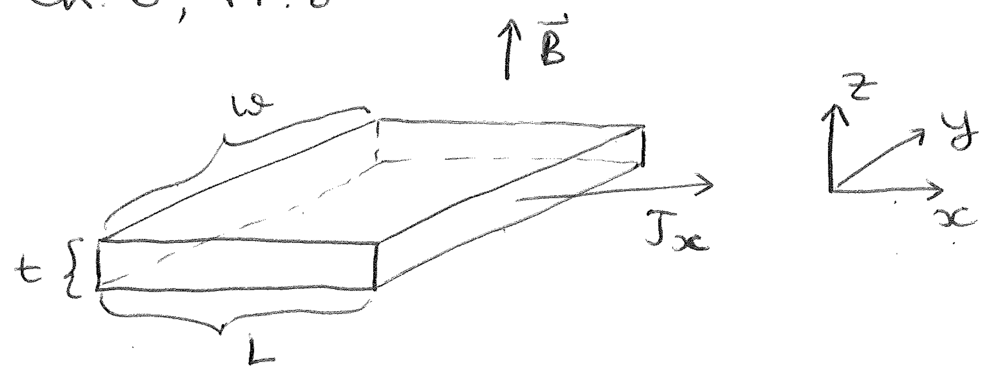
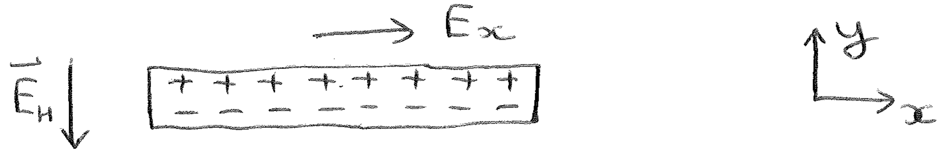
Physics 406
2012

HW #7
Solutions

1. O Ch. 6, Pr. 8





$L = 5\,\text{cm}$ $\quad w = 0.5\,\text{cm}$ $\quad t = 0.1\,\text{cm}$

$B_z = 0.6\,\frac{\text{Wb}}{\text{m}^2}$ $\quad V_H = 8\,\text{mV}$ $\quad J_x = 10\,\text{mA}$

$$R_H = \frac{E_y}{j_x B_z}$$

Extrinsic sc $\Rightarrow$ dominant carrier type (sign of R_H tells us holes or $\bar{e}$'s)

$$E_y = \frac{V_H}{w} = 1.6\,\frac{\text{V}}{\text{m}}.$$

$$R_H = \frac{E_y}{\underbrace{(J_x/wt)}_{j_x} B_z} =$$

$$j_x = \frac{10^{-2}\,\text{A}}{5\times10^{-3}\times10^{-3}\,\text{m}^2} = 2\times10^{3}\,\frac{\text{A}}{\text{m}^2}$$

$$= \frac{1.6\,\text{V/m}}{0.6\,\frac{\text{Wb}}{\text{m}^2}\times 2\times10^{3}\,\frac{\text{A}}{\text{m}^2}} = 1.33\times10^{-3}\,\frac{\text{V}\cdot\text{m}^3}{\text{amp}\cdot\text{Wb}}$$

$R_H > 0 \Rightarrow$ p-type sc

$$R_H = \frac{1}{pe} \Rightarrow p = \frac{1}{R_H e}$$

$$p = \frac{1}{1.33 \times 10^{-3} \times 1.6 \times 10^{-19}} = 4.7 \times 10^{21}\ m^{-3}$$

?? too high $\Rightarrow$ the book

$\Rightarrow$ numbers in not plausible

2. 0 Ch. 6, Pr. 19

$$\mu \sim T^{-1.66}$$

$$\mu(300\,K) = 3900\ \frac{cm^2}{V\cdot s}$$

Then $D = \dfrac{\mu k_B T}{e} \Rightarrow$

$$\Rightarrow D(300\,K) = 3900 \times 0.025\ \frac{cm^2}{s} =$$

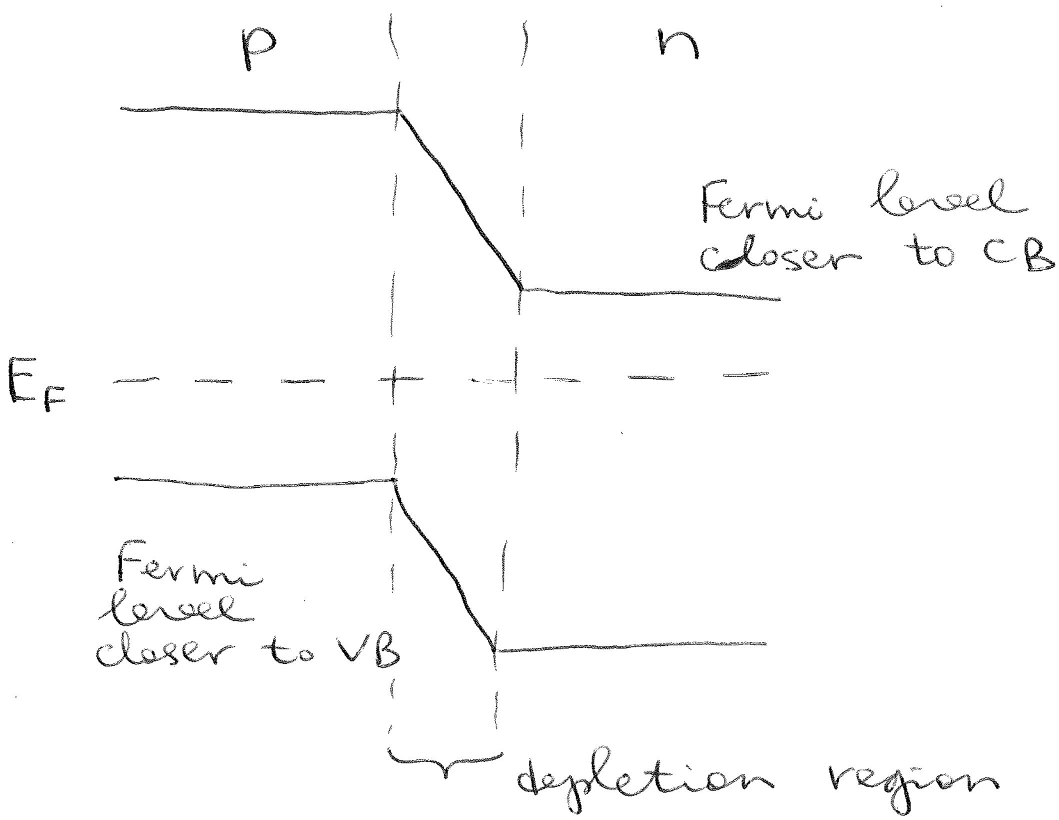
$$= 97.5\ \frac{cm^2}{s}.$$

$$\frac{D(77\,K)}{D(300\,K)} = \frac{\mu(77\,K)\,(k_B \overset{77\,K}{T})}{\mu(300\,K)\,(k_B \underset{300\,K}{T})},\ \text{or}$$

$$D(77\,K) = D(300\,K)\left(\frac{300}{77}\right)^{1.66}\left(\frac{77}{300}\right) \simeq$$

$$\simeq 239\ \frac{cm^2}{s}.$$

3. O. Ch. 7, Q. 1



4. O Ch. 7, Q.6

In indirect-gap sc's such as Si, radiative recombination is significantly inhibited compared to direct-gap sc's. Thus the lifetime of the holes is increased, making Si a useful material for transistors (but not for laser diodes!)

(5) Omar chapter 7, Pr. 1

Forward-biased p-n junction:

$$J_{pg} = J_{pg,0}$$

generation current does not change, even w/ decreased barrier

$$J_{pr} = \underbrace{J_{pr,0}}_{= J_{pg,0}} e^{eV_0/k_BT}$$

recombination current increases since barrier is reduced in height

Electric current:

$$I_p = e(J_{pr} - J_{pg}) = e J_{pg,0}\left(e^{eV_0/k_BT} - 1\right),$$

using the fact that generation & recombination currents are equal at equilibrium if $V_0 = 0$ (no bias).

⑥ Ch. 7, Pr. 4

a) $\varphi_0 = \frac{k_B T}{e} \log\left(\frac{n_{no} p_{po}}{n_i^2}\right) \simeq$

$\simeq \frac{k_B T}{e} \log\left(\frac{N_d N_a}{n_i^2}\right)$.

$n_i = 2\times10^{13}\ cm^{-3}$ @ room T (from before)

$\varphi_0 = 0.025\,V \log\left(\frac{10^{18}\times 5\times10^{16}}{4\times10^{26}}\right) \simeq \underline{\underline{0.47\ V}}.$

b) $w_n = \left[2\epsilon\epsilon_0\varphi_0 \frac{N_a}{N_d(N_a+N_d)} \frac{1}{e}\right]^{1/2}$

$\epsilon = 16$ for Ge

$\varphi_0 = 0.47\ V$

$\epsilon_0 = 8.85\times10^{-12}\ \frac{Coul^2}{N\times m^2}$

$N_d = 10^{24}\ m^{-3}$

$N_a = 5\times10^{22}\ m^{-3}$

$e = 1.6\times10^{-19}\ Coul$

$w_n = \left[\frac{2\times16\times(8.85\times10^{-12})\times0.47}{1.6\times10^{-19}} \frac{5\times10^{22}}{10^{24}(5\times10^{22}+10^{24})}\right]^{1/2} \simeq$

$\simeq 63.1\ \mathring{A}$.

$w_p = w_n \frac{N_d}{N_a} = 63.1\ \mathring{A}\ \frac{10^{24}}{5\times10^{22}} = 1262\ \mathring{A}$

c) $E_0 = \frac{2\varphi_0}{\underbrace{w}_{w_n + w_p}} = \frac{2 \times 0.47\,V}{1325 \times 10^{-8}\,cm} \simeq 7.1 \times 10^{4}\,\frac{V}{cm}$.

d) $\underset{\text{capacitance}}{C} = \frac{\epsilon \epsilon_0 A}{w} \Rightarrow \frac{C}{A} = \frac{\epsilon \epsilon_0}{w} =$

$= \frac{16 \times (8.85 \times 10^{-12})}{1325 \times 10^{-10}} \simeq 1.1 \times 10^{-3}\ \frac{\text{Farad}}{m^2}$.

7. θ Ch. 7, Pr. 6

Forward bias:

$$j \approx j_o e^{eV_o/k_BT}$$

$$I = jA$$

Differential resistance

$$R = \frac{dV_o}{dI} = \underbrace{\frac{1}{j_o A}}_{I_o\text{ - saturation current}} \frac{k_BT}{e} e^{-\frac{eV_o}{k_BT}}$$

$$j_o = en_i^2 \left(\frac{D_n}{L_n N_a} + \frac{D_p}{L_p N_d} \right)$$

$$\begin{cases} L = \sqrt{D\tau}, & \tau_e = \tau_h = 10^{-6}\,s \\ D = \frac{\mu k_BT}{e} \end{cases}$$

$$j_o = en_i^2 \left(\sqrt{\frac{D_n}{\tau_e}} \frac{1}{N_a} + \sqrt{\frac{D_p}{\tau_h}} \frac{1}{N_d} \right)$$

$$\begin{cases} N_a = 5 \times 10^{22}\ m^{-3} = 5 \times 10^{16}\ cm^{-3} \\ N_d = 10^{24}\ m^{-3} = 10^{18}\ cm^{-3} \end{cases}$$

$n_i = 2 \times 10^{13}\ cm^{-3}$ from Pr. 4

Use $\begin{cases} \mu_e = 3900\ \frac{cm^2}{V \cdot s}, \\ \mu_h = 1900\ \frac{cm^2}{V \cdot s} \end{cases}$ $\Leftarrow$ Table 6.3

Then $\begin{cases} D_n = 3900\ \frac{cm^2}{V \cdot s} \times 0.025\ V = 97.5\ \frac{cm^2}{s} \\ D_p = 1900\ \frac{cm^2}{V \cdot s} \times 0.025\ V = 47.5\ \frac{cm^2}{s} \end{cases}$

$$j_0 = 1.6\times10^{-19}C \times (2\times10^{13}\,cm^{-3})^2 \times$$

$$\times\left(\frac{1}{5\times10^{16}\,cm^{-3}}\sqrt{97.5\times10^{6}}\,\frac{cm}{s} + \right.$$

$$\left. + \frac{1}{10^{18}\,cm^{-3}}\sqrt{47.5\times10^{6}}\,\frac{cm}{s}\right) \simeq 1.31\times10^{-5}\,\frac{C}{cm^2\cdot s}.$$

Then $R = 0.025\,V \times e^{-10}\,\dfrac{1}{1.31\times10^{-5}\,\frac{C}{cm^2\cdot s}\times10^{-2}\,cm}$

≈ 8.66 Ohm.

For an intrinsic sample,

$R_i = \rho\,\dfrac{L}{A}$, where $A = 10^{-2}\,cm^2$

$L = w \simeq 1.33\times10^{-5}\,cm$

depletion layer width

$\rho = \sigma^{-1}$, where $\sigma = n_i e(\mu_e + \mu_h)$.

So, $\sigma = 2\times10^{13}\,cm^{-3} \times (1.6\times10^{-19}C)\times$
$\times(3900 + 1900)\,\dfrac{cm^2}{V\cdot s} \simeq 0.02\,\dfrac{1}{cm\times Ohm}$

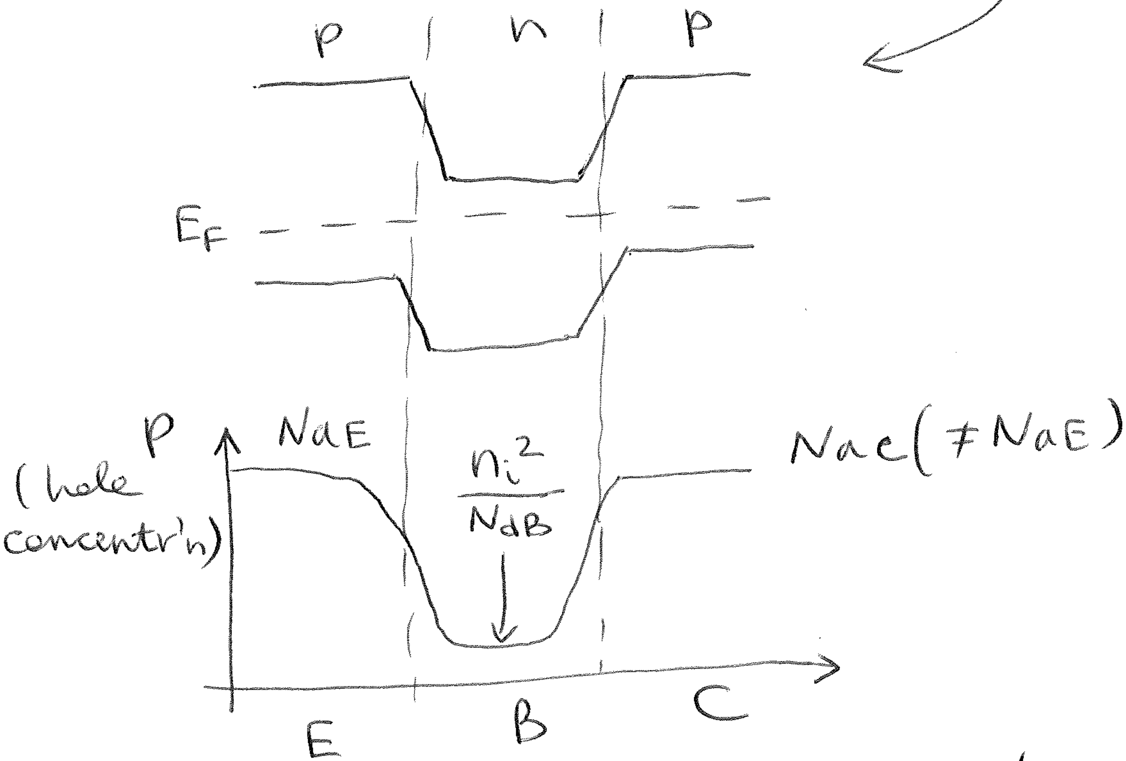
Then $R_i = 50\,Ohm\times cm\,\dfrac{1.33\times10^{-5}\,cm}{10^{-2}\,cm^2} \simeq$
$\simeq 0.07$ Ohm.

Thus $R_i \ll R$, as expected.

⑧ θ Ch. 7, Pr. 7

p-n-p transistor

Energy band diagram:



N_{aE} = # acceptors/cm³ in the emitter region, etc.

(9) Nanoscale electrical & optical devices based on carbon nanotubes

a) Fast-switching FETs with silicon channels replaced by nanotubes; ballistic rather than diffusive transport

b) Ambipolar transistors ($\bar{e}$ & holes injected simultaneously)

c) Use as photoconductors in solar cells - light generates current

d) Use as biosensors: molecules bind, changing field environment & current