OC Problem Set on Semiconductors

Friday, May 29, 2014

Problem 1: Carrier Concentration in Semiconductors

The densities n_T of conduction-band (CB) electrons and the density p of valence-band (VB) holes of an undoped semiconductor can be calculated with the help of the density of states $\rho_C(W)$ of the CB and $\rho_V(W)$ of the VB, and the Fermi-Dirac distributions $f(W)$ and $[1-f(W)]$ for electrons and holes, respectively:

$$n_T = \int_{W_C}^{\infty} \rho_C(W) f(W) \mathrm{d}W \qquad \text{and} \qquad p = \int_{-\infty}^{W_V} \rho_V(W)[1-f(W)]\mathrm{d}W \,.$$

If the energetic distance of the Fermi level from the band edges is $|W_{C,V} - W_F| > 3kT$, then the Fermi functions can be simplified by the Boltzmann approximation, which shall be used for the calculations below. In practice, however, this condition is usually not fulfilled, e. g., for a degenerately doped laser diode, the Fermi level is very close to or even inside the bands. Thus the following considerations illustrate the principle only.

a) Show that the maximum of the electron concentration per energy $\rho_C(W) f(W)$ is found at the energy $kT/2$ above the band edge W_C of the CB.

b) Calculate the effective density of states $N_B = N_V, N_C$ using the relation

$$\int_{W_0}^{W_0+kT} \rho(W)\, dW = \frac{2}{\sqrt{\pi}} \frac{2}{3} N_B \approx 0.75 N_B$$

c) Solve the above given integrals for n_T and p by using the Boltzmann approximation and write the carrier concentration as

$$n_T = N_C \exp\left(-\frac{W_C - W_\mathrm{F}}{kT}\right) \qquad \text{and} \qquad p = N_V \exp\left(-\frac{W_\mathrm{F} - W_V}{kT}\right).$$

d) The bandgap energy of GaAs is W_G = 1.424 eV, the effective masses are $m_n = 0.067 m_0$ and $m_p = 0.48 m_0$, where m_0 is the electron rest mass. Determine the intrinsic carrier concentrations n_T and p of GaAs at T =300 K and calculate the energetic distance of the Fermi level relative to the band edges.

Problem 2: Laser and LED

a) Explain the advantages of a double heterojunction compared to a simple pn-junction with respect to the injected laser current.

b) Consider a GaAs LED with a refractive index $n = 3.5$. Calculate the critical angle of total internal reflection for radiation into air / glass. Calculate the resulting power reflection and transmission factors and compare these factors to perpendicular incidence at the interface.

c) Show graphically the frequency dependence of spontaneous and stimulated emission for $T/T_0 = 0.01$ for the flatband case with different values of $eU = W_{Fn} - W_{Fp}$. Choose $eU_1 = 2kT_0 - W_G$ and $eU_1 = 5kT_0 - W_G$. Explain why in contrast to $r_{ind}^{(M)}$, $r_{sp}^{(eM)}$ does not take negative values.

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