Solutions

HW # 6

ECE 606

Q1

(a) $\lambda = 10^4 A$

$P_{photon} = h/\lambda = 4 \times 10^{-11}$ ev/(cm/sec)

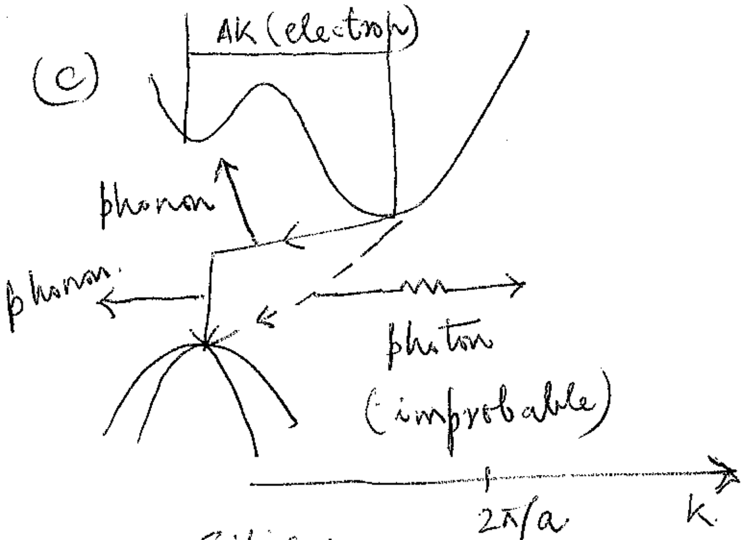
However, the electron moving into or recombining with a hole directly would change its wave-number by $\Delta K = 2\pi/a$. For Si, this would give ~~a~~ electron-momentum change of $\hbar \Delta K = \hbar 2\pi/a = h/a$

$= 4.135 \times 10^{-15}$ (ev-sec) / 5×10^{-8} $= 0.83 \times 10^{-7}$ ev/cm/sec

Thus $\Delta P_{electron} >> P_{photon}$

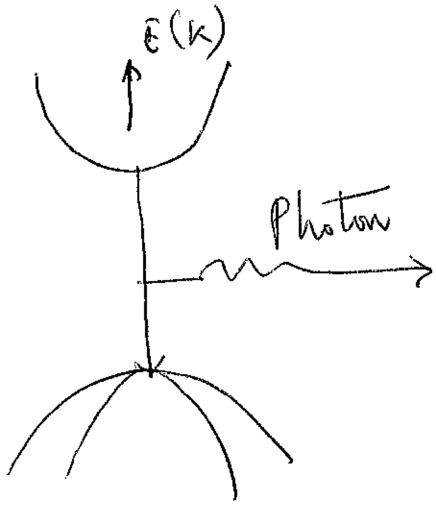
(b) There must be another particle to carry away the large change of electron momentum. This particle is usually a phonon. The probability is low because the process is now a 3-body problem.

(c)



Silicon

Radiative recombination in an indirect semiconductor.



GaAs

Radiative recombination in a direct semiconductor

(d) $\lambda = hc/E$

For $E = 1.2 eV$, $\lambda = 10,000$ Å $\longrightarrow$ far infra-red region. and invisible to human eye.

Q2

(5.6)

(a) In general under steady-state conditions

$$R = \frac{np - n_i^2}{\tau_p(n+n_1) + \tau_N(p+p_1)}$$

Given: $E_T' = E_i \Rightarrow n_1 = p_1 = n_i$ and $\tau_N = \tau_p = \tau$

Noting:

$$n = n_i e^{(F_N - E_i)/kT} \quad ; \quad p = n_i e^{(E_i - F_P)/kT}$$

$$np = n_i^2 e^{(F_N - F_P)/kT} = n_i^2 e^{E_G/4kT} \quad \ldots \text{for } -x_p \le x \le x_N$$

Thus

$$R = \frac{n_i^2 (e^{E_G/4kT} - 1)}{\tau n_i \left[e^{(F_N-E_i)/kT} + e^{(E_i-F_P)/kT} + 2\right]} \simeq \frac{n_i}{\tau}\left[\frac{e^{E_G/4kT}}{e^{(F_N-E_i)/kT} + e^{(E_i-F_P)/kT}}\right]$$

(b) Taking E_i to be a linear function of position between $x = -x_p$ and $x = x_N$, one can write

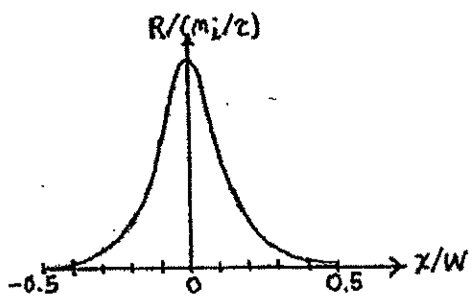
$$F_N - E_i = \frac{E_G}{4}\left(\frac{x_p + x}{x_N + x_p}\right) = \frac{E_G}{4}\left(\frac{x}{W} + \frac{1}{2}\right) \quad \ldots W \equiv x_N + x_p$$

$$E_i - F_P = \frac{E_G}{4}\left(\frac{x_N - x}{x_N + x_p}\right) = -\frac{E_G}{4}\left(\frac{x}{W} - \frac{1}{2}\right) \quad \ldots x_N = x_p = W/2 \text{ in this problem}$$

and

$$\frac{R}{(n_i/\tau)} = \frac{1}{e^{\frac{E_G}{4kT}\left(\frac{x}{W} - \frac{1}{2}\right)} + e^{-\frac{E_G}{4kT}\left(\frac{x}{W} + \frac{1}{2}\right)}} \quad \ldots -\frac{1}{2} \le \frac{x}{W} \le \frac{1}{2}$$

x/W	$R/(n_i/\tau)$
±0.5	1
±0.4	2.95
±0.3	8.68
±0.2	2.53×10^1
±0.1	6.77×10^1
0	1.11×10^2



(c) Under forward-biased conditions, recombination in the depletion region is fairly highly peaked about the point where $n = p$.

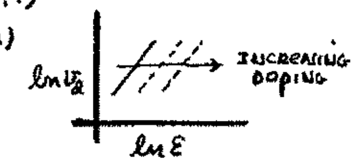
(4)

Q3

PROBLEM SOLUTIONS
CHAPTER 6

(6.1)

(a)



... curves shift in a parallel manner along $\mathcal{E}$-axis

EXPLANATION: Since $v_d = \mu \mathcal{E}$ for small $\mathcal{E}$, on a log-log plot one still sees a unity slope for all dopings. However, as μ decreases with increasing doping, the v_d value at a given $\mathcal{E}$ decreases.

(b) (i) Matthiessen's rule

$$\mu_N = \frac{\mu_{LN}\mu_{IN}}{\mu_{LN}+\mu_{IN}} = \frac{(1360)(2040)}{1360+2040} = \underline{816 \text{ cm}^2/\text{V-sec}}$$

(ii) Using Eq. (6.8)

$$x^2 = \frac{6\mu_{LN}}{\mu_{IN}} = \frac{6(1360)}{2040} = 4$$

$x = 2$

$Ci(x) = 0.42298$
$Si(x) = 1.60541$ } From Standard Math Tables

$$\mu_N = \underline{574 \text{ cm}^2/\text{V-sec}}$$

(c) For intrinsic material

$$\rho = \frac{1}{q(\mu_n+\mu_p)n_i}$$

	Si	GaAs
n_i (300°K)	$1.00\times10^{10}/\text{cm}^3$	$2.25\times10^6/\text{cm}^3$
μ_n	$1360 \text{ cm}^2/\text{V-s}$	8000
μ_p	460	320

} BASIC INFORMATION IN SUBSECTION 6.1.3

(i) $\rho(\text{Si}) = \underline{3.43\times10^5\ \Omega\text{-cm}}$; (ii) $\rho(\text{GaAs}) = \underline{3.34\times10^8\ \Omega\text{-cm}}$

(5)

Q4

Starting equation

$$D_n \frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_n} = 0$$

or $n(x) = c_1 e^{x/L_n} + c_2 e^{-x/L_n}$ ——— (1)

We can determine coeffs by imposing boundary conditions.

First B.C : $n(0) = G\tau_n = c_1 + c_2$

At $x = 0$, excess carriers is $G\tau$

Next B.C : Diffusion of electrons into surface is identical to recombination.

$$D_n \frac{\partial n}{\partial x} = S_n n|_L \quad \text{——— (2)}$$

Using eqn (1) in eqn (2)

$A n|_L = c_1 e^{L/L_n} - c_2 e^{-L/L_n}$ where $A = S_n L_n / D_n$.

$$\therefore c_1 = c_2 e^{-2L/L_n} \left(\frac{A+1}{1-A}\right)$$

Now we use the first B.C. to determine c_1

$$G\tau_n = c_2 \left(e^{-2L/L_n} \left(\frac{A+1}{1-A}\right) + 1\right)$$

$$\Rightarrow c_1 = \frac{G\tau_n}{1 + 2e^{L/L_n}\left(\frac{1-A}{1+A}\right)}$$

Using these coeffs.

$$n(x) = G\tau_n \left[\frac{e^{x/L_n}}{1 + e^{2L/L_n}\left(\frac{1-A}{1+A}\right)} + \frac{e^{-x/L_n}}{e^{-2L/L_n}\left(\frac{A+1}{1-A}\right) + 1} \right] \quad \text{——— (3)}$$

(a) When $S_N \longrightarrow \infty$, all diffused electrons will recombine at surface

$$n(x) = G\tau_n \left[\frac{e^{x/L_n}}{1 - \cancel{2}e^{2L/L_n}} + \frac{e^{-x/L_n}}{1 - e^{-2L/L_n}} \right]$$

(b) $S_n \longrightarrow \infty$, $L_n >> L$.

$$n(x) = G\tau_n \left[\frac{e^{x/L_n}}{1 - \cancel{2}e^{2L/L_n}} + \frac{e^{-x/L_n}}{1 - e^{-2L/L_n}} \right]$$

With increase in L_n $\longrightarrow$ $n(x) = G\tau_n\left[1 - x/L\right]$

(c) $S_n \longrightarrow 0$: No recombination at surface.

$n(x) = G\tau_n$ (by using eqn (3))

Q5 Electron energy at room temperature ($T = 300K$)

$$\frac{3}{2} kT = 1.5 \times 0.026 = 0.039 \text{ eV}$$

Energy for electron-hole pair creation

$$= \frac{3}{2} \times E_g = 1.8 \text{ eV}$$

$\therefore$ 1.8 eV electron would have an equivalent electron temperature of $300 \left(1.8/0.039\right) = 14{,}000 \text{ K}$.

Q6 Energies of conduction and valence bands are given by

$$\mathcal{E}_c(k) = \mathcal{E}_c + \frac{\hbar^2 k^2}{2m_e}, \quad \mathcal{E}_v(k) = \mathcal{E}_v - \frac{\hbar^2 k^2}{2m_h}$$

From conservation of energy

$$h\nu = \mathcal{E}_c(k) - \mathcal{E}_v(k) \Rightarrow k = \left[\frac{2(h\nu - E_g) m_e m_h}{\hbar^2 (m_e + m_h)}\right]^{1/2}$$

where $E_g = \mathcal{E}_c - \mathcal{E}_v$

Energies of electrons and holes can be given as

$$E_e = \mathcal{E}_c + \frac{\hbar^2 k^2}{2m_e} = \mathcal{E}_c + \frac{m_h}{m_e + m_h}(h\nu - E_g)$$

$$E_h = -\mathcal{E}_v + \frac{m_e}{m_e + m_h}(h\nu - E_g)$$