Alexandria University
Faculty of Engineering
Electrical Engineering Department

ECE 336: Semiconductor Devices
Sheet 2

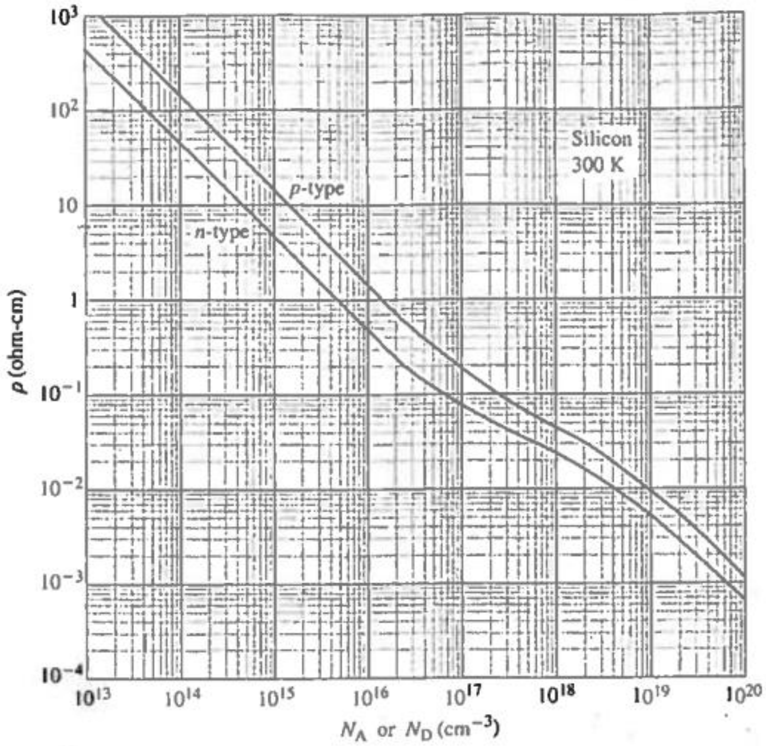
Chapter 3:

1- Using the energy band model for a semiconductor, indicate how one visualizes
   a. The existence of a field in a semiconductor.
   b. An electron with kinetic energy = 0.
   c. A hole with Kinetic energy = $E_G/4$.
   d. Photogeneration

2- Short answer:
   a. An average whole drift velocity of 10^3cm/sec when 2V is applied across a 1-cm-long semiconductor bar. What is the mobility inside the bar?
   b. Name the two dominant carrier scattering mechanisms in nondegenerately doped semiconductors of device quality.
   c. For a given semiconductor the carrier mobilities in intrinsic material are (higher than – lower than – the same as) those in heavily doped material. Briefly explain why the mobilities in intrinsic material are (chosen answer) those in heavily doped material.
   d. Two GaAs wafers, one n-type, one p-type are uniformly doped such that $N_D = N_A >> n_i$ Which wafer will exhibit larger resistivity? Explain.
   e. The electron mobility in a silicon sample is determined to be 1300cm^2/V-sec at room temperature. What is the electron diffusion coefficient?
   f. What is the algebraic statement of low-level injection?

3- More resistivity questions:
   a. A silicon sample maintained at room temperature is uniformly doped with $N_D = 10^{16}$ /cm^3 donors. Calculate the resistivity of the sample using equation (3.8a) compare your results with the ρ deduced from figure 3.8a.
   b. The silicon sample of part (a) is compensated by adding $N_A = 10^{16}$/cm^3 acceptors. Calculate the resistivity of the compensated sample. (Caution in choosing the mobility values to be employed in this part of the problem).
   c. Compute the resistivity of intrinsic ($N_A = 0$, $N_D = 0$) silicon at room temperature. How does your results here compare with that for part (b)?
   d. A 500-ohm resistor is to be made from a bar-shaped piece of n-type Si. The bar has a cross sectional area of $10^{-2}$$cm^2$ and a current-carrying length of 1cm. Determine the doping required.
   e. A lightly doped ($N_D < 10^{14}$/cm^3) Si sample is heated up from room temperature to 100 degrees C. $N_D >> n_i$ at both room temperature and 100 degrees. Is the resistivity of the sample expected to increase or decrease? Explain.

$$\rho = \frac{1}{q\mu_n N_D} \quad \text{. . . n-type semiconductor} \tag{3.8a}$$



4- Making use of the mobility fit relationships and parameters in exercise 3.1, construct a plot of the silicon resistivity vs. impurity concentration at T = 300K. Include both n-type and p-type silicon over the range $10^{13}/cm^3 \le N_A$ or $N_D \le 10^{20}/cm^3$. Compare your results with fig. 3.8a.

(C) Exercise 3.1

There exist surprisingly accurate "empirical-fit" relationships that are widely employed to compute the carrier mobilities at a given doping and temperature. Figures 3.5 and 3.7 were constructed using such relationships. The form of a computational relationship is typically established on an empirical basis by noting the general functional dependencies predicted theoretically and observed experimentally. Parameters in the relationship are then adjusted until an acceptable match is obtained to the best available experimental data.

The majority carrier mobility versus doping at room temperature is popularly computed from

$$\mu = \mu_{min} + \frac{\mu_0}{1 + (N/N_{ref})^\alpha}$$

where μ is the carrier mobility (μ_n or μ_p), N is the doping concentration (N_A or N_D), and all other quantities are fit parameters. To model the temperature dependence, one additionally employs

$$A = A_{300}\left(\frac{T}{300}\right)^\eta$$

A in the above equation represents μ_{min}, μ_0, N_{ref}, or α; A_{300} is the 300 K value of the parameter, T is temperature in Kelvin, and η is the temperature exponent. The fit parameters appropriate for Si are listed in the following table:

Parameter	Value at 300 K Electrons	Holes	Temperature Exponent (η)
N_{ref} (cm^{-3})	1.3×10^{17}	2.35×10^{17}	2.4
μ_{min} (cm^2/V-sec)	92	54.3	−0.57
μ_0 (cm^2/V-sec)	1268	406.9	−2.33 electrons −2.23 holes
α	0.91	0.88	−0.146

P: (a) Construct a log-log plot of μ_n and μ_p versus N_A or N_D for $10^{14}/cm^3 \le N_A$ or $N_D \le 10^{19}/cm^3$ using the quoted fit relationship and the listed Si fit parameters. Compare your result with Fig. 3.5(a).

(b) Construct log-log plots of μ_n versus T and μ_p versus T for $200\ K \le T \le 500\ K$ and N_D or N_A stepped in decade values from $10^{14}/cm^3$ to $10^{18}/cm^3$. Compare your results with Figs. 3.7(a) and 3.7(b), respectively.

5- Resistors in ICs are sometimes thin semiconductor layers near the surface of a wafer. However, formation of the layer by diffusion or ion implantation is likely to give rise to a doping concentration that varies with th depth into the layer. Let us examine how the resistance is computed when the doping varies with depth.

   a. Given a bar-shaped layer of width W, length L and depth d, and assuming arbitrary $N_D(x)$ variation with the depth x from the wafer surface, show that the resistance of the layer is to be computed from

$$R = \frac{L}{W}\left[\frac{1}{q\int_0^d \mu_n(x) N_D(x)\,dx}\right]$$

   b. Taking $N_D(x) = N_{D0}\exp(-ax) + N_{DB}$, compute and plot R versus N_{D0} for $10^{14}/cm^3 <= N_{D0} <= 10^{18}/cm^3$ when L = W, d = 5µm and 1/a = 1µm.

6- Thermal energy alone was noted to contribute to relatively high carrier velocities inside of a semiconductor. Considering a nondegenerate semiconductor maintained at room temperature, compute the thermal velocity of electrons having kinetic energy corresponding to the peak of the electron distribution in the conduction band. Set $m^* = m_0$ in performing your calculation.

7- Six different silicon samples maintained at 300K are characterized by the energy band diagrams in the figure. Answer the questions that follow after choosing a specific diagram for analysis. Possibly repeat using other energy band diagrams. (Excessive repetitions have been known to lead to the onset of insanity.)

   a. Do equilibrium conditions prevail? How do you know?
   b. Sketch the electrostatic potential V inside the semiconductor as a function of x.
   c. Sketch the electric field E inside the semiconductor as a function of x.
   d. The carrier pictured on the diagram moves back and forth etween x=0 and x=L without changing its total energy. Sketch K.E and P.E of the carrier as a function of position inside the semiconductor. Let E_F be the reference level.
   e. Roughly sketch n and p versus x.
   f. On the same set of coordinates, make a rough sketch of the electron drift-current density and the electron diffusion current density inside the Si sample as a function of position. Be sure to graph the proper polarity of

the current densities at all points and clearly identify your two components. Also briefly explain how you arrived at your sketch.

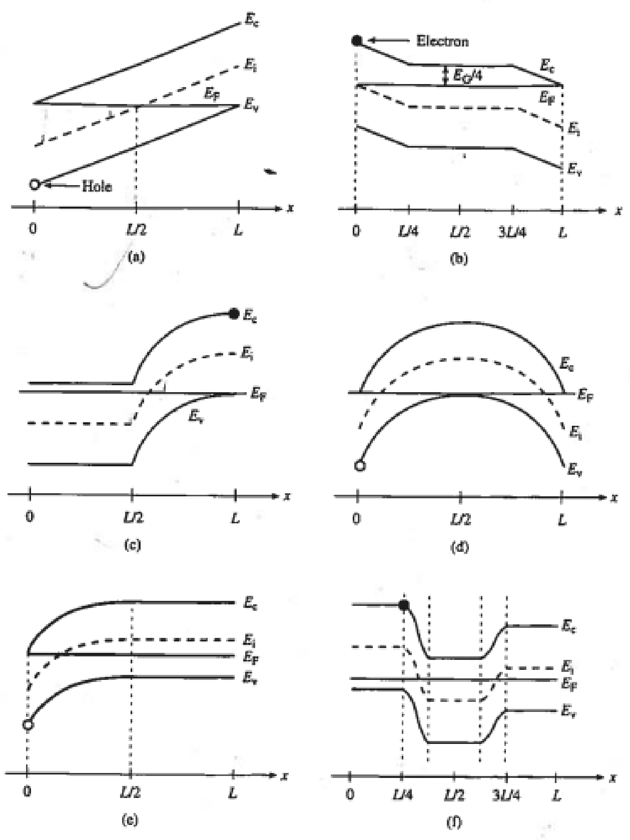


Figure P3.12

8- A nonuniform doping in the central region of bipolar junction transistors creates a build-in field that assists minority carriers across the region and increases the maximum operating speed of the device. Suppose the BJT is a Si device maintained under equilibrium conditions at room temperature with a central region of length L. Moreover the nonuniform acceptor doping is such that

$$p(x) \cong N_A(x) = n_i e^{(a-x)/b} \quad \ldots 0 \le x \le L$$

where a = 1.8µm , b = 0.1µm and L= 0.8µm.

a. Draw the energy band diagram for 0<=x<=L region specifically showing E_c , E_F, E_i , and E_v on your diagram. Explain how you arrived at your diagram.
b. Make a sketch of the E-field inside the region as a function of position, and compute the value of E at x = L/2.
c. Is the built-in electric field such as to aid the motion of minority carrier electrons going from x=0 to x=L? Explain.

9- Answer the following

a. Based on the information found in the text, roughly sketch the expected variation of D_N and D_P versus doping appropriate for 10^{14}/cm^3 <= N_A or N_D <= 10^{18}/cm^3 doped Si maintained at T = 300K. Explain how you arrived at the form of your sketch.
b. Making use of the fit relationships in Exercise 3.1, construct a plot of D_N and D_P versus N_A or N_D for 10^{14}/cm^3 <= N_A or N_D<= 10^{18}/cm^3 doped Si maintained at T = 300k.
c. Why was the upper doping limit taken to be 10^{18}/cm^3 in part b of the computation?