NAME:________________________________ **PUID: :**________________________________

ECE 305 Exam 3 SOLUTIONS: Spring 2015

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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.

There are three equally weighted questions. To receive full credit, you must **show your work** (scratch paper is attached).

The exam is designed to be taken in 50 minutes.

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.

75 points possible, 10 per question

1) 25 points (5 point per part)
2) 25 points (5 points per part)
3) 25 points (5 points per part)

------------------------ Course policy ------------------------

I understand that if I am caught cheating in this course, I will earn an F for the course and be reported to the Dean of Students.

Read and understood: ____________________________________
signature

Answer the **five multiple choice questions** below by **drawing a circle** around the **one, best answer**.

1a) What is $\Delta n = \left(n_i^2/N_A\right)\left(e^{qV_A/k_BT} - 1\right)$ called?

a) The Einstein relation .
b) The Caughey-Thomas relation.
c) The second law of thermodynamics.
d) Moore's Law
e) The Law of the Junction.

1b) What is the primary reason for the strong temperature dependence of the diode saturation current, I_0 in an NP junction with $N_D >> N_A$?

a) The D_n term in I_0 .
b) The L_n term in I_0 .
c) The N_A term in I_0 .
d) The n_i^2 term in I_0 .
e) None of the above.

1c) What is the physical meaning of the area under $\mathcal{E}(x)$ vs. x in equilibrium?

a) It is the total doping density in the transition region.
b) It is equal to the bandgap of the semiconductor.
c) It is the net space-charge density in the transition region.
d) It is the net dipole moment of the junction.
e) It is the built-in potential of the junction.

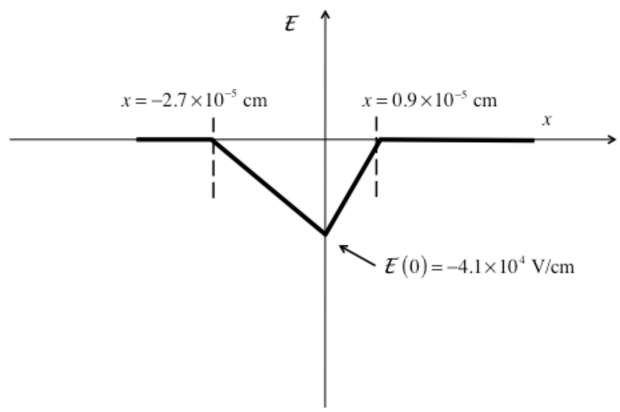
1d) Ion implantation is a technique to do what?

a) Dope a semiconductor.
b) Deposit an insulating layer on a semiconductor.
c) Deposit a metallic layer on a semiconductor.
d) Deposit an insulating layer on an insulator.
e) Deposit a metallic layer on an insulator.

1e) What is "lithography" used for in semiconductor manufacturing?

a) To dope semiconductors.
b) To deposit amorphous films on semiconductors.
c) To deposit polycrystalline films on semiconductors.
d) To grow crystalline films on semiconductors.
e) To produce patterns in the films deposited on semiconductors.

2) The electric field vs. position for a Si junction in equilibrium is sketched below. (The depletion approximation is assumed). Given the information provided, answer the following questions.



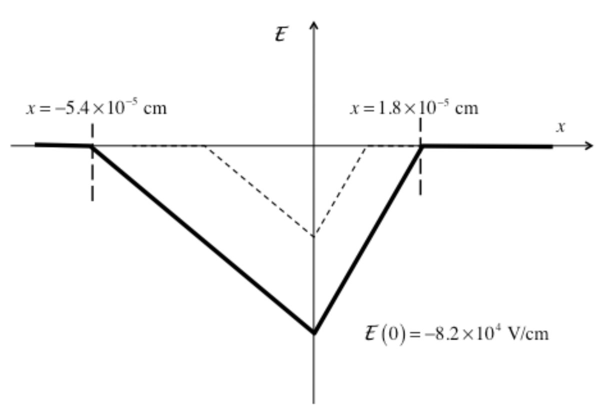
2a) What is the built-in voltage for this junction?

Solution:
Voltage is the integral of the electric field, so the built-in voltage is the area under the curve above (by definition, V_{bi} is positive).

$$V_{bi}=\frac{1}{2}\left|\mathcal{E}(0)\right|W=0.5\times4.1\times10^{4}\times\left(2.71\times10^{-5}+0.9\times10^{-5}\right)=0.74 \quad \boxed{V_{bi}=0.74\text{ V}}$$

2b) Assume that a reverse bias of magnitude $V_R=3V_{bi}$ is applied to this junction. Sketch the electric field versus position being careful to indicate the values on the vertical and horizontal axes. (The dotted line is the equilibrium electric field.) Briefly explain your answer.

Solution:
The total voltage across the junction has increased from V_{bi} to $V_{bi}+V_R=4V_{bi}$. The depletion layer thickness and the peak electric field magnitude both vary as the square root of the voltage across the junction, so both **double.**



2c) What is the doping density on the N-side? (Hint: You will first need to determine which is the N-side.)

Solution:

According to the Poisson equation, on the N-side: $\frac{d\left(\varepsilon_{Si}\mathcal{E}\right)}{dx}=\rho\left(x\right)=+qN_D$. The electric field has a positive slope for $x>0$, so that is the N-side.

$$\frac{d\mathcal{E}}{dx}=\frac{+qN_D}{K_S\varepsilon_0} \qquad N_D=\frac{K_S\varepsilon_0}{q}\frac{d\mathcal{E}}{dx}$$

From the figure: $\frac{d\mathcal{E}}{dx}=-\frac{\left(0-\left(-4.1\times10^4\right)\right)\text{V/cm}}{0.9\times10^{-5}}=4.6\times10^9\ \text{V/cm}^2$

$$N_D=\frac{11.8\times8.854\times10^{-14}\ \text{F/cm}}{1.6\times10^{-19}\ \text{C}}\times\left(4.6\times10^9\ \text{V/cm}^2\right)=3.0\times10^{16}\ \text{cm}^{-3} \quad \boxed{N_D=3.0\times10^{16}\ \text{cm}^{-3}}$$

2d) What is the doping density on the P-side?

Solution:
We could do this just as in 2c), but we can also recognize that charge must balance.

$$N_Ax_p=N_Dx_n$$

$$N_A=N_D\frac{x_n}{x_p}=3.0\times10^{16}\times\frac{0.9}{2.7}=1.0\times10^{16} \qquad \boxed{N_A=1.0\times10^{16}\ \text{cm}^{-3}}$$

2e) If the voltage in equilibrium is zero at $x=0.9\times10^{-5}$ cm, then what is the voltage at $x=0$?

Solution:

Remember the definition of the electric field: $\mathcal{E}=-\frac{dV}{dx}$, so $V\left(x_n\right)-V\left(0\right)=-\int_0^{x_n}\mathcal{E}\,dx$

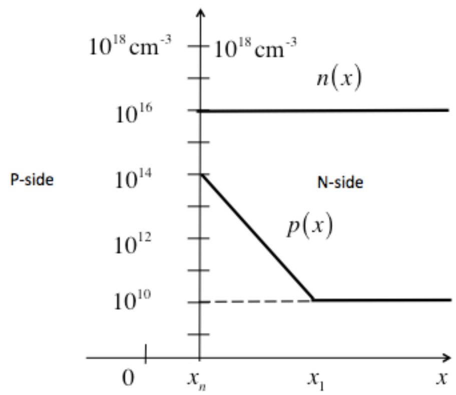
Since $V\left(x_n\right)=0$, we find $V\left(0\right)=\int_0^{x_n}\mathcal{E}\,dx$

The voltage at $x=0$ is just the area under the $\mathcal{E}\left(x\right)$ vs. x curve between $x=0$ and $x=x_n$, but it has a negative sign.

$$V\left(0\right)=\frac{1}{2}\mathcal{E}\left(0\right)x_n=0.5\times\left(-4.1\times10^4\right)\times0.9\times10^{-5}=-0.18$$

$$\boxed{V\left(0\right)=-0.18\ \text{V}}$$

3) The sketch below shows the carrier concentrations in a PN junction at room temperature. Only the quasi-neutral N-side of the junction is shown. Answer the following questions.



3a) Is the junction forward or reverse biased? Explain your answer.

Solution:
Forward biased (FB) because there are excess holes on the N-side.

3b) Is the N-side of this PN junction "long" or "short". Explain your answer.

Solution:
It is long, because the excess holes injected at $x = x_n$ decay to zero before the end of the N-region. (Also, the straight line on a log plot means that the excess carrier density is decaying exponentially, which is the case for a long diode.)

3c) What is the intrinsic carrier concentration?

Solution:
$n_0 p_0 = n_i^2$
On the N-side, after the excess hole concentration has decayed to zero:
$n_0 p_0 = 10^{16} \times 10^{10} = 10^{26}$ $n_i = \sqrt{10^{26}} = 1 \times 10^{13}$ cm^{-3}

$$\boxed{n_i = 1 \times 10^{13} \text{ cm}^{-3}}$$

3d) What voltage is applied to this diode?

Solution:

$$n(x_n)p(x_n) = n_i^2 e^{qV_A/k_BT} \qquad 10^{16}10^{14} = \left(10^{13}\right)^2 e^{qV_A/k_BT}$$

$$e^{qV_A/k_BT} = 10^4$$

$$V_A = \frac{k_BT}{q}\ln 10^4 = 0.026\times 9.21 = 0.24 \text{ V}$$

$$\boxed{V_A = 0.24 \text{ V}}$$

3e) At what location, x, where $x \geq x_n$, is the splitting of the quasi-Fermi levels the biggest? Explain your answer.

Solution:

The N-region is low-level injection, so the electron QFL is where the Fermi level was in equilibrium – it does not vary with position.

The hole QFL is lowest where the hole concentration is highest. (Recall $p(x) = n_i e^{\left(E_i - F_p(x)\right)/k_BT}$. The semiconductor is in equilibrium for $x > x_1$, so $F_n = F_p$ and there is no splitting. The hole concentration is largest at $x = x_n$, so that is where the QFL's split the most.

Answer: The maximum splitting of the QFL's occurs at $x = x_n$.