Ch/ChE 140a
Problem Set #3
2007/2008

SHOW ALL OF YOUR WORK!

(190 Points Total)

Due Thursday, February 28th, 2008

Please read chapter 6 (*pp*. 175-209) of Advanced Semiconductor Fundamentals by Pierret. Also read Section III, "Equilibrium State at a Semiconductor/Liquid Junction" in *"Principles and Applications of Semiconductor Photoelectrochemistry."*

1. The purpose of this question is to get you used to 4-point probe measurements, particularly since these measurements are often performed in device labs. Read the pages handed out in class on resistivity measurements from Sze, Physics of Semiconductor Devices, 2nd ed., *Section 1.5.2*, "Resistivity and Hall Effect" pp.30-33, and then answer the questions below.

   In a rush to get a resistivity measurement made on a piece of silicon before processing it further, you frantically search through the lab for the 4-point probe station. But, of course, it is not where it belongs and this sends you on a wild goose chase through all the labs and bench tops. Not understanding your dilemma, your labmate spots an Ohmmeter, and suggests that you should just take some alligator clips, clip them onto the Si sample and multiply the resistance you measure between the clips by the distance between the clips to get the resistivity of the sample.

   a) Explain the major flaws with this suggestion. *(10 points)*

   b) Explain how a 4-point probe device works:
      i) Why are there 4 probes? What problem does this eliminate? *(5 points)*
      ii) Most experiments apply a voltage and observe a current. Explain why, in this case, we apply a current and observe the potential. Why is the current passed along the outer probes? Draw a little circuit involving the 4-probes and the measurement conditions. *(15 points)*

   Your labmate now understands your need to find the 4-point probe device and helps you look for it. Finally, you find it on a shelf in the computer room along with the micrometer used to measure the thickness of the Si sample! Using the 4-point probe device you apply a current along the outer probes and measure the voltage across the inner probes to get the following data:

   Table 1: 4-Point Probe Voltage vs. Applied Current For Your Si Sample.

Current Through Outer Probes (μA)	**Voltage Across the Inner Probes (μV)**
10.62	349
21.90	590

29.77	757
41.37	1002
49.00	1162
60.71	1409
70.39	1613
79.35	1799
90.47	2032
99.91	2228
110.11	2440
120.78	2658
130.73	2861
140.50	3060

The thickness of your 3-inch diameter n-type Si wafer is 408μm (measured with the micrometer), and the distance between the inner probes on the 4-point probe device is 0.050 inches.

c) Determine the sheet resistance, R_s (Ω/square), and the resistivity, ρ (Ω-cm), of the Si wafer. *(10 points)*

d) What was the maximum electric field (V/cm) between the inner probes during the sample measurement? How large of a potential can be applied between the inner probes before reaching the saturation field of Si (where Ohm's law breaks down). Take $\mathcal{E}_{max}$(Si) as about 2×10^3 V/cm (the text, Fig 6.3, p.178). *(10 points)*

e) From the resistivity, ρ, that you calculated in part (c) and the graph of Fig 6.9 on page 191 of your text (Modular Series), calculate the dopant density. (Your sample is n-type!) *(5 points)*

f) What would the resistivity, ρ, have been if, instead of a 3-inch wafer, the 4-point probe data collected above were obtained for a 1*cm* x 1*cm* piece of Si? *(5 points)*

2. The Fermi-Dirac and Maxwell-Boltzmann statistical distribution functions are widely used in semiconductor physics. We've used the Fermi-Dirac distribution function to calculate the probability of an electron being at a particular energy:

$$f_{FD}(E) = \frac{1}{\exp[(E - E_f)/kT] + 1} \qquad (1)$$

The Maxwell-Boltzmann distribution function is just a simplification of the Fermi-Dirac distribution, which is often used to significantly simplify mathematical calculations (in fact, some calculations cannot be solved analytically without this simplification):

$$f_{MB}(E) = \frac{1}{\exp[(E - E_f)/kT]} = \exp[-(E - E_f)/kT] \qquad (2)$$

The point of the problem is to understand the two different distribution functions and to understand when the Maxwell-Boltzmann distribution is a reasonable simplification for the Fermi-Dirac distribution.

a) Simply looking at the functional form of the two distribution functions, we can see where the Maxwell Boltzmann distribution is a reasonable simplification.

i) For what energy range, (E-E_f), is the Maxwell-Boltzmann distribution a valid simplification for the Fermi-Dirac Distribution. Give energy units in kT and in eV. *(5 points)*

ii) For what energy range, (E-E_f), is the Maxwell-Boltzmann distribution a bad simplification. Give your answer in the same units as above. *(5 points)*

iii) When analyzing the probability of traps in the midgap being filled or empty, which statistical distribution should be used? Why? *(10 points)*

b) Consider the equation: $n = N_C\exp(-(E_C-E_f)/kT)$.

i) Does this equation assume Maxwell-Boltzmann or Fermi-Dirac statistics? *(5 points)*

ii) For most doping conditions (N_D or $N_A = 10^{13} - 10^{16}$ cm^{-3}), is the Maxwell-Boltzmann distribution sufficient to describe the electrons in the conduction band? Explain why or why not. *(5 points)*

iii) If your answer to the above question was "yes," under what doping conditions would the Maxwell-Boltzmann distribution be a bad simplification? Does this answer reason with your answer in (2a,ii) above? *(5 points)*

c) Consider a perfectly intrinsic sample of Si. Re-derive the equation for the intrinsic Fermi level, $E_{F,i}$ relative to the valence band energy E_{VB}. Calculate the energy of the Fermi-level (*vs.* E_{VB}) at T = 0.001, 150, 300 and 600 K. *(20 points)*

d) Plot the electron occupancy (the probability of finding an electron at an energy, E) versus energy, E (relative to E_{VB}: *i.e.* set $E_{VB} = 0$ on this graph) at each of the temperatures above. (So this is a plot of $f_{FD}(E)$ *vs.* E.) **Label E_{VB} and E_{CB} on all plots!**

i. Plot the expected occupancy, $f_{FD}(E)$, on a linear scale from –0.05 to +1.05 (dimensionless probability units) for energies, E, on a linear scale between –0.2 and +1.4 eV on the (x) axis. *(5 points)*

ii. Plot the expected occupancy, $f_{FD}(E)$, on a logarithmic scale from 10^{-10} to 1.0 (dimensionless probability units) for energies, E, again on a linear scale between –0.2 and +1.4 eV on the (x) axis. *(5 points)*

e) Plot the Maxwell-Boltzmann distribution function at the same four temperatures for the same Si sample. **Label E_{VB} and E_{CB} on all plots!**

i. Plot the expected occupancy, $f_{MB}(E)$, on a linear scale; use the same axis limits as you used in part (d,i) so you can compare the two distributions functions directly. *(5 points)*

ii. Plot the expected occupancy, $f_{MB}(E)$, on a logarithmic scale; use the same axis limits as you used in part (d,ii) so you can compare the two distributions functions directly. *(5 points)*

f) Compare the plots you made for the two distribution functions.

i) At what temperatures and energies on your graph does the Maxwell-Boltzmann distribution fail to represent adequately the Fermi-Dirac statistics? *(5 points)*

ii) Do your plots graphically corroborate your answer for (b,ii) above? *(5 points)*

3. When GaAs is grown by molecular-beam epitaxy (MBE), Si dopants are specifically incorporated into Ga sites; when it is grown by organometallic vapor-phase epitaxy (OMVPE), Si dopants are specifically incorporated into As sites. Suppose that you have two samples of GaAs, both doped to 1.3×10^{16} cm^{-3} with Si, but one grown by MBE and the other grown by OMVPE. Where will the Fermi level, E_f, be in each case, relative to E_{VB}? *(10 points)*

4. Consider that a clean (free of surface states) sample of *n*-GaAs is brought into contact with a redox-active solution such that a junction with a stable, reproducible barrier height of 0.90 V is obtained. Plot out the behavior of the following quantities as a function of the dopant density over a dopant concentration range of 10^{15} to 10^{17} cm^{-3}. Show your work in addition to the plots.

   a) the width (W) of the depletion region in the semiconductor in nm.

   b) the value of the maximum electric field, E_{max}, in the GaAs in V/cm.

   c) the number of electrons (Q_{eq}/cm^2) transferred across the interface in forming the junction and indicate the direction in which they moved.

NOTE: You may make the depletion approximation, and the assumption that all of the potential drops across the semiconductor. (15 points total)

5. Thin-film processes offer an inexpensive way to prepare large solar arrays, but the semiconductors formed by such processes are almost inevitably polycrystalline. In such polycrystalline semiconductor samples, the excited-state lifetime of electron-hole pairs is so short that photocurrent collection is efficient only for carriers created within the space-charge (depletion) region. Using semiconductor films thicker than the depletion width is unwise, because the additional thickness contributes only extra grain barrier boundaries for the photogenerated majority carriers to surmount on their way to the back contact. The additional thickness does not provide any additional photocurrent.

   a) For the case of polycrystalline n-GaAs doped to 6.8×10^{16} cm^{-3} in contact with Au ($\phi_b = 0.75$ V), calculate how thick a layer of GaAs would be required to be to collect 99% of the light, and compare this to the width

of the depletion region. (*Because the sample is polycrystalline, assume that no reflection occurs at the back contact; consider the incident light to be monochromatic at 800 nm and normal to the surface. You can find the necessary equations on page 40 and the absorption coefficients in Figure 7 on page 41 of the required article, "Principles and Applications of Semiconductor Photoelectrochemistry."*) *(10 points)*

b) What do your results in part (a) mean with regard to the maximum external quantum yield we might expect from such a thin-film GaAs device? *(5 points)*

c) What simple device manufacturing consideration would be a good way to improve the external quantum yield of such polycrystalline n-GaAs devices? *(5 points)*