Homework 2

ECE 4339

Han Q. Le (copyrighted) U. of Houston

Total is 145 pts. You have to do ONLY 100 pts, but can do more for extra credit.

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1. (15 pts) Drude's model of conductivity

1.1 (3 pts) Current density

Use App "Drude model of electron transport 1" in lecture:
- Select 2 random values (non-vanishing) of carrier density, keep a fixed (non-zero) random value of velocity, use a ruler to measure current (red bar) as a function of carrier density. Plot the two variables along with point zero and infer a relationship. (You should have 3 points including the origin).
- Keep a fixed (non-zero) random value of carrier density, select 2 non-zero random values of velocity, plot the current as a function of velocity (including point zero) and infer a relationship.
- What can you conclude about current density as a function of carrier density and velocity.

1.2 (3 pts) Drift velocity and mobility

We know that applying an E field makes electrons move (drift) in one direction and not randomly in all directions. But what determines their drift velocity? Here, Use App "Concept of mobility" in lecture:
- Select 2 random values (non-vanishing) of E field, keep a fixed (non-zero) random value of mobility, based on your measured current (red bar), can you plot drift velocity and infer a relationship vs. E field.
- Keep a fixed (non-zero) random value of E field, select 2 non-zero random values of mobility, plot the drift velocity as a function of mobility and infer a relationship.

In fact, we **define** mobility to be the coefficient that relates drift velocity to E field (see lecture).

1.3 (6 pts) Conductivity and mobility of metals

Fill the two right most columns of the table below by calculating the carrier density (conduction electron density) and mobility for the metals in the table (see more if interested: **http://www.ptable.com/**)

Element	Conducting electrons	Atomic W	Density (g / cm^3)	Conductivity (/ Ohm cm)	Cond elec density	μ
Au	1	196.966569	19.30	4.51671×10^5	□	□
Cu	1	63.546	8.94	5.959×10^5	□	□
Al	3	26.9815386	2.70	3.546×10^5	□	□
Ni	1	58.6934	8.908	1.443×10^5	□	□

Hint

Conduction electron density n_C can be calculated as follow:

$$n_C = \text{Conducting electrons per atom} * \text{atoms per unit volume}$$

For atoms per unit volume, called it N:

$$N = \text{AvogadroConstant} * \frac{\text{Density}}{\text{Atomic weight}}$$

AvogadroConstant= $6.02214179 \times 10^{23}$

Hence: $$n_C = p\,\text{AvogadroConstant} * \frac{\text{Density}}{\text{Atomic weight}}$$

where p is the number of conducting electrons on the outer shell.
You can use any software to calculate, from *Mathematica* to Excel for example.

1.4 Question 2 (3 pts):

Let's say we have a copper wire 2 meter long (about 6 ft), and we plug it in the outlet. Starting from 120 Volt and assume the other end is at zero volt (treat the whole thing as DC for a very brief moment in time), how long does it take for electrons to flow from one end to the other?

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2. (40 pts) Mobility review.

Mobility is one of the most important properties affecting the conductivity of semiconductor. Below are study questions reviewing mobility. <u>You are encouraged to think and discuss, not just looking for "the right answer"</u>

2.1 Question 1 (4 pts)

Look up the electron and hole mobility at room temperature (300 K) in high purity samples of the following semiconductors: Si, Ge, GaAs, InAs, and InP - along with its effective mass (make a table similarly with the one above). For hole, use the heavy hole mass. You can use data from this web site: http://www.ioffe.ru/SVA/NS-M/Semicond/
(Note: the quoted basic parameters are for 300 K and high purity sample). Make a table (see problem 1).

2.2 Question 2 (10 pts)

Plot the carrier effective mass vs. their mobility on a log log plot for n-type and p-type. Use the heavy hole mass for p-type. Write what you observe. (<u>This is to encourage you to do thinking for yourself</u>. Think like a scientist, if you see this data, what would you think?)

2.3 Question 3 (10 pts)

As an electron (or hole) moves, collision with other particles affects its speed, and hence mobility. The more frequent the collision is, the slower the carrier moves, and hence the lower is its mobility. The collision is called "scattering", which includes carrier-carrier scattering, carrier-phonon scattering, and carrier-impurity (including dopant) scattering. Based on the result in 2.1 and 2.2, make a table of the ratio m_e^* / m_h^* for each semiconductor, and compare with μ_e / μ_h. What would you say about the electron and hole scattering in each semiconductors? (Do you think they have the same relaxation time?)

2.4 Question 4 (3 pts)

As temperature is increased, the lattice vibrates stronger, or, another way to say this quantum mechanically, is that there are more phonons. Do you think the mobility (of both carriers) increases or decreases vs temperature? why?

2.5 Question 5 (10 pts)

Below are empirical temperature dependence of mobilities. (There are theories, but in practice, people just use empirical relations). Plot the mobilities of electron and hole for high-purity Si and GaAs from 250 K to 450 K according to the model below. See also reference at the end of the problem if needed.

© Bart Van Zeghbroeck 2007	Germanium	Silicon	Gallium Arsenide
Electron mobility	$\propto T^{-1.7}$	$\propto T^{-2.4}$	$\propto T^{-1.0}$
Hole mobility	$\propto T^{-2.3}$	$\propto T^{-2.2}$	$\propto T^{-2.1}$

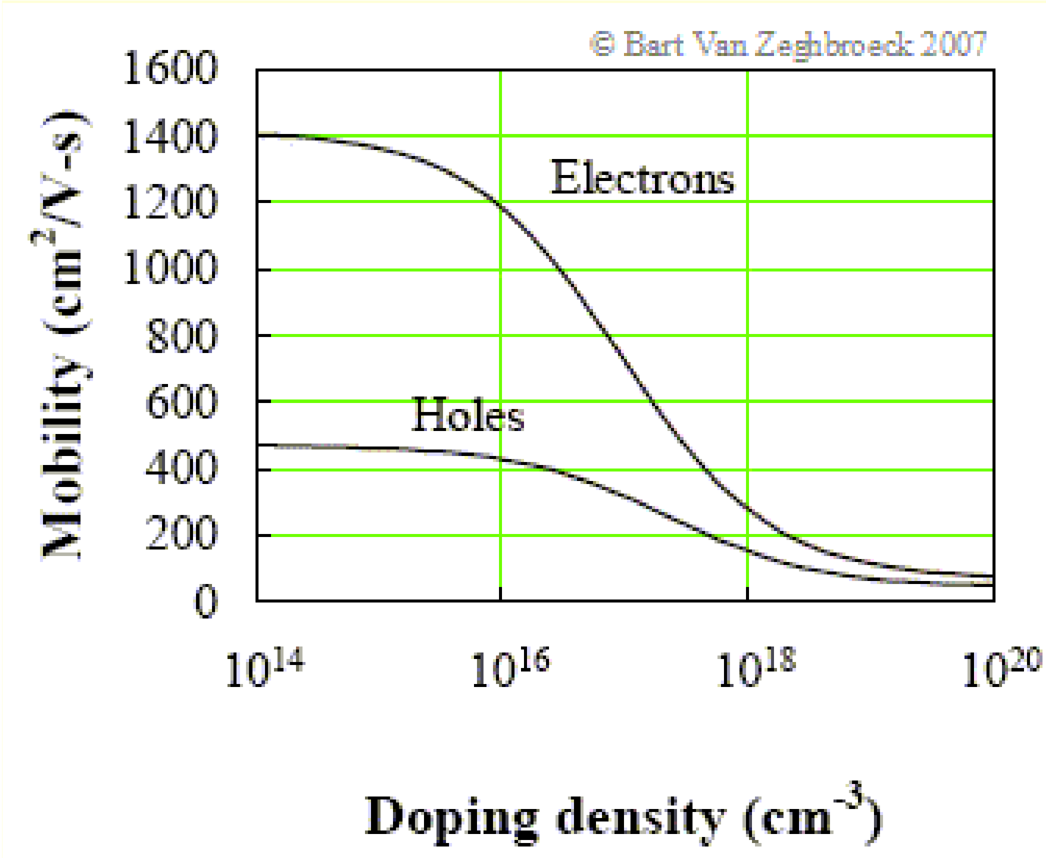
Source: http://ecee.colorado.edu/~bart/book/book/chapter2/ch2_7.htm

2.6 Question 6 (3 pts)

As you dope a semiconductor with more impurities (donors or acceptors), do you think the mobility increases or decreases vs doping concentration? why?

For reference

You may want to read the following information for the question above:
Below are empirical mobilities in Si vs. doping densities (In reality, different types of dopants affect the mobility differently, but for this chart, we just ignore their difference). Download the excel file from the given website: http://ecee.colorado.edu/~bart/book/book/chapter2/xls/fig2_7_3.xls for your own use.



source: http://ecee.colorado.edu/~bart/book/book/chapter2/ch2_7.htm
http://ecee.colorado.edu/~bart/book/book/chapter2/xls/fig2_7_3.xls

3. (15 pts) Basic concept questions about electron distribution

All the Apps referred to in this problem are in Chapter 3 (part 2)

3.1 (3 pts) Refer to App: Electron-Hole Thermal Excitation

As you raise temperature T, there are more and more electrons (red) and holes (the voids of electrons, in blue). If you plot the number of electrons or holes vs T, what do you expect the relationship is approximately? (just write an expression without any numerical value).

3.2 (3 pts) Refer to App: Fermi-Dirac Distribution

At temperature 420 K, what is the probability for a state with energy 0.15 eV above the Fermi level to be occupied?

3.3 (3 pts) Refer to App: 3D Density-of-state of isotropic parabolic bands

Look up data from the website: http://www.ioffe.ru/SVA/NSM/Semicond/ for InP. Obtain a plot (copy and paste) for the density of state functions of electrons and holes. Use the value of electron and hole effecties for DoS calculation. (Which is not the same as actual effective mass for kinetic energy). (Explanation given in lecture).

3.4 (3 pts) Refer to App: Electron Distribution in Conduction Band

Look up data from the website: http://www.ioffe.ru/SVA/NSM/Semicond/ for InAs. (Explanation given in lecture).
- Obtain plots (copy and paste) for electron energy distribution in the conduction band at 375 K and Fermi level at 0.05 eV.
- What is the total population of electrons in conduction band?
- What is the number of electrons between 0.5 and 0.6 eV and how much is its percentage relative to the total population of electrons.

3.5 (3 pts) Refer to 3.4 above

What is the population of electrons between 0.5 and 0.6 eV, and how much is its percentage relative to the total population of electrons. (Use exponential approximation for integration).

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4. (15 pts) Basic concept questions about hole distribution

4.1 (5 pts) Refer to App: Electron Distribution in Valence Band

We have a piece of Si in winter in Bismarck, N Dakota; the temperature is -40 F. The Fermi energy level was -0.01 eV relative to the top of the valence band. Obtain plots of electron distribution in valence band. What is the density of electrons at -0.05 eV relative to the valence band?

4.2 (5 pts) Refer to App: Electron-Void/Hole Distribution in Valence Band

For the same condition as in 4.1, what is the density of holes at -0.05 and -0.1 eV relative to the valence band? What is the total population of holes?

4.3 (5 pts) Use any App appropriate.

The same piece of Si is brought to Houston and left in a car in the middle of summer. The temperature reaches 120 F. The hole population is the same (because the doping is fixed), what is the Fermi level? and what is the hole density at -0.1 eV relative to the valence band? Expain in plain English why this hole density at -0.1 eV in this case (summer in Houston) is different from that of the case in 4.2 (winter in Bismarck) above?

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5. (30 pts) Si optical sensor (use any App appropriate.)

Suppose we want to use intrinsic Si as an optical sensor. Suppose we have a light signal that generate $10^{10} / \text{cm}^3$ electrons and same for holes at steady state. Assume that we apply 1 V across a gap of 100 μm.

5.1 (10 pts) Current density

Calculate the current density due to light signal at Bismarck winter temperature in question 4.1 above and compare with the current density if the light signal is turned off (the latter is known as dark current). (Use mobility in problem 2 or look up, but must state where your mobiliy values comes from, and make sure at the right temperature).

5.2 (10 pts) Current density at higher temperature

The same sensor is now used in summer in Houston at the temperature as in 4.3. Assume the same light level signal. Calculate the current density due to light signal and compare with the dark current density. (Make sure you use mobility with correct temperature).

5.3 (10 pts) Discussion

Do you think the sensor works equally well in both cases, Bismarck winter and Houston summer? why and why not, must discuss for credit.

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6. (30 pts) Studies of various semiconductors

Refer to App: Carrier concentration and distribution at thermal equilibrium

Choose one semiconductor other than Si from the list of the App.
Choose a doping density exponent with 4 digits between 17 and 19. Example: 18.26, the density is $10^{18.26}$

$\mathbf{10^{18.26}}$

1.8197×10^{18}

Choose a temperature with 3 significant digit between 301 and 399 K. Example: 331.

6.1 (5 pts) Carrier densities

What is the electron and hole densities for the condition above for:
a- n-doped
b- p-doped

6.2 (5 pts) Fermi level

What is the Fermi level relative to the corresponding band for each doping case in 6.1? (either conduction or valence band, depending on dope type). Are they symmetric for the 2 doping cases? why or why not?

6.3 (5 pts) Undoped material

For the same material, at the same temperature but it is now undoped. What are the electron and hole densities (intrinsic carrier density) and verify any relationship between intrinsic carrier density here and the e and h densities obtained in 6.1

6.4 (5 pts) Band gap and Fermi level

What are the band gap and the intrinsic Fermi level in 6.3?

6.5 (5 pts) Band gap and Fermi level at lower temperature

Decrease the temperature by a value between 100 to 150 K. (example: decrease by 110 K. The final temperature is: 331-110=221 K).
What are the band gap and carrier density? Use a simple formula to calculate and account for the ratio between the two intrinsic carrier densities of the two different temperatures (in 6.5 and in 6.3).

6.7 (5 pts) Band diagram

Consider now we have a piece of the semiconductor that is n-doped as in 6.1, and another that is p-doped with the same density. If we put the two of them together and let electrons, holes flow freely between them, the Fermi levels for both will be equalized to the same level. Draw a band gap diagram like Secion 9 in lecture (but ignore the band transition near the contact area).