Semiconductor Theory

1. **Carrier velocities in metals versus semiconductors**

   (a) Prove that the average kinetic energy of an electron in the conduction band of a metal is $\frac{3}{5}E_f$. Hint: The density of states in a free electron gas $g(E) = CE^{1/2}$.

   (b) Calculate the average speed of an electron in a conduction band where the effective mass $m_e = 0.5m$ and the carrier density is $n = 10^{23}$ cm^{-3} at T=4K . Hint: What is the relation between Fermi wave-vector k_f and density?

   (c) Calculate the average speed of an electron in an n-type semiconductor where the effective mass $m_e = 0.5m$ and the electron density is $n = 10^{16}$ cm^{-3} at T=4K . Hint: Because the carrier density is so low, the electrons is a semiconductor obey Maxwell-Boltzmann statistics and the equipartition theorem rather than Fermi-Dirac statistics.

   (d) What is the temperature dependence of the average speed of the electron in a semiconductor. Compare with metals and explain.

2. **Semiconductor Doping**
   Consider a hypothetical semiconductor where at 300K, the band gap $E_g = 0.5$ eV, $m_h = m_e = 0.8m$, $\mu_e = 1500$ cm^2/V-s and $\mu_e = 1000$ cm^2/V-s. Hint: in calculating $n_i^2 = np$, calculate kT in eV and use the following constants: $hc = 1.239 \times 10^{-4}$ eV-cm and $mc^2 = 0.511$ MeV. Be very careful about units.

   (a) Determine the concentration of electrons and holes at 300K in intrinsic material.

   (b) Determine the conductivity of intrinsic material.

   (c) Make a rough estimate of the maximum concentration of ionized donors N_D that could be incorporated that would still produce $n \approx p$.

   (d) If $N_A = 10^{17}$ cm^{-3}, $N_D = 0$ and at 300 K all the acceptors are ionized, determine the conductivity

   (e) If $N_A = N_D = 10^{17}$ cm^{-3}, determine the conductivity at 300K. Hint: Consider charge neutrality.

3. **Fermi Level in Gallium Arsenide**
GaAs has a bandgap of 1.43 eV at 300K, an electron mobility of 1.6×10^4 cm^2/Vs, a hole mobility of 4×10^3 cm^2/Vs, an electron effective mass of $0.065m$, and a hole effective mass of $0.45m$.

   (a) Prove that the position of the Fermi Level is

$$E_f = E_v + E_g/2 + \frac{3}{4}k_B T \ln \frac{m_h}{m_e}$$

   (b) Where is the Fermi Level in intrinsic GaAs?

4. **Impurity Orbits**
Indium Antinomide (InSb) has a band gap $E_g = 0.23\text{eV}$ at 300 K, $\epsilon = 18$, electron effective mass $m_e = 0.015m$. Calculate:

   (a) the donor ionization energy

   (b) the radius of the ground state orbit

   (c) At what minimum donor concentration will appreciable overlap effects between the orbits of adjacent impurity atoms occur? This overlap tends to produce an "impurity band" - a band of energy levels which permit conductivity at T=0K presumably by a electron hopping from one impurity site to another.

5. **Maximum Conductivity**
This is a problem from the textbook, "The Oxford State Basics" by Steven H. Simon. There is something misleading about the problem. Solve the problem and then figure out what is wrong about the conclusion.

   Suppose holes and electrons in a particular semiconductor have mobility μ_h and μ_e, respectively. Show that, independent of doping, the maximum conductivity that can be achieved is

$$\sigma = 2en_{intrinsic}\sqrt{\mu_e \mu_h}$$