Semiconductor Physics GATE Problems (Part - II)

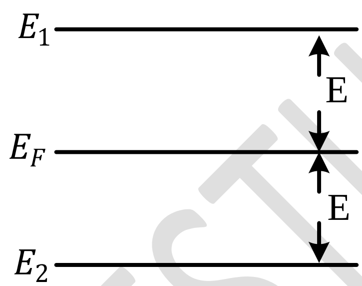
1. Consider two energy levels: E_1, E eV above Fermi level and E_2, E eV below the Fermi level. P_1 and P_2 are respectively the Probabilities of E_1 being occupied by an electron and E_2 being empty. Then
   (a) $P_1 > P_2$
   (b) $P_1 = P_2$
   (c) $P_1 < P_2$
   (d) P_1 and P_2 depend on number of free electrons

[GATE 1987: 2 Marks]

Soln. Given

P_1 – Prob. of E_1 being occupied by electron

P_2 – Prob. of E_2 being empty (not occupied)



Probability that state at energy E_1 is occupied is

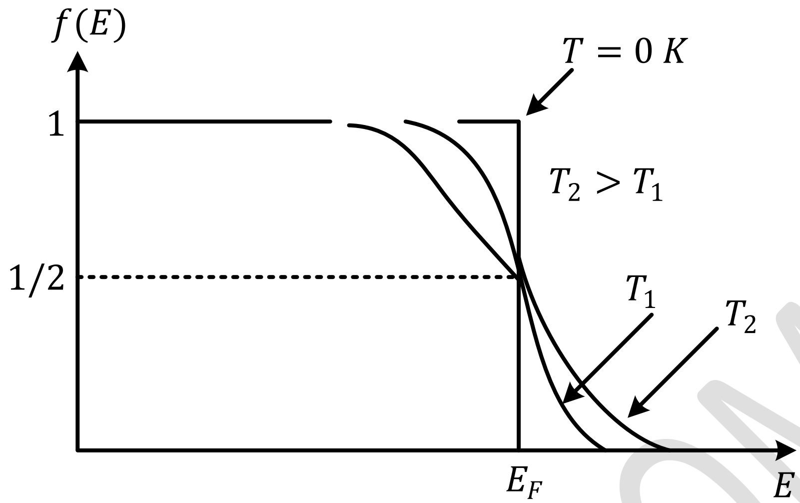
$$f(E_1) = \frac{1}{1+e^{(E_1-E_F)/kT}}$$

Probability that state is empty is given by $1 - f(E_1)$

From the plot of Fermi Prob. function vs energy, it is observed that probability of state being occupied above E_F is relatively very low. While the state not occupying below E_F (top portion of plot) can be written as

$$1 - f(E)$$

Which is much larger



(Fermi Prob. Function vs energy for different temps.)

Note that probability of empty state is holes in the valence band.

So, $P_2 > P_1$

Option (c)

2. In an intrinsic Semiconductor the free electron concentration depends on
   (a) Effective mass of electrons only
   (b) Effective mass of holes only
   (c) Temperature of the Semiconductor.
   (d) Width of the forbidden energy hand of the semiconductor.

[GATE 1987: 2 Marks]

Soln. There is relationship between intrinsic concentration and density of states in conduction and valence band

$$n_i^2 = N_C N_V \,.\, e^{-\frac{Eg}{kT}}$$

Or, $n_i \cong A \,.\, T^{3/2} \,.\, e^{-E_g/2kT}$

Where

N_C – Density of states in conduction band

N_V – Density of states is valence band

Note, both N_C and N_V vary as $T^{3/2}$

So, $n_i^2 \propto T^3 \quad or \quad n_i \propto T^{3/2} \quad or \quad n \propto T^{3/2}$

Option (c)

3. According to the Einstein relation, for any semiconductor the ratio of diffusion constant to mobility of carriers
   (a) Depends upon the temperature of the semiconductor.
   (b) Depends upon the type of the semiconductor.
   (c) Varies with life time of the semiconductor.
   (d) Is a universal constant.

[GATE 1987: 2 Marks]

Soln. The Einstein relation is given by

$$\frac{D}{\mu} = \frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = \frac{T^0 K}{11,600}$$

From the above relation we notice that D/μ depends on temperature.

Option (a)

4. Direct band gap semiconductors
   (a) Exhibit short carrier life time and they are used for fabricating BJT's
   (b) Exhibit long carrier life time and they are used for fabricating BJT's
   (c) Exhibit short carrier life time and they are used for fabricating Lasers.
   (d) Exhibit long carrier life time and they are used for fabricating BJT's

[GATE 1987: 2 Marks]

Soln. Direct band gap Semiconductors. (DBG):

In such semiconductors the transition from max point of valence band to minimum of conduction band takes place without change in momentum.

Ex. GaAs

They exhibit short carrier life time. Thus used for fabricating lasers.

In DBG semiconductor during the recombination the energy is released in the form of light.

Option (c)

5. Due to illumination by light, the electron and hole Concentrations in a heavily doped N type semiconductor increases by $\Delta\, n\ and\ \Delta\, p$ respectively if n_i is the intrinsic concentration then ,

(a) $\Delta\, n < \Delta\, P$

(b) $\Delta\, n > \Delta\, P$

(c) $\Delta\, n = \Delta\, P$

(d) $\Delta\, n \times \Delta\, P$

[GATE 1989: 2 Marks]

Soln. Due to light illumination electron hole pair generation occurs

So, $\Delta_n = \Delta_p$

Where, Δ_n **is increase in electron concentration due to illumination of light.**

Δ_p **is increase in hole concentration due to illumination by light.**

Option (c)

6. A Silicon Sample is uniformly doped with 10^{16} phosphorus atoms / cm^3 and 2×10^{16} boron atoms / cm^3. If all the dopants are fully ionized the material is

(a) n – type with carrier concentration of $10^{16}/cm^3$

(b) p – type with carrier concentration of $10^{16}/cm^3$

(c) p – type with carrier concentration of $2 \times 10^{16}/cm^3$
(d) n – type with carrier concentration of $2 \times 10^{16}/cm^3$

[GATE 1991: 2 Marks]

Soln. Given,

Phosphorus atom of 10^{16} will make n – type semiconductor. Since dopants are fully ionized the number of electrons will be equal to donor atoms i.e. $N_D = n = 10^{16}/cm^3$

Similarly,

$$N_A = p = Boron\ atoms = 2 \times 10^{16}/cm^3$$

Note $N_A > N_D$

The resultant maternal will be p – type semiconductor

Carrier concertation

$$= N_A - N_D$$

$$= 2 \times 10^{6} - 10^{16}$$

$$= 10^{16}/cm^3$$

Option (b)

7. The intrinsic carrier density at 300 ^{0}K is $1.5 \times 10^{10}/cm^3$, in silicon for n – type silicon doped to $2.25 \times 10^{15}\ atoms\ /\ cm^3$ the equilibrium electron and hole densities are
(a) $n = 1.5 \times 10^{15}/cm^3$, $p = 1.5 \times 10^{10}/cm^3$
(b) $n = 1.5 \times 10^{10}/cm^3$, $p = 2.25 \times 10^{15}/cm^3$
(c) $n = 2.25 \times 10^{15}/cm^3$, $p = 1.0 \times 10^{5}/cm^3$
(d) $n = 1.5 \times 10^{10}/cm^3$, $p = 1.5 \times 10^{10}/cm^3$

[GATE 1997: 2 Marks]

Soln. Given,

For n type semiconductor electron density

$$= n = N_D = 2.25 \times 10^{15}\ atoms/cm^3$$

Intrinsic carrier concentration $n_i = 1.5 \times 10^{10}\ /\ cm^3$

Note, here $n \gg n_i$

Using Mass Action Law

$$n.p = n_i^2$$

$$p = \frac{n_i^2}{n} = \frac{(1.5\times10^{10})^2}{2.25\times10^{15}}$$

$$= 10^5 atoms/cm^3$$

Option (c)

8. The electron concentration in a sample of uniformly doped n – type silicon at 300 ^{0}K varies linearly from$10^{17}/cm^3\ \ at\ \ x = 0\ \ \ to\ 6 \times 10^{16}/cm^3\ \ at\ x = 2\mu m$. Assume a situation that electrons are supplied to keep this concentration gradient constant with time. If electronic charge is 1.6×10^{19} coulomb and the diffusion constant $D_n = 35\ cm^2/S$, the current density in the silicon, if no electric field is present is

(a) Zero

(b) 120 A/cm^2

(c) +1120 A/cm^2

(d) –1120 A/cm^2

[GATE 1997: 2 Marks]

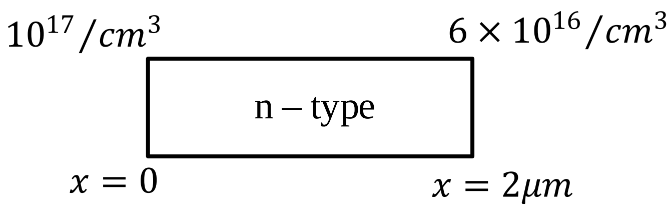
Soln. Since sample is of n – type total electron current density is given by

$$J_n = q\ \mu_n\ .n\ E + q\ D_n\ \frac{dn}{dx}$$

Given E = 0

So, there will be only diffusion current

$$\boldsymbol{J_n = D_n . q . \frac{dn}{dx}}$$



$$\boldsymbol{\frac{dn}{dx} = \frac{6 \times 10^{16} - 17^{17}}{2 \times 10^{-4} - 0} = \frac{6 \times 10^{16} - 10 \times 10^{16}}{2 \times 10^{-4}}}$$

$$\boldsymbol{= \frac{-4 \times 10^{16}}{2 \times 10^{-4}} = -2 \times 10^{20}}$$

$$\boldsymbol{J_n = D_n . q . \frac{dn}{dx}}$$

$$\boldsymbol{= 35 \times 1.6 \times 10^{-19} \times (-2 \times 10^{20})}$$

$$\boldsymbol{= -1120\ A/cm^2}$$

Option (d)

9. An n – type silicon bar 0.1 cm long and 100 μm^2 in cross – sectional area has a majority carrier concentration of $5 \times 10^{20}/m^3$ and the carrier mobility is $0.13 m^2/v - s$ at 300 ^{o}K. If the charge of electron is 1.6×10^{-19} coulomb, then the resistance of the bar is

(a) $10^6 \Omega$
(b) $10^4 \Omega$
(c) $10^{-1} \Omega$
(d) $10^{-4} \Omega$

[GATE 1997: 2 Marks]

Soln. Given,

Si bar = 0.1 cm = 10^{-3} m.

Convert it into meters since all other parameters are in meters. Cross sectional area $(A) = 100\ \mu m^2 = 100 \times 10^{-12} m^2$

$$n = 5 \times 10^{20}/m^3$$

$$\mu_n = 0.13\ m^2/v - s$$

$$q = 1.6 \times 10^{-19}\ \ coulomb$$

Since semiconductor is of n – type

$$\sigma_n = nq\ \mu_n$$

$$Resistivity(\rho) = \frac{1}{\sigma_n} = \frac{1}{nq\mu_n}$$

Also, Resistance $= \frac{\rho l}{A}$

$$\frac{l}{\sigma A} = \frac{10^{-3}}{5 \times 10^{20} \times (1.6 \times 10^{-19})(0.13) \times (100 \times 10^{-12})}$$

$$R = 10^6 \Omega$$

Option (a)

10. The resistivity of a uniformly doped n – type silicon sample is 0.5 $\Omega - cm$. If the Electron mobility (μ_n) is 1250 $cm^2/V - sec$ and the charge of an electron is 1.6×10^{-19} coulomb, the donor impurity concentration (N_D) in the sample is

(a) $2 \times 10^{16}/cm^3$
(b) $1 \times 10^{16}/cm^3$
(c) $2.5 \times 10^{15}/cm^3$
(d) $2 \times 10^{15}/cm^3$

[GATE 2003: 2 Marks]

Soln. Given,

Resistivity of n – type Silicon sample $= \mathbf{0.5\Omega - cm}$

$\mu_n = 1250\ cm^2/v\text{–}s$

Resistivity for n – type sample $(\rho) = \frac{1}{nq\mu_n}$

Assuming complete ionization

$n = N_D$

$So, \quad N_D = \frac{1}{q\,\mu_n\,\rho}$

$$= \frac{1}{1.6\times10^{-19} \times 1250 \times 0.5}$$

$= 10^{16}/cm^3$

Option (b)

11. A silicon sample 'A' is doped with 10^{18} atoms/cm^3 of Boron. Another sample 'B' of identical dimensions is doped with 10^{18} atoms/cm^3 of phosphorus. The ratio of Electron to hole mobility is 1/3. The ratio conductivity of the sample A to B is

(a) 3
(b) 1/3
(c) 2/3
(d) 3/2

[GATE 2004: 2 Marks]

Soln. Sample 'A' doped with 10^{18} atoms / cm^2 of Boron (trivalent) so P – type semiconductor

Sample 'B' doped with same no. of phosphorus (N - type)

$$\frac{\mu_n}{\mu_p} = \frac{1}{3}$$

Note $\boldsymbol{\sigma_n = n\, q\, \mu_n}$

$$\boldsymbol{\sigma_p = pq\ \ \mu_p}$$

$$\boldsymbol{\frac{\sigma_p}{\sigma_n} = \frac{\mu_n}{\mu_p} = \frac{1}{3}}$$

Option (b)

12. A heavily doped n – type semiconductor has the following data.
Hole – electron mobility ratio: 0.4
Doping concentration: $4.2 \times 10^8\ atoms/m^3$
Intrinsic concentration: $1.5 \times 10^4\ atoms/m^3$
The ratio of conductance of the n – type semiconductor to that of intrinsic semiconductor of same material and at the same temperature is given by

(a) 0.00005 (c) 10,000
(b) 2,000 (d) 20,000

[GATE 2005: 2 Marks]

Soln. Given,

Heavily doped n – type semiconductor

$$\boldsymbol{\frac{\mu_p}{\mu_n} = 0.4}$$

$$\boldsymbol{n = 4.2 \times 10^8\ atoms/m^3}$$

$$\boldsymbol{n_i = 1.5 \times 10^4\ atoms/m^3}$$

We have to find

$$\boldsymbol{\frac{\sigma_n}{\sigma_i}}$$

Conductivity of n – type semiconductor

$$\boldsymbol{\sigma_n = nq\,\mu_n}$$

Total conductivity

$$\boldsymbol{\sigma = q(n\,\mu_n + p\,\mu_p)}$$

For intrinsic semiconductor

$$\boldsymbol{\sigma_i = n_i\,q\,(\mu_n + \mu_p)}$$

So, $$\frac{\sigma_n}{\sigma_i} = \frac{n\,q\,\mu_n}{n_i\,q\,(\mu_n+\mu_p)} = \frac{n\,\mu_n}{n_i\,\mu_n\left(1+\frac{\mu_p}{\mu_n}\right)}$$

$$= \frac{n}{n_i\left(1+\frac{\mu_p}{\mu_n}\right)} = \frac{4.2\times10^8}{1.5\times10^4(1+0.4)}$$

$$= 2\times10^4$$

Option (d)

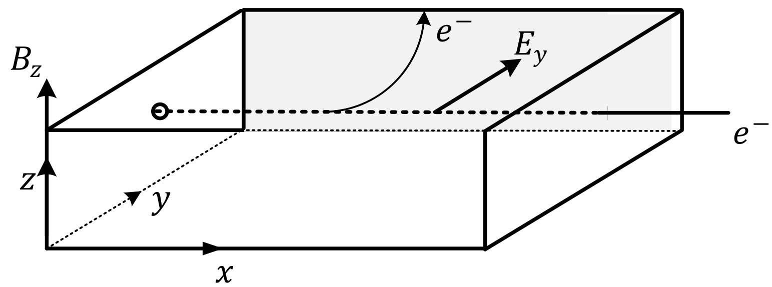
13. The majority carriers in an n – type semiconductor have an average drift velocity 'V' in a direction perpendicular to a uniform magnetic field 'B'. The electric field 'E' induced due to Hall effect acts in the direction.

(a) $V \times B$
(b) $B \times V$
(c) Along 'V'
(d) Opposite to 'V'

[GATE 2005: 2 Marks]

Soln. As per the problem the

Block of n – type semiconductor. Majority carriers will be electrons. Electron motion in x – direction. Magnetic field in z – direction



Using Lorentz force equation.

$$\overline{\boldsymbol{F}} = \boldsymbol{q}\ .\ \vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}$$

$$= (-\boldsymbol{q})\ .\ \boldsymbol{v}\ .\ \boldsymbol{B} \quad \textbf{in } (-\boldsymbol{y}) \textbf{ direction.}$$

So, direction of force will be in y – direction

So, electrons will get collected at the face shown

Option (b)

14. Silicon is doped with boron to a concentration of $4 \times 10^{17}\ atoms/cm.$ Assume the intrinsic carrier concentration of silicon to be $1.5 \times 10^{10}/cm^3$ and the value of $\frac{KT}{q}$ to be 25mV at 300 K. Compared to un - doped silicon, the Fermi level of doped silicon.

(a) Goes down by 0.13 eV
(b) Goes up by 0.13 eV
(c) Goes down by 0.427 eV
(d) Goes up by 0.427 eV

[GATE 2007: 2 Marks]

Soln. $\boldsymbol{S_i}$ **is doped with Boron i.e. P type semiconductor i.e. P – type semiconductor**

$$\boldsymbol{N_A = 4 \times 10^{17}\ atoms/cm^3}$$

$$\boldsymbol{n_i = 1.5 \times 10^{10}\ /\ cm^3}$$

$$\boldsymbol{\frac{kT}{q} = 25\ mv}$$

Since the semiconductor is of p – type, the Fermi level will go down with respect to intrinsic level.

The expression for quasi Fermi level for p – type semiconductor in terms of Acceptor concentration

$$E_{Fi} - E_{Fp} = RT \ln\left(\frac{N_A}{n_i}\right)$$

E_{Fi} – **Fermi level for intrinsic semiconductor**

E_{Fp} – **Fermi level for for p – type Semiconductor**

So, $$E_{Fi} - E_{Fp} = 25 \times 10^{-3} \ln\left(\frac{4 \times 10^{17}}{1.5 \times 10^{10}}\right)$$

$$= 25 \times 10^{-3} \ln(2.66 \times 10^{7})$$

= 0.425 ev

Option (c)

Common Data for Q.18 & Q.19

The silicon sample with unit cross-sectional area shown below is in thermal equilibrium. The following information is given: T = 300°K, electronic charge = $1.6 \times 10^{-19} C$, thermal voltage = 26mV and electron mobility = 1350 cm²/v-s

15. The magnitude of the electric field at $x = 0.5\mu m$ is

(a) 1KV/cm

(b) 5 KV/cm

(c) 10 KV/cm

(d) 25 KV/cm

[GATE 2010: 2 Marks]

Soln. Given silicon sample is in thermal equilibrium i.e. steady state is reached.

$$T = 300\ K$$

Electronics charge = $\mathbf{1.6 \times 10^{-19}\ C}$

Thermal voltage = 26 m V

$$\mu_n = 1350\ cm^2/V - s$$

$$N_D = 10^{16}\ /\ cm^3$$

So, the electric filed in the given sample is

$$E = \frac{1\ V}{1\ \mu m} = \frac{1}{1 \times 10^{-6}} = 10^6 V/\ m$$

Or, $E = 10\ KV\ /\ cm$

Note, the electric filed will be same throughout the sample

Option (c)

16. The magnitude of the electric drift current density x = 0 μm is

(a) $2.16 \times 10^4 A/cm^2$
(b) $1.08 \times 10^4 A/cm^2$
(c) $4.32 \times 10^3 A/cm^2$
(d) $6.48 \times 10^2 A/cm^2$

[GATE 2010: 2 Marks]

Soln. Electron drift current density is given by

$$J = \sigma E = N_D\ q\ \mu_n\ E$$

$$= 10^{16} \times 1.6 \times 10^{-19} \times 1350 \times 10 \times 10^3$$

$$= 1.6 \times 1350 \times 10$$

$$J = 2.16 \times 10^4\ A\ /\ cm^2$$

Note, the drift current density will same throughout the sample, so it will be same at $x = 0.5$

Option (a)

17. Assume electronic charge $q = 1.6 \times 10^{-19}\ C, \frac{kT}{q} = 25\ mV$ and electron mobility $\mu_n = 1000\ cm^2/V - s$. If the concentration gradient of electrons injected into a P – type silicon sample is $1 \times 10^{21}/cm^4$, the magnitude of electron diffusion current density (in A/cm^2) is __________.

[GATE 2014: 2 Marks]

Soln. Given

$$q = 1.6 \times 10^{-19}\ C$$

$$\frac{kT}{q} = 25\ mV$$

$$\mu_n = 1000\ cm^2/\ V$$

Concertation gradient of electrons is $1 \times 10^{21}\ /\ cm^4$

Diffusion current density is given by

$$J_{n(x)} = q\ .D_n \frac{dn}{dx}$$

As per the Einstein relation which relates diffusivity and mobility

$$D_n = \left(\frac{kT}{q}\right) \mu_n = V_T\ \mu_n$$

$$= 25 \times 10^{-3} \times 1000$$

$$D_n = 25$$

So, $J_{n(x)} = q\ D_n\ \frac{dn}{dx}$

$$= 1.6 \times 10^{-19} \times 25 \times 1 \times 10^{21}$$

$$= 40 \times 10^2 = 4000\ A/cm^2$$

Ans. 4000 A / cm^2

18. Consider a silicon sample doped with $N_D = 1 \times 10^{15}/cm^3$ donor atoms. Assume that the intrinsic carrier concentration $n_i = 1.5 \times 10^{10}/cm^3$. If the sample is additionally doped with $N_A = 1 \times 10^{18}/cm^3$ acceptor atoms, the approximate number of electrons/cm^3 in the sample, at T =300K, will be ___

[GATE 2014: 2 Marks]

Soln. When the semiconductor is doped by both type of impurities then it is called compensated semiconductor.

In the present problem semiconductor is doped by donor atoms

$$N_D = 1 \times 10^{15} \ / \ cm^3$$

And also doped by Acceptor atoms

$$N_A = 1 \times 10^{18} \ / \ cm^3$$

Since the acceptor atoms are more so the semiconductor will be p – type. As per the charge neutrality equation

$$N_D^+ + p = N_A^- + n$$

Or, $$P = (N_A^- - N_D^+) + n$$

$$P \cong (N_A - N_D)$$

Also,

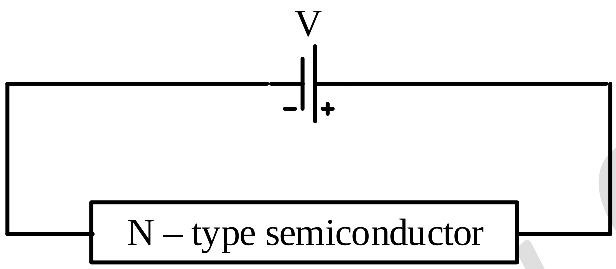
$$n = \frac{n_i^2}{P} = \frac{n_i^2}{(N_A - N_D)}$$

$$= \frac{2.25 \times 10^{20}}{(10^{18} - 10^{15})} = \frac{2.25 \times 10^{20}}{(1000 \times 10^{15} - 10^{15})}$$

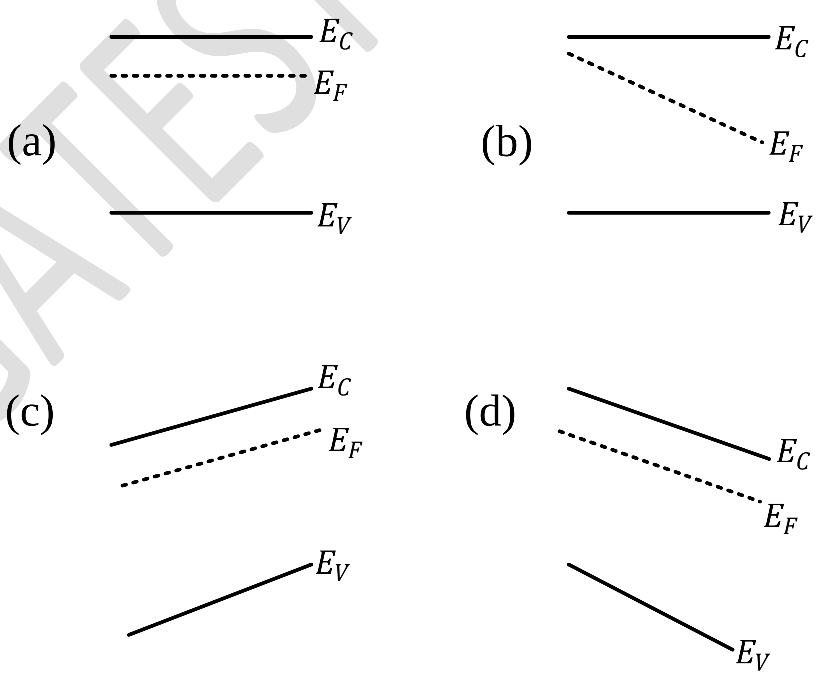
$$= \frac{\mathbf{2.25 \times 10^{20}}}{\mathbf{999 \times 10^{15}}} = \mathbf{2.252 \times 10^{2}}$$

= 225.2 Answer

19. An N – type semiconductor having uniform doping is biased as shown in the figure



If Ec is the lowest energy level of the conduction band, E_V is the highest energy level of the valance band and E_F is the Fermi level, which one of the following represents the energy band diagram for the biased N – type semiconductor?

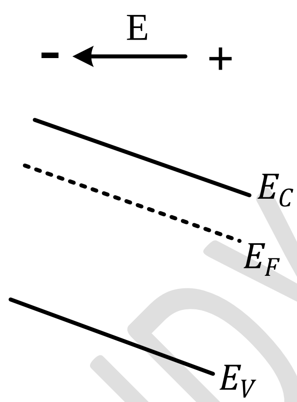


Soln.

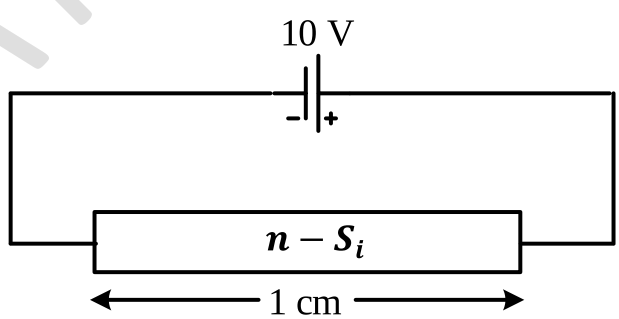
$$\boldsymbol{E(x) = \frac{1}{q} \cdot \frac{dE_1}{dx} \quad for\ electrons}$$

Diagram indicates electron energies. One has to note that slope in the bands must be such that electrons drift downhill in the field. Thus E points uphill in the band diagram (Above equation)

Option (d)



20. A dc voltage of 10 V is applied across an n – type silicon bar having a rectangular cross – section and length of 1 cm as shown in figure. The donor doping concentration N_D and mobility of electrons μ_n are 10^{16} cm^{-3} and $1000\ cm^2\ V^{-1}\ s^{-1}$, respectively. The average time $(in\ \mu s)$ taken by the electrons to move from one end of the bar to other end is ______



[GATE 2015: 2 Marks]

Soln. **Length of bar = 1 cm**

$$N_D = 10^{16} \,/\, cm^3$$

$$\mu_n = 1000\ cm^2 \,/\, V - S$$

Electric filed $(E) = 10\ V/cm$

Drift velocity of electrons

$$V_a = \mu_n E = 1000\ \times 10$$

$$= 10^4\ cm/sec$$

Time taken by electrons to move from one end of the bar to the other end

$$time\ taken = \frac{L}{V_d} = \frac{1}{10^4}$$

$$= 10^{-4}\ sec = 100\ \mu\ sec$$ **Answer**