Problem Set 10

1. Given the data for Si: $\mu_e = 1350$ cm^2/Vs, $\mu_h = 475$ cm^2/Vs, $m_e = 0.19m$, $m_h = 0.16m$ and $E_g = 1.1$ eV, calculate the intrinsic conductivity at room temperature. Compare this with the conductivity of a typical metal.

2. A semiconductor has an energy gap of 1.1 eV at $T = 300$ K. The effective masses for holes and electrons are $m_h = 0.56m$ and $m_e = 1.08m$, where m is the bare electronic mass.
   (a) Find the concentration of electrons in the conduction band for the undoped material, n_i.
   (b) The material is then doped with donor impurities with a concentration of $N_D = 2 \times 10^{15}$ cm^{-3}. Assume all the donors are ionized. Find n and p now.

3. In a particular semiconductor there are 10^{13} donors/cm^3 with an ionization energy $E_D = 1$ meV and an effective mass of $m_e = 0.01m$.
   (a) Estimate the concentration of conduction electrons at 4 K.
   (b) What is the value of the Hall coefficient? Assume there are no acceptor impurities and that $E_g \gg k_B T$.

4. Consider a semiconductor doped with only N_A acceptor impurities. We measure the conductivity of the sample as a function of temperature $\sigma(T)$, and we measure the Hall coefficient as a function of temperature $R_H(T)$.
   (a) Show that the electrical conductivity in the intrinsic region of the semiconductor is given by
   $$\sigma_{intrinsic} = e[\mu_e n + \mu_h(N_A + n)], \tag{1}$$
   where n is the density of electrons in the conduction band and μ_e and μ_h are the electron and hole mobilities (assumed to be temperature independent).
   (b) Find the conductivity in the *extrinsic* region of the semiconductor σ_{ext}, and then find the conductivity of the inversion point, σ_{inv}. Note that the inversion point has to occur in the intrinsic region. Show that
   $$b = \frac{\sigma_{inv}}{\sigma_{inv} - \sigma_{ext}}, \tag{2}$$
   where $b = \mu_e/\mu_h$. Hint: First find $\sigma_{inv}/\sigma_{ext}$.
   (c) Discuss how to experimentally determine the number of acceptor impurities from one of the measurements conducted.
   (d) Solve for the electron and hole mobilities in terms of e and measured quantities: R_H, σ_{inv}, and σ_{ext}. Discuss the implications of the experiment outlined here.

5. The energy gap in germanium is 0.66 eV at room temperature, and it has a dielectric constant of $\varepsilon = 16$, and the effective mass of the electrons in germanium is $1.57m$. We make a junction of area 1 mm^2 between an n-doped region of germanium and a p-doped region. The n-type has $N_D = 10^{21}$ m^{-3} donors and the p-type region has $N_A = 10^{21}$ m^{-3} acceptors.

(a) What is the width of the depletion region at zero applied voltage?

(b) What is the width of the depletion region at an applied voltage of 5V (forward bias)? At an applied voltage of -5V (reverse bias)?

6. In a particular application, there is a potential drop of 0.1 V across an ideal diode. If the maximum permitted ratio of reverse current to forward current is 10^{-5}, determine the maximum operating temperature of the diode. A careful reading of section 6.3 will help here.

7. *For 20 points extra credit!*

   (a) We want to find the increase in total electronic energy for an intrinsic semiconductor at temperature T compared to $T = 0$,

$$\Delta E(T) = E(T) - E(0). \tag{3}$$

   At $T = 0$ recall that the valence band is full. The change in energy as the temperature is raised comes from 2 pieces: the occupation of states in the conduction band and the emptying of states in the valence band. Use the book's convention where the top of the valence band is at $E = 0$ and the bottom of the conduction band to be at $E = E_g$. Assume low temperatures (which allows you to use Eqs. 5.16 and 5.20 from the book) and make reasonable approximations.
   Show that this energy is equal to:

$$\Delta E(T) = \frac{3}{2}(N + P)k_B T + N E_g, \tag{4}$$

   where N is the number of electrons in the conduction band and P is the number of holes in the valence band. Comment on this result. Does this make sense?

   For the electrons in the conduction band, here is a trick: $E(T) = E(T) - NE_g + NE_g$, and $E(T) = \int_0^\infty E f(E,T) g(E - E_g) dE$.

   For the electrons in the valence band, you can do it two ways: treat them as electrons in the valence band (so the band is full at $E(0)$, which means $E(0) \neq 0$ and $E(0)$ is more negative than $E(T)$), or as holes, so the valence band is empty at $E(0)$. The two methods are identical.

   (b) Show that the electronic specific heat, $\frac{1}{V}\frac{dE}{dT}$, for the semiconductor is approximately:

$$c_V \approx \frac{3}{2}(n + p)k_B + \frac{E_g}{2k_B T}\left(\frac{3}{2}(n + p)k_B + n\frac{E_g}{T}\right), \tag{5}$$

   where here n and p are carrier densities of electrons and holes.