ECE 3040B Microelectronic Circuits

Exam 1

September 20, 2001

Dr. W. Alan Doolittle

Print your name clearly and largely: Solutions

Instructions:
Read all the problems carefully and thoroughly before you begin working. You are allowed to use 1 new sheet of notes (1 page front and back) as well as a calculator. There are 100 total points in this exam plus 5 point bonus. Observe the point value of each problem and allocate your time accordingly. SHOW ALL WORK AND CIRCLE YOUR FINAL ANSWER WITH THE PROPER UNITS INDICATED. Write legibly. If I cannot read it, it will be considered a wrong answer. Do all work on the paper provided. Turn in all scratch paper, even if it did not lead to an answer. Report any and all ethics violations to the instructor. Good luck!

Sign your name on ONE of the two following cases:

I DID NOT observe any ethical violations during this exam:

I observed an ethical violation during this exam:
First 25% Multiple Choice and True/False (Circle the letter of the most correct answer)

1.) (2-points) True or False: Drift current results from movement of electrons and holes in response to an applied electric field.

2.) (2-points) True or False: The unit of kT is energy and can be expressed in electron volt (eV) or joules (J).

3.) (2-points) True or False: If Magnesium (Mg is group 2 element) is used to dope GaN (Ga is group 3, N is group 5), a p-type semiconductor will result if the Mg replaces a Ga atom.

4.) (2-points) True or False: A n-type Silicon semiconductor has more electrons than holes AND has more holes than an intrinsic silicon semiconductor.

5.) (2-points) True or False: Silicon is a compound semiconductor.

Select the best answer for 6-10:

6.) (3-points) Given Si, C and Ge are all from group 4, which of the following semiconductors is a valid semiconductor representation of a ternary compound semiconductor?
   a.) Si
   b.) Ge_{0.5}C_{0.5}
   c.) Si_{0.25}Ge_{0.35}C_{0.40}
   d.) Si_{0.5}Ge_{1.5}C_{1.0}

7.) (3-points) The valence band…
   a.) …is mostly filled with electrons.
   b.) …is mostly empty.
   c.) …is higher in energy than the conduction band.
   d.) …is above the fermi energy in a degenerately doped semiconductor.

8.) (3-points) The following energy band diagram indicates the material is:
   a.) p-type $E_c$
   b.) n-type $E_v$
   c.) intrinsic $E_f$
   d.) Silicon $E_f$

9.) (3-points) For the following band diagram, what is known from the information given:
   a.) The device is bent.
   b.) There is no electric field in this material
   c.) There is no current flow in this device.
   d.) There is no diffusion current in this material.

10.) (3-points) In equilibrium:
   a.) The drift current is equal in magnitude and in the same direction as the diffusion current.
   b.) The drift current is equal in magnitude and opposite in direction as the diffusion current.
   c.) There is always no drift current.
   d.) There is always no diffusion current.
   e.) I hear Wal-Mart™ is hiring sales clerks – that could be my new career.
11.) (5-points) Assuming total ionization, what is the electron and hole concentrations and is the material p or n-type?

\[ n = \frac{n_i^2}{p} = \frac{(1.16)^2}{1.54 \times 10^{16}} \Rightarrow n = 6.46 \times 10^{15} \text{ cm}^{-3} \]

\[ \rho = \frac{N_A - N_D}{2} + \sqrt{\left( \frac{N_A - N_D}{2} \right)^2 + n_i^2} \]

\[ = \frac{2 \times 10^{16} - 1.1 \times 10^{16}}{2} + \sqrt{\left( \frac{2 \times 10^{16} - 1.1 \times 10^{16}}{2} \right)^2 + 1 \times 10^6} \]

\[ \rho = 1.54 \times 10^{16} \text{ cm}^{-3} \rightarrow \rho > n \Rightarrow \text{p-type} \]

12.) (5-points) What is \( E_F - E_v \) (where \( E_F \) is the fermi energy and \( E_v \) is the top of the valence band)?

\[ \rho = N_V e^{(E_v - E_F)/kT} \]

\[ E_v - E_F = kT \ln \left( \frac{N_p}{N_V} \right) \]

\[ = 0.0259 \ln \left( \frac{1.54 \times 10^{16}}{2 \times 10^{19}} \right) \]

\[ = -0.185 \text{ eV} \]

\[ E_F - E_v = 0.185 \text{ eV} \]

13.) (5-points) What length of material is needed to make a resistor with resistance 1000 ohms using a cylinder with cross-sectional area 0.0001 cm²?

\[ R = \frac{\rho L}{A} \]

\[ 1000 = \frac{0.76 \Omega \cdot \text{cm}}{0.0001 \text{ cm}^2} \]

\[ L = 0.132 \text{ cm} \]

or 1320 \( \mu \text{m} \)
14.) (5-points) If 10,000 Volts is placed across the resistor in part 13, what are the electron current density, hole current density and the electron drift velocity? (If you found no answer in part 13, then use a resistor length of 1 cm in your calculation).

**Note:** No diffusion!

\[ J_n = q \left( \frac{u_n E}{v_d} \right) \]
\[ J_p = q \left( \frac{u_p E}{v_d} \right) \]

\[ N_d^\text{electrons} = \frac{(800 \text{ cm}^2/\text{Vsec})(75.757 \text{ V/cm})}{6.06 \times 10^4 \text{ cm/sec}} \]

\[ E = \frac{10,100 \text{ V}}{0.132 \text{ cm}} = 75.757 \text{ V/cm} \]

\[ J_n = (1.6 \times 10^{-19})(800)(75.757)(6.46 \times 10^5) \]
\[ J_n = 62,614 \text{ A/cm}^2 \]

\[ J_p = (1.6 \times 10^{-19})(200)(75.757)(1.54 \times 10^6) \]
\[ J_p = 37,336 \text{ A/cm}^2 \]

15.) (5-points) A semiconductor is doped with 5e19 cm\(^{-3}\) very deep acceptors (large binding energy) which are only partially ionized at room temperature. If the fermi energy is 0.1eV above the valence band, and the acceptor energy \( E_A \) is 0.16 eV above the valence band, what is the number of ionized acceptors in this material? You can assume the degeneracy factor, \( g_A = 4 \). Hint: do not make this problem harder than it is.

\[ N_A^- = \frac{N_A}{1 + g_A e^{(E_A - E_F)/kT}} \]

\[ = \frac{5 \times 10^{19}}{1 + 4 e^{(0.16 - 0.1)/0.0259}} \]

\[ N_A^- = 1.2 \times 10^{18} \text{ cm}^{-3} \]
Third 25% Problems (3rd 25%)

16. (25-points total)
A semiconductor has the following parameters:
- Hole Diffusion coefficient, $D_p = 3 \text{ cm}^2/\text{Sec}$
- Hole Mobility, $\mu_p = 200 \text{ cm}^2/\text{VSec}$
- Substrate relative Dielectric Constant, $\varepsilon_{\text{r, semiconductor}} = K_0 = 11.7$
- Dielectric Constant of free space, $\varepsilon_0 = 8.854 \times 10^{-14} \text{ F/cm}$
- Substrate intrinsic concentration, $n_i = 1 \times 10^{10} \text{ cm}^{-3}$

The hole concentration in NON-EQUILIBRIUM in the material is maintained at

$$p(x) = 1 \times 10^{15} e^{(x/100 \text{ um})} \text{ cm}^{-3} \quad \text{for} \quad x = 0 \text{ to } x = 100 \text{ um}$$

a.) (20 points) Plot and label (label the maximum and minimum values) the hole current density if an electric field of $1 \text{ MV/cm}$ is applied across the material.

b.) (5 points) Explain why we cannot determine the electron concentration as a function of position.

\[ J_p = q \mu_p p \frac{dE}{dx} - q \frac{\partial p}{\partial x} \]

\[ = (1.6 \times 10^{-19}) (200) (10) \left[ 1 \times 10^{15} e^{x/0.01 \text{ cm}} \right] -
\]

\[ (1.6 \times 10^{-19}) (5.18) \left[ \frac{1 \times 10^{15}}{0.01} e^{x/0.01 \text{ cm}} \right] \]

\[ = \left[ 0.32 - 0.0828 \right] e^{x/0.01 \text{ cm}} \]

\[ = 0.237 e^{x/0.01 \text{ cm}} \text{ A/cm}^2 \]

b) In non-equilibrium, $np \neq n_i^2$
Pulling all the concepts together for a useful purpose: (4th 25%)

17.) (25-points)
Light is absorbed in a silicon wafer of thickness 500 μm (the wafer is similar to that passed around in class). The wafer is p-type and is uniformly doped with \(10^{17}\) cm\(^{-3}\) acceptors. The light has been on for a very long time and can be approximated as being absorbed uniformly throughout the material. If the excess HOLE generation rate is \(10^{17}\) cm\(^{-3}\)/sec and the minority carrier lifetime is 1 milliseconds (1e-3 seconds); \( \mu_n = 1000\) cm\(^2\)/Vsec

- a.) (4 points) Should the absorption coefficient be large or small for such a condition to occur?
- b.) (5 points) What is the excess electron concentration for all positions in the wafer.
- c.) (16 points) What would be the electron concentration as a function of time for all times after the light is turned off?

**Bonus:** (5 points-no partial credit on this bonus) Determine what electron current density flows in the material. Support your answer thoroughly for credit.

Given: \(0 = D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n}\) General Solution is: \(\Delta n_p(x) = Ae^{-\frac{x}{\tau_n}} + Be^{\frac{x}{\tau_n}}\)

Given: \(0 = D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_L\) General Solution is: \(\Delta n_p(x) = Ae^{-\frac{x}{\tau_n}} + Be^{\frac{x}{\tau_n}} + G_L x\)

Given: \(0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_L\) General Solution is: \(\Delta n_p(x) = A x^2 + Bx + C\)

Given: \(\frac{d\Delta n_p}{dt} = -\frac{\Delta n_p}{\tau_n}\) General Solution is: \(\Delta n_p(t) = \Delta n_p(t = 0) e^{-\frac{t}{\tau_n}}\)

Given: \(0 = -\frac{\Delta n_p}{\tau_n} + G_L\) General Solution is: \(\Delta n_p = G_L \tau_n\)

*Almost Identical to the problem done in class!*

a.) \(I = I_0 e^{-\frac{d}{\alpha}} \rightarrow \alpha\) must be small for weak absorption \(G(x) = G_0 e^{-\alpha x}\) \(G(x) = G_0 e^{-\alpha x}\)

b.) \(\frac{d\Delta n_p}{dx} = \Delta n_0 \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + 6L\)

\(\Delta n_0 = G_L \tau_n\)

\(\Delta n_p = 10^{17} (\text{cm}^{-3})(1\text{e-3 sec})\)

\(\Delta n_p = 10^{14}\) cm\(^{-3}\)

C.) See next page
Extra work can be done here, but clearly indicate with problem you are solving.

\( \frac{3}{2n} \frac{\Delta n}{dx} = 0 \Rightarrow \frac{\Delta n}{dx} = \frac{\Delta n}{2n} + C \)

General Solution:

\[ \Delta n(x) = \Delta n(x=0) e^{-x/cn} \]

equal to value just before the light was turned off

\[ \Rightarrow \Delta n(x) = 10^{14} e^{-x/(1 \text{e-3})} \text{cm}^{-3} \]

**Bonus**: Uniformly doped \( \Rightarrow \) No Electric Field

\[ J_n = q \frac{dn}{dx} \text{ uniform doping} \]

\[ = q \frac{dn}{dx} (n_0 + \Delta n) \]

\[ \Rightarrow J_n = q \frac{dn}{dx} (0) \]

\[ J_n = 0 \text{ A/cm}^2 \]