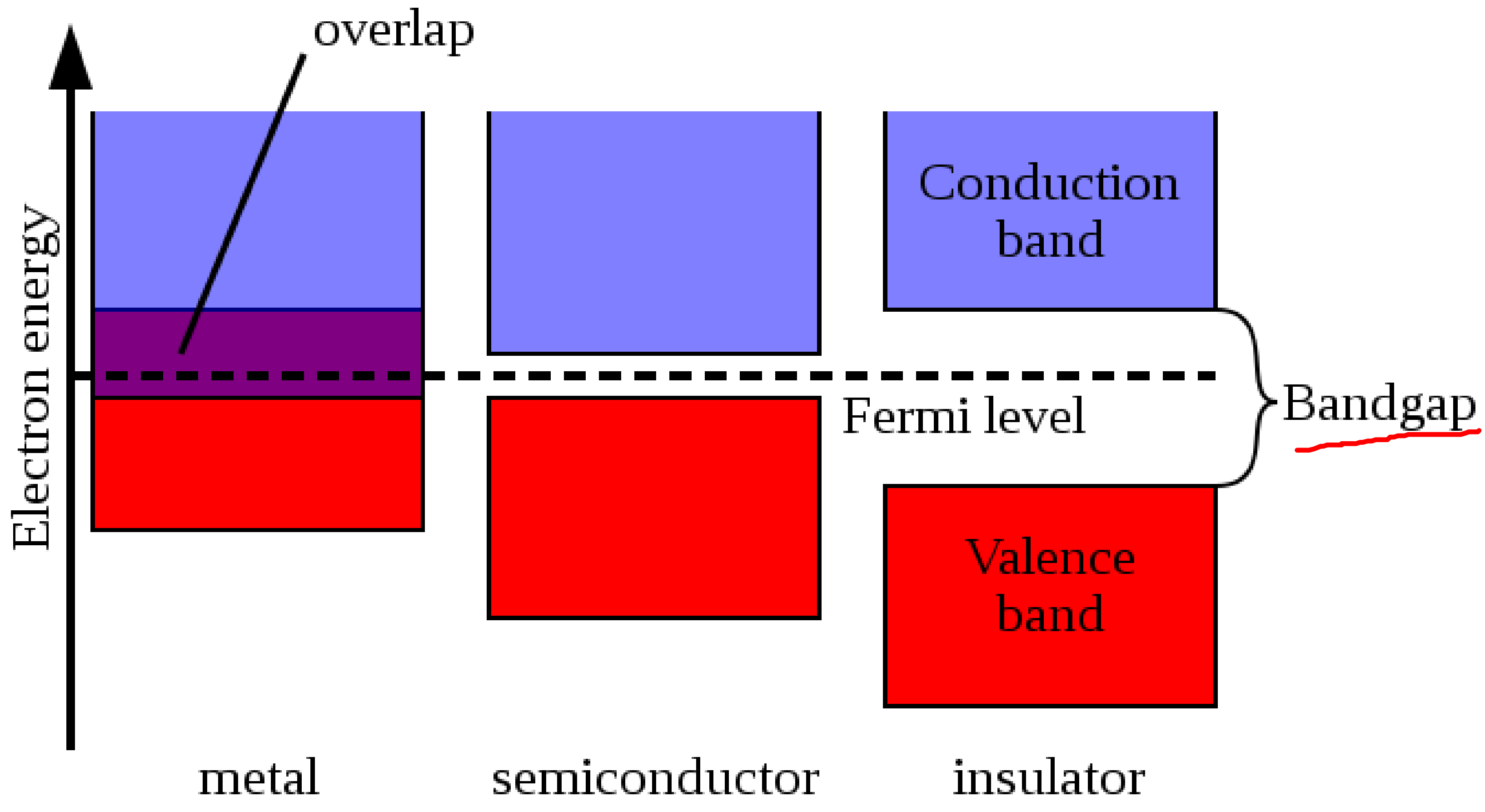
- 3 atoms have triplet energy levels, etc.

Energy Bands



- many atoms in crystal → energy bands

Band Diagrams



Fermi-Dirac Distribution

Fermi-Dirac statistics

- ***Distribution of electrons over a range of allowed energy levels at thermal equilibrium***

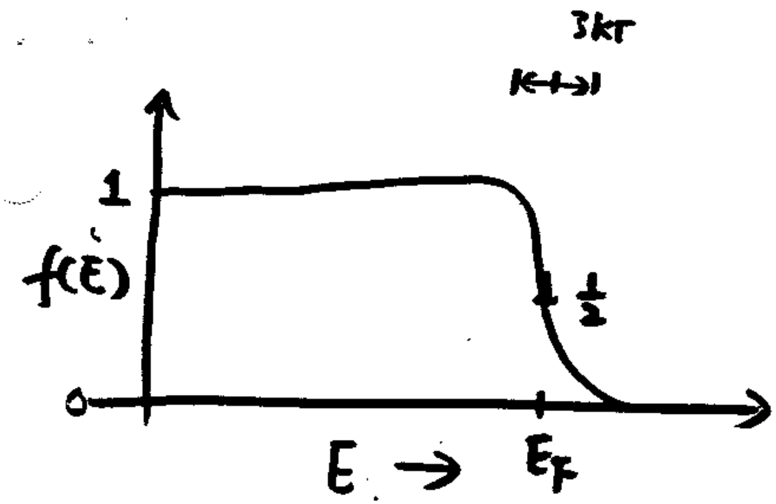
$$F(E) = \frac{1}{1 + \exp\left[\frac{(E - E_F)}{kT}\right]}$$

Probability that an available energy state at E will be occupied by an electron at absolute temperature T

Mathematically, E_F (Fermi Energy/Fermi Level) is the energy at which f(E) = 1/2

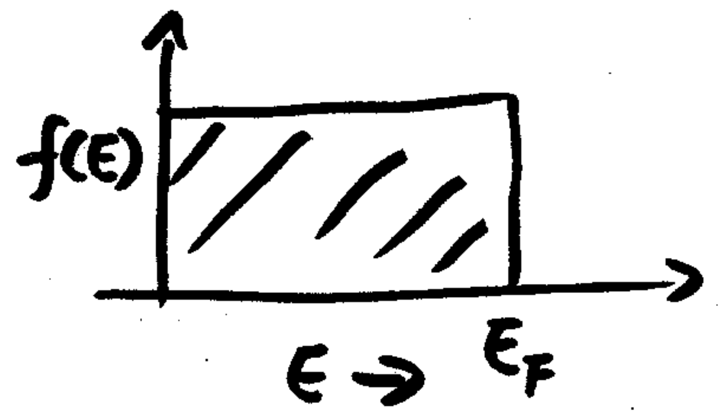
Fermi-Dirac Distribution

$$F(E) = \frac{1}{1 + \exp\left[\frac{(E - E_F)}{kT}\right]}$$

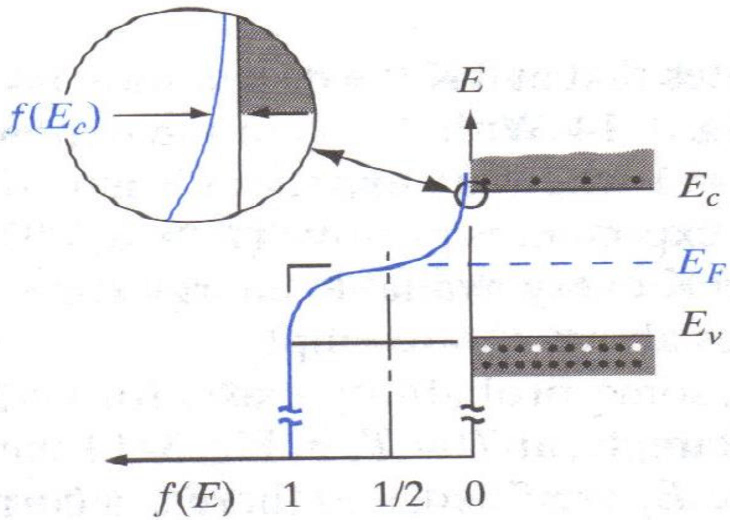


The transition region in $(E - E_F)$ from $f(E) = 1$ to $f(E) = 0$ is within 3 k T.

When $T \rightarrow 0$,
E is discontinuous at $E = E_F$.



Fermi-Dirac Distribution



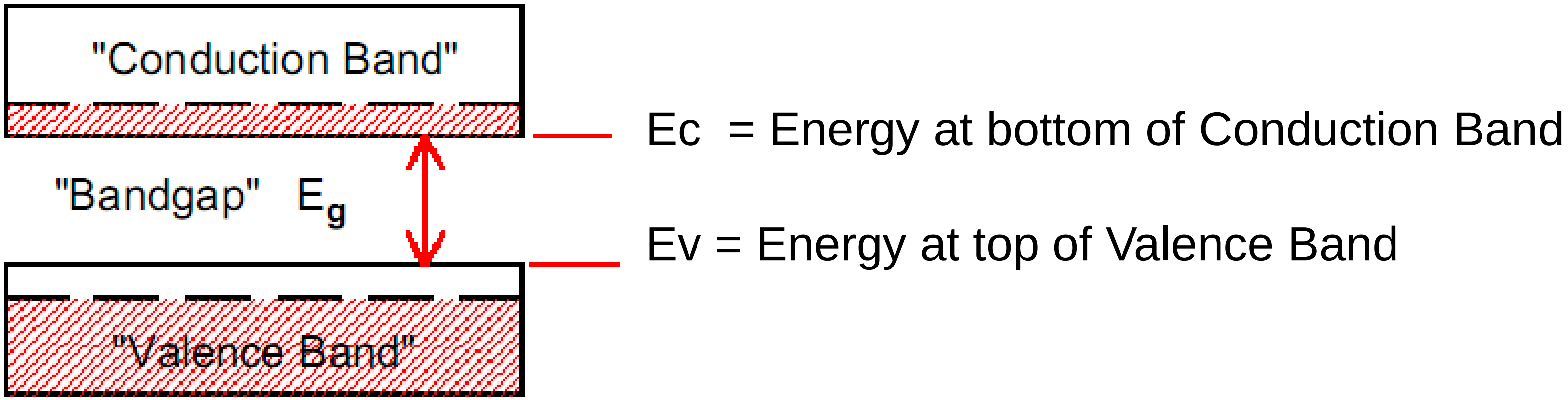
(a) Intrinsic

a) $f(E)$ = Probability that a quantum state at E is filled w/ electron

b) 1 - $f(E)$ = Probability that a quantum state at E is empty

Carrier Concentration at Thermal Equilibrium

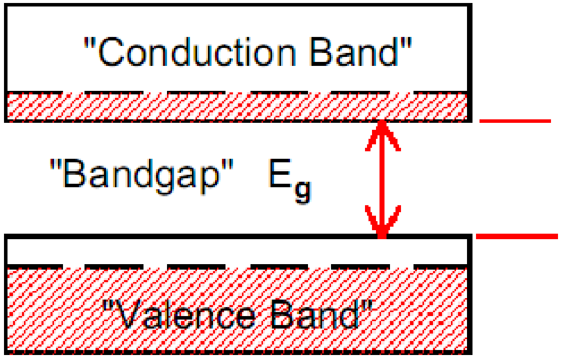
•To calculate semiconductor electrical properties, we **must know the number of charge carriers per cm³** of the material



QUESTION OF THE HOUR: HOW MANY ELECTRONS / HOLES ARE IN THESE BANDS ?

Carrier Concentration at Thermal Equilibrium

Number of electrons at E = (# of available quantum states) x (probability state at E filled)



= g(E) x f(E)

Number of electrons in band = $\int_{bottom\_of\_band}^{top\_of\_band} g(E) \cdot f_F(E)\, dE$

Carrier Concentration at Thermal Equilibrium

Intrinsic Semiconductor:

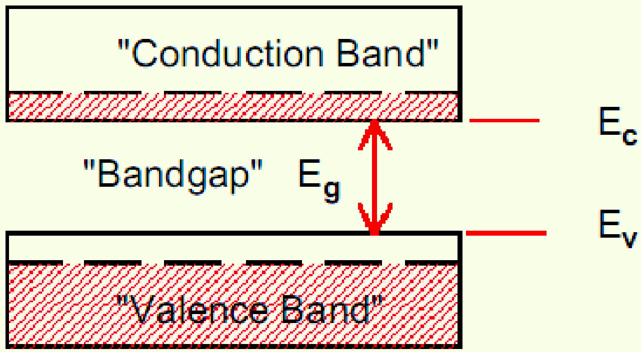
dn= D(E) density of states* F(E) *dE

D(E) =[8root2 pie m^3/2 (E-Ec)^1/2]/h^3

$$n_o = N_c \cdot e^{\frac{-(E_c - E_F)}{k_B \cdot T}} \quad \text{with} \quad N_c = \frac{2 \cdot (2 \cdot \pi \cdot m_{n\_eff} \cdot k_B \cdot T)^{\frac{3}{2}}}{h^3} \quad \text{equals =>}$$

effective density of states

$$p_o = N_v \cdot e^{\frac{-(E_F - E_v)}{k_B \cdot T}} \quad \text{with} \quad N_v = \frac{2 \cdot (2\pi \cdot m_{p\_eff} \cdot k_B \cdot T)^{\frac{3}{2}}}{h^3} \quad \text{equals =>}$$



$$p_o = n_o \qquad \text{or,} \qquad N_v \cdot e^{\frac{-(E_F - E_v)}{k_B \cdot T}} = N_c \cdot e^{\frac{-(E_c - E_F)}{k_B \cdot T}}$$

Solve for the value of E_F

$$E_{Fi} = E_{midgap} + \frac{3 \cdot k_B \cdot T}{4} \cdot \ln\left(\frac{m_{p\_eff}}{m_{n\_eff}}\right)$$

$$\parallel$$

E(c)+E(v)/2

To finally get n_i

$$n_i^2 = p_o \cdot n_o = \left[N_V \cdot e^{\frac{-(E_{Fi}-E_V)}{k_B \cdot T}} \right] \cdot \left[N_c \cdot e^{\frac{-(E_c-E_{Fi})}{k_B \cdot T}} \right] = N_V \cdot N_c \cdot e^{\frac{E_V-E_c}{k_B \cdot T}} = N_V \cdot N_c \cdot e^{\frac{-E_g}{k_B \cdot T}}$$

$$n_i = \sqrt{N_c \cdot N_V} \cdot e^{\frac{-E_g}{2k_B \cdot T}}$$

The number of carriers that are thermally promoted across the bandgap

= Spontaneous (equilibrium) number of electrons in Conduction Band

= Spontaneous number of holes in Valence Band

Types of Semiconductor Materials

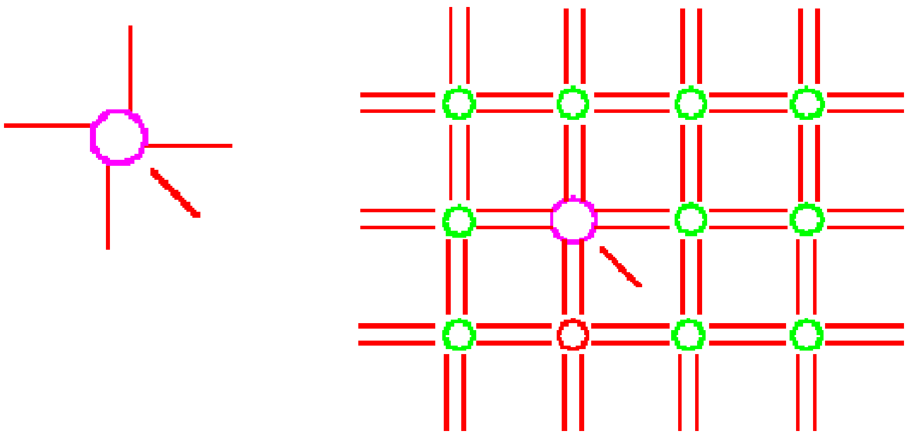
- One of most important properties of a semiconductor is that it can be **doped with different types and concentrations of impurities**
- **Intrinsic material:** No impurities or lattice defects
- **Extrinsic:** doping, purposely adding impurities
  - N-type mostly electrons
  - P-type mostly holes

To make semiconductors really useful, must introduce other means of creating holes and electrons !!!

Doping = engineered introduction of foreign atoms to modify semiconductor electrical properties

A. DONORS:

- Introduce electrons to semiconductors (but not holes)
- For Si, group V elements with 5 valence electrons (As,P, Sb)



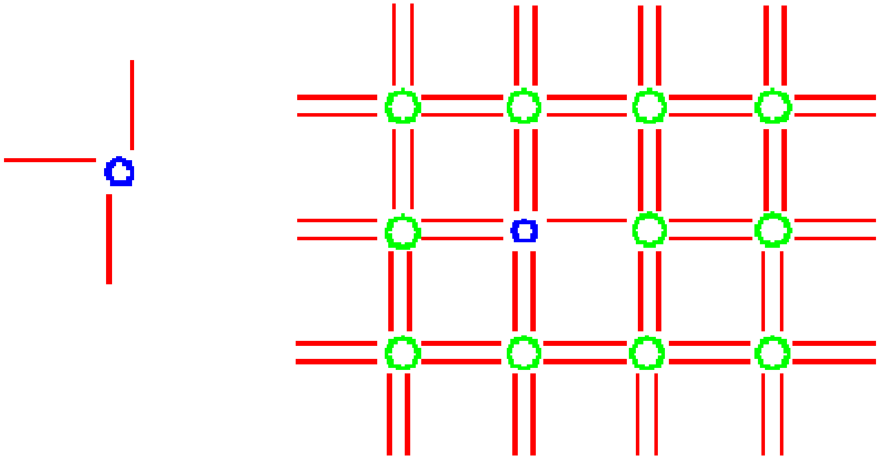
N-Type Si

Can write as an ionization reaction:

$N_d^o \leftrightarrow N_d^{plus} + n$ n = concentration of electrons created

B. ACCEPTORS:

- Introduce holes to semiconductors (but not electrons)
- For Si, group III elements with 3 valence electrons (B)



P-Type Si

Notation: N_a^o = Neutral acceptor concentration (not ionized, hasn't yet accepted additional electron)

N_a^- or N_a^{minus} = Ionized acceptor concentration (has added 4th bonding electron)

Written as ionization reaction:

$N_a^o \leftrightarrow N_a^{minus} + p$ p = concentration of holes created

Charge neutrality

$$p + N_d^{plus} = n + N_a^{minus}$$

Notice what happens when we multiply together the n and p equations:

$$p(E_F)\cdot n(E_F) = N_v\cdot e^{\frac{-(E_F-E_v)}{k_B\cdot T}}\cdot N_c\cdot e^{\frac{-(E_c-E_F)}{k_B\cdot T}} = N_v\cdot N_c\cdot e^{\frac{E_c-E_v}{k_B\cdot T}}$$

E_F cancels out of product

further:

$$N_v\cdot N_c\cdot e^{\frac{E_c-E_v}{k_B\cdot T}} = n_i^2$$

The carrier concentration we had in the pure semiconductor

$$\boxed{p\cdot n = n_i^2}$$

ni=1.5*10^10

n and p may no longer equal n_i

As one increases, the other decreases to precisely compensate

Case1 : Intrinsic Semiconductor, $N_{d\_total} = N_{a\_total} = 0$

get: $n_0 = p_0 = n_i$

Case 2: n-type semiconductor, $N_{d\_total} >> N_{a\_total}$

or $(N_{d\_total} - N_{a\_total}) >> n_i$

get: $n_0 \approx N_{d\_total}$ and $p_0 = n_i^2 / N_{d\_total}$

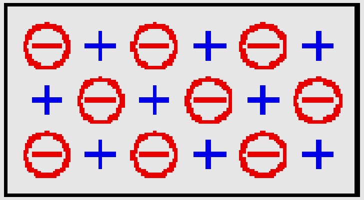
Case 3: p-type semiconductor, $N_{a\_total} >> N_{d\_total}$

$(N_{a\_total} - N_{d\_total}) >> n_i$

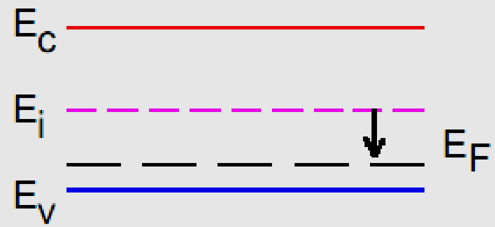
get: $p_0 = N_{a\_total}$ and $n_0 = n_i^2 / N_{a\_total}$

Consider separate pieces of P-type and N-type semiconductor

P-type:



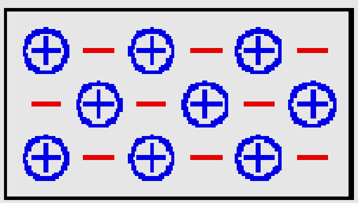
=>



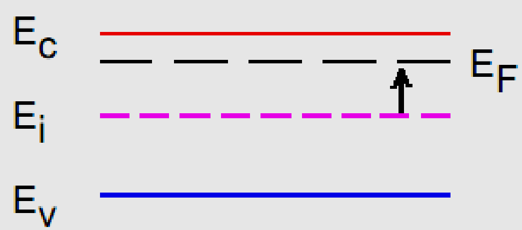
- Neutral Si atoms (not shown)
- Fixed negative acceptor ions
- Mobile positive holes

By catching electrons, acceptors pull down Fermi Energy (electron filling level)

N-type:



=>



- Neutral Si atoms (not shown)
- Fixed positive donor ions
- Mobile negative electrons

By giving up electrons, donors push up Fermi Energy (electron filling level)

Transport of Carriers

Carrier transport can be classified into two types:

Drift: Motion under an applied field
Diffusion: Motion due to a gradient of concentration

Most of the transport mechanisms considered classically (not quantum mechanically).

Often, the both the drift and diffusion are adequate for many situations and applications.

Carrier Transport: DRIFT of carriers in an Electric Field

Carrier Drift:

"Drift" = Net carrier movement induced by force (such as electric field)

"Carrier" = **Mobile charge carrier** = Conduction band electron / valence band hole

For a P-type (acceptor doped) semiconductor: p >> n

$J_{Total} = J_{valence\ band\ holes}$ = [charge on a hole] [density of holes] [average hole velocity]

$= [+q]\ [p]\ [v_p]$

$= q\, p\, v_p$

$v_p = \mu_p \xi$, where μ_p is 'hole mobility' and ξ is the electric field

$$J = q \cdot p \cdot v_p = q \cdot p \cdot \mu_p \cdot \xi = (q \cdot p \cdot \mu_p) \cdot \xi$$

$$J_p = \sigma_p \mathcal{E}$$

σ_p is Conductivity of Semiconductor

$$\sigma_p = q \cdot p \cdot \mu_p$$

Total DRIFT CURRENT
(due to both electrons and holes in the same electric field)

$$J_{drift\_total} = J_{p\_drift\_} + J_{n\_drift} = \sigma_p \cdot \xi + \sigma_n \cdot \xi = q \cdot \left(\mu_p \cdot p + \mu_n \cdot n\right) \cdot \xi = \sigma \cdot \xi = \frac{1}{\rho} \cdot \xi$$

$$J_{drift} = q \cdot \left(\mu_p \cdot p + \mu_n \cdot n\right) \cdot \xi$$

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

$$\rho = \frac{1}{\sigma}$$ "Resistivity"

Electron and hole currents ADD!

With ξ field to right:

Positive holes move right = current to right!

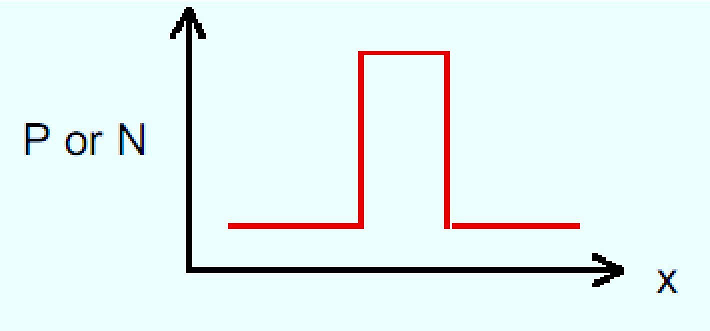
Negative electrons move left = current to right!

Carrier Transport: Diffusion = Spontaneous Rearrangement

SECOND POSSIBLE SOURCE OF CURRENT: Spontaneous redistribution of carriers:

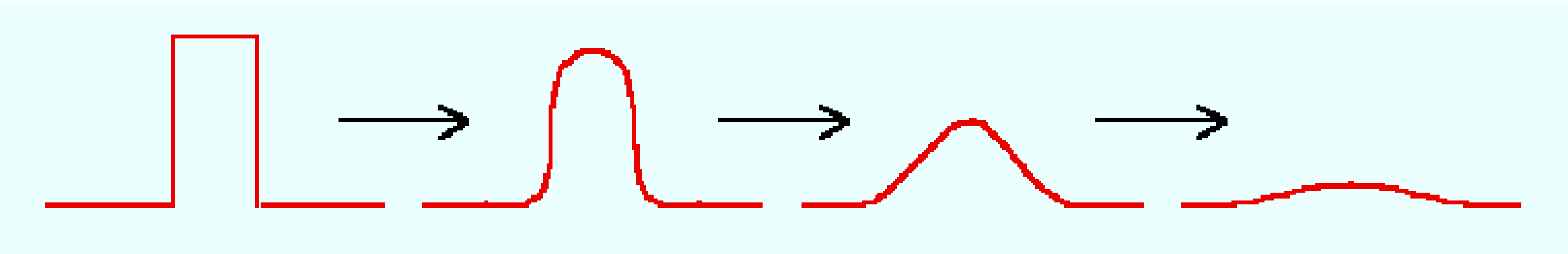
DIFFUSION of carriers

At t=0, start with a blip of electrons



What happens at t > 0 ?

Obviously, it is going to spread out!



$$J_p = -q \cdot D_p \cdot \frac{d}{dx} p$$

$$J_{diffusion} = J_{diffusion\_p} + J_{diffusion\_n}$$

$$J_n = q \cdot D_n \cdot \frac{d}{dx} n$$

Combine these new DIFFUSION currents with DRIFT currents to get TOTAL currents:

$$\boxed{J_{total\_n} = q \cdot \mu_n \cdot n \cdot \xi + q \cdot D_n \cdot \frac{d}{dx} n \qquad J_{total\_p} = q \cdot \mu_p \cdot p \cdot \xi - q \cdot D_p \cdot \frac{d}{dx} p}$$

Where mobilties μ = q x (scattering time) / (effective mass)

And diffusivities D = (scattering length)^2 / (scattering time)

$$\frac{D}{\mu} = \frac{k_B \cdot T}{q}$$ "Einstein Relationship"

1. What are n and p in a Si sample with $N_D = 6 \times 10^{16}$ /cm^3 and $N_A = 2 \times 10^{16}$ /cm^3. With additional 6×10^{16} of acceptors, what would be the result?

$n = N_D - N_A = 4 \times 10^{16}/cm^3$

$p = n_i^2/n = 5.6 \times 10^3/cm^3$

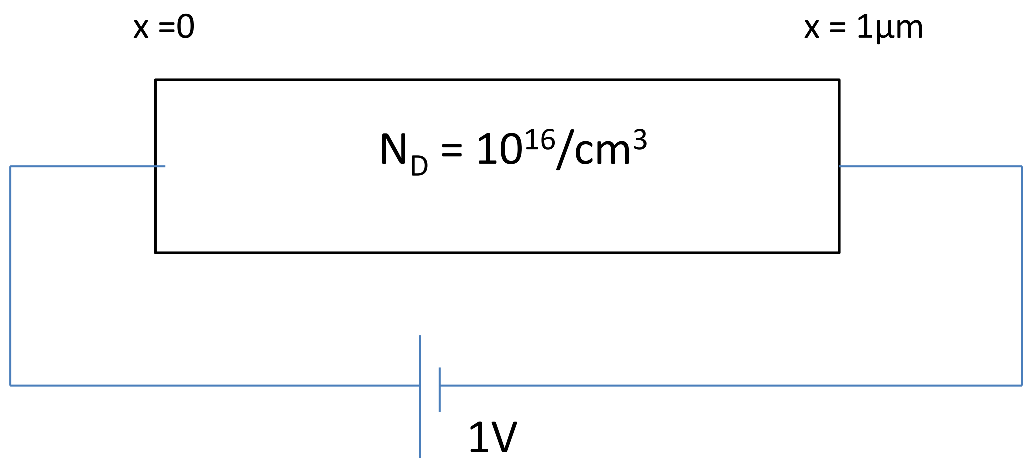
With additional $N_A = 8 \times 10^{16}$ /cm^3

$p = N_A – N_D = 2 \times 10^{16}$ /cm^3

$n = n_i^2/p = 1.12 \times 10^4$ /cm^3

2. A Si sample is doped with 10^{18} atoms/cm^3 of boron. Another sample of identical dimensions is doped with 10^{18} atoms/cm^3 of phosphorus. The ratio of electron to hole mobility is 3. Find the ratio of the conductivity of sample A to B.

$\sigma_p = pq\mu_p$
$\sigma_n = nq\mu_n$
$\sigma_p/\sigma_n = \mu_p/\mu_n = 1/3$



Find the electron drift current density at x =0.5μm. Electron mobility = 1350 cm^2/V-sec

$J_n = nq\mu_n E = 2.16 \times 10^4 A/cm^2$