Alexandria University
Faculty of Engineering
Electrical Engineering Department

ECE 336: Semiconductor Devices
Sheet 3

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1. Applying the depletion approximation to a linearly graded junction with $N_d - N_a = ax$, derive expressions for
   a. the electric field distribution,
   b. the potential distribution,
   c. the built-in potential, and
   d. the depletion-layer width.

2. Consider a silicon PN step junction diode with $N_d = 10^{16}\text{cm}^{-3}$ and $N_a = 5 \times 10^{15}\text{cm}^{-3}$.Assume T =300 K.
   a. Calculate the built-in potential
   b. Calculate the depletion-layer width (W_{dep}) and its length on the N side (x_n) and P side (x_p).
   c. Calculate the maximum electric field.
   d. Sketch the energy band diagram, electric potential, electric field distribution, and the space-charge profile.
   e. Now let $N_a = 10^{18}\text{cm}^{-3}$ Repeat (a), (b), and (c). Compare these to the previous results. How have the depletion widths changed?

3. A silicon sample maintained at 300 K is characterized by the energy band diagram in Fig. 4–48:

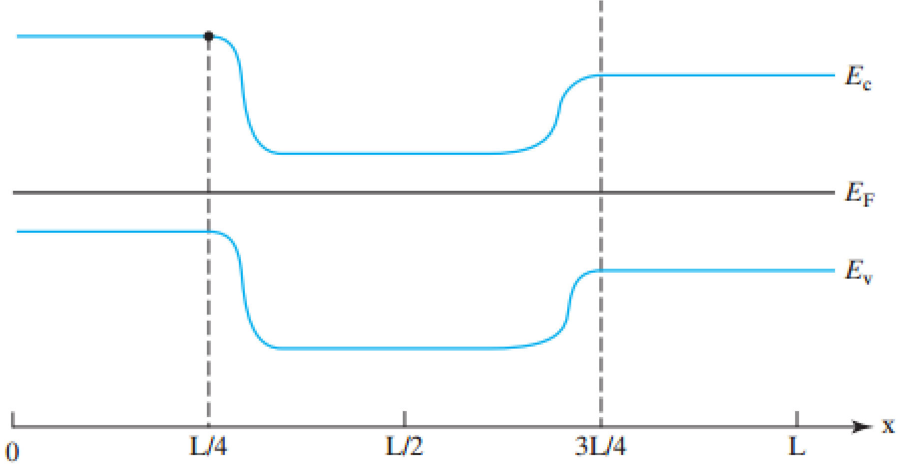


FIGURE 4–48

   a. Does the equilibrium condition prevail? How do you know?
   b. Roughly sketch n and p versus x.
   c. Sketch the electrostatic potential (Φ) as a function of x.
   d. Assume that the carrier pictured on Fig. 4–48 by the dot may move without changing its total energy. Sketch the kinetic and potential energies of the carrier as a function of its position x.

4. Consider the P-I-N structure shown in (Fig. 4–49). The I region is intrinsic. Determine the quantities in (a) and (c). Assume that no bias is applied. (Hint: It may be helpful to think of the I region as a P or N and then let the doping

concentration approach zero. That is, $N_d \cong N_a \cong 0$.)

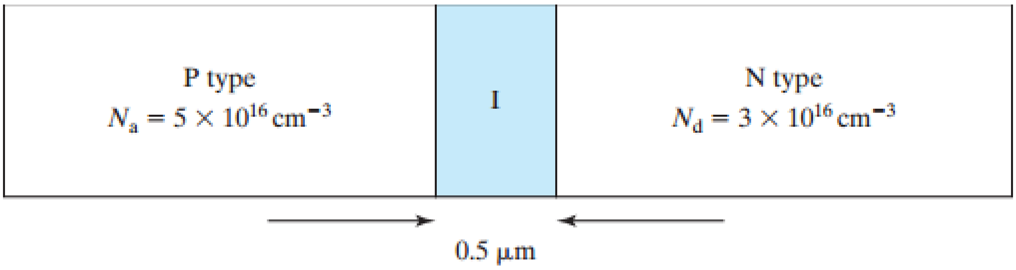


FIGURE 4–49

   a. Find the depletion-layer width (W_{dep}) and its widths on the N side (x_n) and the P side.
   b. Calculate the maximum electric field.
   c. Find the built-in potential.
   d. Now assume that a reverse bias is applied. If the critical field for breakdown in silicon is 2×10^5V/cm, compare the breakdown voltages between the P-I-N structure and a P-N structure (without the I region) with the doping levels shown above.
   If interested, you can find more P-I-N diode examples at http://jas.eng.buffalo.edu/education/pin/pin2/index.html.

5. Consider a P^+N junction diode with $N_d = 10^{16}$ cm^{-3} in the N region.
   a. Determine the diffusion length Lon the N-type side.
   b. What are the excess hole density and excess electron density at the depletion-layer edge on the N-type side under (a) equilibrium and (b) forward bias V= 0.4 V?

6. Consider an ideal, silicon PN junction diode with uniform cross section and constant doping on both sides of the junction. The diode is made from 1 Ωcm P-type and 0.2Ωcm N-type materials in which the recombination lifetimes are $\tau_n = 10^{-6}$s and $\tau_p = 10^{-8}$s, respectively.
   a. What is the value of the built-in voltage?
   b. Calculate the density of the minority carriers at the edge of the depletion layer when the applied voltage is 0.589 V (which is 23 × kT/q).
   c. Sketch the majority and minority carrier current as functions of distance from the junction on both sides of the junction, under the bias voltage of part (b).
   d. Calculate the location(s) of the plane (or planes) at which the minority carrier and majority carrier currents are equal in magnitude.

7. Consider the silicon P^+N junction diode pictured in Fig. 4–52. $\tau_p = \infty$ for $0 \le \times \le x$ band $\tau_p = 0$ for $x_b \le \times \le x_c$. Excluding biases that would cause high-level injection or breakdown, develop an expression for the IV characteristic of the diode. Assume the depletion-layer width (W_{dep}) never exceeds x_b for all biases of interest. The tinted regions are simply the metal contacts.

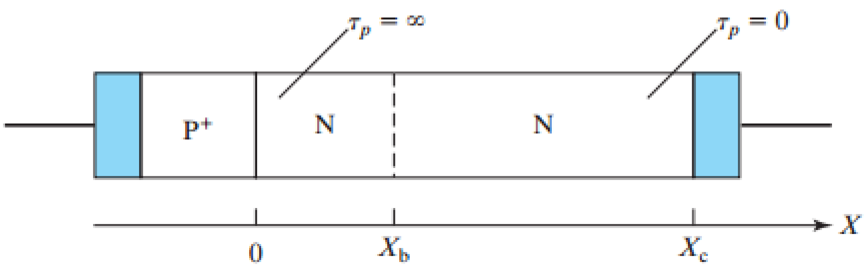


FIGURE 4–52

8. Consider an ideal, long-base, silicon abrupt P^+N junction diode with uniform cross section and constant doping on either side of the junction. The diode is made from a heavily doped P-type material and $0.5\,\Omega$cm N-type materials in which the minority carrier lifetime is $\tau_p = 10^{-8}$s. Answer the following questions on the n side of the junction only.
    a. Calculate the density of the minority carriers as a function of x(distance from the junction) when the applied voltage is 0.589 V (which is $23 \times kT/q$).
    b. Find and sketch the majority and minority carrier currents as functions of x (distance from the junction), under the applied bias voltage of part (a).
    c. What is the majority carrier diffusion current as a function of x?
       The purpose of the following questions is to showthat the minority drift current is negligible.
    d. Use the results of parts (b) and (c) to find the majority carrier drift current, J_{ndrift}. Then find electric field (x), and finally the minority drift current J_{pdrift}. Is $J_{pdrift} << J_{pdiff}$? Sketch J_{pdrift} and J_{pdiff} in the same graph.
    e. Justify the assumption of n' = p'.

9. The forward-bias voltage (V) required to maintain a PN diode current (I) is a function of the temperature (T).
    a. Derive an expression for $\delta V/\delta T$.
    b. What is a typical value for a silicon diode?
    c. Compare the result of (b) with a numerical value extracted from Fig. 4–21.

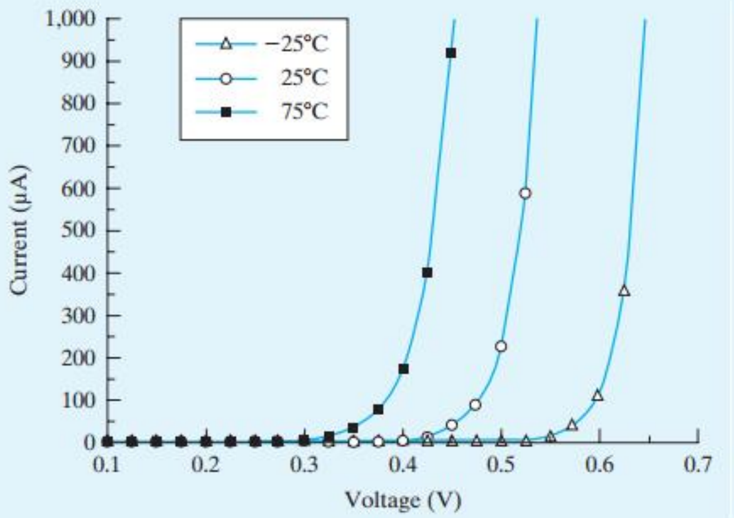


FIGURE 4–21 The *IV* curves of the silicon PN diode shift to lower voltages with increasing temperature.

10. Assume that the neutral regions of a PN diode present a series resistance Rsuch that the voltage across the PN junction is not V but V-RI.
    a. How should Eq. (4.9.4) be modified?

$$I = I_0(e^{qV/kT} - 1)$$

    b. Find an expression of Vas a function of I.
    c. Sketch a typical I–Vcurve without Rfor Ifrom 0 to 100 mA. Sketch a second I–V curve in this figure for R= 200 Ωwithout using a calculator.

11. A PN diode with lengths much larger than the carrier diffusion length such as shown in Fig. 4–18 is called a long-base diode. A short-base diode has lengths much shorter than the diffusion lengths, and its excess carrier concentration is similar to that shown in Fig. 8–6. A uniformly doped short-base Si diode has Nd= 10^{17}cm^{-3} and N_a= 10^{16}cm^{-3}, $\tau_p = \tau_n = 1$ μs, D_p= 10 cm^2/s, D_n= 30 cm^2/s, and cross-sectional area = 10^{-5}cm^{-2}. The length of the quasi-neutral N-type and P-type regions W_E'= W_B'= 1 μm. The diode is at room temperature under applied forward bias of 0.5 V. Answer the following questions:

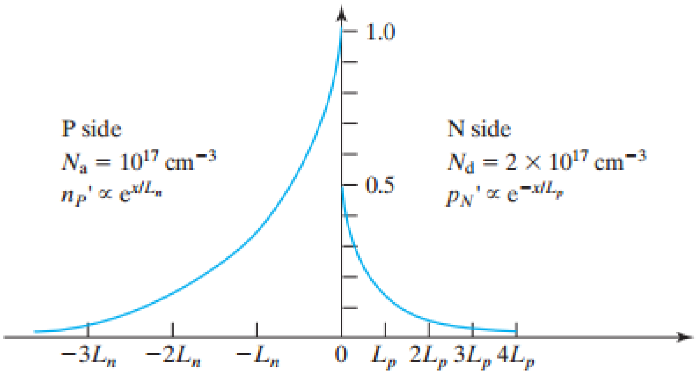
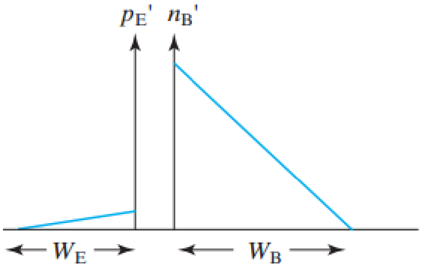


FIGURE 4–18 Normalized n' and p'. $n'(0) = 2p'(0)$ because $N_d = 2N_a$. $L_n = 2L_p$ is assumed.



(b)

FIGURE 8–6 (a) Schematic of electron and hole flow paths in BJT; (b) hole injection into emitter closely parallels electron injection into base.[2]

    a. Show that the total current and the sum of the charge stored on both N and P sides of the junction are proportional to each other: $Q_t = I_t \tau_s$. Find the expression for τ_s. Use the short-base approximation, i.e., assume that the excess minority carrier concentration decreases linearly from its maximum value at the edge of the depletion region to zero at the ohmic contacts at either end of the diode.
    b. τ_s is called the charge-storage time. Show that it is significantly smaller than τ_p and τ_n.
    c. Which diode can operate at a higher frequency, short-based or long-based?