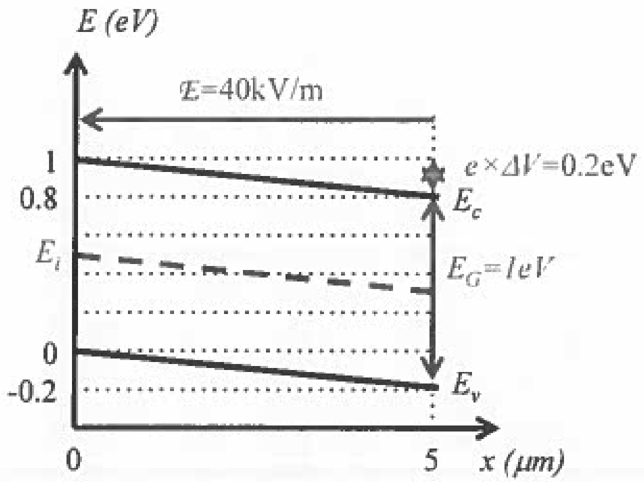
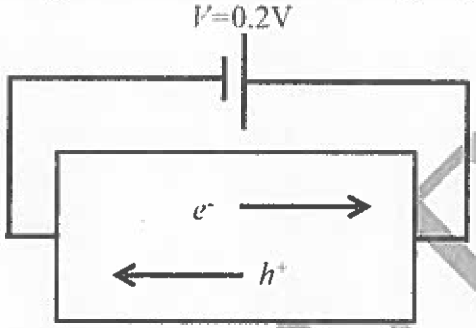
ANSWERS

1.a)





i)	The bandgap $E_G = E_c - E_v = 1$ eV.	[2]
ii)	The intrinsic level E_i. lies midgap when $N_c = N_v$	[2]
iii)	$\Delta V = (1\text{ eV} - 0.8\text{ eV})/(1\text{eV/V}) = 0.2$V. When drawn on energy plot is must be in eV though and ΔV multiplied by e.	[4]
iv)	$\mathcal{E} = 0.2\text{V}/5\mu\text{m} = 0.2\text{V}/(5\ 10^{-6}\text{ m}) = 40000\text{V/m} = 40$ kV/m.	[4]
v)	applying a positive voltage is lowering the PE. If $\Delta V = 0.2$ V then the battery needs to supply this voltage.	[4]
vi)	polarity of the electrons flow "down the hill" – reducing their PE or opposite to the direction of the electric field. The holes go in the opposite direction.	[4]

b)

i)	$\phi_m < \phi_{pSi}$.	[2]
ii)	With reference to the energy band diagram below.	

$$\phi_p = E_F - E_v$$

$$p = N_v exp\left(\frac{E_v - E_f}{kT}\right) = N_v exp\left(\frac{-\phi_p}{kT}\right)$$

$$p = N_A = N_v exp\left(\frac{-\phi_p}{kT}\right)$$

$$-\phi_p = kTln\left(\frac{N_A}{N_v}\right) = 0.026 \times ln\left(\frac{10^{16}}{1.8\times10^{19}}\right)$$

$\phi_p = 0.195$ eV

$\phi_{pSi} - \phi_m = \phi_B - \phi_p = 0.395\text{ eV} - 0.195 = 0.2$ eV

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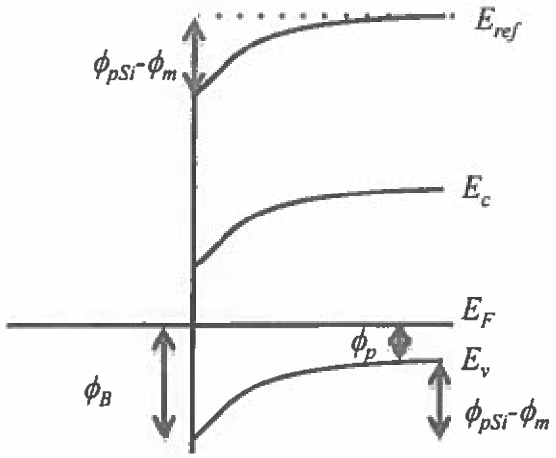

iii) built-in voltage p+n junction

$$V_{bi} = 0.026ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.026ln\left(\frac{10^{16}\times10^{18}}{(1.45\times10^{10})^2}\right) = 0.82\ eV.$$

V_{bi} for the Schottky contact is $\phi_{pSi} - \phi_m = 0.2$ eV.

Thus a smaller forward voltage (V_{ON}) will need to be applied for carriers to diffuse across the smaller Schottky contact than the pn diode. Therefore V_{ON} Schottky diode < V_{ON} pn diode [4]

c) Answer the following questions with "yes" or "no".

i) yes. [1]

ii) yes [1]

iii) no [1]

iv) no [1]

v) no [1]

vi) no [1]

vii) no [1]

viii) yes. [1]

ix) yes [1]

x) yes [1]

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2. a) $p - n + N_D - N_A = 0.$ [4]

p: free hole concentration

n: free electron concentration

N_D: ionised donor atoms

N_A: ionised acceptor atoms

b) [4]

From the formulae sheet: $n = N_c exp\left(\frac{E_F - E_c}{kT}\right)$ & $p = N_v exp\left(\frac{E_v - E_F}{kT}\right)$ thus

$n \times p = N_c \times N_v exp\left(\frac{E_v - E_c}{kT}\right) = N_c \times N_v exp\left(\frac{-E_G}{kT}\right)$

from the formulae sheet we find the expression of $n_i = \sqrt{N_c \times N_v} exp\left(\frac{-E_G}{2kT}\right)$

proving that $n \times p = n_i^2$

c) In the region with compensated n-doping, extract the majority carrier concentration (n) from charge neutrality and mass action law:

$n \times p = n_i^2$ thus $p = \frac{n_i^2}{n}$ put into charge neutrality equation and rewrite: [10]

$-n^2 + (N_D - N_A)n + n_i^2 = 0$

solve quadratic equation:

$$n = \frac{-(N_D - N_A) - \sqrt{(N_D - N_A)^2 + 4 \times n_i^2}}{-2}$$

$$n = \frac{-9\times10^{17} - \sqrt{(9\times10^{17})^2 + 4\times(1.45\times10^{10})^2}}{-2}$$

$n = 9 \times 10^{17} cm^{-3}$ [4]

[Note, if just $n = N_D - N_A$ is given without calculation or without explanation, only 1 mark will be allocated]

$p = \frac{n_i^2}{n} = \frac{(1.45\times10^{10})^2}{9\times10^{17}} = 2.34 \times 10^2 cm^{-3}$ [2]

In the bulk region where no compensation doping occurs, the usual approximations can be applied:

$p = N_A = 10^{17}$ cm^{-3} [2]

$n = \frac{n_i^2}{p} = \frac{(1.45\times10^{10})^2}{10^{17}} = 2.1 \times 10^3 cm^{-3}$ [2]

d)

i) forward biased [2]

ii) n-region because a) the depletion region is smallest and b) the minority carrier concentration is lowest as determined by the mass action law. [4]

iii) putting all geometrical parameters in cm:

$$J = e \times \left(D_n \frac{\Delta n_p}{X_n} + D_p \frac{\Delta p_n}{X_p}\right) = 1.6 \times 10^{-19} \times \left(50 \times \frac{10^5}{150\times10^{-7}} + 20 \times \frac{10^2}{100\times10^{-7}}\right)$$

$J = 5.33\ 10^{-8}$ A cm^{-2}

Marking scheme: 4 marks for correct equation, 2 marks for correct solution [6]

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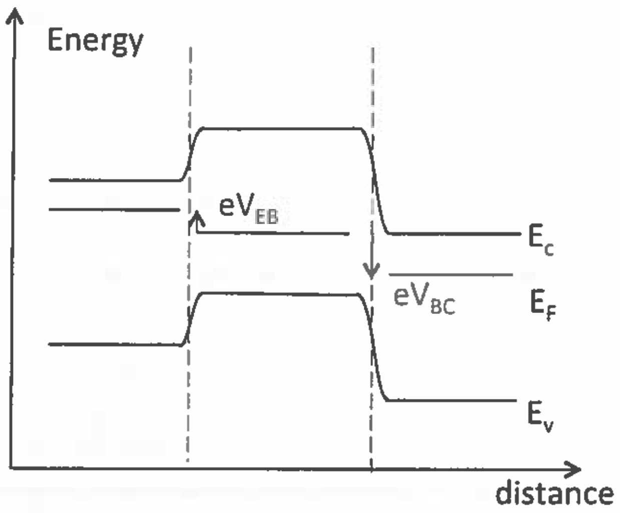
3.a) [10]



marking scheme: ΔE_F correct: [4] ; voltage shifts correct [2] ; general band diagram correct [4].

b)

i) diffusion. [1]

ii) diffusion. [1]

iii) diffusion. [1]

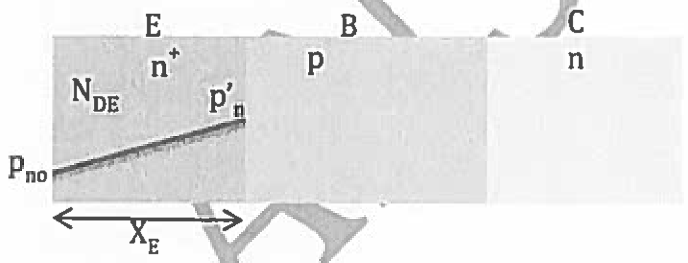
iv) drift. [1]

v) diffusion. [1]

c)

i) v_{be} small such that the variation of the current I_C is linear within that region [4]

ii) referring to the figure below, the base current i_1 is due to the minority carrier gradient in the emitter. [5]



$$i_l = i_b = \frac{eD_{pE}}{X_E}(p'_n - p_{no})A$$

$$i_b = \frac{eD_{pE}p_{no}}{X_E}\left(exp\left(\frac{v_{be}}{V_T}\right) - 1\right)A$$

$$i_b = \frac{eD_{pE}n_i^2}{X_E N_{DE}}\left(exp\left(\frac{v_{be}}{V_T}\right) - 1\right)A$$

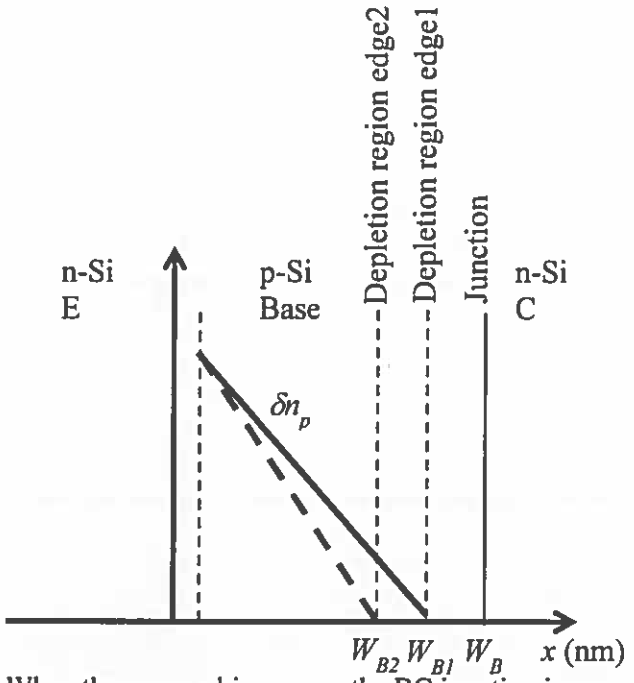
iv) $i_2 = g_m\, v_{be}$ [2]

v) Due to base width modulation. [4]

the output current is the diffusion current of electrons in the base. $I_C = \frac{eD_{nE}n_i^2}{X_B N_{AB}}\left(exp\left(\frac{v_{be}}{V_T}\right) - 1\right)A$

X_B is the undepleted base width. When the output voltage $|V_{CE}|$ increases, the reverse bias $|V_{CB}|$ increases, increasing the depletion width extending into the base and thus decreasing X_B.

A possible sketch can be:



When the reverse bias across the BC junction increases, the depletion region extending from the junction into the base is increasing, decreasing the effective base width (W_{B1} to WB2) as a result the gradient in the minority carrier concentration in the base is increasing (solid line to dashed line) and thus the diffusion current increases. This diffusion current is I_C.