ECE 3040 Microelectronic Circuits

Exam 1

February 19, 2007

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Print your name clearly and largely: Solutions ~32 minutes

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: ______________________

2 minutes

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

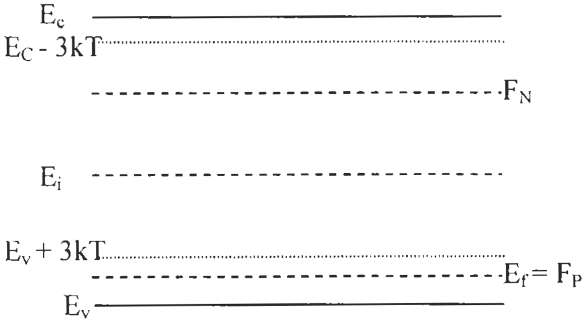
1.) (3-points) True or [✓ False]: MBE is an epitaxy technique performed at very high pressures above atmospheric pressure.
2.) (3-points) True or [✓ False]: If a semiconductor has a large inter-atomic spacing it will likely have a large bandgap.
3.) (3-points) True or [✓ False]: The density of states describes the probability that a particular state at energy, E, is occupied.
4.) (3-points) [✓ True] or False: An indirect bandgap material (such as Germanium and Silicon) results in a longer minority carrier lifetime than a direct bandgap material.
5.) (3-points) [✓ True] or False: For direct bandgap materials there is no difference in momentum between electrons and holes.
6.) (3-points) True or [✓ False]: The probability of occupying a state located at the fermi-energy is always 1.
7.) (3-points) True or [✓ False]: Auger recombination occurs when an electron is captured by a defect inside the bandgap then drops to the valence band killing off a hole.

Select the **best** answer or answer**s** for 6-10:

8.) (4-points) The law of mass action...
- [✓ a.)] ... describes the balance between electrons and holes.
- [✓ b.)] ... indicates that an increase of electron concentration beyond the intrinsic concentration results in a decrease in the hole concentration
- [✓ c.)] ... indicates that at constant temperature the product of electrons and holes is constant
- [✓ d.)] ... only applies to non-degenerate doping conditions.
- e.) Who knows!!!!

9.) (4-points) The electrons in the conduction band ...?
- a.) Are immobile
- b.) Are most often found exactly at the lowest energy, at the conduction band edge
- [✓ c.)] Can be heavier than the free space (vacuum) electron mass
- [✓ d.)] Can be lighter than the free space (vacuum) electron mass
- e.) Are always lighter than the free space (vacuum) electron mass due to their interaction with the atoms in the crystal

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



6 minutes

Second ~~*27*~~ *12%* Short Answer ("Plug and Chug"):

For the following problems (11-12) use the following material parameters:

Assume Total ionization;

n_i=1e6 cm^{-3} N$_A$=1e18 cm^{-3} acceptors $m_p^*=0.5m_o$ $m_n^*=0.5m_o$

E$_G$=1.45 eV Electron mobility, μ_n = 900 cm^2/Vsec Hole mobility , μ_p = 10 cm^2/Vsec

Temperature= 27 degrees C

11.) (~~10~~ 6 points) Where is the intrinsic energy (relative to the valence band which is referenced to zero energy)?

Note:
If you recognized
$m_n^* = m_p^*$
$\Downarrow$
$E_i = E_g/2$
$= 0.725$ eV

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

$$\frac{1.45}{2} + 0.75(0.0259)\ln\left(\frac{0.5}{0.5}\right)$$

$$\boxed{E_i = 0.725 \text{ eV}}$$

12.) (~~10~~ 6 points) What is the resistivity of the semiconductor?

$$n_o = \frac{(1e6)^2}{1e18} \quad \frac{n_i^2}{p_o} = 1e\text{-}6 \text{ cm}$$

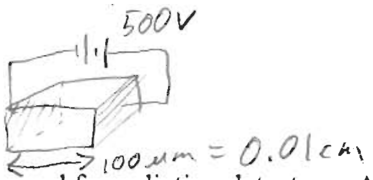
$$=$$

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)} = \frac{1}{(1.6e\text{-}19)(900(1e\text{-}6) + (10)(1e18))}$$

$$\boxed{\rho = 0.625 \ \Omega\text{-cm}}$$

10:27

8 minutes



Third 25%

13.) (25-points total) Sometimes semiconductors are used for radiation detectors. A 100 um x 100 um x 100 um cube of intrinsic silicon-carbide (SiC) material with bandgap E_g=3.0 eV is to be used as an x-ray detector. The semiconductor has an intrinsic concentration, n_i=1e-9 cm^{-3}, an electron mobility of 500 cm^2/V-sec and a hole mobility of 50 cm^2/V-sec. The cube is biased on two opposing sides with 3,000 volts. Each x-ray photon has an energy of 30,000 eV meaning that each x-ray photon has enough energy to produce **many** electron hole pairs. If a single x-ray photon strikes the semiconductor...

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

$\mathcal{E}$-field ⇒ drift

Intrinsic ⇒ both electrons + holes are important

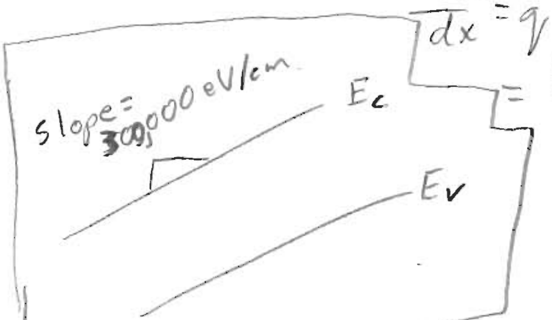
$$\boxed{J_{n\,Drift} \text{ and } J_{p\,Drift}}$$

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).

$$\mathcal{E} = \frac{1}{q}\frac{dE_c}{dx} = \frac{3000\text{V}}{0.01\text{cm}} = 300{,}000 \text{ V/cm}$$

$$\frac{dE_c}{dx} = q\,\mathcal{E} = (1.6\text{e-19 Coulombs})(300{,}000 \text{ V/cm})\left(\frac{1\text{eV}}{1.6\text{e-19J}}\right)$$

$$= 300{,}000 \text{ eV/cm}$$



c) (15 – points) Assuming all photogenerated electrons and holes are collected instantaneously as current, what is the **current** (not current density) that results? Hint: consider how much energy it takes to generate an electron-hole pair verses how much energy the x-ray photon has.

$$n = n_0 + \Delta n = p_0 + \Delta p = p$$

Both equal!

$$n = p = 1\text{e-9} + \frac{30{,}000 \text{ eV/photon}}{3.0 \text{ eV/ehp}} (1\text{photon}) \frac{1}{(0.01)^3}$$

Volume

$$n = p = 10^{10} \text{ cm}^{-3} \simeq \Delta n = \Delta p$$

cross sectional area

$$I = A\,J_{Drift} = q(p\mu_p + n\mu_n)\mathcal{E} A$$

$$= (1.6\text{e-19})(500 + 50)\,1\text{e}10\,(300{,}000)(0.01)^2$$

$$\boxed{I = 26.4\ \mu A}$$

16 minutes

Pulling all the concepts together for a useful purpose:

14.) (30-points)

Surfaces of a crystalline semiconductor represent regions where recombination is higher than in the bulk (inside the semiconductor) and thus, lower the excess minority carrier concentrations near the crystal surfaces. George Washington (America's 1st president) lit a candle that shines on a 50~~0~~ μm thick p-type GaAs semiconductor held at room temperature (27 degrees C). The light uniformly generates 10^{22} additional holes per cm^3 per second throughout the semiconductor but the surface recombination is such that there are no excess carriers at both the surfaces. Determine the minority carrier current density at all positions in the semiconductor. Assume a minority carrier lifetime of 10 nanoseconds (1e-8 seconds), and minority carrier diffusion coefficient at room temperature of 4.0 cm^2/sec.

$\frac{\partial \Delta n_p}{\partial x} = 0$

$= G_L$

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

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

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

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

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

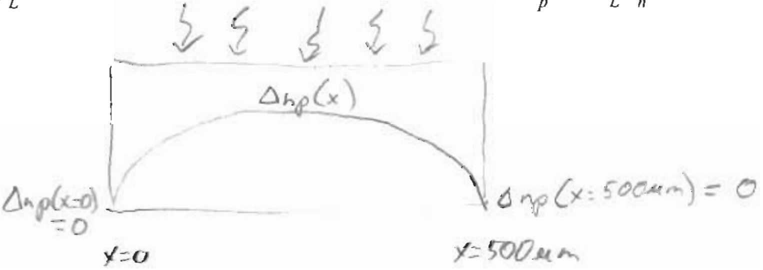
Given: $\dfrac{d\Delta n_p}{dt} = -\dfrac{\Delta n_p}{\tau_n}$ General Solution is: $\Delta n_p(t) = \Delta n_p(t=0)e^{-t/\tau_n}$

Given: $0 = -\dfrac{\Delta n_p}{\tau_n} + G_L$ General Solution is: $\Delta n_p = G_L \tau_n$

$L_n = \sqrt{D_n \tau_n}$

$= \sqrt{(4)(1e-8)}$

$= 2 \times 10^{-4}$ cm $= 2$ um



Boundary Condition

1) $\Delta n_p(x=0) = A + B + G_L \tau_n = 0 = A + B + 1e14$

2) $\Delta n_p(x = 50 \text{ um}) = Ae^{-50/2} + Be^{+50/2} + 1e14 = 0$

$A = (-1e14 - B)$

$\parallel$

$(-1e14 - B)e^{-25} + Be^{+25} + 1e14 = 0$

Extra work can be done here, but clearly indicate which problem you are solving.

Cont'd

$$B\left(e^{+25} - \cancelto{\approx 0}{e^{-25}}\right) + 1e14\left(1 - \cancelto{\approx 0}{e^{-25}}\right) = 0$$

$$B = -\frac{1e14}{e^{25}} = -1,388.8\ cm^{-3}$$

$$\Downarrow$$

$$A = -1e14 - B$$

$$A \cong -1e14\ cm^{-3}$$

$$\Delta n_p(x) = -1e14\, e^{-x/2um} - 1388.8\, e^{+x/2um} + 1e14\ cm^{-3}$$

$$J_n = q D_n \frac{\partial \Delta n}{\partial x}$$

$$= (1.6e-19)(4.0)\left(\frac{+1e14}{2\times10^{-4}\,cm}\right)e^{-x/2um} - \left(\frac{1388.8}{2\times10^{-4}}\right)e^{+x/2um}$$

$$\boxed{J_n = +0.32\, e^{-x/2um} - \left(4.44\times10^{-12}\right)e^{+x/2um}\ A/cm^2}$$