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# ESE (Mains) 2019

## Electronic Devices & Circuits Imp. Questions with Solutions

1. A. Derive the condition for minimum conductivity in case of a semiconductor material. Find expression for minimum conductivity & give relation between intrinsic conductivity & minimum conductivity.

B. Find minimum conductivity in case of a semiconductor which has electron mobility = 1000 cm$^2$ / V-sec, hole mobility = 600 cm$^2$ / V-sec and intrinsic conductivity is $10^{-6}/\Omega$ – cm.

Ans.

A. Conductivity of a semiconductor is given by,

$$\sigma = nq\mu_n + pq\mu_p \qquad .........(1)$$

$$\& \; n = \frac{ni^2}{p} \qquad ...........(mass\ action\ law)$$

Putting this value in equation (1)

$$\therefore\ \sigma = \frac{ni^2}{p} q\ \mu_n + pq\,\mu_p$$

For minimum conductivity

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

$$\therefore\ \frac{d\sigma}{dp} = -\frac{ni^2}{p^2} q\mu_n + q\,\mu_p = 0$$

$$\therefore q\,\mu_p = \frac{ni^2}{p^2} q\ \mu_n$$

$$\therefore\ p = ni\sqrt{\frac{\mu_n}{\mu_p}} \qquad .........(ii)$$

From mass action law

$$n = \frac{ni^2}{p}$$

$$n = \frac{ni^2}{ni\sqrt{\dfrac{\mu_n}{\mu_p}}}$$

$$\therefore n = ni\sqrt{\frac{\mu_p}{\mu_n}} \qquad ........(iii)$$

∴The condition for minimum conductivity is

$$p = ni\sqrt{\frac{\mu_n}{\mu_p}}\ and\ n = ni\sqrt{\frac{\mu_p}{\mu_n}}$$

Substituting these values in equation (i)

$$\therefore\ \sigma_{\min} = ni\sqrt{\frac{\mu_p}{\mu_n}}.\,q.\ \mu_n + ni\sqrt{\frac{\mu_n}{\mu_p}}.\,q\ .\ \mu_p$$

$$\therefore\ \sigma_{\min} = 2niq\sqrt{\mu_n\mu_p} + niq\sqrt{\mu_n\mu_p}$$

$$\boxed{\sigma_{\min} = niq\sqrt{\mu_n\mu_p}}$$

This is the expression for minimum conductivity

$$\therefore\ \frac{\sigma_{\min}}{\sigma_i} = \frac{2niq\sqrt{\mu_n\mu_p}}{niq\,q\,\mu_n + niq\,\mu_p}$$

$$\therefore\ \frac{\sigma_{\min}}{\sigma_i} = \frac{2\sqrt{\mu_n\mu_p}}{\mu_n + \mu_p}$$

$$\therefore \boxed{\sigma_{\min} = \frac{2\sigma i\sqrt{\mu_n\mu_p}}{\mu_n + \mu_p}} \qquad .........(iv)$$

B. Given μ$_n$ = 1000 cm$^2$/ v – sec, μ$_p$ = 600 cm$^2$ / v – sec & ni = $10^{-6}$ / Ω – cm

From equation (iv)

$$\sigma_{\min} = \frac{2\times 10 - 6\times\sqrt{1000\times 600}}{1000 + 600}$$

$$\boxed{\therefore \sigma_{\min} = 9.68\times 10^{-7}\,/\,\Omega - cm}$$

We can observe it is less than intrinsic conductivity.

2. An abrupt Ge junction diode has N$_A$ = $10^{16}$ atoms /cm$^3$ and N$_D$ = $10^{14}$ atoms / cm$^3$ at room temperature is forward biased with a 0.15 volt. Plot the carrier concentration and hole and electron current densities as a function of distance. Assume junction area as 2 mm$^2$, diffusion length of electrons and holes as 0.04 cm and 0.05 cm respectively.

(Assume D$_n$ = 100 cm$^2$ / sec and D$_p$ = 50 cm$^2$ / sec)

Ans.

N$_A$ = $10^{16}$ atoms / cm$^3$ and N$_D$ = $10^{14}$ atoms / cm$^3$

$$n_n = N_D \;\&\; p_n = \frac{ni^2}{n_n}$$

$$\therefore p_n = \frac{6.25\times10^{26}}{10^{14}}$$

$$\therefore p_n = 6.25\times10^{12}\ atoms/cm^3$$

$$now\ p_p = N_A\ \&\ n_p = \frac{ni^2}{p_p}$$

$$\therefore n_p = \frac{6.25\times10^{26}}{10^{16}}$$

∴ $n_p$ = 6.25 × $10^{16}$ atoms / $cm^3$

Now we know that,

$P_n$ (o) = $P_{no}$ ($e^{v/v_T}$ -1)

= 6.25 × $10^{12}$ × ($e^{0.15/0.0259}$ −1)

$P_n$ (o) = 2.04 × $10^{15}$

& $n_p$(o) = $n_{po}$ ($e^{v/v_T}$ -1)

= 6.26 × $10^{10}$ ($e^{0.15\,/\,0.0259}$−1)

∴ $n_p$(o) = 2.04 × $10^{13}$

Now $L_n$ = 0.04 cm and $L_p$ = 0.05 cm

∴ $n_p$(x) = $n_p$(o) $e^{-x/Ln}$

∴ $n_p$(x) = 2.04 × $10^{13}$ $e^{-x/0.04}$

& $P_n$(x) = $P_n$(o) $e^{-x/Lp}$

∴ $P_n$(x) = 2.04 × $10^{15}$ $e^{-x/0.05}$

Hole diffusion current $I_p(o) = -qDp\dfrac{dP}{dx}$

$$= \frac{AqD_P P_{no}}{L_p}(e^{v/vT} - 1)$$

$$= \frac{0.02\times1.6\times10^{-19}\times50\times2.04\times10^{15}}{0.05}$$

∴ Hole diffusion current $I_P$(o) = 6.53 mA

And $I_P$(x) = $I_P$(o) $e^{-x/Lp}$

Similarly

Electron diffusion current

$I_n(o) = qD_n\dfrac{dn}{dx}$

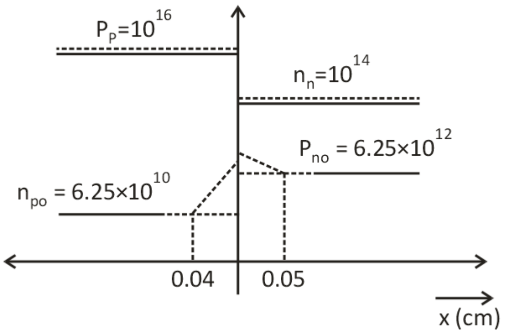
$$= \frac{A\,q\,D_n\,n_{po}\,(e^{v/vT} - 1)}{L_n}$$

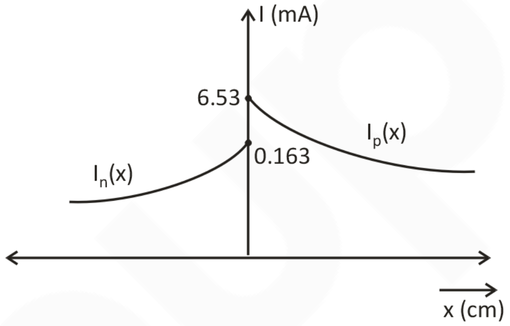
$$= \frac{0.02\times1.6\times10^{-19}\times100\times2.04\times10^{13}}{0.04}$$

∴ Electron diffusion current $I_n$(o)

= 0.163 mA

And $I_n$(x) = $I_n$(o) $e^{-x/ln}$

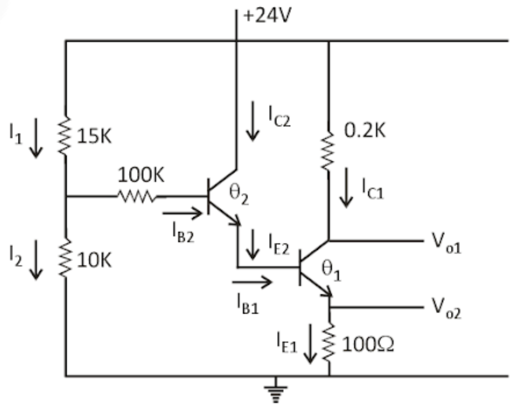




3. For the circuit shown transistor θ₁ & θ₂ both operate in active region with $V_{BE1} = V_{BE2} = 0.7$ V, $\beta_1 = 75$ & $\beta_2 = 50$ then

a) Find the currents $I_{B1}$, $I_{C1}$, $I_{E1}$, $I_{B2}$, $I_{C2}$, $I_{E2}$, $I_1$, $I_2$

b) Find output voltages $V_{o1}$ and $V_{o2}$



Applying Thevenin's theorem we get

$$Vth = \frac{vcc}{R_1 + R_2}\times R_2$$

$$= \frac{24}{15+10}\times10$$

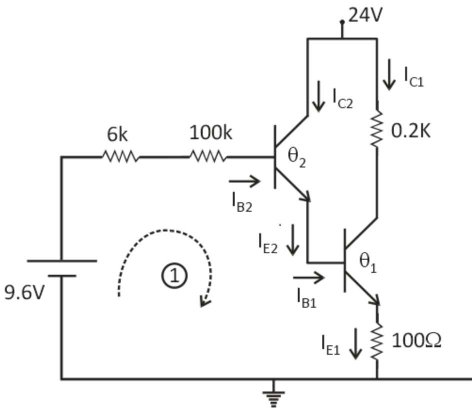
∴ vth = 9.6V

& Rth = $R_1$ || $R_2$

= 15 || 10

Rth = 6 kΩ

∴ Equivalent circuit will be



Applying KVL in loop (1)

$-9.6 + (106)\ I_{B2} + 0.7 + 0.7 + 0.1\ I_{E1} = 0$ (i)

Now $I_{E2} = I_{B1}$

$\therefore (1 + B_2)\ I_{B2} = I_{B1}$

& $I_{E1} = (1+B_1)\ I_{B1}$

$= (1+B_1)\ (1+B_2)\ I_{B2}$

$I_{E1} = 76 \times 51 \times I_{B2}$

$\therefore I_{E2} = 3876\ I_{B2}$

∴ Equation (I) become,

$-9.6 + 106\ I_{B2} + 0.7 + 0.7 + 0.1 \times 3876\ I_{B2} = 0$

$\therefore 493.6\ I_{B2} = 8.2$

$\therefore I_{B2} = 0.01661$ mA

$\therefore I_{B2} = 16.61\ \mu A$

$\therefore I_{C2} = B_2\ I_{B2}$

$= 50 \times 0.01661$

$\therefore I_{C2} = 0.83$ mA

& $I_{E2} = I_{B2} + I_{C2}$

$= 0.01661 + 0.83$

$I_{E2} = 0.8472$ mA

Now $I_{E2} = I_{B1}$

$\therefore I_{B1} = 0.8472$ mA

$\therefore I_{C1} = B_1\ I_{B1}$

$= 75 \times 0.8472$

$\therefore I_{C1} = 63.54$ mA

& $I_{E1} = I_{C1} + I_{B1}$

$= 63.54 + 0.8472$

$I_{E1} = 64.38$ mA

Now $V_{O1} = V_{CC} - I_{C1} \times 0.2$

$= 24 - 63.54 \times 0.2$

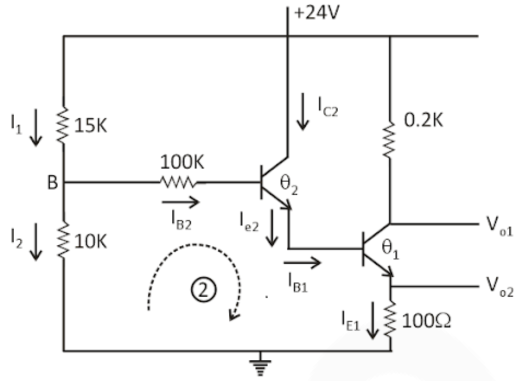
$\therefore V_{O1} = 11.292$ V

And $V_{O2} = I_{E1} \times 0.1$

$= 64.38 \times 0.1$

$\therefore V_{O2} = 6.438$ V

Now again redrawing the given circuit.



Applying KVL in loop (2)

$\therefore -10\ I_2 + 100\ I_{B2} + 0.7 + 0.7 + 0.1\ I_{E1} = 0$

$\therefore 10\ I_2 = 100 \times 0.01661 + 0.7 + 0.7 + 0.1 \times 64.38$

$\therefore 10\ I2 = 9.497$

$\therefore I_2 = 0.9497$ mA

Now applying KCL at node B

$\therefore I_1 = I_2 + I_{B2}$

$= 0.9497 + 0.01661$

$\therefore I_1 = 0.9663$ mA

4. A step-graded germanium diode has a resistivity of 2.5 Ω-cm on the p side and 1.5 Ω-cm on the n side. Calculate the height of the potential barrier.
For germanium $\mu_p = 1800$ cm²/V-s and $\mu_n = 3800$ cm²/V-s and $n_i = 2.5 \times 10^{13}/\text{cm}^2$ at 300°K. Prove formula used.

Sol.

Given, step-graded germanium diode has resistivity $\rho_p = 2.5$ Ω-cm

Resistivity of n-side $\rho_n = 1.5$ Ω-cm

Mobility of hole = 1800 cm²/V-s,

Mobility of electron = 3800 cm²/V-s

Intrinsic concentration $n_i = 2.5 \times 10^{13}/\text{cm}^2$

Acceptor concentration $N_A$ = ?

$\sigma_p = pq\mu_p \approx N_A q\ \mu p$ …………(for p-type)

$$\frac{1}{\rho_p} = N_A q \mu_p \Rightarrow N_A = \frac{1}{\rho_p q \mu_p}$$

$$= \frac{1}{2.5 \times 1.6 \times 10^{-19} \times 1800}$$

$N_A = 1.388 \times 10^{15}$ atoms/cm³

Donor concentration $N_D$ = ?

$\sigma = nq\mu_n \approx N_D\ q\ \mu n$ (for n-type)

$$\frac{1}{\rho_n} = N_D q \mu_n \Rightarrow N_D = \frac{1}{\rho_n q \mu_n}$$

$$= \frac{1}{1.5 \times 1.6 \times 10^{-19} \times 3800}$$

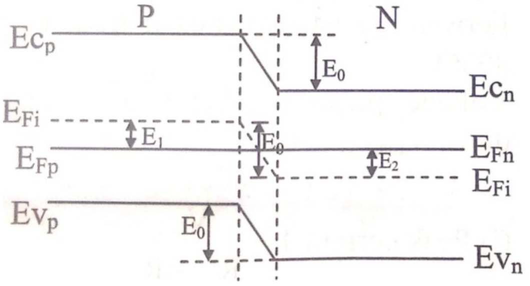
$N_D$ = 1.096 × $10^{15}$ atoms/cm$^3$

Height of potential barrier

$$V_0 = \frac{KT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$\Rightarrow V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

**Formula proof**



$$E_1 = E_{Fp_i} - E_{F_p} = KT\ln\left(\frac{N_A}{n_i}\right)$$

$$E_2 = E_{F_n} - E_{Fn_i} = KT\ln\left(\frac{N_D}{n_i}\right)$$

⇒ $E_0$(eV) = $E_1$ + $E_2$ = $E_{Cp}$ − $E_{Cn}$ = $E_{Vp}$ − $E_{Vn}$

$$\Rightarrow E_0(eV) = E_1 + E_2 = KT\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$V_0(V) = V_T\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$E_{Fi}$→ Fermi level in intrinsic

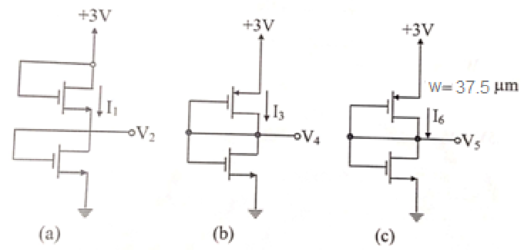
$E_{Fp}$→ Fermi level in P-type semiconductor

$E_{Fn}$→ Fermilevel in n-type semiconductor

$$\therefore V_o = 0.026\ln\left(\frac{1.388\times10^{15}\times1.096\times10^{15}}{\left(2.5\times10^{13}\right)^2}\right)$$

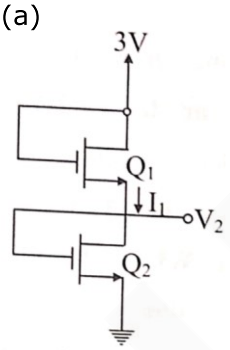
= 0.2027 V

5. For the circuits in fig. $\mu_n C_{ox} = 2.5\ \mu_p C_{ox}$ = 20μA/V$^2$, $|V_t| = 1V$, λ = 0, γ = 0, L = 5 μm, and W = 15 μm, unless otherwise specified. Find the labelled currents and voltages.



Sol.

(a)



(a)

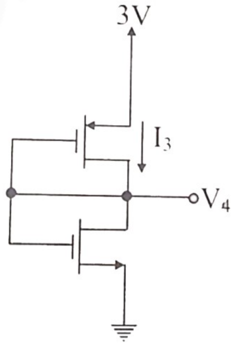
$Q_2$, $Q_1$ operating in saturation $i_{D1}$ = $i_{D2}$

Also $V_{GS1}$ = $V_{GS2}$

∴ 3V = $V_{GS1}$ + $V_{GS2}$⇒ $V_{GS1}$ = $V_{GS2}$ = 1.5V, $V_2$ = 1.5V

$$I_1 = \frac{1}{2}\times20\times\frac{15}{5}(1.5-1)^2 = 7.5\mu A$$

(b)



(b)

Both transistors have $V_D$ = $V_G$ and therefore they are operating in saturation $i_{D1}$ = $i_{D2}$

$$\frac{1}{2}\mu_n C_{OX}\frac{W}{L}(V_4-1)^2 = \frac{1}{2}\mu_p C_{OX}\frac{W}{L}(3-V_4-1)^2$$

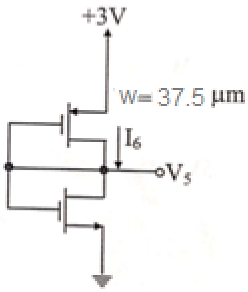
∴ 2.5 $(V_4 - 1)^2$ = $(2 - V_4)^2$

1.58 $(V_4 - 1)^2$ = ±$(2 - V_4)$ ⇒ $V_4$ = 1.39

$V_4$ ≃ 1.4V

$$I_3 = \frac{1}{2}\times20\times\frac{15}{5}(1.39-1)^2 = 4.6\mu A$$

(c)



(c)

$$\frac{W_1}{L_1}=\frac{37.5}{5}=7.5$$

$$\frac{W_2}{L_2}=\frac{15}{5}=3$$

$$\frac{W_1}{L_1}=2.5\times\frac{W_2}{L_2}$$

Now $\mu_n C_{OX}\frac{W_2}{L_2}=\mu_p C_{OX}\frac{W_1}{L_1}$

So $i_{D1} = i_{D2}$

$$\Rightarrow V_{GS1}=V_{GS2}=\frac{3}{2}=1.5V=V_5$$

$$I_6=\frac{1}{2}\times 20\times\frac{15}{5}(1.5-1)^2=7.5\mu A$$