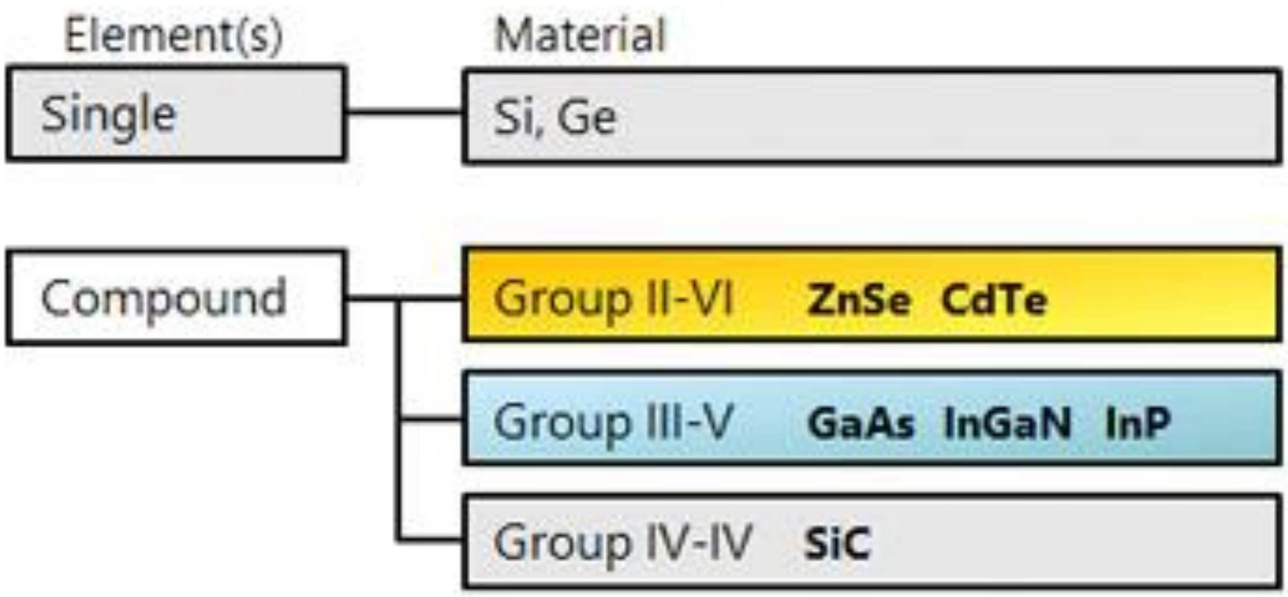
UNIT 5 SOLID STATE PHYSICS

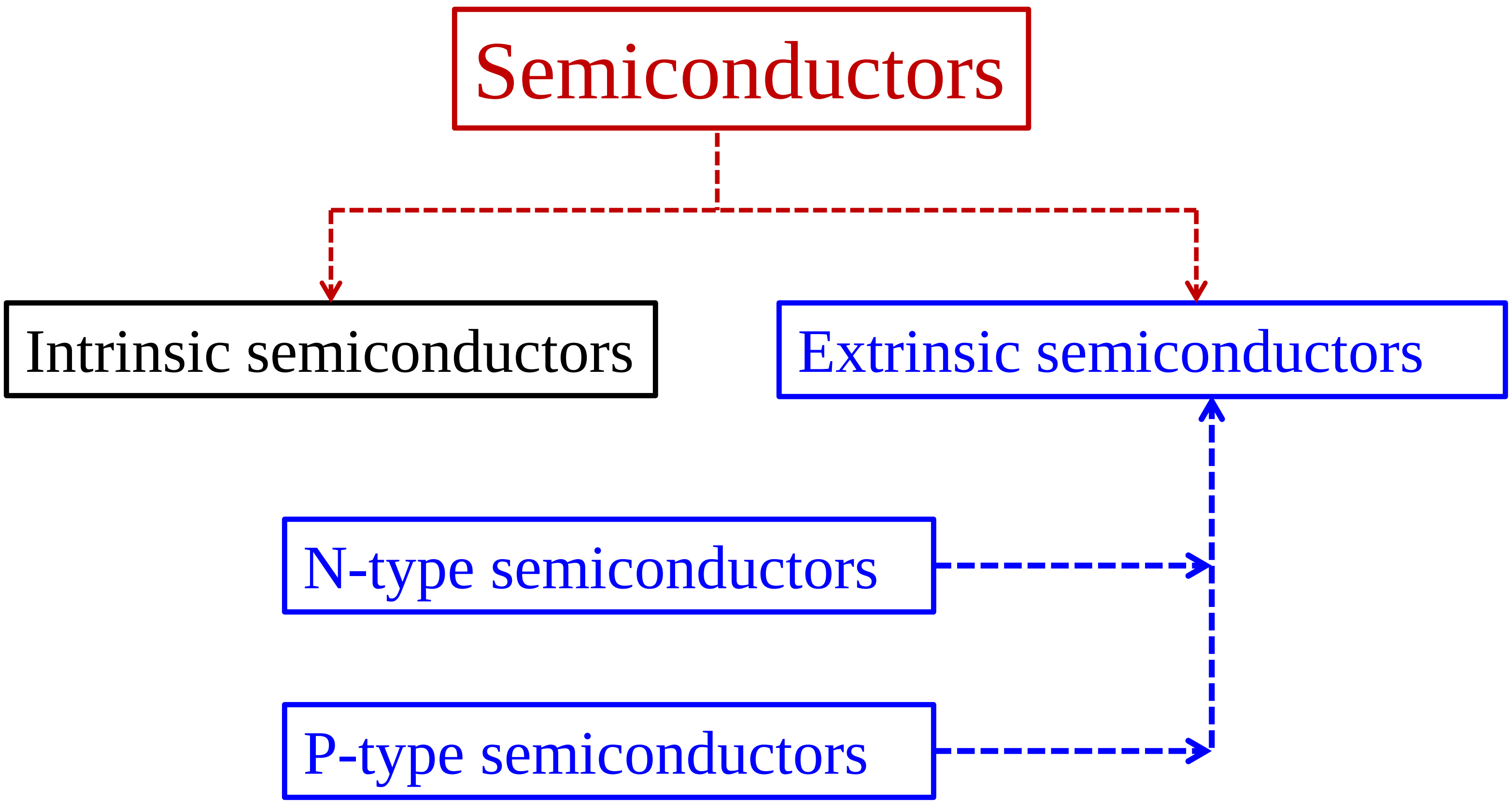
LECTURE 4

Semiconductors



CLASSIFICATION OF SEMICONDUCTORS

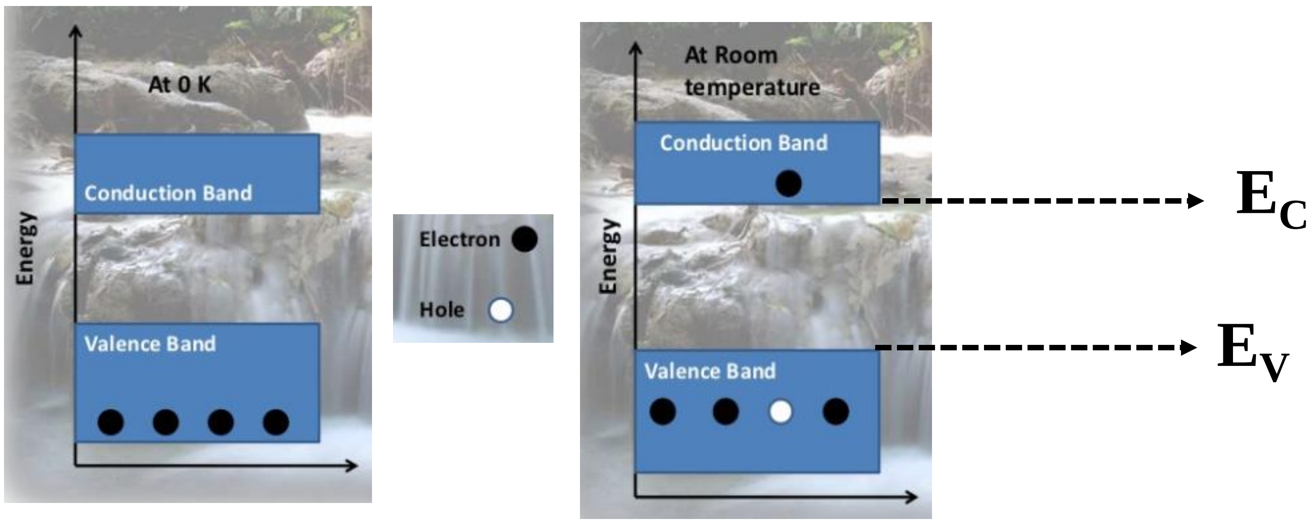
Semiconductors: 10^{-8}S/cm < **σ** < 10^{3}S/cm **or 10^{8}Ω-cm >** ρ **>10^{-3} Ω-cm**) or Band gap less than 3 eV



Intrinsic semiconductors

holes and electrons

In a semiconductor ejection of electron to the conduction band from the valance band is purely by thermal excitation is an intrinsic semiconductor



- The effect is temperature dependent
- Produce equal number of holes and electrons
- Electrons or holes are the intrinsic carriers
- Conductivity is then called the intrinsic conductivity

Concentration of electron in an intrinsic semiconductor

Electrons in the conduction band behave as free particles with an 'effective mass' m_e

The number of conduction electron per cubic meter whose energies lie between E and E+dE is given by

$$dn_e = N(E)f(E)dE \qquad \text{Eq.1}$$

Where N(E) is the density of states at the bottom of the conduction band and according to quantum mechanics is given

$$N(E) = \frac{4\pi}{h^3}(2m)^{3/2}\,(E - E_c)^{1/2}$$

Where E_c is the energy bottom of the conduction band

f(E) , we already know, is the Fermi-Dirac probability function and is given by

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

Where k is the Boltzmann constant, T is the temperature and E_F is the Fermi level of the material

But electrons in the conduction band can have energies between E_C to infinity (∞) and hence total concentration of the electron is obtained by integrating equation 1

$$n_e = \int dn_e = \int_{E_C}^{\infty} N(E) f(E) dE$$

Substitute for N (E) and f (E), we have

$$n_e == \int_{E_C}^{\infty} \frac{4\pi}{h^3} (2m)^{3/2} \ (E - E_c)^{1/2} \frac{1}{1 + e^{(E-E_F)/kT}} dE$$

For $E \geq E_c$ and $E\text{-}E_F >> kT$, 1 in the denominator can be neglected, so the above equation is reduced to

$$n_e = \int_{E_C}^{\infty} \frac{4\pi}{h^3} (2m)^{3/2} \ (E - E_c)^{1/2} \frac{1}{e^{(E-E_F)/kT}} dE$$

Put $x=E-E_C / kT$, and hence $dE=kTdx$; so the above equation becomes

$$n_e = \frac{4\pi}{h^3} (2m)^{3/2} e^{(E-E_F)/kT} \int_0^{\infty} x^{1/2} (kT)^{1/2} e^{-x} kT \, dx$$

$$n_e = \frac{4\pi}{h^3}(kT)^{3/2}(2m)^{3/2} e^{(E-E_F)/kT} \int_0^\infty x^{1/2} e^{-x}\, dx$$

$$n_e = \frac{4\pi}{h^3}(kT)^{3/2}(2m)^{3/2} e^{(E-E_F)/kT} \frac{\sqrt{\pi}}{2}$$

$$\therefore \int_0^\infty x^{1/2} e^{-x}\, dx = \frac{\sqrt{\pi}}{2}$$

So the concentration of electrons in the conduction band is given by

$$\boldsymbol{n_e = 2\left[\frac{2\pi m_e kT}{h^2}\right]^{3/2} e^{(E_F-E_c)/kT}} \qquad \text{Eq.2}$$

$$\boldsymbol{n_e = n}$$

Similarly we can determine the concentration of holes in the valance band. Since holes signifies the vacancy created by the removal of electron from the valance band, the Fermi function for the holes is 1-f(E)

$$1 - f(E) = 1 - \frac{1}{1 + e^{(E-E_F)/kT}}$$

For $E\text{-}E_F/kT << 1$. Fermi function for the holes is 1-f(E)

$$1 - f(E) = 1 - 1 + e^{\frac{E-E_F}{kT}} = e^{(E-E_F)/kT} \qquad \text{Eq.3}$$

Hole concentration n_h

For the top of the valance band (maximum energy) the density of states of holes given by

$$N(E) = \frac{4\pi}{h^3}(2m_h)^{3/2}\,(E_V - E)^{1/2}$$

Where m_h is the effective mass of the holes at the top of the valance band , where the energy is E_v. So the density of holes is given the similar integration, but lower limit is -∞ and upper limit is E_V

$$n_h = \int_{-\infty}^{E_V} N(E)[1 - f(E)]dE = \int_{-\infty}^{E_V} \frac{4\pi}{h^3}(2m_h)^{3/2}\,(E_V - E)^{1/2} e^{(E-E_F)/kT} dE$$

By doing the similar exercise we did for the electrons we get an expression for the holes concentration as

$$\boldsymbol{n_h = 2\left[\frac{2\pi m_h kT}{h^2}\right]^{3/2}\; e^{(E_v - E_F)/kT}} \qquad \text{Eq.4}$$

Fermi level of intrinsic semiconductor

Electron concentration n_e

$$n_e = 2\left[\frac{2\pi m_e kT}{h^2}\right]^{3/2} e^{(E_F - E_c)/kT}$$

Hole concentration n_h

$$n_h = 2\left[\frac{2\pi m_h kT}{h^2}\right]^{3/2} e^{(E_v - E_F)/kT}$$

For intrinsic semiconductor $n_e = n_h$

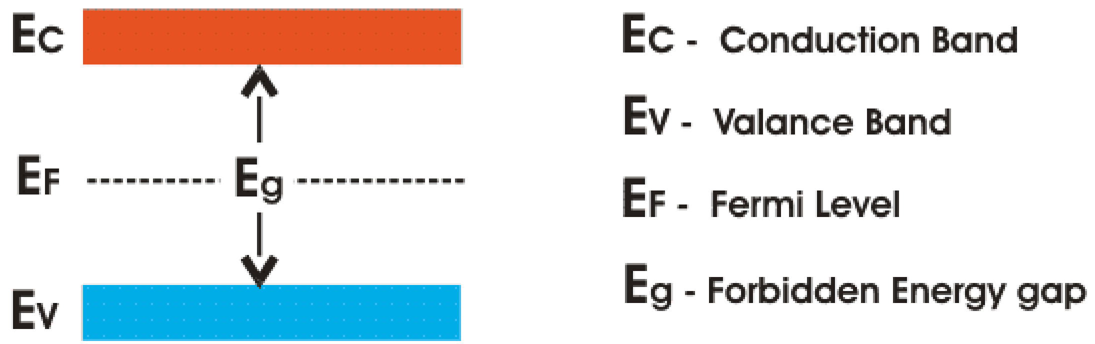
$$2\left[\frac{2\pi m_e kT}{h^2}\right]^{3/2} e^{(E_F - E_c)/kT} = 2\left[\frac{2\pi m_h kT}{h^2}\right]^{3/2} e^{(E_v - E_F)/kT}$$

$$e^{(2E_F - E_c - E_v)/kT} = \left(\frac{m_h}{m_e}\right)^{3/2}$$

$$\frac{2E_F - E_c - E_v}{kT} = \frac{3}{2} ln \frac{m_h}{m_e} \quad \Longrightarrow \quad E = \frac{E_c + E_v}{2} + \frac{3}{4} kT \, ln \frac{m_h}{m_e}$$

If m_e and m_h are same then $E_F = \frac{E_c + E_v}{2}$ what does that means???

$$E_F = \frac{E_c + E_v}{2}$$



$\mathrm{E_g = E_C - E_V}$, is the band gap of the material, electron with energy lies in the gap is forbidden in the material

Fermi level of an intrinsic semiconductor is at the middle of the band gap

And the product of the two carriers concentration is a constant for given material and a given temperature

$$n_e n_h = AT^3\, e^{(E_v - E_c)/kT} \qquad \mathrm{A} = \frac{32\pi^3 k^3}{h^6}(m_e m_h)^{3/2}$$

For an intrinsic semiconductor $\mathrm{n = p = n_i}$

$$np = n_i^2 = AT^3\, e^{(E_v - E_c)/kT}$$

Very important relation called law of action?
Hold good for extrinsic semiconductors as well

In an intrinsic semiconductor electrons and holes are generated always

a) Individually
b) In pairs
c) All of the above
d) None of the above

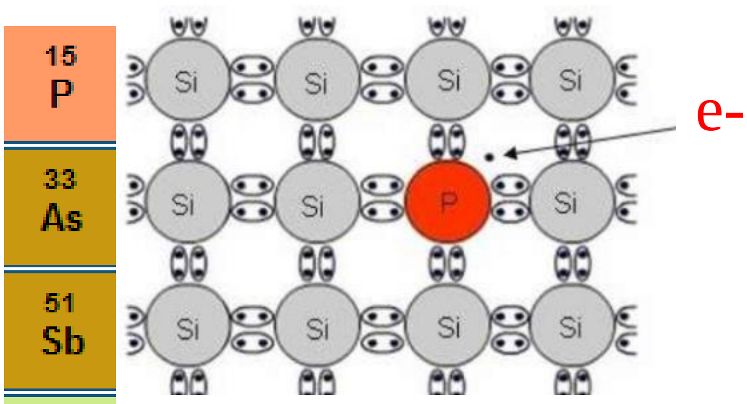
Ans: B

The Fermi level of an intrinsic semiconductor lies

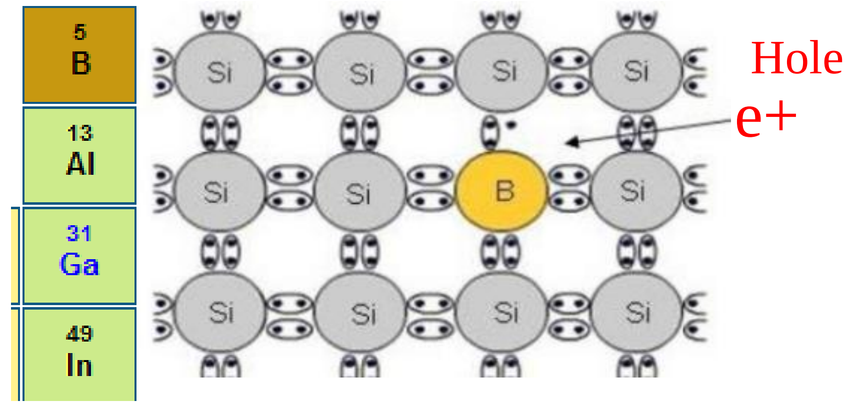
a) Near the conduction band
b) Near the valence band
c) At the middle of the band gap
d) In conduction band

Ans: C

Extrinsic semiconductors



Group V



Group III

N-Type semiconductor

- By doping Si or Ge with **Group V** elements
- Majority carriers: **electrons**

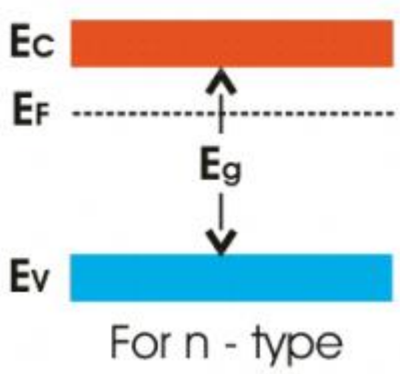
Group IV

P-Type semiconductor

- ✓By doping Si or Ge with **Group III** elements
- ✓Majority carriers: **holes**

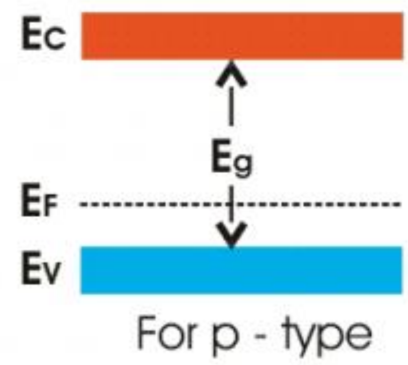
Fermi level Extrinsic semiconductors

N-Type semiconductor



$$E_F = E_c - kT \ln \frac{N_c}{N_d}$$

P-Type semiconductor



$$E_F = E_V + kT \ln \frac{N_V}{N_a}$$

k-Boltzmann's constant, T-temperature, N_a and N_d density of acceptor and donor atoms, Nv and Nc density of holes in the valance band and density of electrons in the conduction band

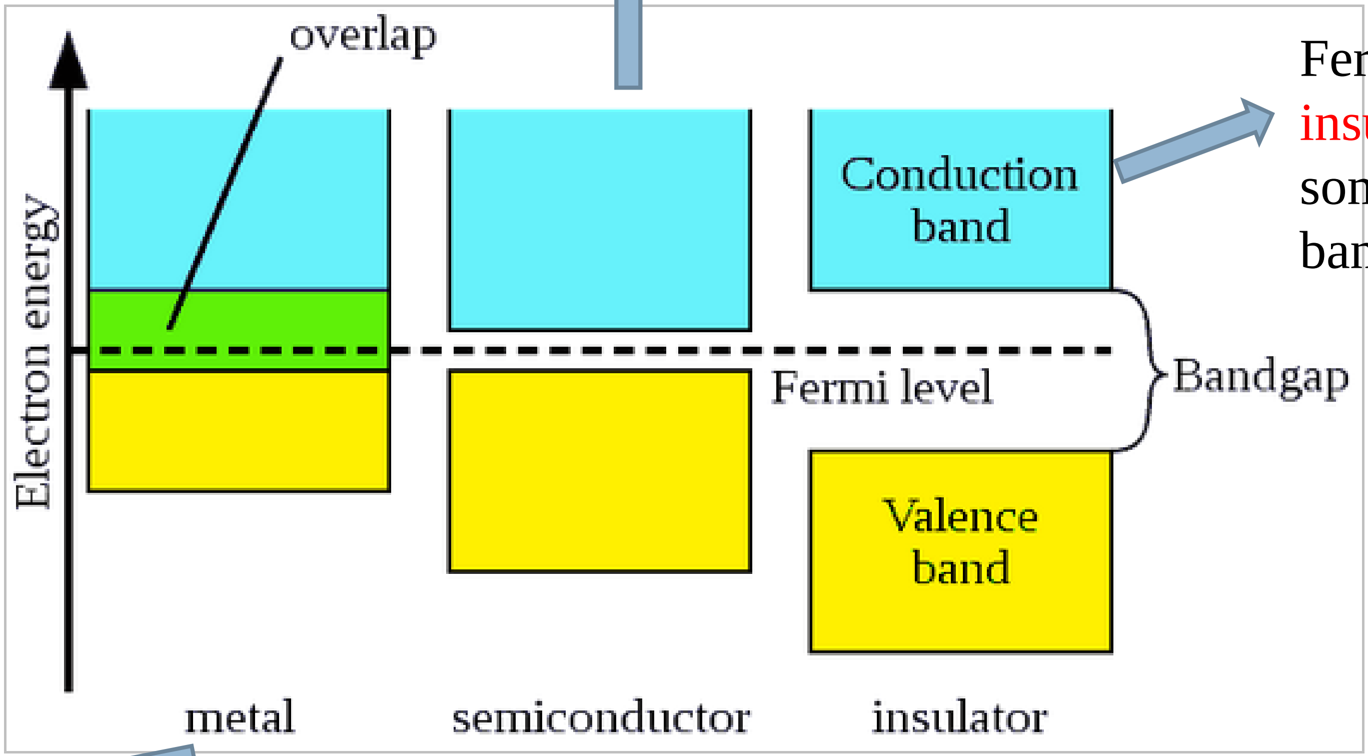
Fermi level lies just below the conduction band

Fermi level lies just above the valence band

In intrinsic semiconductor Fermi level is at the middle of the band gap

Fermi level comparison

Fermi level of an intrinsic semiconductor is at the middle of the bandgap



Fermi level of an insulator somewhere in the bandgap

Fermi level of a metal is the energy of the top most filled level at absolute zero. Or the Energy of the electron for which probability of finding an electron at any temperature is half at Fermi level.

The energy level of an acceptor atom typically lies very close to

a) Conduction band
b) Valence band
c) Middle of the band gap
d) In conduction band

Ans: B

Fermi level of an P-type semiconductor typically lies very close to

a) Conduction band
b) Valence band
c) Middle of the band gap
d) In conduction band

Ans: B

The energy level of a donor atom typically lies very close to

a) Valence band
b) Conduction band
c) Middle of the band gap
d) In conduction band

Ans: B

Fermi level of an N-type semiconductor typically lies very close to

a) Conduction band
b) Valence band
c) Middle of the band gap
d) In conduction band

Ans: A

PHY110 – ENGINEERING PHYSICS

Text Books: ENGINEERING PHYSICS by HITENDRA K MALIK AND A K SINGH, MCGRAW HILL EDUCATION, 1st Edition, (2009)

References:

- ENGINEERING PHYSICS by B K PANDEY AND S CHATURVEDI, CENGAGE LEARNING, 1st Edition, (2009).

- ENGINEERING PHYSICS by D K BHATTACHARYA, POONAM TONDON OXFORD UNIVERSITY PRESS.

- FUNDAMENTALS OF PHYSICS by HALLIDAY D., RESNICK R AND WALKER J, WILEY, 9th Edition, (2011)