Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology

6.012 Electronic Devices and Circuits

Exam No. 1

Wednesday, October 8, 2003
Room 34-101
7:30 to 9:30 pm

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. Closed book; one sheet (2 pages) of notes permitted (to be handed with exam).

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 the formula sheet, 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 35)
Problem 2: _________ (out of a possible 30)
Problem 3: _________ (out of a possible 35)
Total
This problem concerns a specimen of gallium arsenide, GaAs, which has \(2 \times 10^{16} \text{ cm}^{-3}\) donors and an unknown number of acceptors.

A measurement is made on the specimen and it is found that it is p-type with an equilibrium hole concentration, \(p_o\), of \(5 \times 10^{17} \text{ cm}^{-3}\).

At room temperature in GaAs, the intrinsic carrier concentration, \(n_i\), is \(10^7 \text{ cm}^{-3}\), the hole mobility, \(\mu_h\), is 300 cm\(^2\)/V-s, and the electron mobility, \(\mu_e\), is 4000 cm\(^2\)/V-s. The minority carrier lifetime, \(\tau_{\text{min}}\), is \(10^{-9}\) s.

a) [6 pts] What is the net acceptor concentration, \(N_A = N_a - N_d\), in this sample, and what is the total acceptor concentration, \(N_a\)?

\[N_A = \text{______________ cm}^{-3}\]

\[N_a = \text{______________ cm}^{-3}\]

b) [4 pts] What is the equilibrium electron concentration, \(n_o\), in this sample at room temperature?

\[n_o = \text{______________ cm}^{-3}\]

c) [4 pts] What is the electrostatic potential, \(\phi\), in this sample at room temperature relative to intrinsic gallium arsenide?

\[\phi = \text{______________ V}\]

d) [4 pts] What is the electrical conductivity, \(\sigma\), of this sample in thermal equilibrium at room temperature?

\[\sigma = \text{______________ S/cm}\]
Problem 1 continued

e) [5 pts] This sample is illuminated by a steady state light which generates hole-electron pairs uniformly throughout its bulk, and the conductivity of the sample is found to increase by 1% (that is, to 1.01 \( \sigma \)). What are the excess hole and electron concentrations, \( p' \) and \( n' \), in the illuminated sample, assuming that the illumination has been on for a long time?

\[ p' = n' = \text{______________ cm}^{-3} \]

f) [4 pts] What is the optical generation rate, \( G_L \), in Part e? Note: If you could not evaluate \( p' \) and \( n' \) in Part e, give an algebraic expression in terms of \( p' \) and \( n' \).

\[ G_L = \text{______________ hole-electron pairs/cm}^3\text{-s}^{-1} \]

g) [4 pts] If the illumination in Part e is extinguished at \( t = 0 \), write an expression for the sample conductivity as a function of time for \( t > 0 \). Express your answer in terms of \( \sigma_0 \), rather than the numerical value.

\[ \sigma(t) = \text{______________ S/cm} \]

h) [4 pts] What is the minority carrier diffusion length, \( L_{\text{min}} \), in this sample?

\[ L_{\text{min}} = \text{______________ cm} \]

End of Problem 1
Problem 2 (30 points)

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; \(L_{\text{min}} >> 2 \mu m\). The n-side has a net donor concentration, \(N_{Dn}\) of \(10^{16} \text{ cm}^{-3}\). The hole and electron mobilities, \(\mu_h\) and \(\mu_e\) are 600 cm²/V-s and 1600 cm²/V-s, respectively, throughout the device. (Ignore any dependence of the mobilities on doping level.) The cross-sectional area of the diode is \(10^{-4} \text{ cm}^2\).

a) When the bias voltage, \(V_{AB}\) is 0.48 V, what are the following quantities?
   i) [3 pts] The total hole population at the contact on the right end of the device, \(w_n\).

   \[ p(w_n) = \text{_________ cm}^{-3} \]

   ii) [4 pts] The total hole population at the edge of the depletion region on the n-side, \(x_n\).

   \[ p(x_n) = \text{_________ cm}^{-3} \]

   iii) [4 pts] The excess hole charge stored in the quasi neutral region, QNR, on the n-side of the diode, \(q_{\text{QNR,n-side}}\).

   \[ q_{\text{QNR,n-side}} = \text{_________ coul} \]

   iv) [4 pts] The net hole current density crossing the junction, \(J_h(0)\).

   \[ J_h(0) = \text{_________ A/cm}^2 \]

Problem 2 continues on the next page
Problem 2 continued

b) You are not told explicitly the doping level of the p-side of this diode, $N_{Ap}$, but you are told that the total minority carrier (electron) population at the edge of the depletion region on the p-side, $n(-x_p)$ is one tenth that of the total 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) [4pts] What must the net acceptor concentration on the p-side, $N_{Ap}$, be?

\[
N_{Ap} = \text{____________________ cm}^{-3}
\]

ii) [4 pts] What is the magnitude of the ratio of the excess electron charge, $q_{QNR,p-side}$, stored on the p-side of this diode to the excess hole charge, $q_{QNR,n-side}$, stored on the n-side at this bias?

\[
|q_{QNR,p-side}/q_{QNR,n-side}| = \text{____________________}
\]

iii) [4 pts] 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?

\[
J_e(0)/J_h(0) = \text{____________________ A/cm}^2
\]

iv) [3pts] 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 biased junction?

\[
\phi(x>x_n) - \phi(x<-x_p) = \text{___________ Volts}
\]

End of Problem 2
Problem 3 - (35 points)

The p-side of the p-n diode pictured above is 2 µm wide and has a net acceptor concentration, \( N_{Ap} \), of \( 10^{17} \) cm\(^{-3}\). The n-side is also 2 µm wide and has a net donor concentration, \( N_{Dn} \), of \( 5 \times 10^{16} \) cm\(^{-3}\). The minority carrier diffusion lengths, \( L_e \) and \( L_h \), are both much greater than 2 µm, and the hole and electron mobilities, \( \mu_h \) and \( \mu_e \), are 600 cm\(^2\)/V-s and 1600 cm\(^2\)/V-s, respectively, throughout the device (independent of doping level). The cross-sectional area of the diode is \( 10^{-4} \) cm\(^2\).

A constant bias, \( V_{AB} \), is applied on this diode, and it is illuminated across the plane at \( x = -1 \) µm so that the resulting excess minority carrier concentration profile on the p-side is as illustrated in the figure below.

\[
\begin{align*}
\text{p', n'} & \quad 10^{14} \text{ cm}^{-3} \\
-w_p & \quad -w_p/2 & \quad -x_p & \quad 0 & \quad x_n & \quad w_n
\end{align*}
\]

a) i) [6 pts.] What is the electron current density as a function of position, \( J_e(x) \), on the p-side of this device, that is, for \(-w_p < x < -x_p\) ?

\[
J_e(x) \text{ [Amps/cm}^2]\text{]}
\]

Problem 3 continues on the next page
Problem 3 continued

ii) [6 pts.] The optical generation function can be expressed mathematically as an impulse at \( x = -w_p/2 \) \([-1 \mu m]\): \( g_L(x) = M \delta(x + w_p/2) \). What is the intensity, \( M \), of the impulse excitation?

\[
M = \text{_________________________ hole-electron pairs/s-cm}^2
\]

b) i) [4 pts.] What is the excess hole concentration, \( p' \), at the ohmic contact on the right of the device at \( x = w_n \)?

\[
p'(w_n) = \text{_________________________ cm}^{-3}
\]

ii) [4 pts.] What is the excess hole concentration, \( p' \), at the edge of the depletion region on the n-side of the device, that is at \( x = x_n \)?

\[
p'(x_n) = \text{_________________________ cm}^{-3}
\]

iii) [4 pts.] What is the hole current density as a function of position, \( J_h(x) \), on the n-side of this device, that is, for \( x_n < x < w_n \)? Assume \( x_n \ll w_n \) for any calculations.

\[
J_h(x) \text{ [Amps/cm}^2]\text{:}
\]

c) [6 pts.] What is the total diode current, \( I_D \), through the device when it is excited with light and biased in this way?

\[
I_D = \text{_________________________ Amps}
\]

Problem 3 continues on the next page
Problem 3e continued

d) [5 pts.] What is the value of the bias voltage, $V_{AB}$? [Note: This question could have been asked as Part a; the second figure gives you the information you need to answer it.]

\[ V_{AB} = \underline{\phantom{00000000}} \text{ Volts} \]

End of Problem 3; End of Exam