6.2 The energy of an electron in a crystalline solid is related to the wave vector k by the relation

$$E = 10\frac{\hbar^2 k^2}{m}$$

Calculate the velocity and effective mass.

Hint : $$v = \frac{1}{\hbar}\frac{dE}{dk} = \frac{1}{\hbar}\frac{d}{dk}\left(\frac{10\hbar^2 k^2}{m}\right) = \frac{20\hbar m}{m}$$

and $$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)} = \frac{\hbar^2 m}{20\hbar^2} = \frac{m}{20}$$

6.3 For an intrinsic semiconductor having a band gap $E_g = 0.7$ eV, calculate the density of holes and electrons at room temperature ($= 27°$C). **[GGSIPU, May 2015 (4 marks) ; May 2019 (2.5 marks)]**

Hint : $$n_e = n_h = 2\times\left[\frac{2\pi k_B Tm}{h^2}\right]^{3/2}\exp.\left[\frac{E_F - E_C}{k_B T}\right] = 2\times\left[\frac{2\pi k_B Tm}{h^2}\right]$$

$$\exp.\left[\frac{E_g}{k_B T}\right] = 2\times\left[\frac{2\times 3.14\times(1.38\times10^{-23})\times300\times(9.1\times10^{-31})}{(6.623\times10^{-34})^2}\right]\times\exp.\left[\frac{-(0.07\times1.6\times10^{-19})}{(1.38\times10^{-23}\times300)}\right]$$

$$= 3.6\times10^{19}/\text{m}^3.$$

6.4 The energy gap of two intrinsic semiconductors A and B are 0.36 eV and 0.72 eV respectively. Compare the intrinsic carrier density of A to B at 300 K. (Given $m_h^* = m_e^* = 9.1\times10^{-31}$ kg and $2k_B T = 0.052$ eV).

Hint : $$n_i = 2\frac{2\pi k_B Tm}{h^2}\times\frac{m_e^* m_h^*}{m^2}\exp\left(-\frac{E_g}{2k_B T}\right).$$

Then $$\frac{(n_i)_A}{(n_i)_B} = \exp\left[\frac{0.36\text{ eV}}{0.052\text{ eV}}\right] = 1.0154\times10^3.$$

The ratio of the intrinsic carrier densities of the materials A and B is 1.0154×10^3.

6.5 Show that the integral

$$I = \int_{E_C}^{\infty}(E-E_C)^{1/2}e^{-E/k_BT}\,dE = (k_BT)^{3/2}e^{-\frac{E_C}{k_BT}}\sqrt{\frac{\pi}{2}}$$

Hint : $$\frac{E-E_C}{k_BT} = x\ ;\ \text{so that } (E-E_C) = k_BTx\ ;$$

$$\frac{E}{k_BT} = \frac{E_C}{k_BT} + x \text{ and } dE = k_BT\,dx$$

$$I = (k_BT)^{3/2}e^{-E_C/k_BT}\int_0^{\infty}x^{1/2}e^{-x}\,dx = (k_BT)^{3/2}e^{-E_C/k_BT}\frac{\sqrt{\pi}}{2}$$

6.6 In a n-type semiconductor, the Fermi level lies 0.3 eV below the conduction band at 300 K. If the temperature is increased to 330 K. Find the new position of Fermi level.

Hint : At 300 K E_F lies 0.3 eV below E_F

We know that $E_C - E_F = k_B T \ln \frac{N_c}{N_d}$ $\Rightarrow$ $0.3\,\text{eV} = 300\,k_B T \ln \frac{N_c}{N_d}$ ...(*i*)

At 330 K $E_C - E_F = 330\,k_B T \ln \frac{N_c}{N_d}$ ...(*ii*)

Dividing Eq. (*ii*) by Eq.(*i*), we get $\frac{E_C - E_F}{0.3} = \frac{330}{300}$ or $E_C - E_F = 0.3\,\text{eV}$

Thus the Fermi level lies 0.33 eV below the conduction band.

6.7 Fermi energy of an intrinsic semiconductor is 0.6V. The low lying energy levels in conduction band is 0.2 eV above the Fermi level. Calculate the probability of occupation of this level by an electron at room temperature.

Hint : $E_F = 0.6\text{ eV}, \quad E = (0.6 + 0.2)\,\text{eV} = 0.8\text{ eV}$

Probability $f(E) = \dfrac{1}{1 + \exp\dfrac{E - E_F}{k_B T}} = 0.0004 = 0.04\%$

6.11 In the circuit shown in Fig. 6.84, find the current flowing through Zener diode.

[GGSIPU, April 2009 (2 marks)]

Hint: $I = \dfrac{E_{in} - E_Z}{R_S} = \dfrac{(120-50)V}{5 \times 10^3} = 14 \text{ mA}$;

$$I_L = \frac{E_Z}{R_L} = \frac{50}{10 \times 10^3} = 5 \text{ mA}$$

$\therefore \quad I_Z = I - I_L = (14-5) \text{ mA} = 9\text{mA}$

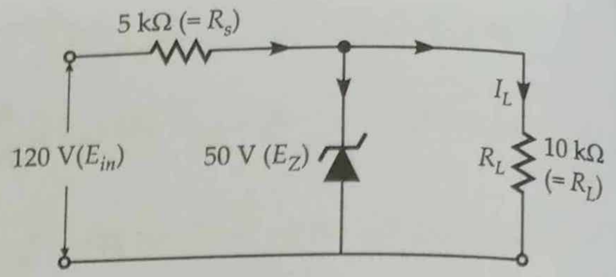

Fig. 6.84

6.12 For the circuit shown in Fig. 6.85 : Find (*i*) output voltage, (*ii*) voltage drop across series resistance, (*iii*) current through Zener diode. **[GGSIPU, April 2010 (2 marks)]**

Hint : $V = \dfrac{R_L E_i}{R_S + R_L} = \dfrac{10 \times 130}{10 + 10} = 65\text{V}$;

$V_Z = 60\text{V} > 65\text{V}$, Zener is *ON*

$V_0 = V_Z = 60\text{V}$,

then $V_S = 130 - 60 = 70$ V

$$I_L = \frac{V_Z}{R_L} = \frac{60\text{V}}{10\text{k}\Omega} = 6\text{mA},$$

$$I_S = \frac{70}{10} = 7\text{mA}, \quad I_Z = I_S - I_L = 1\text{mA}$$

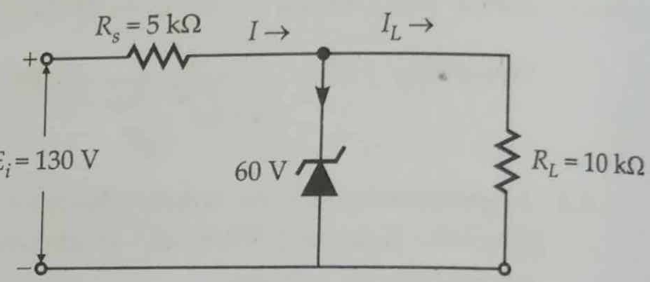

Fig. 6.85

6.13 Assume that the supply voltage V_i is 9V and the Zener voltage V_0 is 6V. If the maximum Zener current that can safely flow is 20 mA, determine that value of Zener resistance. If a load resistance of 1 kΩ is connected across the Zener diode. Calculate the load current. **[April 2009 (4 marks)]**

Hint. Go through example 6.13 at page $I_L = 6$ mA

6.14 A 10 V Zener diode is used to regulate the voltage across a variable load resistor. The input voltage varies between 13V and 16V and the load current varies between 10 mA and 85 mA. The minimum Zener current is 15 mA. Calculate the value of series resistance R_S.

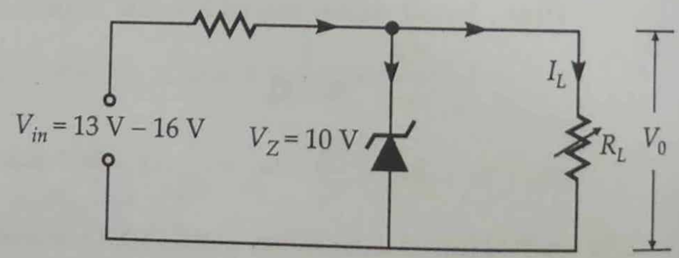

Fig. 6.86

Hint : $R_S = \dfrac{V_i - V_0}{(I_Z)_{\min} + (I_L)_{\max}} = \dfrac{30-10}{(15+85) \times 10^{-3}} \Omega = 30\,\Omega.$

6.15 For a Zener regulator circuit shown in Fig. 6.87. Find load current through the Zener diode.

Hint : $I = \dfrac{(40-30)V}{40\text{k}\Omega} = 2.5 \text{ mA},$

$$I_L = \frac{30\text{V}}{60\text{k}\Omega} = 0.5\text{mA},$$

$$I_Z = 2.5 - 0.5 \text{ mA} = 2.0 \text{ mA}.$$

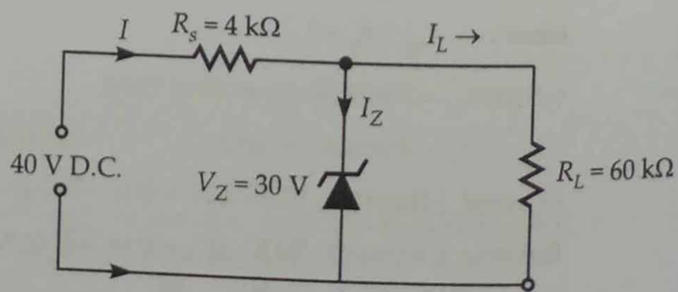

Fig. 6.87

6.20 *Distinguish between intrinsic and extrinsic semiconductors.*

[GGSIPU, May 2010 (2.5 marks) ; May 2017 (2.5 marks)]

Ans.

	Intrinsic Semiconductor	*Extrinsic Semiconductor*
1.	It is a semiconductor in its pure form.	It is a semiconductor doped with impurities.
2.	These semiconductors have low electrical conductivity.	These semiconductors have high electrical conductivity.
3.	The operating temperature is low for this type of semiconductors.	The operating temperature is high for this type of semiconductors.
4.	Charge carriers are produced due to thermal excitation.	Additional charge carriers are also produced due to added impurities.
	Examples : Ge, Si	*Examples* : Ge and Si doped with P, As, Bi, Sb etc.

6.21 *What is difference between N-type and P-type semiconductors ?*

[GGSIPU, April 2010-Reappear (2 marks)]

Ans.

	N-type Semiconductor	*P-type Semiconductor*
1.	These are materials, which have **pentavalent** impurity atoms (donors) added and conduct by "electron" movement and are called N-type semiconductors.	These are materials, which have **trivalent** impurity atoms (acceptors) added and conduct by "hole" movement are called P-type semiconductors.
2.	In these types of materials : ■ The donors are positively charged. ■ These are large number of free electrons. ■ A small number of holes in relation to the number of free electrons. ■ Doping gives : positively charged donors negatively charged free electrons ■ Supply of energy gives : negatively charged free electrons positively charged holes.	In these types of materials : ■ The acceptors are negatively charged. ■ These are large number of holes. ■ A small number of free electrons in relation to the number of holes. ■ Doping gives : negatively charged acceptors positively charged holes. ■ Supply of energy gives : positively charged holes negatively charged free electrons.

Both P-and N-types as whole are electrically neutral.

6.22 *What is the effect of dopant concentration on the Fermi energy and carrier concentration of N- and P-type semi-conductors ?*

Ans. In N-type semiconductor, increase in dopant concentration increases the majority charge carrier concentration and the Fermi level move closer to the bottom of the conduction band.

In P-type semiconductor, increase in dopant concentration increases the majority charge carrier concentration and pushes the Fermi level closer to the top of the valence band.

6.23 *What is an ideal P-N junction diode ?*

Ans. An ideal diode has zero resistance when forward biased and infinite resistance when reverse biased. It acts like an open switch in reverse bias and closed switch in forward bias.

6.12 *In doped semiconductor how does the free carrier concentration change with increase in temperature ?*

Ans. In doped semiconductors there are three regions as far as the carrier concentration versus temperature variation is concerned.

- At low temperature the electron (hole) from the donor (acceptor) is bound to the dopant. This is the freezeout region.
- With increase of temperature the fraction of ionized donors or acceptors increases and ultimately all the donors and acceptors are ionized and the free carrier concentration becomes equal to the dopant concentration. This is called saturation region. Semiconductor devices are normally preferred to operate in the temperature range at which saturation occurs.
- As the temperature is further increased beyond saturation region, the carrier concentration again increases due to increases the intrinsic generation across the band gap and becomes larger then the doping concentration. This is called intrinsic region.

6.13 *What do you mean by thermal equilibrium in a semiconductor ?*

Ans. Equilibrium or thermal equilibrium in a semiconductor means that no external forces such as electric field, magnetic field, radiation or temperature gradient act on the semiconductor. All properties of the semiconductor will be independent of time in thermal equilibrium.

6.14 *Where is Fermi energy level located in an intrinsic semiconductor ?*

Ans. The Fermi level is located very close to the middle of the band gap slightly upwards towards the edge of the conduction band due to the difference of the effective mass of the electrons and holes.

6.15 *Why do metals have a positive temperature coefficient of resistance and semiconductor have negative temperature coefficient of resistance ?*

Ans. A large number of free electrons participate in conduction in metals. With increase of temperature these electrons are scattered more frequently by increasing number of phonons and the relaxation time for collision decreases. As a result mobility decreases and resistivity increases with the increase mobility decreases and resistivity increases with the increase of temperature in metals. In case of semiconductors, as temperature increases large number of electron-hole pairs are generated thermally. Therefore, conductivity increases and resistivity decreases.

6.16 *How does a doped semiconductor behave with the increase of temperature ?*

Ans. A doped or extrinsic semiconductor tends to become an intrinsic one as temperature increases.

6.17 *How does the Fermi level of doped semiconductor shift its position with increase of temperature ?*

Ans. As temperature increases the Fermi level of a doped semiconductor shifts towards the intrinsic level *i.e.*, towards the midgap.

6.18 *What is the effect of dopant concentration on the Fermi energy and carrier concentration of N- and P-type semiconductors ?*

Ans. In *N*-type semiconductor, increase in dopant concentration increases the majority charge carrier concentration and the Fermi level move closer to the bottom of the conduction band.

In *P*-type semiconductor, increase in dopant concentration increases the majority charge carrier concentration and pushes the Fermi level closer to the top of the valence band.

6.19 *What are the various forces acting on charge carriers in a P-N junction ?*

Ans. There are two types of forces – one due to diffusion of carriers and another due to electric field created in the space region of the *P-N* junction.

6.1 *State the Bloch theorem.*

Ans. The Bloch theorem is a mathematical statement regarding the form of the one electron wave [functi]ons for a perfectly periodic potential.

6.2 *What is Kronig-Penney model ?*

Ans. Kronig and Penney in 1931 solved the Schrödinger's equation for electrons in a simple idealised [perio]dic field. The model is of considerable importance because it interprets the main features of the band [struc]ture of metals.

6.3 *What is the basic assumption in Kronig-Penney model ?*

Ans. In Kronig-Penney model, it is assumed that potential energy of an electron in a linear array of [posi]tive nuclei has the form a periodic array of square wells with period $(a+b)$.

At the bottom of the well, *i.e.*, for $0 < x < a$ the electron is assumed to be in the vicinity of a nucleus and [pot]ential energy is taken as zero whereas outisde a well *i.e.*, for $-b < x < 0$ the potential energy is assumed to [be] V_0 as shown in Fig. 6.7.

6.4 *What are Brillouin zones ?*

Ans. If Schrödinger wave equation for electron energies is solved with a periodic function $u(k)$ to give [th]e energies of an electrons in a solid, the solutions falls into permitted energy bonds. If the solutions are [pl]otted in the reciprocal lattice of the crystal being considered, the zones enclosing the solutions for [n] $= 1, 2, 3, \ldots, n$ are called *Brillouin zones.*

6.5 *Define the effective mass of electron.* **[GGSIPU, May 2014 (2.5 marks), May 2018 (3 marks)]**

Ans. When an electron in a periodic potential is accelerated by an electric field or a magnetic field then [t]he mass of the electron varies with velocity. This means the mass of the electron is a function of velocity and [i]s termed as effective mass of the electron.

6.6 *How is an energy band formed ?*

Ans. When N number of atoms are brought together to form a solid, all the different discrete energy levels of electrons of the constituent atoms of the solid come close together to form a continuous band of energies. The Pauli's exclusion principle is not violated during the formation of an energy band.

6.7 *Define energy band.*

Ans. The range of energies possessed by the electrons in solid is known as energy band.

6.8 *Where is Fermi energy level located in an intrinsic semiconductor ?*

Ans. The Fermi level is located very close to the middle of the band gap slightly upwards towards the edge of conduction band due to difference of effective mass of electrons and holes.

6.9 *How does a doped semiconductor behave with the increase of temperature ?*

Ans. A doped extrinsic semiconductor tends to become an intrinsic one as temperature increases.

6.10 *How does the Fermi level of doped semiconductor shifts its position with increase of temperature ?*

Ans. As temperature increases the Fermi level of a doped semiconductor shifts towards the intrinsic level *i.e.*, towards the midgap.

6.11 *What is the hole ?*

Ans. The vacant place due to absence of electron is called hole.

Problem 6.4 *In an intrinsic semiconductor ($E_g = 0.676$ eV), $m_e = 0.09$ m and $m_h = 0.36$ m. Calculate the concentration of intrinsic charge carriers at 300 K.*

Solution. $E_g = 0.676$ eV, $m_e = 0.09$ m and $m_h = 0.36$ m

Then carrier concentration

$$n_i = 2\left(\frac{k_B T}{2\pi\hbar^2}\right)^{3/2}(m_e m_h)^{3/4}\exp\left(-\frac{E_g}{2k_B T}\right)$$

$$= CT^{3/2}(0.3\times 0.6)^{3/2}\exp-\frac{0.676}{0.052}$$

$$C = 2\left(\frac{k_B}{2\pi\hbar^2}\right)^{3/2}(9.1\times 10^{-31})^{3/2} = 4.83\times 10^{21}/\text{m}^3$$

$$T^{3/2} = (300)^{3/2} = 5.19\times 10^3 \text{ K}$$

$$\therefore \quad n_i = 4.83\times 10^{21}\times(5.19\times 10^3)\times(0.0763)\times(2.266\times 10^{-6}) = 4.33\times 10^{18}/\text{m}^3$$

Problem 6.5 *For copper at 1000 K, find the energy at which the probability $f(E)$ that a conduction electron*

Problem 6.7 *In a voltage regulator a 12 V Zener diode is connected in series with a resistance of 150Ω. A load resistance of 1 kΩ is connected in parallel with diode. If minimum Zener current is zero and maximum Zener current is 20 mA. Calculate the operating range of input voltage.* **[GGSIPU April 2008 (4 marks)]**

Solution. $V_Z = 12\text{ V}, R = 150\Omega, R_L = 1\text{k}\Omega, (I_Z)_{min} = 0, (I_Z)_{max} = 20\text{ mA}, V_i = \text{Range} = ?$

This is case of fixed R_L and variable V_i

(i) For $(V_i)_{min}$:

$$V_0 = V_Z = \frac{R_L V_i}{R + R_L}$$

$$(V_i)_{min} = \frac{(R + R_L)V_Z}{R_L} = \frac{(150 + 1000) \times 12}{1000} = 1.150 \times 12 = 13.800 = 13.8\text{ V}$$

(ii) For $(V_i)_{max}$:

$$I_L = \frac{V_0}{R_L} = \frac{V_Z}{R_L} = \frac{12}{1000} = 12\text{ mV}$$

is fixed, the value of I will maximum when Zener current is maximum

$$I_{max} = I_{ZM} + I_L$$

Now

$$V_i = IR + V_0 \qquad \because \; V_0 = V_Z$$

$$(V_i)_{max} = I_{max} R + V_Z$$

$$= (12 + 20) \times 10^{-3} \times 150 + 12 = 32 \times 50 \times 10^{-3} + 12 = 4800 + 12 = 16.8\text{ V}$$

$\because$ Operating range of input voltage = 13.8 V to 16.8 V

Problem 6.8 *For what voltage will the reverse current in a P-N junction germanium diode attain a value of 90% of its saturation value at room temperature ?*

Solution. Give $I = 90\%$ of I_S, $T = 300\text{ K}$, $V = ?$

The general form of the rectifier equation is

$$I = I_S\left[\exp.\left(\frac{eV}{k_B T}\right) - 1\right] \qquad \text{or} \qquad \frac{I}{I_S} = \exp.\left(\frac{eV}{k_B T}\right) - 1$$

or

$$0.9 = \exp.\left(\frac{eV}{k_B T}\right) \qquad \text{or} \qquad \frac{eV}{k_B T} = \ln 0.9$$

or

$$V = \frac{\ln 0.9 \times k_B T}{e} = \frac{\ln 0.9 \times 1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} = 0.017\text{ volt}$$

Example 6.5 *In an N-type semiconductor, the Fermi level lies 0.3 eV below the conduction band at 300 K. If the temperature is increased to 330 K, find the new position of the Fermi level.*

Solution. Given $(E_C - E_F) = 0.3$ eV or $(E_F - E_C) = -0.3$ eV at temperature 300 K

$(E_C - E_F) = ?$ at temperature 330 K

We know that
$$n_e = 2\left(\frac{2\pi m_e^* k_B T}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_C}{k_B T}\right)$$

Assuming that the density of electrons in the conduction band of intrinsic semiconductor (n_e) remains unchanged by changing temperature 300 K to 330 K

$$(n_e)^{300\text{K}} = (n_e)^{330\text{K}}$$

$$\exp\left[\frac{E_F - E_C}{k_B \times 300}\right] = \exp\left[\frac{E_F - E_C}{k_B \times 330}\right] \quad \Rightarrow \quad \frac{0.3}{300\text{ K}} = \frac{(E_C - E_F)_{330}}{330\text{ K}}$$

$$(E_C - E_F) \text{ at } 330\text{K} = \frac{0.3 \times 330}{300} = 0.33 \text{ eV}$$

Thus at 330 K, the Fermi energy level lies 0.33 eV below the conduction band.

__Example 6.4__ *In a certain semiconductor, the mobility of electrons is 0.3 $m^2 V^{-1} s^{-1}$. The mobility of holes is 0.2 $m^2 V^{-1} s^{-1}$ and forbidden energy band is 0.7 eV. Calculate the intrinsic carrier concentration in semiconductor at 300 K if effective mass of electrons and holes are respectively 0.55 and 0.37 times the rest mass of the electron.*

Solution. Given : $T = 300\,\text{K}$, $E_g = 0.7 \times 1.6 \times 10^{-19}\,\text{J}$, $m_e^* = 0.55\, m_e = 0.55 \times 9.1 \times 10^{-31}\,\text{kg}$,
$m_h^* = 0.37\, m_e = 0.37 \times 9.1 \times 10^{-31}\,\text{kg}$, $k_B = 1.38 \times 10^{-23}\,\text{J K}^{-1}$ and $h = 6.626 \times 10^{-34}\,\text{J s}$

The intrinsic concentration $n_i = 2\left\{\dfrac{2\pi k_B T}{h^2}\right\}^{3/2} (m_e^* m_h^*)^{3/4} \exp\left[\dfrac{-E_g}{2 k_B T}\right]$

$$= 2\left\{\frac{2 \times \pi \times 1.38 \times 10^{-23}}{(6.626 \times ^{-34})^2}\right\}^{3/2} [(0.55 \times 9.1 \times 10^{-31} \times (0.37 \times 9.1 \times 10^{-31})] \exp\left[-\frac{0.7 \times 1.6 \times 10^{-19}}{2 \times 1.38 \times 10^{-23} \times 300}\right]$$

$= 1.35 \times 10^{13}\,\text{m}^{-3}$