Midterm Exam 2
Solid State Electronic and Optoelectronic Devices
95.577
Instructor: Prof. Wasserman
11/21/08
1-2:20 p.m.

Name: Instructor Copy
ID: ____________________

The exam is 80 minutes long and consists of 4 problems (100 points). The point values for each problem are given in parentheses before the problem. You are allowed 1 index card sized "cheat-sheet" with physical constants and formulas. No solved problems may be on your cheat sheet. A calculator will be required for this exam.
CHECK UNITS!!!!
Please write your answers clearly in the space provided and SHOW YOUR WORK!! Partial credit will be awarded (assuming your work is legible).

Please put your last name on each page of the exam.

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1) (30pts) Imagine an n-doped semiconductor (Si, Eg=1.1eV, n_i=1.5E10cm^{-3}, N_d=1E17cm^{-3}) at 300K.
   a) If you assume E_i sits directly in the middle of the band-gap, where is the equilibrium Fermi level in this system? (5pts)

$N_d = n = 1\times10^{17} = 1.5\times10^{10}\, e^{(E_F-E_i)/kT}$

$E_F - E_i = 0.025875 \cdot \ln \frac{10^{17}}{1.5\times10^{10}}$

$E_F - E_i = 0.4066$ eV

or

$E_F - E_v = 0.956$ eV

   b) The Si is illuminated by an instantaneous HeNe laser (632nm) pulse with a Energy density of 1mJ/cm^2 at t=0. The absorption coefficient for Si at 632 nm is α=1μm^{-1}. Assume that each absorbed photon generates one EHP. Calculate and plot (in the coordinates given) the distribution of carriers at t=0 (5pts)

$1\,mJ/cm^2 = 6.25\times10^{15}\, eV/cm^2 = 3.188\times10^{15}$ photons/cm^2

$632\,nm = 1.96\,eV$

Intensity → $I = I_0 e^{-\alpha x}$

⇓

photons → $N = N_0 e^{-\alpha x}$

⇓

photons absorbed / EHPs generated $-\partial N/\partial x = N_0 \alpha e^{-\alpha x}$

→ $EHPs(x) = 3.188\times10^{15} \cdot 1\mu m^{-1}\, e^{-x(\mu m)}$

$EHPs(x) = 3.188\times10^{19}\, e^{-x(\mu m)}$

$n(x) = 10^{17} + 3.188\times10^{19}\, e^{-x}$

$p(x) \cong 3.188\times10^{19}\, e^{-x}$

   c) Calculate the position of the quasi Fermi levels vs x, and plot in the coordinate system given (10 pts).

$n = N_d + \Delta n = 10^{17} + 3.188\times10^{19} e^{-x} = n_i e^{(F_n-E_i)/kT}$

For $n \approx \Delta n$, or $x < 5\mu m$

For $n = N_d$, $\Delta n = 0$, $x > 5$

$F_n - E_i = \frac{kT}{q} \ln (2.125\times10^{9}\, e^{-\alpha x})$

$F_n - E_i = 0.4066$ eV

$F_n - E_i = 0.556 - 0.02587 \cdot x(\mu m)$ $x < 5\mu m$

$p = \Delta p = 3.188\times10^{19} e^{-x} = n_i e^{(E_i - F_p)/kT}$

$E_i - F_p = 0.556 - 0.02587 \cdot x(\mu m)$

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d) In Si, assume $\tau_{n,p}$ are very long and equal in magnitude. What is the current density $J_{diff.}(x)=J_{ndiff.} + J_{pdiff.}$ in the sample right after t=0 if $D_n = 2D_p=25cm^2/s$? (10pts)

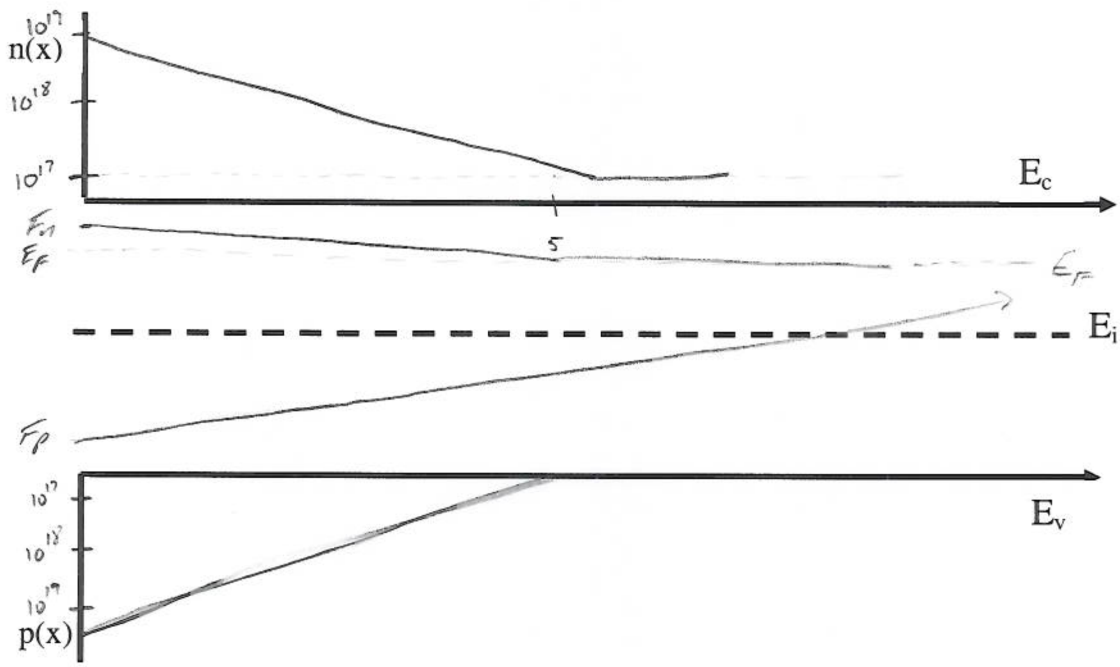
$$J_{diff} = -qD_p \frac{\partial p(x)}{\partial x} + qD_n \, \partial n/\partial x$$

$$\partial p(x)/\partial x = \frac{\partial n(x)}{\partial x} = 3.2\times10^{+19} \cdot -1\,nm^{-1} \, e^{-x(nm)}$$

$$= -3.2\times10^{23} \, e^{-x(nm)}$$

$$J_{diff} = +12.5\ cm^2/s \cdot 1.6\times10^{-19}\ C \cdot -3.2\times10^{-23} \, e^{-x(nm)}$$

$$J_{diff} = -6.376\times10^{5}\ C/cm^2 s$$



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2. (30 pts) Imagine you have a GaAs pn junction with $N_a=10^{17}cm^{-3}$ and $N_d=10^{16}cm^{-3}$. At 300K, $\varepsilon_{GaAs}=13.2$ and $n_i = 2x10^6cm^{-3}$.

a) What are W and V_o at equilibrium? (10pts)

$\epsilon = \epsilon_s \epsilon_o$

$= 13.2 \times 8.85E{-14}$

$= 1.168E{-12}$

$V_o = \frac{kT}{q} \ln (p_p/p_n)$ $\quad p_p = 10^{17}$ $\quad p_n = \frac{(2\times10^6)^2}{10^{16}} = 0.004\ cm^{-3}$

$V_o = 1.215\ eV$

$$W = \left[\frac{2\epsilon V_o}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)\right]^{1/2} = \left[1.775E7\left(\frac{1}{10^{17}}+\frac{1}{10^{16}}\right)\right]^{1/2}$$

$W = 0.442\ \mu m$

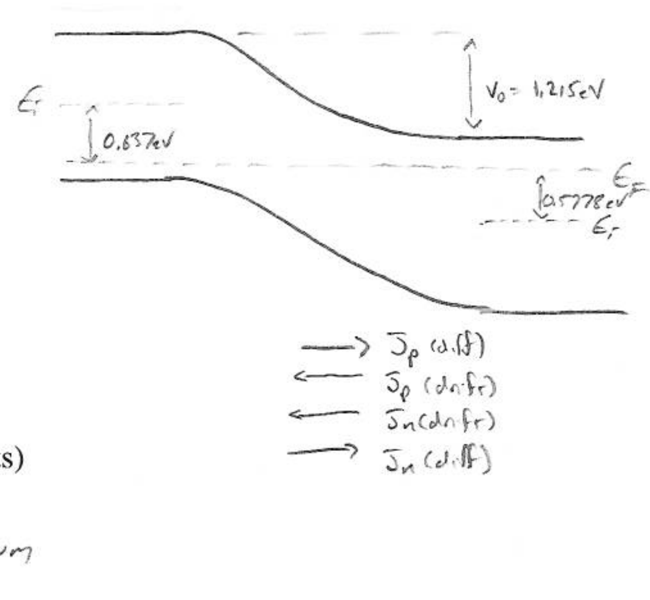
b) Draw the band diagram for the pn-junction, including the Fermi Level and E_i, and show the direction and relative magnitudes of the components of current through the depletion region. (5pts)

$E_{F_n} \Rightarrow 10^{16} = n_i e^{(E_F-E_i)/kT}$

$E_F - E_i = kT/q \ln \frac{10^{16}}{2E6}$

$E_{F_n} - E_i = 0.5778\ eV$

$E_i - E_{F_p} = 0.637$



⟶ J_p (diff)
⟵ J_p (drift)
⟵ J_n (drift)
⟶ J_n (diff)

c) What are x_{no} and x_{po} at equilibrium? (5pts)

$$x_{no} = \frac{W}{1 + N_d/N_a} = \frac{W}{1.1} = 0.402\ \mu m$$

$$x_{po} = \frac{W}{1 + N_a/N_d} = \frac{W}{11} = 0.0402\ \mu m$$

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d) What is the value of the charge in the n and p side of the depletion region? (5pts)

$$Q = A \cdot N_d \cdot X_{no} \cdot q = A N_a X_{po} q$$

$$Q/A = 6.426 \times 10^{-8} \, C/cm^2 = 6.426 \times 10^{-8} \, C/cm^2$$

e) What is the maximum electric field in the junction? Use Poisson's Eq. → ∇E=(1/ε)ρ. (5pts)

$$\partial E / \partial x = \frac{1}{\epsilon} \rho$$

for p-side

$\rho = 10^{17} \, cm^{-3}$

$x \rightarrow 0 \rightarrow x_{po}$

$$\int \partial E / \partial x = \frac{1}{\epsilon} \int_0^{x_{po}} 10^{17} \cdot q \, dx$$

$$E_{max} = \frac{1}{\epsilon} q \, 10^{17} \cdot x_{po}$$

$$|E_{max}| = 5.5 \times 10^4 \, V/cm$$

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3. (20 pts) Imagine a Ge pn-junction, with E_g=0.7eV, A=0.01cm^2, N_a=10^{16} cm^{-3}, N_d=10^{15} cm^{-3}, μ_n=3900 cm^2/V-s, μ_p =1900cm^2/V-s , τ_p=0.1 μs , τ_n=1 μs and n_i=2.5x10^{13} cm^{-3} at 300K.

$$p_n = \frac{(2.5\times10^{13})^2}{10^{15}} = 6.25\times10^{11}$$

$$n_p = \frac{(2.5\times10^{13})^2}{10^{16}} = 6.25\times10^{10}$$

a) Calculate the reverse saturation current for this device (5pts).

$$D_p = \frac{KT}{q}\mu_p = 49.16$$

$$D_n = \frac{KT}{q}\mu_n = 100.91$$

$$L_p = \sqrt{D_p\tau_p} = 0.0022 \text{ cm}$$

$$L_n = \sqrt{D_n\tau_n} = 0.01 \text{ cm}$$

$$I_o = qA\left(\frac{D_p}{L_p}p_n \cdot \frac{D_n}{L_n}n_p\right)$$

$$I_o = 1.6\times10^{-21}(1.386\times10^{16} \cdot 6.278\times10^{14})$$

$$I_o = 2.32\times10^{-5} \text{ A}$$

b) What are the currents for this device for a forward and reverse bias across the junction of 0.6V and -5V, respectively? (10pts)

$$V_F = 0.6V$$

$$I = I_o(e^{qV/kT} - 1)$$

$$= I_o \cdot 1.176\times10^{10}$$

$$I = 2.72\times10^5 A \text{ !!}$$

$$I(-5V) = -I_o = -2.32\times10^{-5} A$$

c) Assume you shine a 10mW laser at the transition region of this device. All of the laser light is absorbed, and the laser emits of energy 1eV. What is the change in the reverse saturation current? (5pts)

$$10mW = \frac{.01 \times}{1.6\times10^{-19}} = 6.25\times10^{16} \text{ eV/s}$$

$$= \frac{6.25\times10^{16} \text{ eV/s}}{1 \text{ eV/EHP}} = 6.25\times10^{16} \text{ EHP/s}$$

This adds 6.25×10^{16} EHP/s $\cdot$ 1.6×10^{-19} C/EHP

$$I_{scn} = 10mA$$

$$I_{r,total} = -2.32\times10^{-5} - 10\times10^{-3} = -10.02mA$$

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4. (20pts) Design a GaAs pn-junction varactor that can provide capacitances from 5pF to 25 pF. Assume ε_{GaAs}=13.2 and $n_i = 2x10^6 cm^{-3}$. Explain the decisions that went into your device design, and why this design should be feasible (doping reasonable, lengths scales makes sense, etc.)

VARACTOR -> FROM C_J -> REVERSE BIAS!

ASSUME $V_{BR} = -15V$

V_r CAN GO FROM V -> -15V

$$C_j = \frac{A}{2}\left[\frac{2q\epsilon}{(V_0 - V)} \frac{N_d N_a}{N_d + N_a}\right]^{1/2}$$

SAY WE USE A p^+n JUNCTION

$$C_j = \frac{A}{2}\left[\frac{2q\epsilon}{V_0 - V}\left(\frac{1}{\frac{1}{N_a} + \frac{1}{N_d}}\right)\right]^{1/2}$$

$$V_0 < V \qquad \frac{1}{N_a} << \frac{1}{N_d}$$

$$C_j = \frac{A}{2}\left[\frac{2q\epsilon}{-V}(N_d)\right]^{1/2}$$

NEED TO CHOOSE A, N_d, COULD SOLVE SYSTEM OF EQS, OR JUST CHOOSE 1,

if $N_d = 10^{16}$

$$C_j(-15V) = 5pF = 5\times10^{-12} = \frac{A}{2}\left[\frac{2q\epsilon}{15}(10^{16})\right]^{1/2}$$

$$A = 0.000896\ cm^2$$

$$C_j(V_r) = 25pF = 25\times10^{-12} = \frac{0.000896}{2}\left[\frac{2q\epsilon}{V_r}(10^{16})\right]^{1/2}$$

$$V_r(25pF) \approx -1.2V$$