NAME:_____FULL SOLUTION___________ **PUID:______________________**

ECE 305 – Spring 2018

Exam 2 – Thursday, February 15, 2018

This is a closed book exam. You may use a calculator and the formula sheet at the end of this exam. Following the ECE policy, the calculator **must** be a Texas Instruments TI-30X IIS scientific calculator.

To receive full credit, you must **show your work** (scratch paper is attached).
The exam is designed to be taken in 60 minutes (or less). Be sure to fill in your name and Purdue student ID at the top of the page. DO NOT open the exam until told to do so, and stop working immediately when time is called. The last page is an equation sheet, which you may remove, if you want.

100 points possible,

I) 40 points (8 points per question)
II) 30 points
III) 30 points

Course policy

If I am caught cheating, I will earn an F in the course & be reported to the Dean of Students.

I repeat: ____

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Signature: ____

Part I: Answer the 5 multiple choice questions below by entering them on your IDP-15 Scantron.

1 (8 points). To increase the resistivity of a semiconductor, we can

A. Decrease the carrier density.
B. Increase the mobility.
C. Decrease the electric field.
D. Increase the cross-sectional area of the resistor
E. Decrease the length of the resistor

2 (8 points). The discontinuity in the valence band alignment in a heterojunction is calculated from:

A. Difference in bandgaps of the materials
B. Difference in electron affinities of the materials
C. Discontinuity of electric field at the junction
D. A and B
E. A and C

4 (8 points). If a device is in equilibrium, which of the following is true?

A. Sum of all the drift currents is equal to sum of all the diffusion currents.
B. Drift current due to electrons is equal to diffusion current due to electrons.
C. Drift current due to holes is equal to diffusion current due to holes.
D. B and C
E. A, B and C

4 (8 points). For a high-quality crystalline silicon device operating at a very high voltage, what is the most important scattering mechanism?

A. Lattice scattering
B. Ionized impurity scattering
C. Auger scattering
D. Impact ionization scattering
E. Polar optical phonon scattering

5 (8 points). As the doping density of a semiconductor decreases, the mobility generally

A. Stays the same
B. Increases or stays the same
C. Decreases
D. First increases, then decreases
E. First decreases, then increases

Part II (Free Response, 30 points)

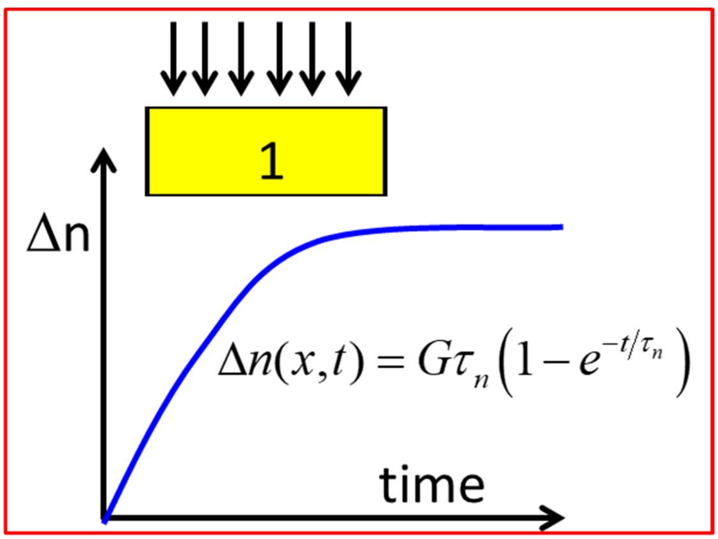
Assume that an n-type region of spatially uniform crystalline silicon with $\mu_p = 450\ \mathrm{cm^2/V\cdot s}$ and lifetime $\tau_p = 10\ \mu\mathrm{s}$. It is initially in equilibrium in the dark, and then uniformly illuminated by a photon flux $G_L = 10^{18}$ /cm^3·s starting at t=0 .

a. Write down the simplest form of the minority carrier diffusion equation that describes its behavior at all times. Justify your answer.

$$\frac{\partial \Delta p}{\partial t} = G_L u(t) - \frac{\Delta p}{\tau_p}$$

The minority carriers here are holes. We can drop the diffusion term (with the second spatial derivative) because of spatial uniformity. Because of the time-dependent behavior of the generation and recombination, we must keep all the other terms.

b. Sketch the time-dependent behavior of the excess minority carrier concentration from t=0 to t=50 μs. Be sure to label both the x and y axes, and include at least 3 numerical values on each axis (with justification).

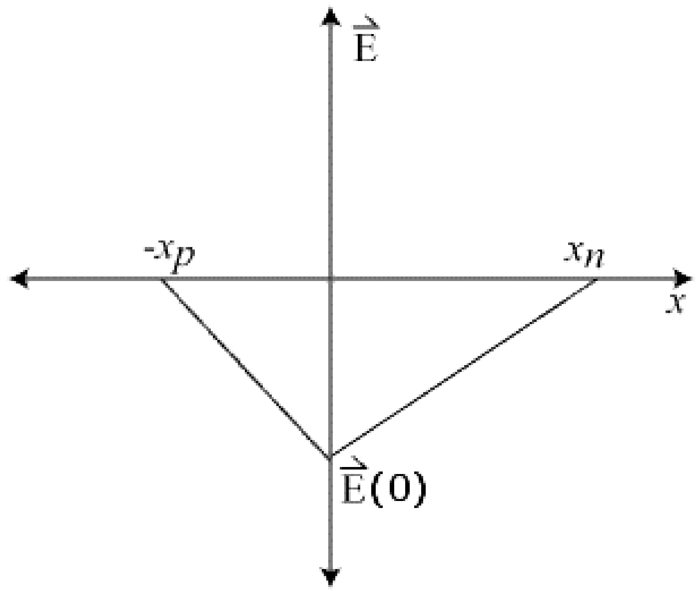


c. When the experiment is repeated with a different light source, it is not absorbed uniformly through the sample, resulting in an actual $G_L = 10^{10} e^{-x}\ \mathrm{cm^{-3}} s^{-1}$, where x is the distance from top of the sample in μm. Given that the sample is 5 μm thick, write down the excess minority carrier concentration in the steady state (a very long time after the light switches on).

Now the system is spatially non-uniform. We calculate that the diffusion length $L_D = \sqrt{D_p \tau_p} = \sqrt{11.7 \cdot 10^{-5}}\ \mathrm{cm} = 0.0108\ \mathrm{cm} = 108\ \mu\mathrm{m}$. This indicates that the sample is 'short'. Therefore, we expect that we can use $0 = D_p \frac{d^2 \Delta p}{dx^2} + G_L(x)$. This yields a solution $\Delta p(x) = \frac{10^{10}\ \mathrm{cm^{-3}} s^{-1}}{\left(\frac{11.7\mathrm{cm^2}}{\mathrm{s}}\right) \cdot 10^{-8}\ \mathrm{cm^{-2}}} e^{-x} + Cx = 8.5 \cdot 10^{16} e^{-x} + Cx\ \mathrm{cm^{-3}}$.

Part III (Free Response, 30 points)

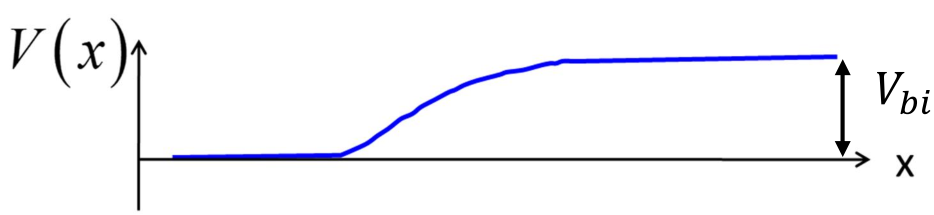
The electric field versus position for a crystalline silicon ($K_s = 11.68$) pn homojunction is given by the following graph (may not be precisely to scale):



For this problem, assume that the junction is abrupt at $x = 0$ with a flat doping profile on each side, $\mathcal{E}(0) = -12$ kV/cm, the n-type depletion length $x_n = 520$ nm, and the p-type depletion length $x_p = 120$ nm.

a. Sketch the potential profile, clearly showing the numerical value of V_{bi}. Assume that the left-hand side is grounded (i.e., $\lim_{x \to -\infty} V(x) = 0$).

$V_{bi} = \frac{1}{2}\mathcal{E}(0)W = 0.5 \cdot \left(1.2 \cdot 10^4 \frac{\text{V}}{\text{cm}}\right) \cdot (520 + 120) \cdot 10^{-7}\text{cm} = 0.384\text{ V}$



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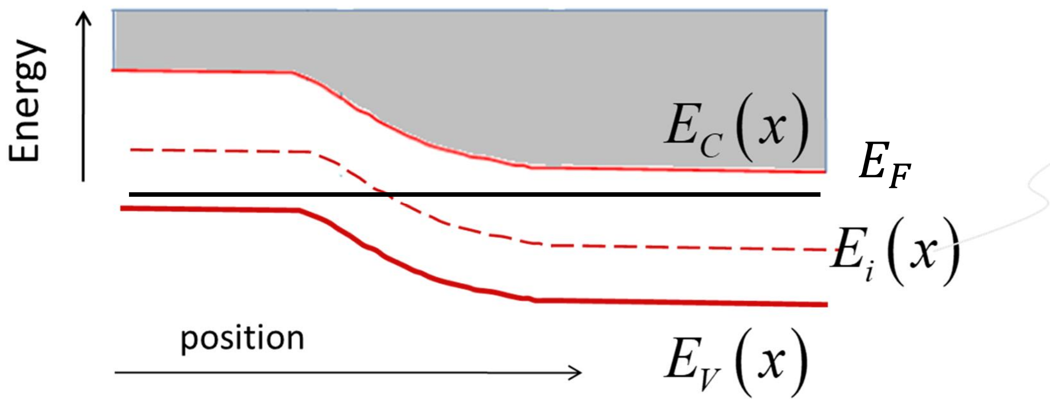
b. Sketch the band diagram vs position, showing the values of E_C-E_F away from the junctions.

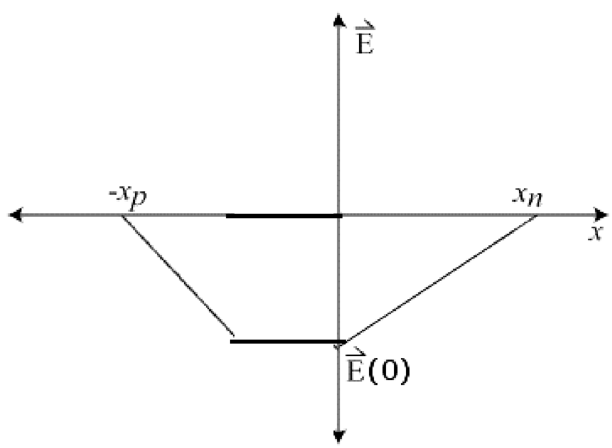


On the left-hand side, $E_C - E_F = 0.91$ eV

c. Sketch the electric field versus position if there is a region of intrinsic silicon of length 160 nm sandwiched between the p and n regions. Calculate and show the value of the peak electric field on the sketch, assuming that the intrinsic silicon is uncharged, and that V_{bi}, x_n, and x_p remain the same.

Now the area under the curve will be $V_{bi} = \left[\frac{1}{2}(x_n + x_p) + x_i\right]\mathcal{E}'(0) = (480\ \text{nm})\mathcal{E}'(0)$

So $\mathcal{E}'^{(0)} = \left(-12\frac{\text{kV}}{\text{cm}}\right)\cdot\frac{320}{480} = -8\ \text{V/cm}.$



ECE 305 Exam 2 Formula Sheet (Spring 2018)

You may remove this page from the exam packet, and take it with you.

Physical Constants	**Silicon parameters ($T = 300$ K)**
$\hbar = 1.055 \times 10^{-34}$ J·s	$N_C = 3.23 \times 10^{19}$ cm^{-3}
$m_0 = 9.109 \times 10^{-31}$ kg	$N_V = 1.83 \times 10^{19}$ cm^{-3}
$k_B = k = 1.38 \times 10^{-23}$ J/K	$n_i = 1.1 \times 10^{10}$ cm^{-3}
$q = 1.602 \times 10^{-19}$ C	$K_s = 11.8$
$\epsilon_0 = 8.854 \times 10^{-12}$ F/m	

Miller Indices: (hkl) {hkl} [hkl] <hkl>

Density of states $g_C(E) = \frac{(m_n^*)^{3/2}\sqrt{2(E-E_C)}}{\pi^2\hbar^3}$

Fermi function $f(E) = \frac{1}{1+e^{(E-E_F)/kT}}$

Intrinsic carrier concentration $n_i = \sqrt{N_C N_V} e^{-E_g/2kT}$

Equilibrium carrier densities: $N_C = \frac{1}{4}\left(\frac{2m_n^* kT}{\pi\hbar^2}\right)^{3/2}$ $\quad N_V = \frac{1}{4}\left(\frac{2m_p^* kT}{\pi\hbar^2}\right)^{3/2}$

$n_0 = N_C e^{(E_F-E_C)/kT} = n_i e^{(E_F-E_i)/kT}$ $\quad p_0 = N_V e^{(E_V-E_F)/kT} = n_i e^{(E_i-E_F)/kT}$

Space charge neutrality: $p - n + N_D^+ - N_A^- = 0$

Law of Mass Action: $n_0 p_0 = n_i^2$

Non-equilibrium carriers: $n = N_C e^{(F_N-E_C)/kT}$ $\quad p = N_V e^{(E_V-F_P)/kT}$ $\quad np = n_i^2 e^{(F_N-F_P)/kT}$

Conductivity/resistivity: $\sigma = \sigma_n + \sigma_n = q(n\mu_n + p\mu_p) = 1/\rho$

Drift-diffusion current equations:

$$J_n = nq\mu_n \mathcal{E}_x + qD_n \frac{dn}{dx} = n\mu_n \frac{dF_n}{dx} \qquad \frac{D_n}{\mu_n} = \frac{kT}{q}$$

$$J_p = pq\mu_p \mathcal{E}_x - qD_p \frac{dp}{dx} = p\mu_p \frac{dF_p}{dx} \qquad \frac{D_p}{\mu_p} = \frac{kT}{q}$$

Carrier conservation equations:

$$\frac{\partial n}{\partial t} = +\nabla \cdot \left(\frac{J_n}{q}\right) + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\nabla \cdot \left(\frac{J_p}{q}\right) + G_p - R_p$$

Poisson's equation: $\nabla \cdot (\epsilon\mathcal{E}) = \rho$

SRH carrier recombination: $R = \Delta n/\tau_n$ or $R = \Delta p/\tau_p$

Minority carrier diffusion equation: $\frac{\partial \Delta n}{\partial t} = D_n \frac{\partial^2 \Delta n}{\partial x^2} - \frac{\Delta n}{\tau_n} + G_L$ $\quad L_{D,n} = \sqrt{D_n \tau_n}$

PN homojunction electrostatics: $V_{bi} = \frac{kT}{q} \ln\left(\frac{N_D N_A}{n_i^2}\right)$ $\quad \frac{d\mathcal{E}}{dx} = \frac{\rho(x)}{K_s\epsilon_o}$

$$W = \sqrt{\frac{2K_s\epsilon_o V_{bi}}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)} \quad x_n = \left(\frac{N_A}{N_A+N_D}\right)W \quad x_p = \left(\frac{N_D}{N_A+N_D}\right)W \quad \mathcal{E}(0) = \sqrt{\frac{2qV_{bi}}{K_s\epsilon_o}\left(\frac{N_A N_D}{N_A+N_D}\right)}$$