

**ESE | GATE | PSUs**

**State Engg. Exams**

**MADE EASY**  
**WORKBOOK 2024**



**Detailed Explanations of  
Try Yourself Questions**

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**Electronics Engineering**  
**Electronic Devices and Circuits**



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Publications



## Detailed Explanation of Try Yourself Questions

**T1. Sol.**

$$J_n = qD_n \frac{dn}{dx} = q \times D_n \times \left( \frac{-10^{16} \times (2x)}{L} \right) = -64 \text{ A/m}^2$$

**T2. Sol.**

Here  $E_i$  is not exactly as in the middle of the gap because the density of states  $N_C$  and  $N_V$  are different.

$$N_C \cdot e^{-\frac{E_C - E_i}{kT}} = \sqrt{N_C N_V} e^{-E_g/2kT} = n_i$$

$$e^{-\frac{E_C - E_i + E_g/2}{kT}} = \frac{\sqrt{N_V}}{\sqrt{N_C}} = \left( \frac{m_p^*}{m_n^*} \right)^{3/4}$$

$$\frac{E_g}{2} - (E_C + E_i) = kT \cdot \frac{3}{4} \cdot \ln \left( \frac{m_p^*}{m_n^*} \right) = 0.0259 \cdot \frac{3}{4} \ln \left( \frac{0.56}{1.1} \right) = -0.013 \text{ eV}$$

So  $E_i$  is about  $\frac{kT}{2}$  below the centre of the band gap.

**T3. (b)**

Given the probability of state being empty is 0.9258

i.e.  $1 - f(E) = 0.9258$

The energy level being occupied by electron is  $f(E)$

$\therefore f(E) = 1 - 0.9258 = 0.0742$

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

$$0.0742 = \frac{1}{1 + e^{\left( \frac{E - E_F}{kT} \right)}}$$

$$1 + e^{\left(\frac{E-E_F}{kT}\right)} = 13.477$$

$$\frac{E-E_F}{kT} = 2.523$$

$$\therefore \begin{aligned} E-E_F &\approx 2.52 \text{ kT} \\ E &= E_F + 2.52 \text{ kT} \end{aligned}$$

The energy level 2.52 kT above the Fermi energy is occupied by electron with probability 0.0742.

**T4. Sol.**

The diffusion current density is defined as

$$J_n = qD_n \frac{dn}{dx}$$

substituting the given values, we get

$$0.09 = (1.6 \times 10^{-19}) \times 25 \left( \frac{4 \times 10^{14} - n(0)}{0.010 - 0} \right)$$

$$\begin{aligned} \frac{0.09 \times 0.010}{1.6 \times 10^{-19} \times 25} &= 4 \times 10^{14} - n(0) \\ n(0) &= 1.75 \times 10^{14} \text{ cm}^{-3} \end{aligned}$$

**T5. (c)**

Intrinsic carrier concentration in semiconductor is given by

$$n_i = \sqrt{N_C N_V} \exp[-E_g / 2kT]$$

Given the bandgap energy

$$E_{gA} = 1.21 \text{ eV}; \quad E_{gB} = 2.4 \text{ eV}$$

The ratio of intrinsic carrier concentration of semiconductor B to semiconductor A is obtained as,

$$\begin{aligned} \frac{n_{iB}}{n_{iA}} &= \frac{\sqrt{N_C N_V} \exp[-E_{gB} / 2kT]}{\sqrt{N_C N_V} \exp[-E_{gA} / 2kT]} \\ &= \exp[-(E_{gB} - E_{gA}) / 2kT] \\ &= \exp\left[\frac{-(2.4 - 1.21) \text{ eV}}{2 \times 0.026 \text{ eV}}\right] \end{aligned}$$

$$\frac{n_{iB}}{n_{iA}} = 1.152 \times 10^{-10}$$

**T6. Sol.**

(i) Minimum conductivity,  $\sigma_{\min} = 2qn_i\sqrt{\mu_n\mu_p}$   
 $\sigma_{\min} = 2 \times 1.6 \times 10^{-19} \times 3.6 \times 10^{12} \sqrt{7500 \times 300}$   
 $\sigma_{\min} = 1.728 \times 10^{-3} \text{ } \Omega/\text{cm}$

(ii) We know that,  
 The conductivity of semiconductor,

$$\sigma = n_q \mu_n + p q \mu_p \quad \dots(i)$$

By mass action law,  $p = \frac{n_i^2}{n}$  ... (ii)

$$\therefore \sigma = n q \mu_n + \frac{n_i^2}{n} q \mu_p$$

For minimum conductivity,

$$\frac{d\sigma}{dn} = 0$$

$$\frac{d\sigma}{dn} = q\mu_n + \left(-\frac{1}{n^2}\right) n_i^2 q\mu_p$$

$$0 = q\mu_n - \frac{1}{n^2} n_i^2 q\mu_p$$

$$\frac{n_i^2}{n^2} = \frac{\mu_n}{\mu_p} \Rightarrow n = n_i \sqrt{\frac{\mu_p}{\mu_n}}$$

Similarly,

$$p = n_i \sqrt{\frac{\mu_n}{\mu_p}}$$

$$\therefore n = 3.6 \times 10^{12} \sqrt{\frac{7500}{300}} = 1.8 \times 10^{13} \text{ cm}^{-3}$$

From equations (i) and (ii),

$$p = 3.6 \times 10^{12} \sqrt{\frac{300}{7500}} = 7.2 \times 10^{11} \text{ cm}^{-3}$$

(iii) Minimum conductivity,  $\sigma_{\min} = n_i \sqrt{\frac{\mu_p}{\mu_n}} q\mu_n + n_i \sqrt{\frac{\mu_n}{\mu_p}} q\mu_p$

$$\sigma_{\min} = n_i q \left[ \sqrt{\mu_p \mu_n} + \sqrt{\mu_p \mu_n} \right]$$

$$\sigma_{\min} = 2n_i q \sqrt{\mu_p \mu_n} \text{ } \Omega/\text{cm}$$

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### Detailed Explanation of Try Yourself Questions

**T1. Sol.**

$$I = qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) (e^{qV/kT} - 1) = I_o (e^{qV/kT} - 1)$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5 \times 10^{10})^2}{10^{15}} = 2.25 \times 10^5 \text{ cm}^{-3}$$

$$n_p = \frac{n_i^2}{p_p} = \frac{(1.5 \times 10^{10})^2}{10^{17}} = 2.25 \times 10^3 \text{ cm}^{-3}$$

For minority carriers,

$$D_p = \frac{kT}{q} \mu_p = 0.0259 \times 450 = 11.66 \text{ cm}^2/\text{s on the } n \text{ side}$$

$$D_n = \frac{kT}{q} \mu_n = 0.0259 \times 700 = 18.13 \text{ cm}^2/\text{s on the } p \text{ side}$$

$$L_p = \sqrt{D_p \tau_p} = \sqrt{11.66 \times 10 \times 10^{-6}} = 1.08 \times 10^{-2} \text{ cm}$$

$$L_n = \sqrt{D_n \tau_n} = \sqrt{18.13 \times 0.1 \times 10^{-6}} = 1.35 \times 10^{-3} \text{ cm}$$

$$\begin{aligned} I_o &= qA \left( \frac{D_p}{L_p} p_n + \frac{D_n}{L_n} n_p \right) \\ &= 1.6 \times 10^{-19} \times 0.0001 \left( \frac{11.66}{0.0108} 2.25 \times 10^5 + \frac{18.13}{0.00135} 2.25 \times 10^3 \right) \\ &= 4.370 \times 10^{-15} \text{ A} \end{aligned}$$

$$I = I_o (e^{0.5/0.0259} - 1) \approx 1.058 \times 10^{-6} \text{ A in forward bias.}$$

$$I = -I_o = -4.37 \times 10^{-15} \text{ A in reverse bias.}$$

**T2. Sol.**

Built in voltage, with no. external voltage applied the voltage ( $V_o$ ) across the p-n junction is given by

$$V_o = V_T \ln \left( \frac{N_A N_D}{n_i^2} \right)$$

$$V_o = 25 \text{ mV} \ln \left( \frac{10^{17} \times 10^{16}}{(1.5 \times 10^0)^2} \right)$$

$$\Rightarrow 25 \times 29.12 \text{ mV}$$

$$V_o \Rightarrow 728 \text{ mV}$$

width of the depletion region.

$$W_{\text{dep}} = x_n + x_p = \sqrt{\frac{2\epsilon_0}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) V_o} = 0.32 \text{ mm} \quad \dots(i)$$

$$\frac{x_n}{x_p} = \frac{N_A}{N_D} = \frac{10^{17}}{10^{16}} = 10 \quad \dots(ii)$$

$$x_n = 10 x_p$$

By solving equation (i) and (ii)

$$x_p = 0.03 \text{ } \mu\text{m} \text{ and } x_n = 0.29 \text{ } \mu\text{m}$$

**T3. (a)**

For  $P^+N$  junction diode

$$N_A \gg N_D \quad (\text{or}) \quad \frac{1}{N_A} \ll \frac{1}{N_D}$$

$$W = \sqrt{\frac{2\epsilon_s}{q} \left[ \frac{1}{N_A} + \frac{1}{N_D} \right] V_{bi}}$$

$$W = \sqrt{\frac{2\epsilon_s}{q} \cdot \frac{1}{N_D} \cdot V_{bi}}$$

$$\therefore \frac{1}{N_A} \ll \frac{1}{N_D}$$

$$W = \sqrt{\frac{2 \times 1.04 \times 10^{-12}}{1.6 \times 10^{-19}} \times \frac{1}{3 \times 10^{16}} \times 0.75}$$

$$\therefore \epsilon_{\text{Si}} = 1.04 \times 10^{-10} \text{ F/m} = 1.04 \times 10^{-12} \text{ F/cm}$$

$$W = 1.802 \times 10^{-5} \text{ cm}$$

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# 3

## Optoelectronic Devices



### Detailed Explanation of Try Yourself Questions

**T1. (b)**

Given photocurrent density  $J_L = 10 \text{ mA/cm}^2$   
The open circuit voltage of solar cell is

$$V_{oc} = V_t \ln \left( 1 + \frac{I_L}{I_S} \right)$$

or

$$V_{oc} = V_t \ln \left( 1 + \frac{J_L}{J_S} \right)$$

$$J_S = qn_i^2 \left[ \frac{D_n}{L_n N_a} + \frac{D_p}{L_p N_d} \right]$$

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

$$L_n = \sqrt{D_n \tau_{n0}} = \sqrt{25 \times 5 \times 10^{-7}} = 35.4 \mu\text{m}$$

$$L_p = \sqrt{D_p \tau_{p0}} = \sqrt{10 \times 10^{-7}} = 10 \mu\text{m}$$

$$J_S = (1.6 \times 10^{-19}) \times (1.5 \times 10^{10})^2 \times \left\{ \frac{25}{(35.4 \times 10^{-4})(5 \times 10^{18})} + \frac{10}{(10 \times 10^{-4})(10^{16})} \right\}$$

$$\therefore J_S = 3.6 \times 10^{-11} \text{ A/cm}^2$$

since the solar intensity is increased by 10 times

$$\Rightarrow J_L = 10 \times 10 \text{ mA/cm}^2 = 100 \text{ mA/cm}^2$$

Given temperature remains constant hence the reverse saturation current density also constant.

$$\therefore J_S = 3.6 \times 10^{-11} \text{ A/cm}^2$$

$\therefore$  The open-circuit voltage is

$$V_{OC} = (0.026) \ln \left( 1 + \frac{100 \times 10^{-3}}{3.6 \times 10^{-11}} \right)$$

$$\therefore V_{OC} = 0.565 \text{ V}$$

**T2. Sol.**

- (i) Entire junction is uniformly illuminated

$$I_{SC} = I_L = Aq(W + L_n + L_p) G_L$$

$$V_o = V_T \ln \left( \frac{N_A N_D}{n_i^2} \right) = 0.026 \ln \left( \frac{10^{16} \times 10^{15}}{(1.5 \times 10^{10})^2} \right)$$

$$= 0.6374 \text{ Volt}$$

$$W = \sqrt{\frac{2\epsilon_{si} V_o}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right)} = \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14} \times 0.6374}{1.6 \times 10^{-19}} \left( \frac{1}{10^{15}} + \frac{1}{10^{16}} \right)}$$

$$W = 95.26 \times 10^{-6} \text{ cm}$$

$$L_n = \sqrt{D_n \tau_n} = \sqrt{25 \times 10^{-6}} = 5 \times 10^{-3} \text{ cm}$$

$$L_p = \sqrt{D_p \tau_p} = \sqrt{10 \times 5 \times 10^{-7}} = 2.236 \times 10^{-3} \text{ cm}$$

- (ii) Short circuit current

$$I_{SC} = 5 \times 1.6 \times 10^{-19} (95.26 \times 10^{-6} + 5 \times 10^{-3} + 2.236 \times 10^{-3})$$

$$I_{SC} = 4000(0.00733) = 29.32 \text{ Amp.}$$

- (iii)

$$I_o (\text{dark current}) = Aq \frac{D_p}{L_p} \frac{n_i^2}{N_D} + Aq \frac{D_n}{L_n} \frac{n_i^2}{N_A}$$

$$= Aq n_i^2 \left( \frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A} \right)$$

$$= 5 \times 1.6 \times 10^{-19} \times (1.5 \times 10^{10})^2 \left[ \frac{10}{2.236 \times 10^{-3} \times 10^{15}} + \frac{25}{5 \times 10^{-3} \times 10^{16}} \right]$$

$$= 895.0089 \times 10^{-12} \text{ Amp}$$

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# 5

## Field Effect Transistor



### Detailed Explanation of Try Yourself Questions

**T1. Sol.**

Since  $V_{DS} > V_{GS}$ , MOSFET is in saturation region

$$I_{dsat} = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{ds})$$

$$100 \mu A = k(2 - V_T)^2 (1 + 3\lambda)$$

$$110 \mu A = k(2 - V_T)^2 (1 + 5\lambda)$$

$$\frac{100}{110} = \frac{1 + 3\lambda}{1 + 5\lambda}$$

$$\lambda = 0.0588 \text{ V}^{-1}$$

**T2. (c)**

**T3. (d)**

$n$  = new concentration of electrons at the surface

$n_0$  = equilibrium concentration of electrons

$$n_0 = \frac{n_i^2}{p_0} \approx \frac{n_i^2}{N_A} = 1.8 \times 10^5 \text{ cm}^{-3}$$

$$n = n_0 e^{\Psi/V_t}; \quad V_t = \frac{kT}{q}, \quad \Psi = \text{surface potential}$$

$$\Psi = \frac{kT}{q} \ln\left(\frac{n}{n_0}\right) = 0.026 \ln\left(\frac{3 \times 10^{10}}{1.8}\right) \approx 0.612 \text{ V}$$

**T4. (b)**

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