MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Electrical Engineering and Computer Science

6.012 MICROELECTRONIC DEVICES AND CIRCUITS

Problem Set No. 4

Issued: September 30, 2009 **Due**: Monday, October 5, 2009 by 5 pm

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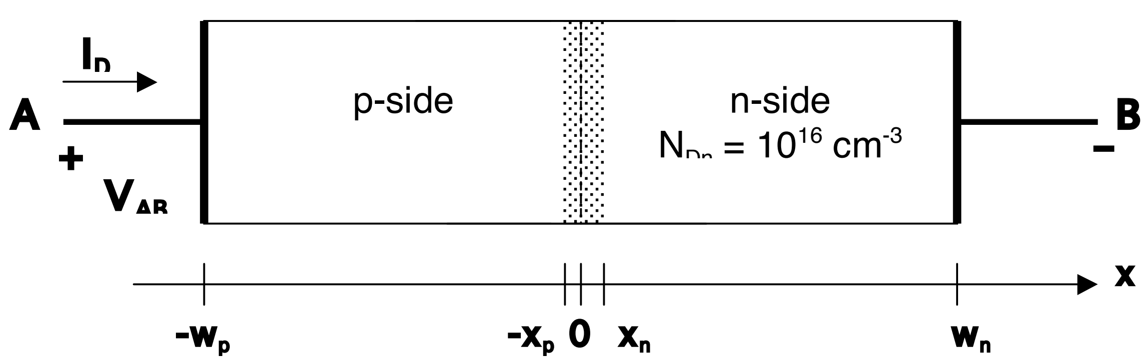
Reading Assignments:
Lecture 7 (10/1/09) - Chap. 8 (8.1)
Lecture 8 (10/6/09 - Chap. 7 (7.5, 7.6)
Lecture 9 (10/8/09) - Chap. 9 (9.1, 9.2)

Exam 1: The first hour exam is scheduled for Wednesday night, October 7, from 7:30 to 9:30 pm Please let me know as soon as possible (by e-mail) if you have a conflict so we can resolve it as painlessly as possible. The exam is closed book and will cover the material through 10/2/09 and Problem Set #4 (i.e. through p-n junction diodes and BJT basics). A formula sheet will be provided (see below); you can also bring one two-sided 8.5 x 11 crib sheet (and a magnifying glass if necessary). Old exams and solutions will be posted on Stellar soon.

Formula Sheet: A draft copy of the formula sheet has been posted on Stellar. Suggestions for additions, corrections, and/or deletions are welcome.

Problem 1 - The p- and n-sides of the silicon p-n diode shown above are each 2 μm wide; the depletion regions on either side of the junction are both much narrower than this and their widths can be neglected relative to 2 μm; also, $L_{min} >> 2\ \mu$m. . The n-side has a net donor concentration, N_{Dn}, of 10^{16} cm^{-3}. The hole and electron mobilities, μ_h and μ_e, are 600 cm^2/V-s and 1600 cm^2/V-s, respectively, throughout the device. (Ignore any dependence of the mobilities on doping level.) The cross-sectional area is 10^{-4} cm^2.



a) When the bias voltage, V_{AB}, is 0.48 V, what are the following quantities?

i) The total hole population at the contact on the right end of the device, w_n

ii) The total hole population at the edge of the depletion region on the n-side, x_n.

iii) The <u>excess</u> hole charge stored in the quasi neutral region, QNR, on the n-side of the diode, $q_{QNR,n\text{-}side}$.

iv) The net hole current density crossing the junction, $J_h(0)$.

b) You are not told explicitly the doping level of the p-side of this diode, N_{Ap}, but you are told that the <u>total</u> minority carrier (electron) population at the edge of the depletion region on the p-side, $n(-x_p)$ is one tenth that of the <u>total</u> minority carrier (hole) population at x_n, $p(x_n)$, when the applied voltage, V_{AB}, is 0.48 V, that is $p(x_n)/n(-x_p) = 10$.

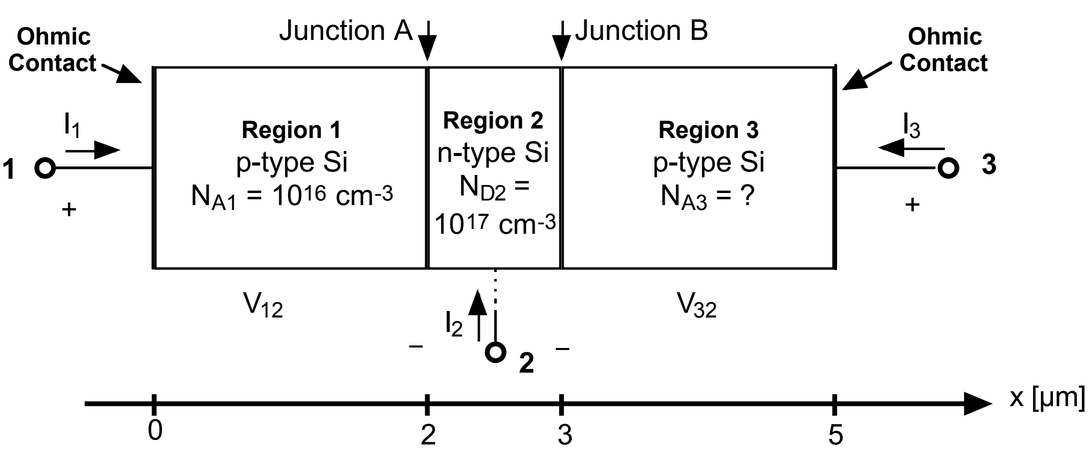
i) What must the net acceptor concentration on the p-side, N_{Ap}, be?

ii) What is the magnitude of the ratio of the excess electron charge, $q_{QNR,p\text{-}side}$, stored on the p-side of this diode to the excess hole charge, $q_{QNR,\ n\text{-}side}$, stored on the n-side at this bias?

iii) What is the ratio of the net electron current density crossing the junction, $J_e(0)$, to the net hole current density, $J_h(0)$, at this bias point?

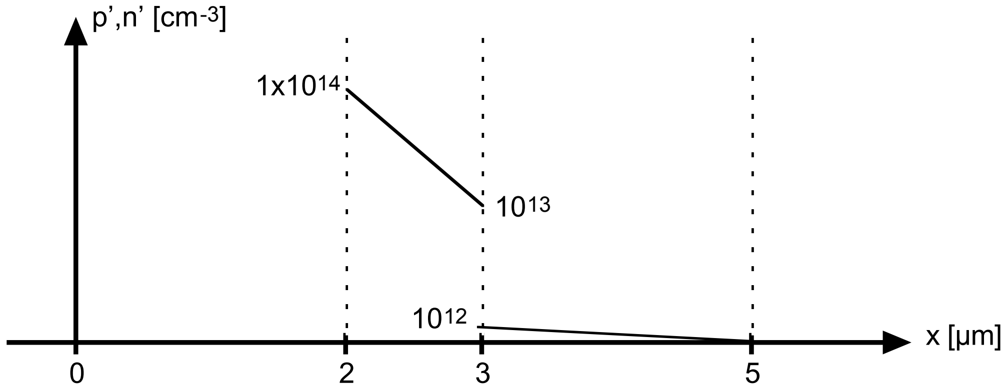
iv) What is the total potential step going from the quasi-neutral region on the p-side to the quasi-neutral region on the n-side of the <u>biased</u> junction?

<u>Problem 2</u> - This question concerns the silicon sample illustrated below which has three uniformly doped regions: Regions 1 and 3 are p-type, and Region 2 is n-type. There are ohmic contacts on either end of the sample, and there is a contact to Region 2 off to the side (much as it is in a bipolar junction transistor). Throughout the sample the electron diffusion coefficient, D_e, is 40 cm^2/s, the hole diffusion coefficient, D_h, is 15 cm^2/s, and $\tau_{min} \approx \infty$. The cross-sectional area is 10^{-4} cm^2.



When Terminal 2 is grounded and bias voltages, V_{12} and V_{32}, are applied to this device, the excess minority carrier profiles shown at the top of the next page result in Regions 2 and 3. (You have to figure out what happens in Region 1 yourself.)

You can ignore the widths of the depletion regions for purposes of working this problem.



(a) Looking at Junction B:

(i) What is $J_{Electron\text{-}B}$, the <u>electron</u> current density crossing Junction B? Recall that this is the minority carrier diffusion current density in Region 3.

(ii) What is $J_{Hole\text{-}B}$, the <u>hole</u> current density crossing Junction B?

(iii) What is the terminal current I_3?

(iv) What is N_{A3}, the doping level in Region 3?

(b) Looking at Junction A:

(i) What is $n'(2^-)$, the excess electron concentration at the edge of the quasi-neutral region on the p-side of this junction, i.e. just to the left of the edge of the depletion region at $x = 2^-$?

(ii) What is V_{12}, the voltage bias on Junction A?

(c) Looking now at the entire sample, removing the biases V_{12} and V_{32}, and thinking of the structure as a bipolar junction transistor:

(i) What is the best terminal to use as the emitter, and why?

(ii) For your choice of emitter above, what is the forward current gain, β_F, of this transistor?

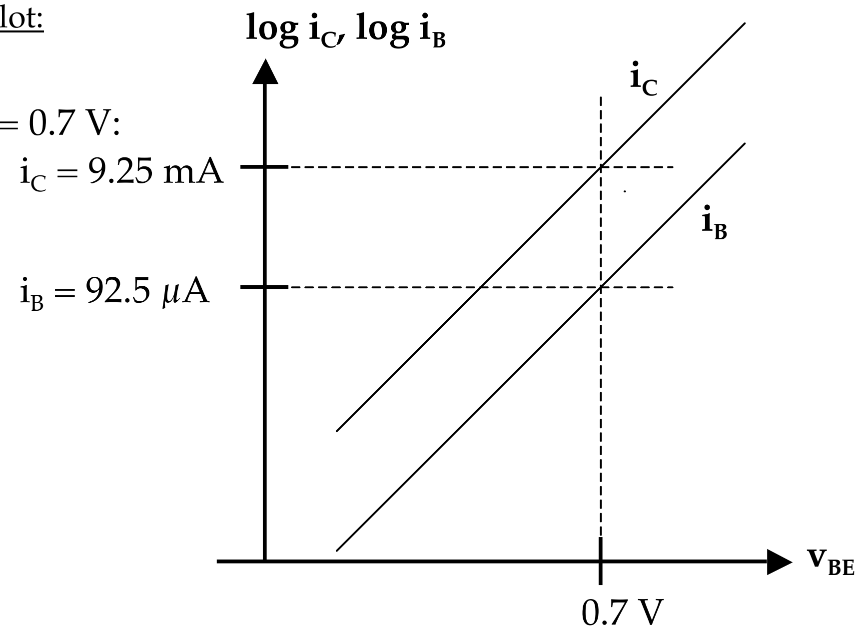
<u>Problem 3</u> - You are given a silicon npn bipolar transistor with the following parameters:

$W_E = 0.25\ \mu m$, $W_B = 0.5\ \mu m$ $W_C = 1.0\ \mu m$
Active device cross-sectional areas: $A_E = A_C = 10^{-4}\ cm^2$
$D_h = 10\ cm^2/s$, $D_e = 20\ cm^2/s$
Minority carrier lifetime, $\tau_{min} = \infty$ (recombination only at contacts)
Collector doping, $N_{DC} = 5 \times 10^{16}\ cm^{-3}$
$V_A = 100$ V

A plot of log i_C and log i_B vs v_{BE} for this device is shown at the top of the next page. Such a plot is called a Gummel Plot, after the researcher who first realized that it was a useful tool for measuring β_F for BJTs and seeing if and how it varies with v_{BE}:

Gummel plot:

Values @ v_{BE} = 0.7 V:



a) What is the forward current gain, β_F, in this transistor?

b) What is the base defect, δ_B, in this transistor? (Hint: No calculation necessary.)

c) Calculate the ratio, r, defined as $r = (w_{E,eff} \cdot N_{DE})/(w_{B,eff} \cdot N_{AB})$.

d) Calculate the net acceptor concentration in the base, N_{AB}. (Hint: Do not use your answer in Part c.)

e) Calculate the net donor concentration in the emitter, N_{DE}.

f) Plot the excess minority carrier profiles between $x = -w_E$ and $x = w_B+w_C$ for the bias condition V_{BE} = 0.7 V, V_{BC} = - 1V. Label the numerical values of the excess minority carrier concentrations at the edges of the depletion regions at x = 0 and $x = w_B$, and at the contacts. (Note: Neglect the depletion region widths relative to the emitter, base, and collector widths.)

g) Consider the total number of excess minority carriers in the base of this transistor, $Q_{B,diff}$, under each of the following two bias conditions,

Bias A:	V_{BE} = 0.7 V	V_{BC} = -1 V
Bias B:	V_{BE} = 0.7 V	V_{BC} = 0.7 V

What is the ratio of the $Q_{B,diff}$'s under the two bias conditions? (Suggestion: Try sketching n'(x) for $0 < x < w_B$ for each of these biases.)

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