

YOUR NAME _____

*Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology*

6.012 Electronic Devices and Circuits

Exam No. 1

Notes:

1. Unless otherwise indicated, assume room temperature and that kT/q is 0.025 V. You may also approximate $[(kT/q) \ln 10]$ as 0.06 V.
2. Open book; 6.012 text and any other notes permitted.
3. All of your answers and any relevant work must appear on these pages. Any additional paper you hand in will not be graded.
4. Make reasonable approximations and assumptions. State and justify any such assumptions and approximations you do make.
5. Be careful to include the correct units with your answers when appropriate.
6. Be certain that you have all eight (8) pages of this exam booklet and make certain that you write your name at the top of this page in the space provided.

6.012 Staff Use Only	PROBLEM 1	_____	(out of a possible 28)
	PROBLEM 2	_____	(out of a possible 40)
	PROBLEM 3	_____	(out of a possible 32)
	TOTAL		

Problem 1 (28 points)

a) A sample of indium phosphide, InP, (In: column III; P: column V) contains 10^{17} cm^{-3} dopant atoms which can be modeled as shallow donors.

i) If these donor dopant atoms are known to replace indium when they are incorporated into the crystal lattice, what column of the periodic table must they come from?

Column _____, because

ii) What are the net hole and electron concentrations in this sample at thermal equilibrium if the intrinsic carrier concentration, n_i , in indium phosphide is 10^7 cm^{-3} at room temperature?

$$n_0 = \text{_____} \text{ cm}^{-3}$$

$$p_0 = \text{_____} \text{ cm}^{-3}$$

b) A p-type silicon sample ($N_A = 10^{17} \text{ cm}^{-3}$, $\tau_{\text{min}} = 10^{-5} \text{ s}$) has been uniformly illuminated for a long time with light generating 10^{18} hole-electron pairs $\text{cm}^{-3} \text{ s}^{-1}$ throughout. At $t = 0$, the intensity of the light is doubled and left at that level. Write expressions for the excess electron population, $n'(t)$, in this sample for $t < 0$ and $0 < t$.

$$t < 0: n'(t) = \text{_____}$$

$$0 < t: n'(t) = \text{_____}$$

c) Imagine that your 6.0XX lab kit contains a handful of npn transistors known to be well designed*. These transistors have opaque black plastic packages with three leads, one of which is clearly marked "base"; unfortunately however, it is not clear which of the other two leads is the emitter, and which is the collector. To figure out which is which you do some measurements:

Problem 1 continues on the next page

* In a well designed npn transistor $N_{DE} \gg N_{AB} \gg N_{DC}$, $w_B \ll L_{eB}$, $w_E \sim w_B \sim w_C$, and $D_e = 3 D_h$.

Problem 1 continued

- i) You measure the magnitude of the reverse breakdown voltage, V_B , of each junction, and find that V_B of one is much lower. Remembering that breakdown occurs when the magnitude of the electric field in the depletion region exceeds the breakdown field, you know that the junction with the smaller reverse breakdown voltage is the

emitter-base junction collector-base junction could be either
because:

- ii) You measure the reverse saturation current, I_S , of each junction (with the other junction short circuited) and find that the I_S of one junction is much larger than that of the other. The junction with the larger reverse saturation current is the

emitter-base junction collector-base junction could be either
because:

- iii) You measure the small signal capacitance of each junction (unbiased) and find that the small signal capacitance of one junction is much larger than that of the other. The junction with the larger small signal capacitance at zero bias is the

emitter-base junction collector-base junction could be either
because:

- iv) You don't trust your answers in parts (i), (ii), and (iii), and you still don't have any idea which way to connect the transistors. The question is, "So what?" If you connect the transistors wrong what will happen?

They won't work at all

They will work but have a much smaller current gain.

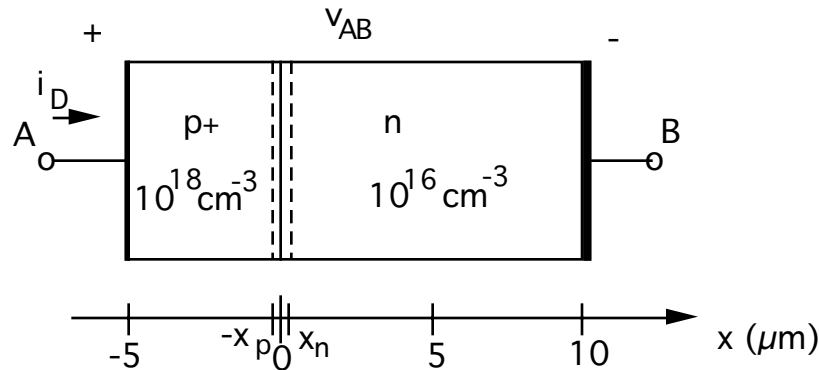
It won't make much difference.

Explain your answer.

End of Problem 1

Problem 2 (40 points)

This question concerns the p⁺-n diode pictured below. The doping level on the p⁺-side is 10^{18} cm^{-3} ; that on the n-side is 10^{16} cm^{-3} . The width of the p⁺-side, w_p , is $5 \mu\text{m}$; the n-side is $10 \mu\text{m}$ wide. You may assume that the diode is at room temperature and that throughout the device the electron mobility, μ_e , is $1600 \text{ cm}^2/\text{V}\cdot\text{s}$; the hole mobility, μ_h , is $600 \text{ cm}^2/\text{V}\cdot\text{s}$; the minority carrier lifetime, τ_{min} , is 10^{-4} s ; and the intrinsic carrier concentration, n_i , is 10^{10} cm^{-3} . Assume also that $L_e, L_h \gg w_n, w_p \gg x_n, x_p$.



- a) What is the built-in potential, ϕ_b , at this junction?

$$\phi_b = \underline{\hspace{2cm}}$$

- b) What is the ratio of the depletion region width on the n-side, x_n , to that on the p-side, x_p ?

$$x_n/x_p = \underline{\hspace{2cm}}$$

- c) At what level of applied bias, V_{AB} , is $p'(x_{n+})$, the excess hole population at the edge of the depletion region on the n-side of the junction, equal to 1% of the equilibrium electron population on the n-side, n_{n0} ? Assume that all of the applied voltage appears across the space charge layer.

$$V_{AB} \text{ [such that } p'(x_{n+}) = 0.01 n_{n0}] = \underline{\hspace{2cm}}$$

- d) What is the hole current density, $J_h(x_n)$, at the edge of the depletion region on the n-side (i.e., at $x = x_n$) when V_{AB} has the value you found in Part (c)? Note that you do not need to have answered Part (c) to answer this question.

$$J_h(x_n) \text{ [when } p'(x_{n+}) = 0.01 n_{n0}] = \underline{\hspace{2cm}}$$

Problem 2 continues on the next page

Problem 2 continued

e) What is the ratio of $J_e(-x_p)$, the electron current density at $x = -x_p$, to $J_h(x_n)$, the hole current density at $x = x_n$?

$$J_e(-x_p)/J_h(x_n) = \underline{\hspace{4cm}}$$

f) Assume that $J_e(-x_p)$, the electron current density at $x = -x_p$, is negligibly small compared to $J_h(x_n)$, the hole current density at $x = x_n$ (i.e., $J_e(-x_p) \approx 0$). If the hole current density for $x_n < x < w_n$ is $J_h(x)$, and if $J_h(x_n)$ is 0.1 A/cm^2 , what are the following?

i) The total electron current density, $J_e(x)$, for $x_n < x < w_n$.

$$J_e(x), \text{ for } x_n < x < w_n = \underline{\hspace{4cm}}$$

ii) The electron diffusion current density, $J_e^{\text{dif}}(x)$, for $x_n < x < w_n$.

$$J_e^{\text{dif}}(x), \text{ for } x_n < x < w_n = \underline{\hspace{4cm}}$$

iii) The electric field, $E(x)$, for $x_n < x < w_n$.

$$E(x), \text{ for } x_n < x < w_n = \underline{\hspace{4cm}}$$

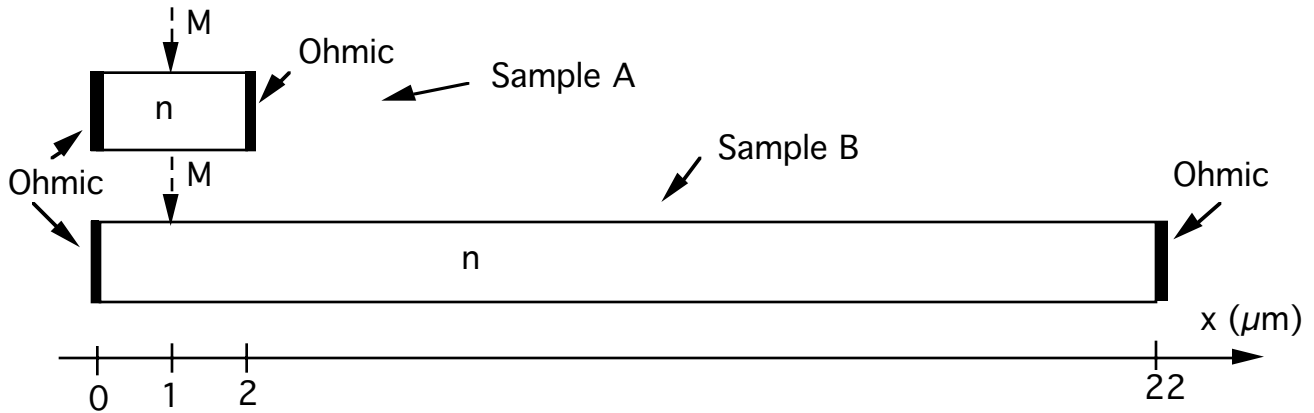
g) When the diode is biased as in Parts (c) and (d) (i.e., so that $p'(x_{n+})$ is $0.01 n_{no}$), what is the difference between the hole current injected across the junction, i.e., $J_h(x_n)$ and that reaching the ohmic contact at $x = w_n$? Hint and caution: The difference is small, but "zero" is not the answer we are looking for.

$$J_h(x_n) - J_h(w_n) = \underline{\hspace{4cm}}$$

End of Problem 2

Problem 3 (32 points)

This question concerns the two samples illustrated below. Both are n-type silicon samples with a net donor concentration, N_D , of 10^{16} cm^{-3} ; electron mobility, μ_e , of $1600 \text{ cm}^2/\text{V}\cdot\text{s}$; hole mobility, μ_h , of $600 \text{ cm}^2/\text{V}\cdot\text{s}$; and minority carrier lifetime, τ_{min} , of 10^{-6} s . One bar, Sample A, is $2 \mu\text{m}$ long; the other, Sample B, is $22 \mu\text{m}$ long. Both samples are illuminated with light which generates qM hole-electron pairs $\text{cm}^{-3}\cdot\text{s}^{-1}$ uniformly across the plane at $x = 1 \mu\text{m}$.

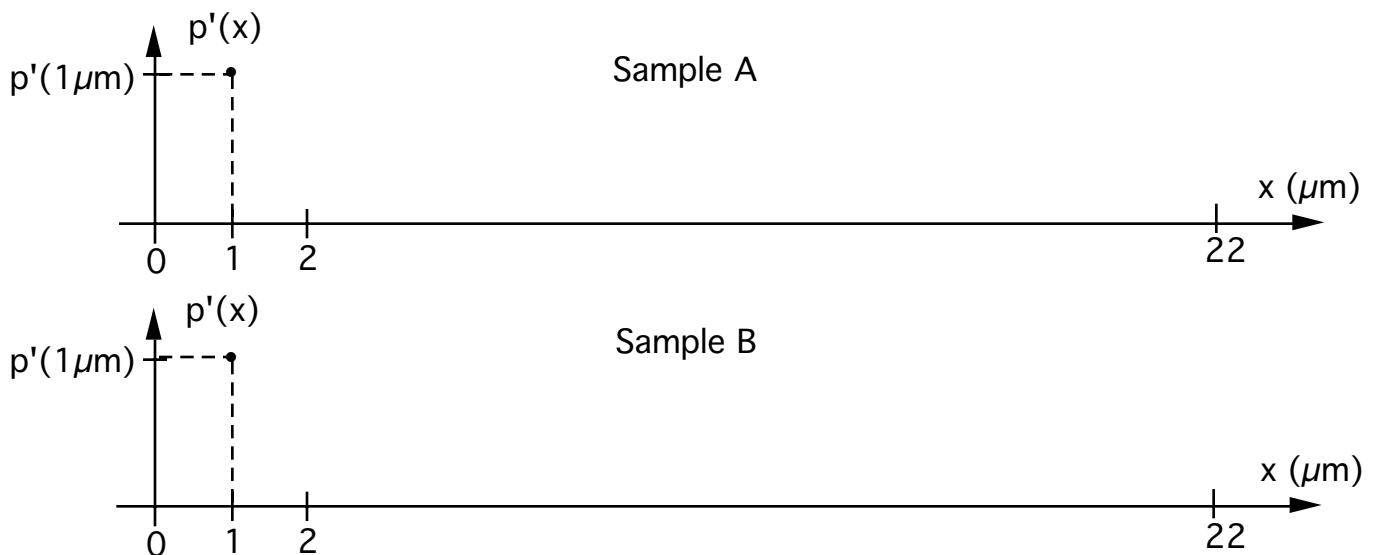


a) What are the minority carrier diffusion coefficient, D_h , and the minority carrier diffusion length, L_h , in these samples?

$D_h = \underline{\hspace{2cm}}$

$L_h = \underline{\hspace{2cm}}$

b) On the axes provided below, sketch the excess minority carrier profiles in the two samples. Assume $L_h \gg 22 \mu\text{m}$, in spite of what you may have calculated in Part (a). You need not calculate $p'(1 \mu\text{m})$.



Problem 3 continues on the next page

Problem 3 continued

- c) i) In Sample A, what fraction of the injected hole-electron pairs recombine at the ohmic contact at $x = 0$?

Fraction = _____

- ii) In Sample B, what fraction of the injected hole-electron pairs recombine at the ohmic contact at $x = 0$?

Fraction = _____

- d) In which sample, A or B, if any, is $p'(1 \mu\text{m})$, the excess hole concentration at $x = 1 \mu\text{m}$, larger? Explain your answer.

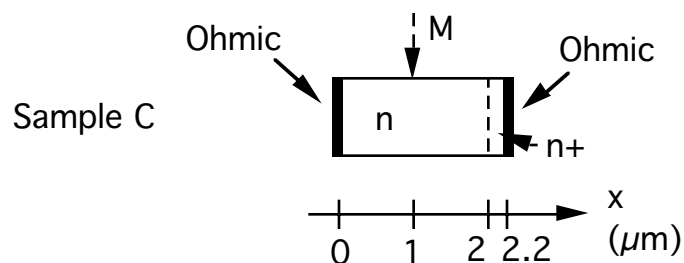
Sample A

Sample B

Neither (i.e., same in both)

because

- e) Now consider a third sample, Sample C, which, as pictured below, has a heavily doped n-region $0.2 \mu\text{m}$ thick starting at $2 \mu\text{m}$. The doping in this region is 10^{18}cm^{-3} .



What is the electrostatic potential, ϕ , in the n and n^+ regions of Sample C?

$\phi_n =$ _____

$\phi_{n^+} =$ _____

Problem 3 continues on the next page

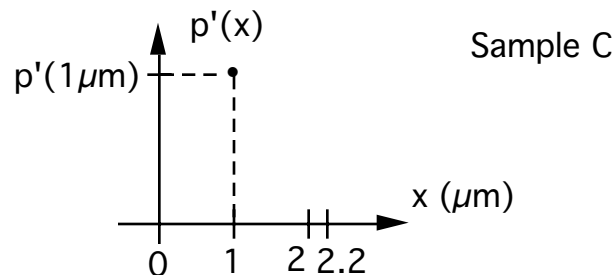
Problem 3 continued

f) The change of potential, $\phi_{n^+} - \phi_n$, at $x = 2\mu\text{m}$ between the n and the n^+ regions represents a potential energy barrier for holes so the excess hole concentration to the right of the step, $p'(2^+)$ is much smaller than that to left, $p'(2^-)$. [Given time and under less pressure, you should be able to find that it is actually 100 times smaller, which is $\exp -q(\phi_{n^+} - \phi_n)/kT$, and which is also the ratio of the doping levels on either side of the n- n^+ interface.]

This question concerns the slope of the excess hole concentration crossing the interface at $x = 2\mu\text{m}$. How is the slope in the excess population at $x = 2^+\mu\text{m}$ related to that at $x = 2^-\mu\text{m}$? In the space provided below write an expression for $dp'/dx|_{x=2^+}$ in terms of $dp'/dx|_{x=2^-}$

$$dp'/dx|_{x=2^+} \text{ (in terms of } dp'/dx|_{x=2^-}) = \underline{\hspace{10em}}$$

g) Use the information in Part (f) and your answer in that part to sketch the excess minority carrier profile in Sample C when it is illuminated with light which generates qM hole-electron pairs $\text{cm}^{-3}\text{-s}^{-1}$ uniformly across the plane at $x = 1\mu\text{m}$. Use the axes provided below. Assume $L_h \gg 2.2\mu\text{m}$, inspite of what you may have calculated in Part (a). You need not calculate $p'(1\mu\text{m})$.



End of Problem 3

End of the exam