ECE 3040 Microelectronic Circuits

Exam 1

February 20, 2008

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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. 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 33%* Multiple Choice and True/False**
(Circle the letter of the most correct *answer or answers*)

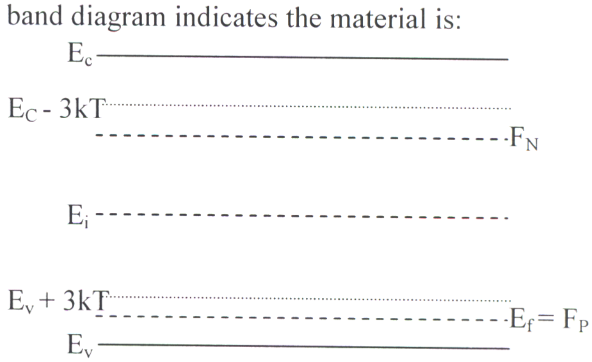
Only This part is False

1.) (3-points) True or False: Various energy bandgaps can be produced in research laboratories using either MOCVD or MBE tools but these tools are not suited for large scale manufacturing due to their low growth rates resulting from the atom by atom layering they implement .
2.) (3-points) True or False: The bandgap results from the splitting of energy levels, typically the s and p sub-orbitals of atoms.
3.) (3-points) True or False: The term (1-f(E)), where f(E) is the fermi distribution function, describes the probability that a state at energy E is occupied.
4.) (3-points) True or False: Since both energy and momentum must be conserved when electron-hole recombination happens, indirect semiconductors require a phonon (lattice vibration) to allow the transition to occur.
5.) (3-points) True or False: Strong atomic bonds lead to large energy bandgaps.
6.) (3-points) True or False: The density of states predicts that at energies equal to the bandgap energy (E=Eg), the there is no available state for electrons to occupy.
7.) (3-points) True or False: Impact ionization occurs under very high electric fields when electrons slam into atoms and knock free another electron.

Select the **best** answer or answer**s** for 6-10:
8.) (4-points) The minority carrier diffusion equation ...
   a.) ... can predict drift currents .
   b.) ... cannot be used when drift current is present
   c.) ... can determine the majority carrier concentrations if one also uses the law of the junction to relate n to p.
   d.) ... is a simplification of the current continuity equation.
   e.) ... is something I really do not understand and thus I might not pass this exam!

9.) (4-points) The valence electrons ...?
   a.) Disappear when the crystal is formed.
   b.) Participate in bonding the crystal's atoms together.
   c.) Can be captured by an acceptor thus creating a free hole.
   d.) Cannot be promoted into the conduction band unless they are in a direct bandgap material.

10.)(4-points) The following energy band diagram indicates the material is:
   a.) Degenerate and n-type
   b.) In equilibrium
   c.) Non-degenerate n-type
   d.) Degenerate and p-type
   e.) In low level injection
   f.) Non-degenerate p-type
   g.) In steady state



Second 17% Short Answer ("Plug and Chug"):
For the following problems (11-12) use the following material parameters and <u>assuming total ionization</u>:

n_i=1e-14 cm^{-3} (not a mistake) N_A=1e16 cm^{-3} acceptors $m_p^*=0.8m_o$ $m_n^*=0.1m_o$
E_G=3.4 eV Electron mobility, μ_n = 1200 cm^2/Vsec Hole mobility , μ_p = 50 cm^2/Vsec
Temperature= 27 degrees C

11.) (10-points) Where is the fermi energy (relative to the valence band which is referenced to zero energy)? ~~Note you may need to find E_i first.~~

$$E_i = \frac{E_G}{2} + \frac{3kT}{4}\ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$= \frac{3.4}{2} + 0.04\,eV$$

$$E_i = 1.74\,eV$$

$$E_f - E_i = -kT\ln\left(\frac{N_A}{n_i}\right)$$

$$= -1.789\,eV$$

$$\boxed{E_f = -0.049\,eV}$$

Note: In reality this would imply the material is degenerate making us normally solve problem with $n = F_{1/2}(\eta)$....

12.) (7-points) What is the resistivity of the semiconductor?

$$\rho = \frac{1}{q(\mu_n n_o + \mu_p p_o)}$$

$$n_o = \frac{n_i^2}{p_o} \cong \frac{n_i^2}{N_A} = 1e\text{-}44\,cm^{-3}$$

$$= \frac{1}{1.6\times10^{-19}(1200\times 1e\text{-}44 + 50(1e16))}$$

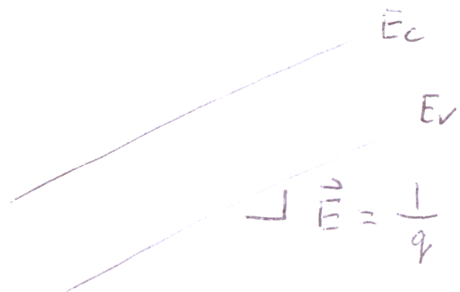
$$\boxed{\rho = 12.5\ \Omega\text{-}cm}$$

13.) (20-points total) A 0.2mm x 6 um x 1cm semiconductor resistor is made from the semiconductor from problems 11 and 12. It is biased on two opposing sides (longest dimension) with 120 volts.

a) (3 points) What type (diffusion, drift, electron dominated, hole dominated, etc...) of current results?

Hole dominated, Drift current

b) (7 points) Draw the 1 dimensional energy band diagram in the direction of the electric field indicating the actual slope of the bands (numeric answer).



$$\vec{E} = \frac{1}{q}\frac{dE_v}{dx} = \frac{120V}{1cm}$$

slope $\Rightarrow 120\ eV/cm$

(or $q\,120$ J/cm)

c) (10 – points) Determine <u>both</u> the electron and hole <u>current density</u> and <u>currents</u> flowing in the device.

Area = $A = (0.02 \times 6\times10^{-4})$ =

σ_p

$$J_p = \frac{\vec{E}}{\rho_p} = \vec{E}(q\mu_p p_o) = 9.6\ A/cm^2$$

$$I_p = A J_p = (0.02 \times 6\times10^{-4}) J_p = 115.2\ \mu A$$

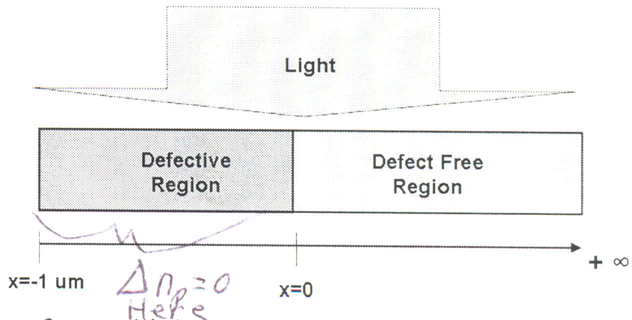
$$J_n = E\sigma_n = \vec{E}(q\mu_n n_o) = 2.3\times10^{-58}\ A/cm^2 \approx 0$$

$$I_n = A J_n = 2.76\times10^{-63} A \approx 0$$

Setup: 9
Solution: 15
J_n: 6

Pulling all the concepts together for a useful purpose:

14.) (30-points)



An infinite length of GaN semiconductor is grown in a Clemson University epitaxy reactor. In the middle of the growth, the Clemson student drops his gold wedding ring in the growth system creating midgap impurities, enhancing Shockley - Read - Hall recombination, resulting in a region of very high recombination. In this defective region, the minority carrier lifetime is 0.0 seconds indicating zero excess minority carriers in this region. Next to this defective region is a region of very high minority carrier lifetime, 10 nanoseconds. The sun has been shining uniformly on the entire semiconductor (including x=infinity) for more than 10 seconds and is uniformly absorbed, generating 1e17 extra electron-hole pairs per cm^3 per second in the defect free region. If the semiconductor is held at room temperature (27 degrees C), determine the minority carrier diffusion current density at all positions in the semiconductor. Assume a minority carrier mobility of 4.0 cm^2/Vsec.

$\tau_n = 10\,ns$

$G_L = 10^{17}\ cm^{-3}/s$

Note: Since 10sec >>> 10ns, $\frac{\partial \Delta n_p}{\partial t} = 0$

$u_n = 4\,cm^2/Vsec$

$D_n = \mu_n \frac{kT}{q} = 0.1036\,cm^2/sec$

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

Main Problem → Given: $\boxed{0 = D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_L \quad \text{General Solution is: } \Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n} + G_L \tau_n}$

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

$L_n = \sqrt{D_n \tau_n}$
$= 3.2 \times 10^{-5}\,cm$
or 0.32 um

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

Given: $0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_{LO} f(x)$ General Solution is: $\Delta n_p(x) = \left[-\frac{G_{LO}}{D_N} \iint f(x) dx \right] + Bx + C$

B.C. @ x = ∞

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

Given: $\boxed{0 = -\frac{\Delta n_p}{\tau_n} + G_L \quad \text{General Solution is: } \Delta n_p = G_L \tau_n}$ = 0 for defective region

BC:

At x = 0 $\Delta n_p = 0$

At x = ∞ Minority Carrier Diffusion equation must be solved

$0 = -\frac{\Delta n_p}{\tau_n} + G_L \Rightarrow \Delta n_p = G_L \tau_n$

$= 10^{17}(10 \times 10^{-9})$

$= 10^{9}\ cm^{-3}$

Use this page for additional work.

$$\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n} + G_L \tau_n$$

Apply B.C.

Since @ $x=0$ $\Delta n_p(x) = 0$

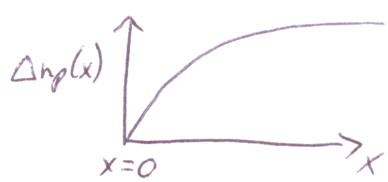
$$\Delta n_p(x) = 0 = A + B + G_L \tau_n$$

Since @ $x = \infty$ $\Delta n_p(x) = G_L \tau_n$, $B \Rightarrow 0$ for $\Delta n_p(x)$ to be finite.

Together $\Rightarrow$ $A = -G_L \tau_n$

$$\therefore \Delta n_p(x) = G_L \tau_n \left(1 - e^{-x/L_n}\right)$$

$$\Delta n_p(x) = 1 \times 10^{9} \left(1 - e^{-x/0.32\,\mu m}\right) \text{ cm}^{-3}$$



$$J_n(x) = \begin{cases} 0 & \text{for } x \leq 0 \\ q D_n \frac{dn}{dx} & \text{for } x > 0 \end{cases}$$

$$n = n_0 + \Delta n \;\Downarrow\; \frac{dn}{dx} = \frac{d\Delta n}{dx}$$

$$\Rightarrow J_n(x) = \begin{cases} 0 & \text{for } x \leq 0 \\ \frac{q D_n G_L \tau}{L_n} e^{-x/L_n} \text{ A/cm}^2 \end{cases}$$

$$\boxed{J_n(x) = \begin{cases} 0 & \text{for } x \leq 0 \\ (518 \text{ nA/cm}^2) e^{-x/0.32\,\mu m} & \text{for } x > 0 \end{cases}}$$