

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 one sheet of 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 33)
	PROBLEM 2	_____	(out of a possible 33)
	PROBLEM 3	_____	(out of a possible 34)
	TOTAL		

Problem 1 - (33 points)

This question concerns several silicon samples. In these samples the electron mobility, μ_e , is $1600 \text{ cm}^2/\text{V-s}$; the hole mobility, μ_h , is $600 \text{ cm}^2/\text{V-s}$; the minority carrier lifetime, τ_{min} , is 10^{-5} s ; and the intrinsic carrier concentration, n_i , is 10^{10} cm^{-3} at room temperature. Except in Part e, there are no contacts on these samples and all of their surfaces are reflecting boundaries, i.e. there is no extra recombination there.

- a) One sample is doped with $1 \times 10^{16} \text{ cm}^{-3}$ boron atoms and $2 \times 10^{16} \text{ cm}^{-3}$ phosphorous atoms. Indicate whether this sample is n-type or p-type, and determine the thermal equilibrium hole and electron concentrations, p_o and n_o , respectively, in it and its electrostatic potential, ϕ_o , relative to intrinsic silicon. Show your work and/or explain your answer.

Type: _____

$p_o =$ _____ cm^{-3}

$n_o =$ _____ cm^{-3}

$\phi_o =$ _____ Volts

- b) What are the diffusion lengths of holes and electrons, L_h and L_e , respectively, in the sample of Part a? Show your work and/or explain your answer.

$L_h =$ _____ cm

$L_e =$ _____ cm

- c) A second silicon sample is measured and found to be n-type with a thermal equilibrium resistivity, ρ_o , of 1 Ohm-cm . What are the thermal equilibrium hole and electron concentrations, p_o and n_o , respectively, in this sample? Show your work.

$p_o =$ _____ cm^{-3}

$n_o =$ _____ cm^{-3}

Problem 1 continues on the next page

Problem 1 continued

- d) A third sample, which is p-type with a net acceptor concentration, N_A , of 10^{17} cm^{-3} , has been illuminated for a long time with steady-state penetrating light which generates 10^{19} electron-hole pairs per cubic centimeter per second uniformly throughout its bulk, i.e., $g_L = 10^{19} \text{ cm}^{-3}\text{-s}^{-1}$. What are the new hole and electron concentrations, p and n , respectively, in the sample with this illumination, and what is the change in its conductivity, $\Delta\sigma = (\sigma - \sigma_0)$? Show your work.

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

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

$$\Delta\sigma = \text{_____} \text{ S/cm}$$

- e) The intensity of the illumination the sample in Part d is now modulated with a sinusoidal intensity variation so that $g_L = 10^{19} [1 + \sin(2 \cdot 10^2 t)] \text{ cm}^{-3}\text{-s}^{-1}$. What are the average and time varying electron concentrations, n_{ave} and $[n(t) - n_{\text{ave}}]$, respectively? Show your work.

$$n_{\text{ave}} = \text{_____} \text{ cm}^{-3}$$

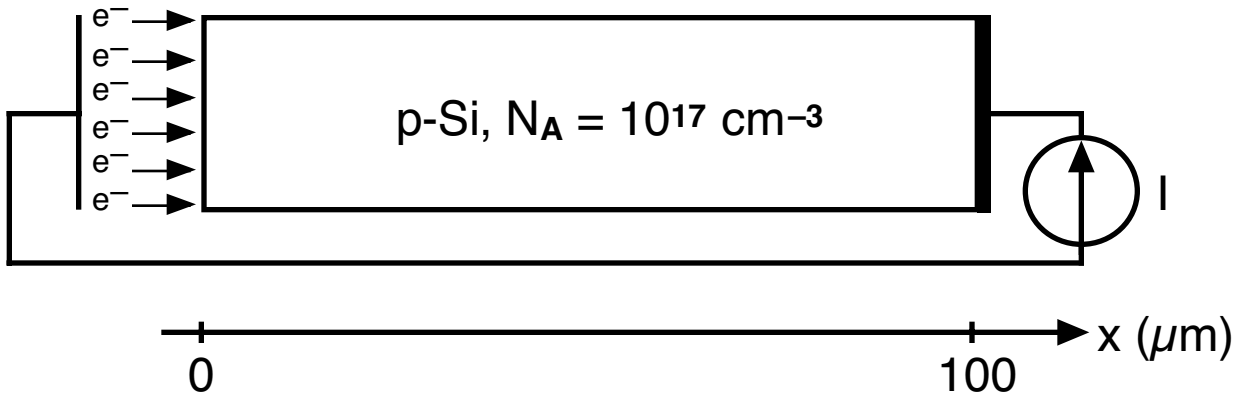
$$n(t) - n_{\text{ave}} = \text{_____} \text{ cm}^{-3}$$

End of Problem 1

Problem 2 (33 points)

This problem concerns a bar of p-type silicon, $N_A = 10^{17} \text{ cm}^{-3}$, irradiated on its left end with a uniform electron beam having an electron flux of $10^{19} \text{ cm}^{-2}\text{s}^{-1}$ as illustrated below.*

As shown, the sample is $100 \text{ }\mu\text{m}$ long and has an ohmic contact on its right end; this contact is connected to the electron source to complete the circuit as indicated. In this sample the hole mobility, μ_h , is $600 \text{ cm}^2/\text{V}\cdot\text{s}$; the electron mobility, μ_e , is $1600 \text{ cm}^2/\text{V}\cdot\text{s}$; the electron diffusion length, L_e , is $10 \text{ }\mu\text{m}$; and the intrinsic carrier concentration at room temperature, n_i , is 10^{10} cm^{-3} .



- (a) What is the electron current density just inside the bar at the left end, i.e. what is $J_e(0^+)$? Show your work and/or explain your answer.

$$J_e(0^+) = \text{_____} \text{ A/cm}^2$$

- (b) Write a formula for $n'(x)$ in terms of $n'(0)$ and then determine the value of $n'(0)$.

$$n'(x) = \text{_____}$$

$$n'(0^+) = \text{_____} \text{ cm}^{-3}$$

Problem 2 continues on the next page

* In case you are concerned: The electron beam hitting the left end of the bar behaves like an injecting contact. The injected electrons do not have sufficient energy to generate more hole-electron pairs; also, no holes can leave the left end of the bar.

Problem 2 continued

(c) Write an expression for the electron current density, $J_e(x)$, valid for $0 < x < 100 \mu\text{m}$.

$$J_e(x) = \text{_____} \text{ A/cm}^2$$

(d) Write an expression for the hole current density, $J_h(x)$, valid for $0 < x < 100 \mu\text{m}$.

$$J_h(x) = \text{_____} \text{ A/cm}^2$$

(e) Write an expression for the electric field, $E_x(x)$, valid for $0 < x < 100 \mu\text{m}$.

$$E_x(x) = \text{_____} \text{ V/cm}$$

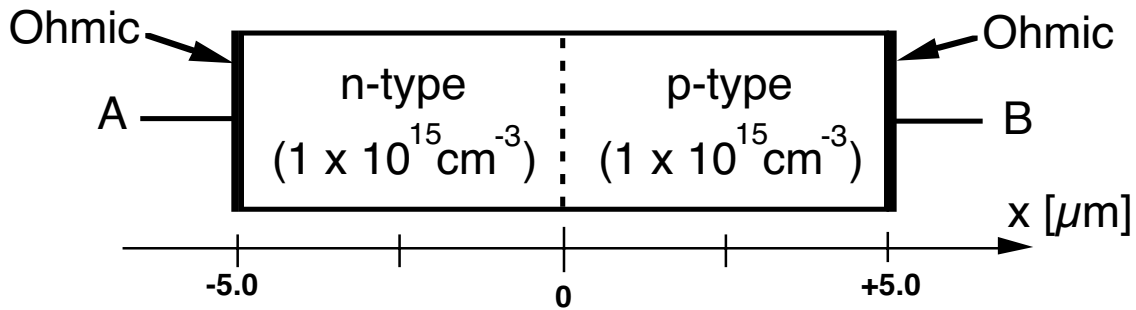
(f) What is the voltage drop from end to end in this sample? Note: this is the same as the change in electrostatic potential between $x = 0$ and $100 \mu\text{m}$.

$$\phi(x = 100\mu\text{m}) - \phi(x = 0\mu\text{m}) = \text{_____} \text{ V}$$

End of Problem 2

Problem 3 - (34 points)

This question concerns a p-n diode like that pictured below which is made out of a semiconductor in which the intrinsic carrier concentration, n_i , is 10^6 cm^{-3} at room temperature; the electron mobility, μ_e , is $3200 \text{ cm}^2/\text{V-s}$; the hole mobility, μ_h , is $600 \text{ cm}^2/\text{V-s}$; and the minority carrier diffusion lengths, L_e and L_h , are much larger than $5 \mu\text{m}$. Notice that the n-side is to the left in this device; we often draw it on the right. The dielectric constant of this material is the same as that of silicon, 10^{-12} F/cm .



- (a) What are the equilibrium hole and electron concentrations on the n-side of this diode? Remember that for this material n_i is 10^6 cm^{-3} at room temperature.

$p_{on} = \text{_____} \text{ cm}^{-3}$

$n_{on} = \text{_____} \text{ cm}^{-3}$

- (b) What is the built-in potential, ϕ_b , of this diode? Is it greater than, less than, or similar to that of a comparably doped silicon diode, and why?

$\phi_b = \text{_____} \text{ Volts}$

This is _____ greater than, _____ less than, _____ comparable to that of a similar Si diode, because

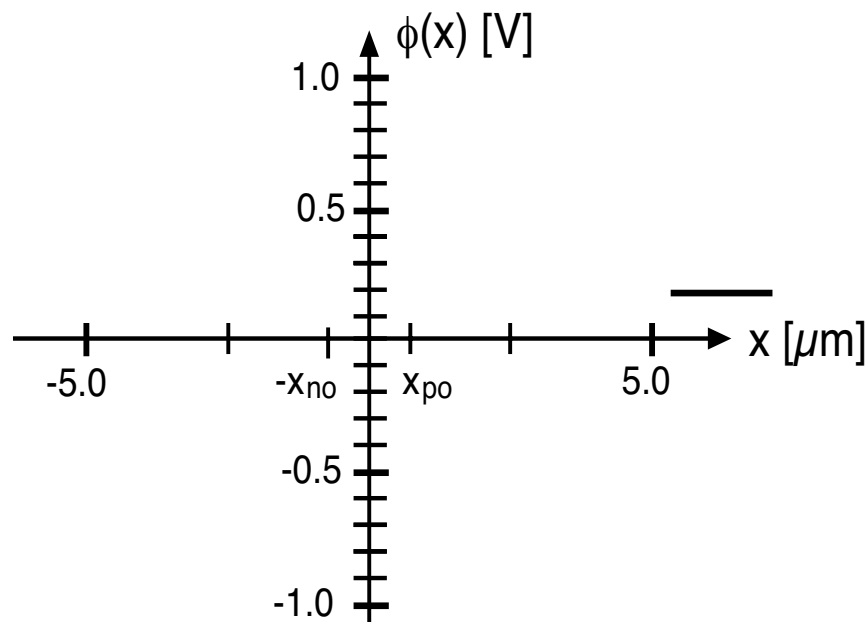
Problem 3 continues on the next page

Problem 3 continued

- (c) Is the zero-bias depletion width of this junction greater than, less than, or similar to that of a comparably doped silicon diode, and why?

It is ____ greater than, ____ less than, ____ comparable to that of a similar Si diode, because

- (d) On the axes provided below sketch the electrostatic potential, $\phi(x)$, going from the metal on the left, through the semiconductor, and into the metal on the right, with $v_{AB} = 0$ V. The electrostatic potential of the metal relative to the intrinsic semiconductor is $+0.2$ V as is indicated on the right side of the axes below. Dimension your sketch and label any significant features, including the shape of $\phi(x)$ in the depletion region and the value of $\phi(0)$. Use the x_{no} and x_{po} indicated on the horizontal axis.



- (e) (i) With a forward bias of 0.6 Volts applied, i.e., $v_{AB} = -0.6$ V, what are the excess minority carrier concentrations at the edges of the quasineutral regions? That is, what are $p'(-x_n)$ and $n'(x_p)$?

$$p'(-x_n) = \text{_____ cm}^{-3}$$

$$n'(x_p) = \text{_____ cm}^{-3}$$

Problem 3e continues on the next page

Problem 3e continued

- (ii) At the same bias level, i.e., $v_{AB} = -0.6$ V, what are the electron, hole, and total current densities crossing this junction, that is what are $J_e(0)$, $J_h(0)$, and J_{tot} , respectively? You may neglect the depletion region widths relative to $5 \mu\text{m}$ in your calculations. Note that the "(0)" refers to $x = 0$; it does not mean that $v_{AB} = 0$.

$$J_e(0) = \text{_____} \text{ A/cm}^2$$

$$J_h(0) = \text{_____} \text{ A/cm}^2$$

$$J_{tot} = \text{_____} \text{ A/cm}^2$$

- (f) Now consider a diode like that pictured at the start of this problem on page 6 with the n-side unchanged, but with the p-side made of silicon with a net acceptor concentration, N_A , of 10^{15} cm^{-3} and having the same properties as the silicon used in Problem 1 (see page 2). You can assume that the minority carrier diffusion length in the silicon is much greater than $5 \mu\text{m}$ regardless of what you found in Part b of Problem 1. Also assume that intrinsic silicon and an intrinsic sample of the other semiconductor have the same electrostatic potential, i.e., both are zero.
- (i) In this new diode, $J_e(0)$ is changed from its value in Part e at the same bias level. What is its new value, and what is the ratio of electron to hole current density crossing this junction now, that is what is $J_e(0)/J_h(0)$? You may again neglect the depletion region widths relative to $5 \mu\text{m}$ in your calculations.

$$J_e(0) = \text{_____} \text{ A/cm}^2$$

$$J_e(0)/J_h(0) = \text{_____}$$

- (ii) How does this ratio compare with its value in Part e, and do you see any possible application of this structure?

End of Problem 3; End of Exam