Homework #2 - September 16, 2005

Due: September 23, 2005 at recitation (Rm. 13-3101, 2 PM latest)
(late homework will not be accepted)

Please write your recitation session time on your problem set solution.

1. *[20 points]* Consider a p-type Si sample with a resistivity of 2 $\Omega.cm$ at 300 K. At 300K, estimate the magnitude of:
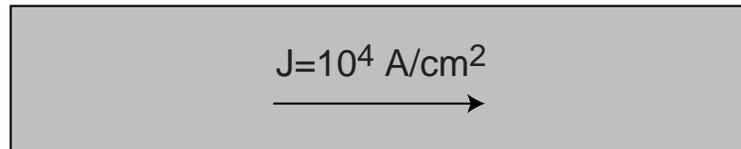
1a. *[5 points]* Hole concentration, p_o.

1b. *[5 points]* Electron concentration, n_o.

1c. *[5 points]* What is an appropriate value for the hole mobility, μ_p?

1d. *[5 points]* What is an appropriate value for the electron mobility, μ_n?

State whatever assumptions you need to make.

2. *[20 points]* Consider a sample prepared from the same material as in problem 1. This sample is at 300K. The geometry of the sample is such that it can be considered a one-dimensional situation. At a certain location in this sample, we measure a drift current density of 10^4 A/cm^2.
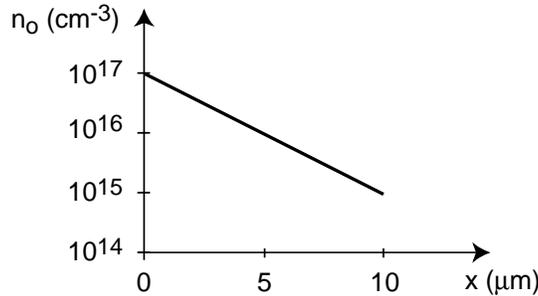
$$J = 10^4 \ A/cm^2$$
$$\longrightarrow$$

2a. *[5 points]* Estimate the magnitude of the electric field at this location.

2b. *[5 points]* Estimate the relative contribution of electron and hole drift to the total current.

2c. *[5 points]* Estimate the hole drift velocity.

2d. *[5 points]* Estimate the electron drift velocity.

3. *[20 points]* Consider a piece of n-type Si in thermal equilibrium at 300 K. In a region defined by $0 \leq x \ (\mu m) \leq 10$, there is a spatially varying electron concentration as sketched below.

$$n_o(x) = 10^{17-0.2x} \ cm^{-3} \quad \text{with } x \text{ in } \mu m$$

3a) *[5 points]* Derive an analytical equation for the minority carrier concentration in space. Quantitatively sketch the result in a suitable diagram.

3b) *[5 points]* Derive an analytical equation for the electrostatic potential in space. Quantitatively sketch the result in a suitable diagram.

3c) *[5 points]* Derive an analytical equation for the electric field in space. Quantitatively sketch the result in a suitable diagram.

3d) *[5 points]* Derive an analytical expression for the charge distribution that supports this electric field. Quantitatively sketch the result in a suitable diagram.

4. *[40 points]* **I-V characteristics of pn diode** (cont.)

This exercise continues the pn diode characterization problem of homework #1. It utilizes the data for the current-voltage characteristics for a pn diode that you obtained through the MIT Microelectronics WebLab last week. In this exercise, your task is to derive a simple equivalent circuit model for this pn diode. You should study Appendix A at the end of this package.

Do the following:

4a) (*10 points*) Study the ideal model for the I-V characteristics of the pn diode in Appendix A. Devise a simple scheme to extract from the measured data the saturation current, I_s (in A) and the temperature of the diode, T (in K). Illustrate your procedure graphically and give the extracted values. Give a higher weight to estimations of

I_s that come from the ideal looking portion of the forward branch of the I-V characteristics where the accuracy of the model is most important. Compare the temperature that you extract with the temperature of the lab as measured by WebLab. Comment on discrepancies.

4b) (*10 points*) Compare the experimental I-V characteristics with those predicted by the ideal theoretical model by graphing them together. For this, you will need to use MATLAB, a spreadsheet program, or some other mathematical program with graphing capabilities.

Turn in the following graphs:

graph 1: Linear plot of I-V characteristics (V in x axis in linear scale, I in y axis in linear scale). Show experimental data points with symbols and ideal model with continuous line. Print out this graph.

graph 2: Semilogarithmic plot of I-V characteristics (V in x axis in linear scale, I in y axis in logarithmic scale). Show experimental data points with symbols and ideal model with continuous line. Print out this graph.

4c) (*10 points*) A more realistic model for a pn diode includes a parasitic series resistance, as discussed in Appendix A. Using the values of I_s and T derived in the previous section, devise a simple scheme to extract from the measured data the series resistance, R_s (in Ω), of the diode. Illustrate your procedure graphically and give the extracted value.

4d) (*10 points*) Compare the experimental characteristics with those predicted by the theoretical model by graphing them together. Plotting the I-V characteristics of the model that includes series resistance is a bit tricky because I is on both sides of the equation. A good way to do it is to solve for V, then compute V vs. I, and finally plot I vs. V.

Turn in the following graphs:

graph 3: Linear plot of I-V characteristics (V in x axis in linear scale, I in y axis in linear scale). Show experimental data points with symbols and second-order model with continuous line. Print out this graph.

graph 4: Semilogarithmic plot of I-V characteristics (V in x axis in linear scale, I in y axis in logarithmic scale). Show experimental data points with symbols and second-order model with continuous line. Print out this graph.

Turn in these four graphs and comment on how the measured I-V characteristics of the diode compare with those that you studied in 6.002.

The required graphs need not be too fancy, just simply correct and unambigous. They must have proper tickmarks, axis labelling, and correct units.

Appendix A: DC I-V characteristics of pn diode

Ideal model

The ideal I-V characteristics of a pn diode are given by:

$$I = I_s \left(\exp \frac{qV}{kT} - 1 \right)$$

where I_s is the *saturation current*, q is the electron charge (in this expression, $q = 1\ e$,where e stands for electron, and NOT $q = 1.6 \times 10^{-19}\ C$), T is the temperature (in K), and K is Boltzmann constant ($K = 8.62 \times 10^{-5}\ eV/K$).

Second-order model

"Real" diodes suffer from a number of parasitics. One of the most important ones is the presence of parasitic *series resistance*, R_s. This reduces the voltage that is available to the junction from an external one V to an internal one $V - IR_s$. Hence, the DC I-V characteristics of the diode are given by:

$$I = I_s \left[\exp \frac{q(V - IR_s)}{kT} - 1 \right]$$

The I-V characteristics predicted by both models look as in the graphs below.
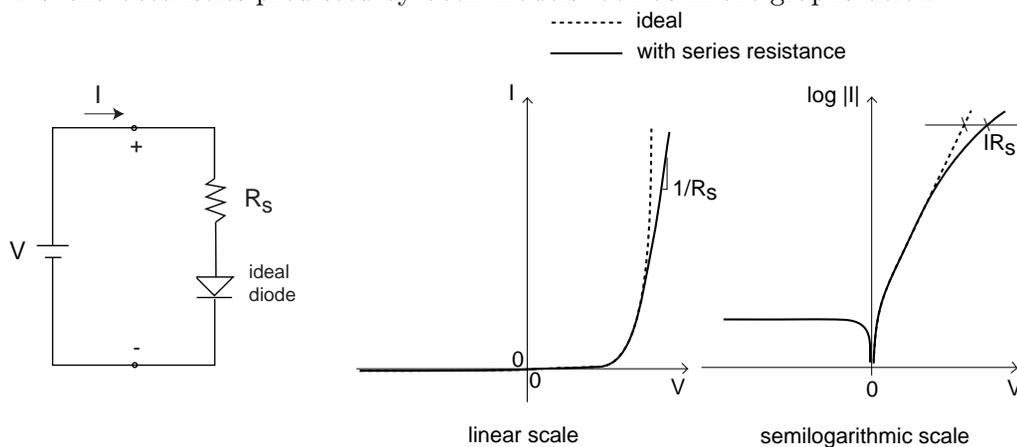

Figure 1: Sketch of I-V characteristics (ideal and with series resistance) of p-n junction in linear and semilogarithmic scales.