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EEE 207 : Semiconductors for Electronics and Devices.

Problem sheet 1 Solutions.

1) Intrinsic, so $n_i = n = p$

conductivity, $\sigma = (n\mu_e + p\mu_h)e$
$= n_i e(\mu_e + \mu_h)$ [intrinsic]

current density, $J = \sigma E$
$= n_i e(\mu_e + \mu_h) E$
$= \underline{1.16\ \mathrm{kA/m^2}}$

2) Resistivity, $\rho = \frac{1}{\sigma}$
$\sigma = n_i e(\mu_e + \mu_h)$

$\therefore \quad n_i = [\rho e(\mu_e + \mu_h)]^{-1}$

$= \underline{1.0 \times 10^{16}\ \mathrm{m^{-3}}}$

3) velocity, $v = \mu_e E$

From $J = \sigma E$
$E = J/\sigma = J\rho \quad [\rho = \frac{1}{\sigma}]$

$\Rightarrow \quad v = \mu_e J\rho$

From $v = \frac{s}{t}$ [s = displacement]
$\therefore \quad t = \frac{s}{v}$
$= s/(\mu_e J\rho) = \underline{2.56\ \mu s}$

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4) $$v_{drift} = \mu_e E$$
$$= 3.9 \text{ km/s} \quad (\text{For Germanium})$$

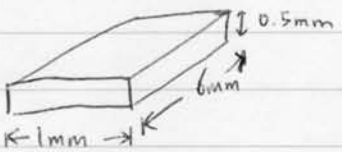
In vacuum $$\underbrace{\tfrac{1}{2} m v_{final}^2}_{\text{kinetic energy}} = \underbrace{eV}_{\text{potential energy}}$$

$$\therefore \; v_{final} = \sqrt{\frac{2eEd}{m}} \quad [V = Ed]$$

d : distance.

$$= \underline{5.9 \text{ Mm/s}}$$

5)



$$\rho = \frac{RA}{\lambda}$$

$$\sigma = pe\mu_h$$

$$\sigma = \frac{1}{\rho}$$

$$\therefore \quad \sigma = \frac{\lambda}{RA} = pe\mu_h$$

$$\Rightarrow \quad p = \frac{\lambda}{RAe\mu_h}$$

$$= \underline{\underline{3.29 \times 10^{21} \text{ m}^{-3}}}$$

$$n_i^2 = np, \Rightarrow \quad n = \frac{n_i^2}{p} = \frac{n_i^2 RAe\mu_h}{\lambda}$$

and $$\sigma = e(\mu_h p + n\mu_e)$$

$$\Rightarrow \text{proportion due to } e^- = \frac{en\mu_e}{e(n\mu_e + p\mu_h)} \quad \cancel{\frac{\mu_e n_i^2 R^2 A^2 e^2 \mu_h^2}{\mu_h \lambda^2}}$$

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5) proportion due to e^-

$$= \frac{n\mu_e}{n\mu_e + p\mu_h} \approx \frac{\mu_e \dfrac{n_i^2 RAe\mu_h}{l}}{\mu_h \dfrac{l}{RAe\mu_h}} \quad \text{[since p-type, "n" negligible]}$$

$$\approx \frac{\mu_e}{\mu_h} \cdot n_i^2 R^2 A^2 e^2 \mu_h^2$$

$$\approx \mu_e \mu_h \left(\frac{n_i RAe}{l} \right)^2$$

$$= \frac{1}{8.43 \times 10^3}$$

6) Let $\mu_e = kT^{-1.6}$

@ RT. $0.38 = k(290)^{-1.6}$

$$k = \frac{0.38}{(290)^{-1.6}}$$

$$\Rightarrow \mu_e = \frac{0.38}{(290)^{-1.6}} \times T^{-1.6}$$

$$= 0.38 \left(\frac{T}{290} \right)^{-1.6}$$

same to μ_h, $\mu_h = 0.18 \left(\frac{T}{290} \right)^{-2.3}$

Since intrinsic, $\sigma = n_i e (\mu_e + \mu_h)$

$$= 5 \times 10^{21} T^{3/2} e^{-\frac{E_g}{2kT}} \cdot e \cdot \left[0.38 \left(\frac{T}{290} \right)^{-1.6} + 0.18 \left(\frac{T}{290} \right)^{-2.3} \right]$$

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6) $\sigma = 5\times10^{21} \times e \cdot \left[0.38\times 290^{1.6}\, T^{-0.1} + 0.18\times 290^{+2.3}\, T^{-0.8}\right] e^{-\frac{E_g}{2kT}}$

$= 5\times10^{21}\, e \left[0.38\times 290^{1.5} \left(\frac{290}{T}\right)^{0.1} + 0.18\times 290^{1.5}\left(\frac{290}{T}\right)^{0.8}\right] e^{-\frac{E_g}{2kT}}$

Hence $C_1 = 5\times10^{21} \times 1.6\times10^{-19} \times 0.38\times 290^{1.5}$

$= \underline{1.5\times10^{6}\ \Omega^{-1} m^{-1}}$

$C_2 = 5\times10^{21} \times 1.6\times10^{-19} \times 0.18\times 290^{1.5}$

$= \underline{7.1\times10^{5}\ \Omega^{-1} m^{-1}}$

$C_3 = \frac{E_g}{2k}$

$= \frac{0.67\times 1.6\times10^{-19}}{2\times 1.38\times10^{-23}}$

$= \underline{3884\ K}$

@ 958 °C, $T = 273 + 958 = 1231\,K$.

$\therefore\ \sigma = \underline{6.5\times10^{4}\ \Omega^{-1} m^{-1}}$

7) $\sigma = e(n\mu_e + p\mu_h)$ and $np = n_i^2$

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

$\therefore\ \sigma = e\left(n\mu_e + \frac{n_i^2}{n}\mu_h\right)$

To find minimum σ, differentiate both sides w.r.t n.

$\frac{1}{e}\frac{d\sigma}{dn} = \mu_e - \frac{n_i^2}{n^2}\mu_h = 0$

$\Rightarrow \underline{n^2 = n_i^2 \cdot \mu_h/\mu_e}$, $\underline{p = \frac{n_i^2}{n} = n_i \cdot \sqrt{\frac{\mu_e}{\mu_h}}}$

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7) ① Intrinsic, $\sigma = n_i e(\mu_e + \mu_n)$

$= \underline{2.28\ \Omega^{-1} m^{-1}}$

② Minimum σ : $\sigma = e\left(n_i\sqrt{\frac{\mu_n}{\mu_e}}\ \mu_e + n_i\sqrt{\frac{\mu_e}{\mu_n}}\ \mu_n\right)$

$= en_i\left(2\sqrt{\mu_n\mu_e}\right)$

$= \underline{2.15\ Sm^{-1}}$ $\quad [\,[S] = [\Omega^{-1}]\,]$

Let intrinsic $\sigma = \sigma_{int}$

non-intrinsic $\sigma = \sigma_x$

$$\sigma_{int} = \sigma_x$$

$$en_i(\mu_e + \mu_n) = e\left(n\mu_e + \frac{n_i^2}{n}\mu_n\right)$$

$$\therefore \underbrace{en^2\mu_e}_{a} - \underbrace{nen_i(\mu_e + \mu_n)}_{b} + \underbrace{en_i^2\mu_n}_{c} = 0$$

$$\therefore n = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$= \frac{en_i(\mu_e + \mu_n) \pm \sqrt{e^2 n_i^2(\mu_e + \mu_n)^2 - 4e^2\mu_e n_i^2\mu_n}}{2e\mu_e}$$

$$= \frac{n_i}{2}\left[1 + \frac{\mu_n}{\mu_e} \pm \sqrt{\left(1 + \frac{\mu_n}{\mu_e}\right)^2 - 4\frac{\mu_n}{\mu_e}}\right]$$

$$= \frac{n_i}{2}\left[1 + \frac{\mu_n}{\mu_e} \pm \left(1 - \frac{\mu_n}{\mu_e}\right)\right]$$

*

$$\boxed{\begin{aligned} &1 + 2\frac{\mu_n}{\mu_e} + \frac{\mu_n^2}{\mu_e^2} - 4\frac{\mu_n}{\mu_e} \\ &= 1 - 2\frac{\mu_n}{\mu_e} + \frac{\mu_n^2}{\mu_e^2} \\ &= \left(1 - \frac{\mu_n}{\mu_e}\right)^2 \end{aligned}}$$

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7) $n = \frac{n_i}{2}\left[2\frac{\mu_h}{\mu_e} \right]$

$= n_i \mu_h / \mu_e$

$= \underline{1.25 \times 10^{19}\ m^{-3}}$

$p = n_i / {}^{\mu_e}/_{\mu_h} = \underline{5 \times 10^{19}\ m^{-3}}$

8) No. of CB electrons $= n = n_{total}\, e^{-E_g/2kT}$ where n_{total} = total no. of e^-

$\therefore$ fraction of CB $e^- = \frac{n}{n_{total}} = e^{-E_g/2kT}$

(a) fraction (pure Ge) $= e^{-E_g/2kT}$

$= \exp\left(-\frac{0.72 \times 1.6\times10^{-19}}{2 \times k \times 290}\right)$

$= \underline{10^{-6}}$

(b) fraction (pure Si) $= \exp\left(-\frac{1.1 \times 1.6\times10^{-19}}{2\times k\times 290}\right)$

$= \underline{10^{-9.3}}$

(c) fraction (diamond) $= \exp\left(-\frac{5.6 \times 1.6\times10^{-19}}{2k\times 290}\right)$

$= \underline{10^{-47}}$

Comment: As E_g increases, n/n_{total} reduces exponentially. Therefore fewer e^-s in CB and so material becomes insulating at high E_g.

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(9) 'Pure' in this context $\equiv$ intrinsic and

$$\sigma_i = n_i e(\mu_e + \mu_h)$$

or $$\frac{1}{2000} = n_i e(\mu_e + 0.26\mu_e)$$

also $n = p = n_i = 1.4 \times 10^{16}/cm^3$

So $$\frac{1}{2000} = 1.4 \times 10^{16} \times (1.6 \times 10^{-19})(1.26)\mu_e$$

Which gives $\mu_e = 0.18$, so $\mu_h = 0.26 \times 0.18 = \underline{\underline{0.046\,m^2V^{-1}s^{-1}}}$

Doped p type $\sigma = \cancel{pe\mu_h}\ pe\mu_h$

$= N_a e\mu_h$ at RT

$$\therefore \rho = \frac{1}{\sigma} = \frac{1}{N_a e\mu_h} = \frac{1}{10^{21}(1.6 \times 10^{-19})(0.046)} = \underline{\underline{0.136\,\Omega m}}$$

when $N_a = 10^{23}$

$$\rho = \frac{1}{10^{23}(1.6 \times 10^{-19})(0.046)} = \underline{\underline{0.00136\,\Omega m}}$$

(10) Book work (JA p110) gives

$$n = N\exp(-E_g/2kT) \quad \text{—— (1)}$$

Now for intrinsic semiconductor

$$\sigma = n_i e(\mu_e + \mu_h) \quad \text{—— (2)}$$

n_i is given by (1) same as $n = p = n_i$

and $\mu_e = C_1 T^{-3/2}$ and $\mu_h = C_2 T^{-\frac{3}{2}}$

So (2) becomes:

$$\sigma = N\exp\left(\frac{-E_g}{2kT}\right) e\,(C_1 + C_2)T^{-3/2}$$

or $$\rho = \frac{1}{\sigma} = CT^{\frac{3}{2}}\exp[E_g/2kT] \quad \text{—— (3)}$$

Could substitute one value of (T, ρ) to find E_g, but this does not prove material is intrinsic.

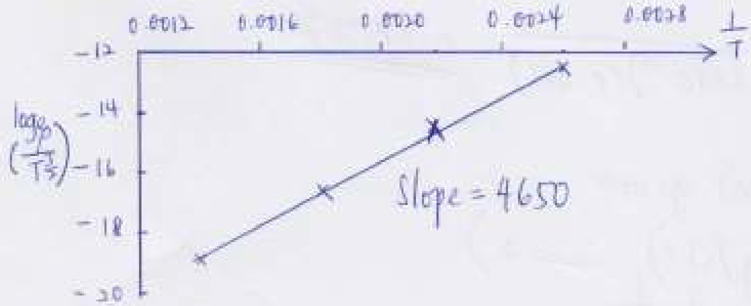
To rearrange (3) to give a straight line relationship which hopefully fits the data :-

(3) gives:

$$\log_e\left(\frac{\rho}{T^{\frac{3}{2}}}\right) = \log C + \frac{E_g}{2kT}$$

Is a plot of $\log_e\left(\frac{\rho}{T^{\frac{3}{2}}}\right)$ versus $\frac{1}{T}$ should be a straight line of slope $\frac{E_g}{2k}$.

$T =$	384	458	556	714
ρ	0.028	0.0061	0.0013	0.00027
$\frac{1}{T}$	0.00260	0.00218	0.00182	0.00140
$\log_e\left(\frac{\rho}{T^{\frac{3}{2}}}\right)$	-12.5	-14.3	-16.13	-18.08



$$\frac{E_g}{2k} = 4650$$

$$E_g = 4650\,(1.38\times10^{-23})(2)$$

$$= \underline{0.8\,eV}$$