$$R = \frac{np - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)} = \frac{np - n_i^2}{\tau(n + p + 2n_i)} \tag{24}$$

since $\tau_p = \tau_n = \tau$ and $n_1 = p_1 = n_i$ ($E'_T = E_i$).

$$n = n_i e^{(F_N - E_i)/kT} \tag{25}$$

$$p = n_i e^{(E_i - F_P)/kT} \tag{26}$$

At the points specified in the band diagram can be used to determine the value of n and p. At $x = 0$

$$F_N << E_i \Longrightarrow n << n_i \tag{27}$$

$$F_P >> E_i \Longrightarrow p << n_i \tag{28}$$

$$R = \frac{-n_i}{2\tau} \tag{29}$$

At $x = -x_{pp}$

$$F_N << E_i \Longrightarrow n << n_i \tag{30}$$

$$F_P = E_i \Longrightarrow p = n_i \tag{31}$$

$$np << n_i^2 \tag{32}$$

$$R = \frac{-n_i}{3\tau} \tag{33}$$

At $x = x_{nn}$

$$F_N = E_i \Longrightarrow n = n_i \tag{34}$$

$$F_P >> E_i \Longrightarrow p << n_i \tag{35}$$

$$np << n_i^2 \tag{36}$$

$$R = \frac{-n_i}{3\tau} \tag{37}$$

At $x = -x_p$

$$F_N << E_i \Longrightarrow n << n_i \tag{38}$$

$$F_P - E_i = E_{FP} - E_i \Longrightarrow p = p_0 >> n_i \tag{39}$$

since $p_0 \approx N_A$, $n_o p_0 = n_i^2$, and $n << n_0$

$$np << n_i^2 \tag{40}$$

$$R = \frac{-n_i}{p_0}\frac{n_i}{\tau} \tag{41}$$

At $x = x_n$, since $n_0 \approx N_D$

$$F_N - E_i = E_{FN} - E_i \Longrightarrow n = n_0 >> n_i \tag{42}$$

$$F_P >> E_i \Longrightarrow p << n_i \tag{43}$$

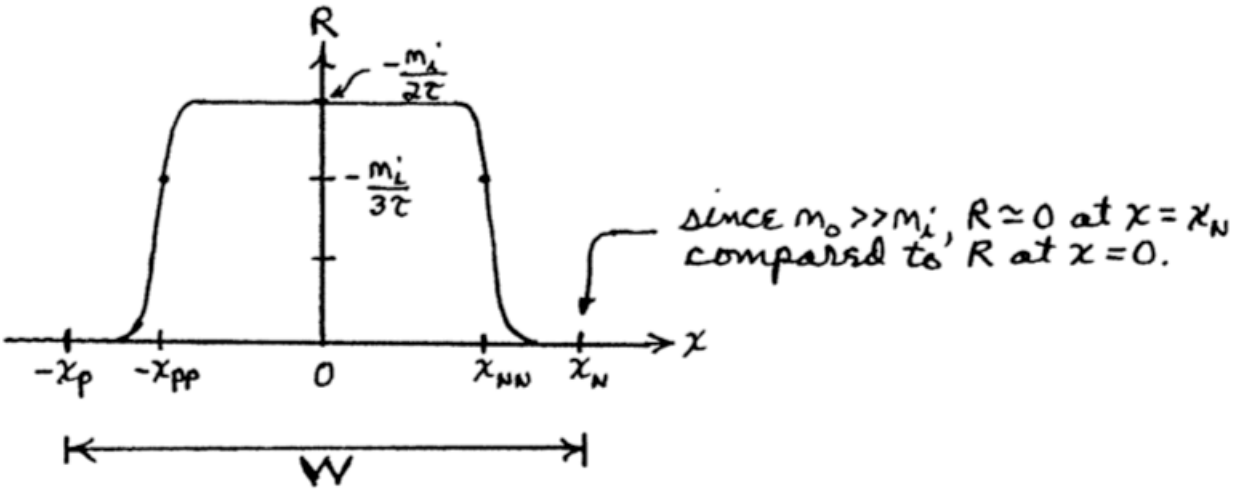
since $n_0 p_0 = n_i^2$ and $p << p_0$

$$np << n_i^2 \tag{44}$$

$$R = \frac{-n_i}{n_0}\frac{n_i}{\tau} \tag{45}$$

Problem 4 (b)

(Please note that the solution for this problem is taken from the official Advanced Semiconductor Fundamentals Solutions Manual.)



Problem 4 (c)

(Please note that the solution for this problem is taken from the official Advanced Semiconductor Fundamentals Solutions Manual.)

(c) Other than a good exercise in the use of quasi-Fermi levels, the problem drives home a point made in the text; namely, $G = -R = n_i/2\tau = n_i/\tau_g$ only in that portion of an electrostatic depletion region where $n << n_1$ and $p << n_1$. The width of the R-G depletion region is always smaller than W -- or there are "dead" zones, nongenerating zones, at the edges of the depletion width.

COMMENT: Please note that at $x = -x_p$ and $x = x_N$, the conditions are met for the "low level injection" situation discussed in Subsection 5.2.5. One should therefore obtain

$$R = \frac{\Delta n}{\tau_n} \qquad \text{at } x = -x_p$$

$$R = \frac{\Delta p}{\tau_p} \qquad \text{at } x = x_N$$

at $x = -x_p$, $n = n_o + \Delta n \simeq 0$. Thus $\Delta n = -n_o = -n_i^2/p_o$. With $\tau_n = \tau$, we can then write $R = \Delta n/\tau_n = -(n_i^2/p_o)/\tau$. This is of course the same answer obtained in part (a-iv). All our results are consistent.

Problem 5 (a)

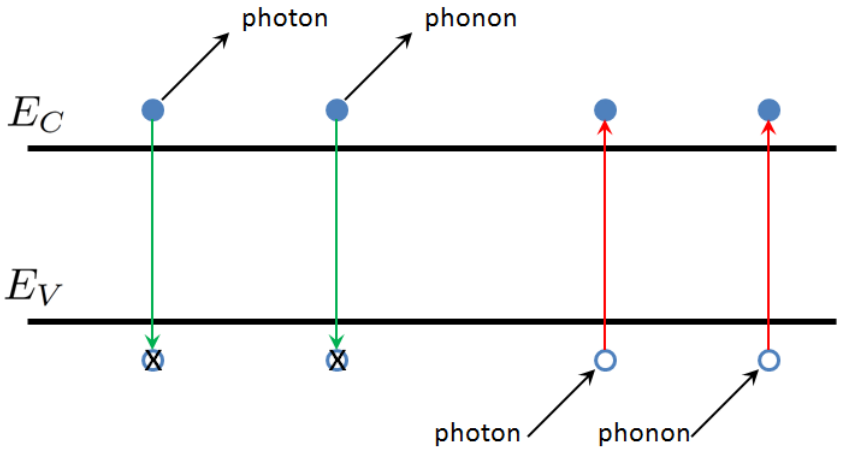


Figure 2: Band to Band Recombination (green) and Generation (red)

As shown in Figure 2, band-to-band recombination occurs when a conduction band electron loses energy and overlaps with a hole. The energy loss is predominately due to photoemission, but for shallow band-gaps it can be a result of heat loss to phonons. Similarly for generation, when a valence band electron receives a photon with the energy required for a transition to the conduction band, an electron-hole pair is created. This is the dominant means for generation as opposed to phonon based generation.

Problem 5 (b)

The change in the concentration of electrons is related to the rate of photo-absorbtion by valence band electrons and the rate of photo-emission by conduction band electrons. The rate of generation is proportional to the number of filled valence band states and the number of empty conduction band states. The generation of electrions is related to the rate of electron emission from the valence band, e_n and the rate of recombination between the two bands proportional to c_b.

$$\frac{\partial n}{\partial t} = \frac{\partial n}{\partial t}\Big|_g + \frac{\partial n}{\partial t}\Big|_r = e_n - c_b np \tag{46}$$

Under equilibrium conditions, the principle of detailed balance can be used to relate the rate of electron recombination and generation

$$e_n = c_b n_i^2 \tag{47}$$

Further approximating the capture and emission coefficients by assuming they remained unchanged under stead-state conditions, the recombination rate can be found

$$r_n = -\frac{\partial n}{\partial t} = c_b np - c_b n_i^2 \tag{48}$$

$$r_n = c_b(np - n_i^2) \tag{49}$$

As mentioned in the problem statement, $r_n = r_p = r_b$ as the recombination and generation occurs simultaneously for both bands.

Problem 5 (c)

Let $\Delta n = n - n_0$ and $\Delta p = p - p_0$ represent the change in carrier concentration as a result of low-level injection from the equilibrium values.

$$r_n = c_b \left((n_0 + \Delta n)(p_0 + \Delta p) - n_i^2 \right) \tag{50}$$

$$r_n = c_b \left(n_i^2 + n_0 \Delta p + \Delta n p_0 + \Delta n \Delta p - n_i^2 \right) \tag{51}$$

$$r_n = c_b \left(n_0 \Delta p + \Delta n p_0 + \Delta n \Delta p \right) \tag{52}$$

$$r_n = c_b \left(\Delta n (n_0 + p_0) + \Delta n^2 \right) \tag{53}$$

$$r_n = c_b \Delta n (n_0 + p_0 + \Delta n) \tag{54}$$

Using the approximation that $n_0 + p_0 \gg \Delta n$, which is reasonable given the low-level injection conditions, the relationship simplifies to

$$r_n = \Delta n \left[c_b (n_0 + p_0) \right] \tag{55}$$

$$r_n = \frac{\Delta n}{\tau_b} \tag{56}$$

Problem 5 (d)

The effective lifetime of a carrier as related to band-to-band recombination is based on $\tau_b = 1/(c_b(n_0 + p_0))$. Considering donor doped silicon, the donor concentration that results in an effective life on the order of the reconbination effective life can be found ($n \approx N_D \gg p_0$ under extrinsic conditions):

$$0.001 \text{ sec} = \frac{1}{(5 \times 10^{-15} \text{cm}^3/\text{sec}) N_D} \tag{57}$$

$$N_D = 2 \times 10^{17}/\text{cm}^3 \tag{58}$$

For most nondegenerate dopings of Si, recombination will be dominated by R-G center recombination. However, given that Si is considered degenerate when the doping concentration is around $10^{18}/\text{cm}^3$ or greater, there will be doping concentrations where the recombination is a result of both R-G centers and band-to-band recombination.

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Problem 1 (a)

For nondegenerate semiconductors, electrons in the conduction band have an average kinetic energy given by $\langle E \rangle = \frac{3}{2}kT$. At room temperature this results in an average energy of 0.0388 eV. See equation 5.30 from ASF (p.152).

Problem 1 (b)

Assuming that an electron was in the conduction band under the same conditions but had a minimum energy of at least 1.5 E_g, the equivalent temperature for the electron is given by $T = \frac{2(1.5E_g)}{3k}$ where E_g for silicon is 1.125 eV. Therefore

$$T_{\text{electron}} \approx 13000 \text{ K} \tag{1}$$

Clearly, this would qualify as a *hot* electron.

