Some stuff:

1. My OH are M 2-3 and F 1-2 in the Moore Room on 2nd Floor Cory (the room in the centre courtyard).

2. Important things for the upcoming exam: what is a semiconductor, doping and calculating Fermi level, n, p, ni given some parameters, diffusion and drift, mobility, types of recombination.

3. I will post ***lots*** of sample problems on my website @ http://www.ocf.berkeley.edu/~rfguo/

Some problems:

1. Determine the equilibrium electron and hole concentration inside a uniformly doped sample of Si under the following conditions: T = 450 K, $N_A = 0$ cm^{-3}, $N_D = 10^{14}$ cm^{-3}

(d) We deduce from Fig. 2.20 that, at 450K, $n_i(\text{Si}) \approx 5 \times 10^{13}/\text{cm}^3$. Clearly, n_i is comparable to N_D and we must use Eq.(2.29a).

$$n = \frac{N_D}{2} + \left[\left(\frac{N_D}{2}\right)^2 + n_i^2\right]^{1/2} = 1.21 \times 10^{14}/\text{cm}^3$$

$$p = \frac{n_i^2}{n} = \frac{(5 \times 10^{13})^2}{1.21 \times 10^{14}} = 2.07 \times 10^{13}/\text{cm}^3$$

2. A silicon sample is doped with $N_d = 10^{17}$cm^{-3} of As atoms.

(a) What are the electron and hole concentrations and the Fermi level position (relative to E_c or E_v) at 300K? (Assume full ionization of impurities.)
(b) Check the full ionization assumption using the calculated Fermi level, (i.e. find the probability of donor states being occupied by electrons and therefore not ionized.) Assume that the donor level lies 50meV below the conduction band, (i.e. $E_c - E_D = 50$meV.)
(c) For $N_d = 10^{17}$cm^{-3} but T = 30K, what is Nc, Nv, and ni?

a) If we assume full ionization of impurities, the electron concentration is $n \approx N_d = 10^{17}$cm^{-3}. The hole concentration is $p=(n_i)^2/n=(10^{10}\text{ cm}^{-3})^2/10^{17}\text{cm}^{-3}=10^3\text{ cm}^{-3}$.
The Fermi level position, with respect to E_c, is

$$E_c - E_f = kT\ln[N_c/n] = 0.026\ln[2.8\times 10^{19}cm^{-3}/10^{17}cm^{-3}] = 0.15eV.$$

E_f is located 0.15 eV below E_c.

b) In order to check the full ionization assumption with the calculated Fermi level, we need to find the percentage of donors occupied by electrons.

$$E_D - E_f = (E_c - E_f) - (E_c - E_D) = 0.1eV \text{ , and}$$

$$n_D = N_d \frac{1}{1 + e^{(E_D - E_f)/kT}} = \frac{10^{17}(cm^{-3})}{1 + e^{(0.1eV/0.026eV)}} = 2.09 \times 10^{15} cm^{-3} \equiv 2\% \, of \, N_d .$$

Since only 2% of dopants are not ionized, it is fine to assume that the impurities are fully ionized.

c) For T=30 K, we need to use Equation (1.10.2) to find the electron concentration since the temperature is extremely low. First, we calculate N_c and N_v at T = 30 K:

$$N_C(T=30\,K) = 2[\frac{2\pi m_{dn} kT}{h^2}]^{3/2} = 3.217 \times 10^{19} \times (\frac{T}{300\,K})^{3/2} cm^{-3} = 1.0173 \times 10^{18} cm^{-3} \text{ and}$$

$$N_v(T=30\,K) = 2[\frac{2\pi m_{dp} kT}{h^2}]^{3/2} = 1.83 \times 10^{19} \times (\frac{T}{300\,K})^{3/2} cm^{-3} = 5.787 \times 10^{17} cm^{-3}$$

$$n_i = \sqrt{\frac{N_c(30\,K) N_v(30\,K)}{2}} e^{-(E_g)/(2kT)} = 2.32 \times 10^{-75} cm^{-3} .$$

3. a) Consider a Si sample maintained at room temp under equilibrium conditions doped with phosphorus to a concentration of 10^16 cm^-3.
   i. What are the electron and hole concentrations (n and p) in this sample? Is the material n-type or p-type?
   ii. Draw the energy band diagram for this sample.

   b) Suppose the sample is counterdoped to the opposite type by boron s.t. $E_i - E_F = 0.30$ eV.
   i. What are *n* and *p* in the counter-doped sample?
   ii. What is the concentration of boron?

(a) i. Phosphorus atoms are donors (N_d). Therefore, the sample is **n-type** with an electron concentration equal to $N_d = 1\text{x}10^{16}$ cm^{-3} (since it is appropriate to assume full-ionization at room temperature). Thus:

$n = N_d = 1\text{x}10^{16}$ cm^{-3}
$p = (n_i)^2/n = (1\text{x}10^{10} \text{ cm}^{-3})^2/1\text{x}10^{16} \text{ cm}^{-3} = 1 \text{ x}10^4 \text{ cm}^{-3}$

(b) ii. $E_F - E_i = kT \ln[\frac{n}{n_i}] = 6\text{kT} \ln(10) = 0.360\, eV$ 0.360 eV above Ei

b) i. 300 meV below Ei. $p = n_i e^{(E_i - E_F)/kT} = 1 \times 10^{10} \times e^{0.3/0.0259} = 1.03 \times 10^{15} cm^{-3}$
n ~ 10^5 cm^-3

By charge neutrality equation: p – n + N_d+ - N_A- = 0
N_A- = p + N_D+ = 1.1 x 10^16 cm^-3 of Boron

4. A p-type (uncompensated) silicon sample is maintained at 300K. When an electric field with strength 5×10^3 V/cm is applied to the sample, the electron drift velocity is 4×10^6 cm/sec.

a) What is the mean free path of an electron in this sample? (Note: 1 kg cm^2/V/s/C = 10^{-4} sec)

b) What is the resistivity of this sample?

a) Find μ_n and τ_{mp}:

$$\mu_n = \frac{v_d}{\varepsilon} = \frac{4\times 10^6\, cm/s}{5\times 10^3\, V/cm}$$
$$= 800\, cm^2 V^{-1} s^{-1}$$

$$\tau_{mn} = \frac{m_n^* \mu_n}{q} = \frac{0.26\cdot 9.11\times 10^{-31} kg\cdot 800\, cm^2 V^{-1} s^{-1}}{1.6\times 10^{-19} coul}\times 10^{-4} s$$
$$= 1.18\times 10^{-13} s = 0.118\, ps$$

Use v_{th} and τ_{mn} to find l:

$$l = v_{th}\tau_{mn} = 2.30\times 10^7\, cm/s\cdot 0.118\, ps$$
$$= 2.71\times 10^{-6}\, cm = 27.1\, nm$$

b) To find resistivity, we need to know the dopant concentration N_A. Using Figure 3.5 (mobility *vs.* total dopant concentration) on Page 80 of Pierret, we find that for an electron mobility of 800 cm^{2}V^{-1}s^{-1}, $N_A + N_D = 10^{17}$ cm^{-3} and the hole mobility is ~330 cm^{2}V^{-1}s^{-1}. Since the sample is uncompensated, N_D = 0 so $N_A = 10^{17}$ cm^{-3}.

$$\rho = \frac{1}{qp\mu_p} = \frac{1}{1.6\times 10^{-19} C\cdot 10^{17} cm^{-3}\cdot 330\, cm^2 V^{-1} s^{-1}}$$
$$= 0.19\Omega - cm$$

5. A sample of N-type silicon is at room temperature. When an electric field with strength of 1000V/cm is applied to the sample, the hole velocity is measured and found to be 2x10^5 cm/sec.

(a) Estimate the thermal equilibrium electron and hole densities, indicating which is the minority carrier.
(b) Find the position of E_f with respect to E_c and E_v.

The sample is used to make an integrated circuit resistor. The width and height of the sample are 10µm and 1.5µm, respectively, and the length of the sample is 20µm. Calculate the resistance of the sample.

It is given that the sample is n-type, and the applied electric field $\mathcal{E}$ is1000V/cm. The hole velocity υ_{dp} is 2×10^5cm/s.

(a) From the velocity and the applied electric field, we can calculate the mobility of holes:

$\upsilon_{dp} = \mu_p\mathcal{E}$, $\mu_p = \upsilon_{dp}/\mathcal{E} = 2\times10^5/1000 = 200\text{cm}^2/\text{V}\cdot\text{s}$.

From Fig. 3.5 a), we find N_d is equal to $4.5\times10^{17}/\text{cm}^3$. Hence,

$n = N_d = 4.5\times10^{17}/\text{cm}^3$, and $p = n_i^2/n = n_i^2/N_d = 10^{20} / 4.5\times10^{17} = 222/\text{cm}^3$.

Clearly, the minority carrier is hole.

(b) The Fermi level with respect to E_c is

$E_f = E_c - kT\,ln(N_d/N_c) = E_c - 0.107$ eV.

(c) $R = \rho L/A$. Using Equation (2.2.14), we first calculate the resistivity of the sample:

$\sigma = q(\mu_n n + \mu_p p) \approx q\mu_n n = 1.6\times10^{-19} \times 400 \times 4.5\times10^{17} = 28.8/\Omega\text{-cm}$, and
$\rho = \sigma^{-1} = 0.035\ \Omega\text{-cm}$.

Therefore, $R = (0.035) \times 20\mu\text{m} / (10\mu\text{m} \times 1.5\mu\text{m}) = 467\ \Omega$.