Physics of Electronics

Problem Set 3:
Chapters 06 & 07

July – December 2008

Semiconductors

1. Show that the minimum conductivity attainable by a particular semiconductor at a given temperature is of the form

$$\sigma_{\min} = C(\mu_e \mu_h)^{1/2}$$

where μ_e and μ_h are the carrier mobilities and C is a constant to be determined. Why does the conductivity not possess its minimum value when the semiconductor is intrinsic? How might the minimum conductivity be realized in practice?

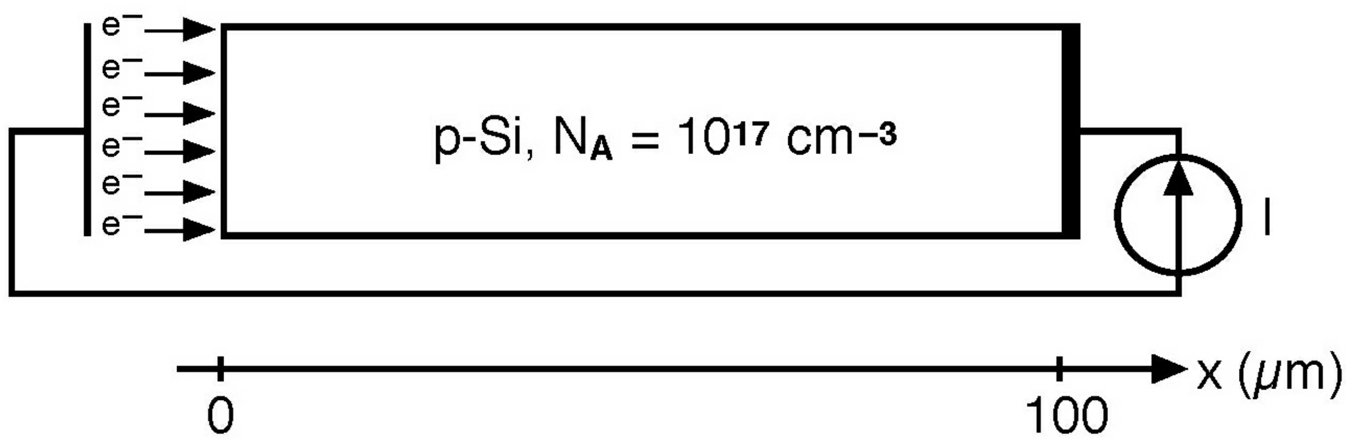
2. An unknown semiconductor has $E_g = 1.1\ eV$ and $N_c = N_v$. It is doped with $10^{15}\ cm^{-3}$ donors where the donor level is 0.2 eV below E_C. Given that E_F is 0.25 eV below E_c, calculate n_i and the concentration of electrons and holes in the semiconductor at 300 K.

3. A bar of n-type germanium $10\ \text{mm} \times 1\ \text{mm} \times 1\ \text{mm}$ is mounted in a magnetic field of 0.2 T. The electron density in the bar is $7 \times 10^{21}\ \text{m}^{-3}$. If 1 mV is applied across the long ends of the bar, determine the current through the bar, the Hall coefficient and the voltage between Hall electrodes placed across the short dimensions of the bar. Assume $\mu_e = 0.39\ \text{m}^2\ \text{V}^{-1}\ \text{s}^{-1}$.

Semiconductors

4. A rod of p-type germanium, 6 mm long, 1 mm wide and 0.5 mm thick, has an electrical resistance of 120 Ω. What is the impurity concentration? Assume $\mu_h = 0.19\ m^2\ V^{-1}\ s^{-1}$, $\mu_e = 0.39\ m^2\ V^{-1}\ s^{-1}$ and $n_i = 2.5 \times 10^{19}\ m^{-3}$. What proportion of the conductivity is due to electrons in the conduction band?

5. This problem concerns a bar of p-type silicon, $N_A = 10^{17}\ cm^{-3}$, irradiated on its left end with a uniform electron beam having an electron flux of $10^{19}\ cm^{-2}s^{-1}$ illustrated below. As shown, the sample is 100 μm 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 cm²/V-s; the electron mobility, μ_e, is 1600 cm²/V-s; the electron diffusion length, L_e, is 10 μm; and the intrinsic carrier concentration at room temperature, n_i, is $10^{10}\ cm^{-3}$.



Semiconductors

5. cont

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.

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

c) Write an expression for the electron current density, $J_e(x)$, valid for $0 < x < 100$ µm.

d) Write an expression for the hole current density, $J_h(x)$, valid for $0 < x < 100$ µm.

e) Write an expression for the electric field, $E_x(x)$, valid for $0 < x < 100$ µm.

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 µm.

GENERAL NOTE: 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.

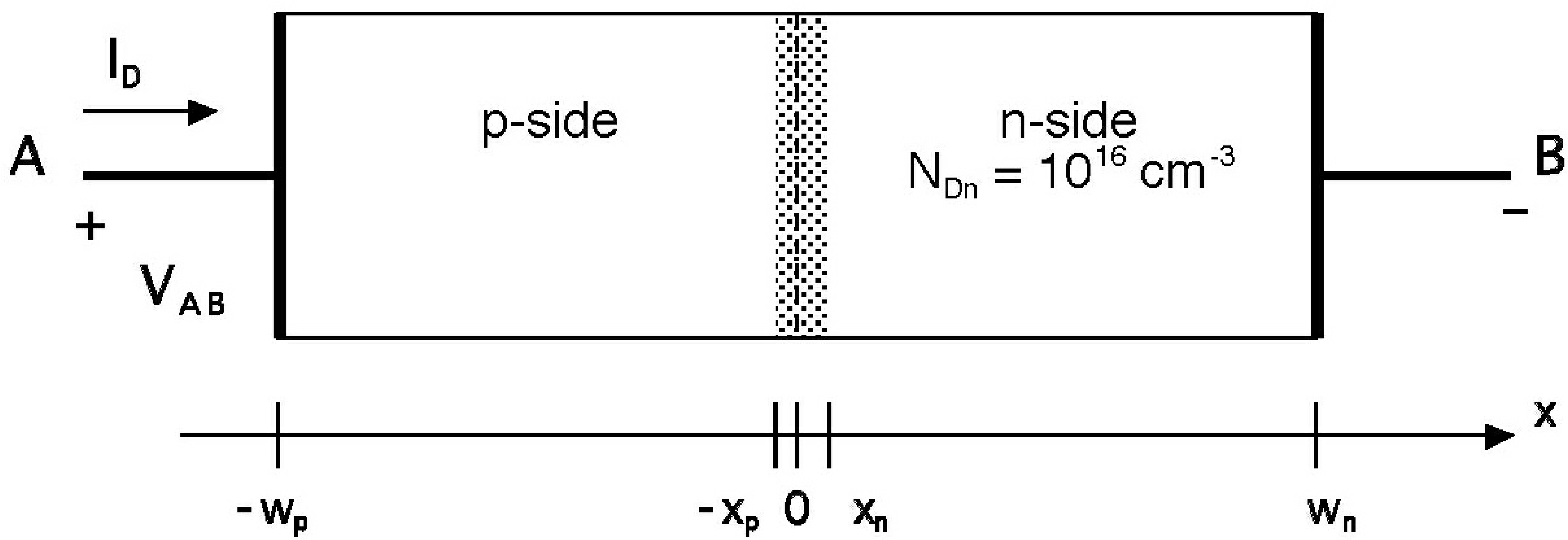
Junction Diodes

7. An ideal abrupt pn junction has the following properties: doping concentration on the p-side, $10^{24}\ \mathrm{m^{-3}}$; doping concentration on the n-side, $10^{22}\ \mathrm{m^{-3}}$; area of cross section, $10^{-6}\ \mathrm{m^2}$; hole mobility, $0.2\ \mathrm{m^2\,V^{-1}\,s^{-1}}$; electron mobility, $0.4\ \mathrm{m^2\,V^{-1}\,s^{-1}}$; diffusion length of minority holes, $2 \times 10^{-4}\ \mathrm{m}$; diffusion length of minority electrons, $3 \times 10^{-4}\ \mathrm{m}$; bulk relative permittivity, 16; intrinsic carrier density, $10^{19}\ \mathrm{m^{-3}}$. Evaluate the following parameters of the diode at room temperature: (a) the majority and minority concentrations; (b) the conductivities of each region; (c) the contact potential; (d) the diffusion constants for each carrier type; (e) the diode saturation current; (f) the current flowing when 0.25 V is applied to the diode with the positive terminal connected to the p-type material; (g) the current flowing for large reverse bias voltages; (h) the battery polarity for the application of reverse bias; (i) the width of the depletion layer when a reverse bias voltage of 10 V is applied; (j) the incremental depletion-layer capacitance under the bias conditions as for (i); and (k) the approximate ratio of hole to electron current across the junction.

8. A planar pn junction in silicon has conductivities of $1000\ \mathrm{S\,m^{-1}}$ and $20\ \mathrm{S\,m^{-1}}$ and minority-carrier lifetimes of $5\ \mu\mathrm{s}$ and $1\ \mu\mathrm{s}$ for the p- and n-regions respectively. Calculate the ratio of hole current to electron current in the depletion layer, the saturation current density and the total current density flowing through the junction with a forward bias of 0.3 V. Assume room temperature, $n_i = 1.4 \times 10^{16}\ \mathrm{m^{-3}}$, $\mu_e = 0.12\ \mathrm{m^2\,V^{-1}\,s^{-1}}$ and $\mu_h = 0.05\ \mathrm{m^2\,V^{-1}\,s^{-1}}$.

Junction Diodes

9. The p- and n-sides of the silicon p-n diode shown below 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_{min} >> 2 μm. 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 of the diode is 10^{-4} cm^2.



Junction Diodes

9. cont

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

i. Total hole population at the contact on the right end of the device, w^n.

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

iii. Excess 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 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.

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 biased junction?