## Homework #3 - September 23, 2005

Due: September 30, 2005 at recitation (2 PM latest)
(late homework will not be accepted)

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

1. *[30 points]* In a certain region of an n-type semiconductor in thermal equilibrium at room temperature, there is an electric field distribution in space as sketched below.

for $0 < x < 1~\mu m$:
$E = 600\{1 + \cos[10^4\pi(2x - 10^{-4})]\}~V/cm$ with x in cm

everywhere else:
$E = 0$
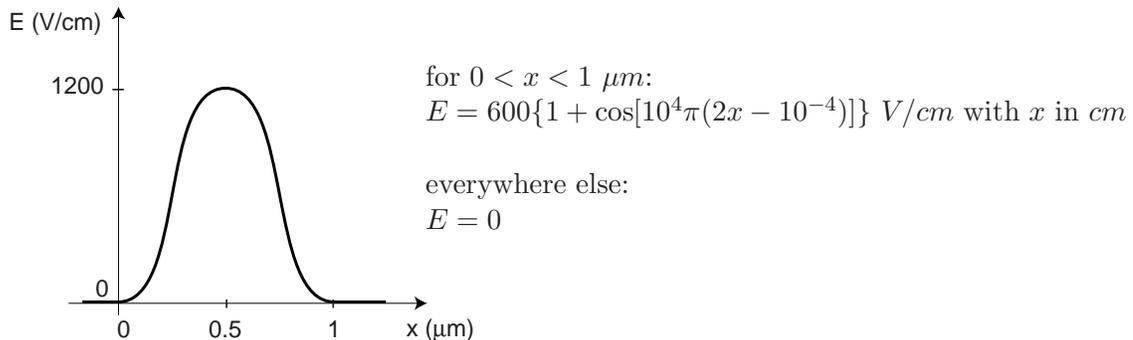
a) *[10 points]* Derive an analytical expression and sketch the electrostatic potential distribution in this region.

b) *[10 points]* Derive an analytical expression and sketch the net volume charge density in this region.

c) *[10 points]* If you are told that the equilibrium electron concentration at $x = 0$ is $n_o = 10^{17}~cm^{-3}$, compute the equilibrium electron concentration at $x = 1~\mu m$?

2. *[20 points]* A device design engineer in a group incharged of developing a very aggressive Si npn bipolar process becomes concerned with the suitability of the company's device simulation tools to do the job. She argues that in an effort to push the frequency response of the transistor, the base might become so thin, that perhaps carriers could cross it without

significant scattering. In this case, a device CAD tool that incorporates "ballistic" transport would be required. The group is considering using a p-type base with a doping level of about 10^{18} cm^{-3}. The tentative base thickness is 50 nm.

Address the engineer's concerns by:

a) *[10 points]* evaluating the mean free path of electrons across the base, and comparing it with the base width;

b) *[10 points]* evaluating the ratio of the transit time for electron diffusion across the base (given by Eq. 7.71 in Howe & Sodini, we will talk about it when we discuss the bipolar transistor) over the electron scattering time in the base.

For this problem, you need the electron "effective mass" in Si, which is $m_n = 1.6 \times 10^{-16}$ $eV \cdot s^2/cm^2$ (such are the units of mass in the strange system of units followed in the semiconductor engineering world!)

3. *[40 points]* Consider an abrupt pn junction with $N_d = 10^{17}$ cm^{-3} and $N_a = 10^{16}$ cm^{-3}, as sketched below.
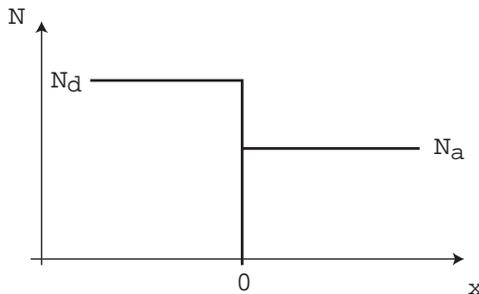
a) *(10 points)* Compute the value of the electrostatic potential at $x = 0$ in thermal equilibrium.

b) *(10 points)* Compute n_o and p_o at $x = 0$ in thermal equilibrium.

c) *(10 points)* Compute the value of x for which $n_o = p_o = n_i$ in thermal equilibrium.

d) *(10 points)* Compute the total amount of charge per unit area on the p side of the junction when a reverse bias voltage of 5 V is applied to the diode.

4. *[10 points]* **I-V characteristics of pn diode** (cont.)

This problem continues the pn diode characterization exercises of homeworks #1 and #2. In this homework you examine to what extent the ideal-looking portion of the forward branch of the current-voltage characteristics of the diode follows the Boltzmann law.

As you know, the ideal I-V characteristics of a pn diode has an equation:

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

Under sufficient forward bias, this equation can be simplified to:

$$I \simeq I_s \exp \frac{qV}{kT}$$

Notice that this equation looks a lot like the Boltzmann relation for electrons derived in lecture:

$$n_o = n_i \exp \frac{q\phi}{kT}$$

In the discussion around the Boltzmann relation in lecture, we derived the "60 mV rule". This states that at 300 K and in thermal equilibrium, every change in the electron concentration in a decade (factor of 10) brings along a change in the electrostatic potential of about 60 mV. In lecture, we showed that, remarkably, the current through a pn diode in the ideal-looking portion of the forward branch behaves in a similar way: every increase of 60 mV brings along an increase in the current of a factor of 10x (provided that the diode sits at around 300 K). This is a direct manifestation of Boltzmann law right out of your instrument! This simple exercise is about demonstrating experimentally that this is indeed the case in a more rigorous way than it was done in class.

What you have to do is to measure the I-V characteristics of the pn diode, or recycle the data that you acquired for homework #1, and compute the slope (it should perhaps be called "inverse slope" but it is usually referred to simply as the slope) of the ideal forward branch in units of V/dec ("volts per decade of current"). You can do this in two ways:

- One way is to work with the downloaded data and write a piece of code in MATLAB, EXCEL, or your favorite mathematical program and derive this slope point by point for all points of the forward branch of the pn diode.

- Another way (faster!) is to take advantage of the *user defined functions* of the Microelectronics WebLab and have the instrument do the computation for you. You can then graph the results in the right-hand y axis of the WebLab canvas and simply print out this graph.

In either case, you have to come up with a simple mathematical algorithm to obtain this slope.

You have to turn in:

- A description of the mathematical algorithm that allows you to obtain the slope of the forward branch of the diode in units of V/dec.

- A graph showing the slope of the forward branch of the pn diode currently placed in WebLab as a function of V. In the same graph or in a separate graph, plot the semilog I-V characteristics of the diode.

- A brief discussion of the range of V for which a Boltzmann-like behavior is observed in the diode.

If you decide to have WebLab do the computation of the slope for you, you should read about the *user defined functions* in Section 1.6 and Appendix A of the WebLab manual (accessible from the Applet launch page in http://ilab.mit.edu).