TASK 12.2

Limit of MB approximation is when $\varepsilon_F - \varepsilon_a = 3k_BT$.
Ionisation energy of Boron is $\varepsilon_F - \varepsilon_a = 0.045$eV (from table on notes)
Assume $\varepsilon_F \simeq \varepsilon_{\text{midgap}}$
$\varepsilon_{Fi} - \varepsilon_F = k_BT \ln \frac{p_0}{n_i}$
$= \frac{\boldsymbol{\varepsilon_g}}{\mathbf{2}} - (\varepsilon_a - \varepsilon_V) - (\varepsilon_F - \varepsilon_a)$
$= 0.56 - 0.045 - 3(0.0259) = 0.437 = 0.0259 \ln\left(\frac{N_a}{n_i}\right)$
$N_a = n_i \exp(0.437/0.0259) = 3.2 \times 10^{17} \text{cm}^{-3}$

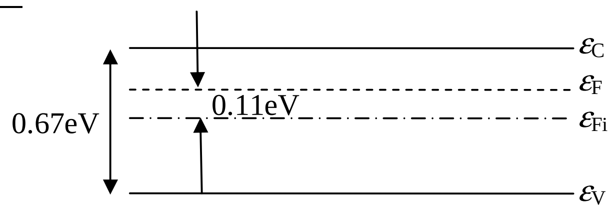
TASK 12.3

(a) $n_i \approx 2.5\times10^{13}$ cm^{-3} at 300K; $N_d = 6\times10^{15}\text{cm}^{-3}$ $N_a = 4\times10^{15}\text{cm}^{-3}$

$\rightarrow$ n-type with $n = N_d - N_a = 2\times10^{15}\text{cm}^{-3}$

$\varepsilon_F - \varepsilon_{Fi} = k_BT\ln\left(\frac{n_0}{n_1}\right) = 0.0259\times\ln\left(2\times10^{15}/2.5\times10^{13}\right)$

$\underline{= 0.11\,\text{eV}}$



(b) At 450K, $n_i \approx 6.5\times10^{15}$ cm^{-3} $> N_a - N_d$ therefore we must use the "full" formula:

$$n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$$

$\underline{n_0 = 7.6\times10^{15}\text{ cm}^{-3};\ \ p_0 = n_i^2/n_0 = 5.6\times10^{15}\text{cm}^{-3}}$

TASK 12.4

(a) $f_{FD}(\varepsilon = \varepsilon_C) = \frac{1}{1+\exp[(\varepsilon_C - \varepsilon_F)/k_BT]} = 1.65\times10^{-9}$

$\exp[(\varepsilon_C - \varepsilon_F)/k_BT] \approx (1.65\times10^{-9})^{-1} = 6.06\times10^{8}$

$\varepsilon_C - \varepsilon_F = k_BT\ln(6.06\times10^{8}) = 0.523\,\text{eV}$

$\varepsilon_{Fi} - \varepsilon_F = \varepsilon_C - \varepsilon_F - \frac{1}{2}\varepsilon_g = 0.193\,\text{eV}$

$\underline{p_0 = n_i\exp[(\varepsilon_{Fi} - \varepsilon_F)/k_BT] = 3.48\times10^{16}\text{ cm}^{-3};\quad n_0 = n_i^2/p_0 = 1.5\times10^{10}\text{ cm}^{-3}}$

(b) $p_0 = N_a - N_d = N_a/2$

$\underline{N_a = 2p_0 = 6.94\times10^{16}\ \text{cm}^{-3};\ \ N_d = N_a/2 = 3.48\times10^{16}\,\text{cm}^{-3}}$

(c) $\varepsilon_F - \varepsilon_{Fi}$ changes with temperature so we cannot use the value from (a).

$n_i(T = 450\text{K}) \approx 6.5\times10^{15}\,\text{cm}^{-3}$. So

$$p_0 = \frac{N_a - N_d}{2} + \sqrt{\left(\frac{N_a - N_d}{2}\right)^2 + n_i^2}$$

$\underline{p_0 = 3.6\times10^{16}\,\text{cm}^{-3}}$ and $\underline{n_0 = n_i^2/p_0 = 1.4\times10^{15}\,\text{cm}^{-3}}$

TASK 12.5

450 K.

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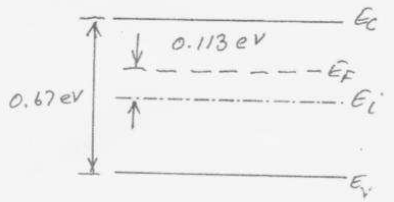
[redacted] $\Rightarrow n_i \simeq 2.5\times10^{13}\ \text{cm}^{-3}$ at 300K

a)



$N_D = 6\times10^{15}\ \text{cm}^{-3}$

$N_A = 4\times10^{15}\ \text{cm}^{-3}$

$\Rightarrow$ n-type and

$n = N_D - N_A = 2\times10^{15}\ \text{cm}^{-3}$

$\underline{\varepsilon_F - \varepsilon_i} = kT \ln n/n_i = 0.02586 \times \ln \frac{2\times10^{15}}{2.5\times10^{13}} = \underline{0.113\ \text{eV}}$

b) At 450 K, $n_i \simeq 6.5\times10^{15}\ \text{cm}^{-3}$ which is larger than our doping densities! So we have to use the "full" formula:

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

$n = 7.58\times10^{15}\ \text{cm}^{-3}$

$\underline{p = n_i^2/n = 5.58\times10^{15}\ \text{cm}^{-3}}$

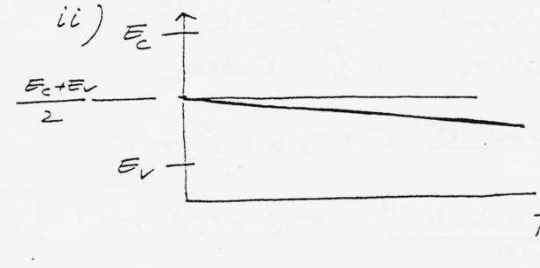
TASK 12.6

5 i) $n_i^2 = N_c N_v \exp - \frac{E_g}{kT}$

$= 10^{19} \cdot 6 \cdot 10^{18} \exp - \frac{660}{26} = 5.67 \cdot 10^{26} \, cm^{-6}$

$n_i = 2.38 \cdot 10^{+13} \, cm^{-3}$

ii)



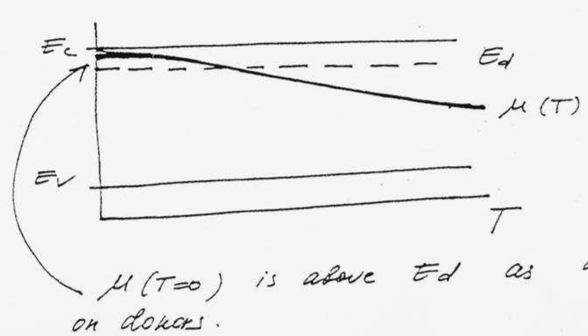
As $\mu = \frac{E_c+E_v}{2} + \frac{1}{2} kT \ln \frac{N_v}{N_c}$ and $N_c > N_v$

iii) This is a donor. As has 5 valence electrons, 4 will contribute to the covalent bonding with Ge, the 5th will be bound to As^- ion.

iv) As $kT > E_i$ all electrons are ionised. The Fermi level lies below E_d.

$n = N_c \exp \left[\frac{-(E_c - \mu)}{kT} \right]$ and $n \simeq N_d$

Hence $E_c - \mu = kT \ln \frac{N_c}{N_d} = 26 \ln \frac{10^{19}}{10^{15}} = 239_{meV}$



$\mu(T=0)$ is above E_d as all the electrons are on donors.