# PROBLEMS

## 2.1 Solid-State Electronic Materials

2.1. Pure aluminum has a resistivity of 2.83 μΩ · cm. Based on its resistivity, should aluminum be classified as an insulator, semiconductor, or conductor?

2.2. The resistivity of silicon dioxide is $10^{15}$ Ω · cm. Is this material a conductor, semiconductor, or insulator?

2.3. An aluminum interconnection line in an integrated circuit can be operated with a current density up to 10 MA/cm². If the line is 5 μm wide and 1 μm high, what is the maximum current permitted in the line?

## 2.2 Covalent Bond Model

2.4. An aluminum interconnection line runs diagonally from one corner of a 20 mm × 20 mm silicon integrated circuit die to the other corner. (a) What is the resistance of this line if it is 1 μm thick and 5 μm wide? (b) Repeat for a 0.5 μm thick line. The resistivity of pure aluminum is 2.82 μΩ-cm.

2.5. Copper interconnections have been introduced into state-of-the-art ICs because of its lower resistivity. Repeat Prob. 2.4 for pure copper with a resistivity of 1.66 μΩ-cm.

2.6. Calculate the intrinsic carrier densities in silicon and germanium at (a) 77 K, (b) 300 K, and (c) 500 K. Use the information from the table in Fig. 2.4.

2.7. (a) At what temperature will $n_i = 10^{13}/\text{cm}^3$ in silicon? (b) Repeat the calculation for $n_i = 10^{15}/\text{cm}^3$.

2.8. Calculate the intrinsic carrier density in gallium arsenide at (a) 300 K, (b) 100 K, (c) 450 K. Use the information from the table in Fig. 2.4.

2.9. Use Eq. (2.1) to calculate the actual temperature that corresponds to the value $n_i = 10^{10}/\text{cm}^3$ in silicon.

## 2.3 Drift Currents and Mobility in Semiconductors

2.10. Electrons and holes are moving in a uniform, one-dimensional electric field $E = +2500$ V/cm. The electrons and holes have mobilities of 700 and 250 cm²/V · s, respectively. What are the electron and hole velocities? If $n = 10^{17}/\text{cm}^3$ and $p = 10^3/\text{cm}^3$, what are the electron and hole current densities?

2.11. The maximum drift velocities of electrons and holes in silicon are approximately $10^7$ cm/s. What are the electron and hole current densities if $n = 10^{18}/\text{cm}^3$ and $p = 10^2/\text{cm}^3$? What is the total current density?

2.12. A current density of –2000 A/cm² exists in a semiconductor having a charge density of 0.01 C/cm³. What are the carrier velocities?

2.13. The maximum drift velocity of electrons in silicon is $10^7$ cm/s. If the silicon has a charge density of 0.4 C/cm³, what is the maximum current density in the material?

2.14. A silicon sample is supporting an electric field of −2000 V/cm, and the mobilities of electrons and holes are 1000 and 400 cm²/V · s, respectively. What are the electron and hole velocities? If $p = 10^{17}/\text{cm}^3$ and $n = 10^3/\text{cm}^3$, what are the electron and hole current densities?

2.15. (a) A voltage of 5 V is applied across a 10-μm-long region of silicon. What is the electric field? (b) Suppose the maximum field allowed in silicon is $10^5$ V/cm. How large a voltage can be applied to the 10-μm region?

2.16. The maximum drift velocity for holes in silicon is $10^7$ cm/s. If the hole density in a sample is $10^{19}/\text{cm}^3$, what is the maximum hole current density? If the sample has a cross section of 1 μm × 25 μm, what is the maximum current?

## 2.4 Resistivity of Intrinsic Silicon

2.17. At what temperature will intrinsic silicon become an insulator, based on the definitions in Table 2.1? Assume that $\mu_n = 2000$ cm²/V · s and $\mu_p = 750$ cm²/V · s.

2.18. At what temperature will intrinsic silicon become a conductor based on the definitions in Table 2.1? Assume that $\mu_n = 100$ cm²/V · s and $\mu_p = 50$ cm²/V · s. (Note that silicon melts at 1430 K.)

## 2.5 Impurities in Semiconductors

2.19. Draw a two-dimensional conceptual picture [similar to Fig. 2.6] of the silicon lattice containing one donor atom and one acceptor atom in adjacent lattice positions. Are there any free electrons or holes?

2.20. Crystalline germanium has a lattice similar to that of silicon. (a) What are the possible donor atoms in Ge based on Table 2.2? (b) What are the possible acceptor atoms in Ge based on Table 2.2?

2.21. GaAs is composed of equal numbers of atoms of gallium and arsenic in a lattice similar to that of silicon. (a) Suppose a silicon atom replaces a gallium atom in the lattice. Do you expect the silicon atom to behave as a donor or acceptor impurity? Why? (b) Suppose a silicon atom replaces an arsenic atom in the lattice. Do you expect the silicon atom to behave as a donor or acceptor impurity? Why?

2.22. InP is composed of equal atoms of indium and phosphorus in a lattice similar to that of silicon. (a) Suppose a germanium atom replaces an indium atom in the lattice. Do you expect the germanium atom to behave as a donor or acceptor impurity? Why? (b) Suppose a germanium atom replaces a phosphorus atom in the lattice. Do you expect the germanium atom to behave as a donor or acceptor impurity? Explain.

2.23. A current density of 10,000 A/cm$^2$ exists in a 0.02-$\Omega \cdot$ cm $n$-type silicon sample. What is the electric field needed to support this drift current density?

2.24. The maximum drift velocity of carriers in silicon is approximately $10^7$ cm/s. What is the maximum drift current density that can be supported in $n$-type silicon with a doping of $10^{17}$/cm$^3$?

2.25. Silicon is doped with $10^{16}$ boron atoms/cm$^3$. How many boron atoms will be in a silicon region that is 0.5 $\mu$m long, 5 $\mu$m wide, and 0.5 $\mu$m deep?

## 2.6 Electron and Hole Concentrations in Doped Semiconductors

2.26. Silicon is doped with $3 \times 10^{17}$ arsenic atoms/cm$^3$. (a) Is this $n$- or $p$-type silicon? (b) What are the hole and electron concentrations at room temperature? (c) What are the hole and electron concentrations at 250 K?

2.27. Silicon is doped with $6 \times 10^{18}$ boron atoms/cm$^3$. (a) Is this $n$- or $p$-type silicon? (b) What are the hole and electron concentrations at room temperature? (c) What are the hole and electron concentrations at 200 K?

2.28. Silicon is doped with $2 \times 10^{18}$ arsenic atoms/cm$^3$ and $8 \times 10^{18}$ boron atoms/cm$^3$. (a) Is this $n$- or $p$-type silicon? (b) What are the hole and electron concentrations at room temperature?

2.29. Silicon is doped with $5 \times 10^{17}$ boron atoms/cm$^3$ and $2 \times 10^{17}$ phosphorus atoms/cm$^3$ (a) Is this $n$- or $p$-type silicon? (b) What are the hole and electron concentrations at room temperature?

2.30. Suppose a semiconductor has $N_D = 10^{16}$/cm$^3$, $N_A = 5 \times 10^{16}$/cm$^3$, and $n_i = 10^{11}$/cm$^3$. What are the electron and hole concentrations?

2.31. Suppose a semiconductor has $N_A = 10^{15}$/cm$^3$, $N_D = 10^{14}$/cm$^3$, and $n_i = 5 \times 10^{13}$/cm$^3$. What are the electron and hole concentrations?

2.32. Suppose a semiconductor has $N_A = 2 \times 10^{17}$/cm$^3$, $N_D = 3 \times 10^{17}$/cm$^3$, and $n_i = 10^{17}$/cm$^3$. What are the electron and hole concentrations?

## 2.7 Mobility and Resistivity in Doped Semiconductors

2.33. Silicon is doped with a donor concentration of $5 \times 10^{16}$/cm$^3$. Find the electron and hole concentrations, the electron and hole mobilities, and the resistivity of this silicon material at 300 K. Is this material $n$- or $p$-type?

2.34. Silicon is doped with an acceptor concentration of $2.5 \times 10^{18}$/cm$^3$. Find the electron and hole concentrations, the electron and hole mobilities, and the resistivity of this silicon material at 300 K. Is this material $n$- or $p$-type?

2.35. Silicon is doped with an indium concentration of $8 \times 10^{19}$/cm$^3$. Is indium a donor or acceptor impurity? Find the electron and hole concentrations, the electron and hole mobilities, and the resistivity of this silicon material at 300 K. Is this material $n$- or $p$-type?

2.36. A silicon wafer is uniformly doped with $4.5 \times 10^{16}$ phosphorus atoms/cm$^3$ and $5.5 \times 10^{16}$ boron atoms/cm$^3$. Find the electron and hole concentrations, the electron and hole mobilities, and the resistivity of this silicon material at 300 K. Is this material $n$- or $p$-type?

2.37. Repeat Example 2.5 for $p$-type silicon. Assume that the silicon contains only acceptor impurities. What is the acceptor concentration $N_A$?

2.38. Repeat Ex. 2.5 using the equations presented with the graph in Fig. 2.8.

2.39. Repeat Prob. 2.37 using the equations presented with the graph in Fig. 2.8.

*2.40. A $p$-type silicon wafer has a resistivity of 0.5 $\Omega \cdot$ cm. It is known that silicon contains only acceptor impurities. What is the acceptor concentration $N_A$?

*2.41. It is conceptually possible to produce extrinsic silicon with a higher resistivity than that of intrinsic silicon. How would this occur?

*2.42. $n$-type silicon wafers with a resistivity of 3.0 $\Omega \cdot$cm are needed for integrated circuit fabrication. What donor concentration $N_D$ is required in the wafers? Assume $N_A = 0$.

2.43. (a) What is the minimum donor doping required to convert silicon into a conductor based on the definitions in Table 2.1? (b) What is the minimum acceptor doping required to convert silicon into a conductor?

2.44. A silicon sample is doped with $5.0 \times 10^{19}$ donor atoms/cm$^3$ and $5.0 \times 10^{19}$ acceptor atoms/cm$^3$. (a) What is its resistivity? (b) Is this an insulator, conductor, or semiconductor? (c) Is this intrinsic material? Explain your answers.

*2.45. Measurements of a silicon wafer indicate that it is $p$-type with a resistivity of 1 $\Omega \cdot$cm. It is also known that it contains only boron impurities. (a) What additional acceptor concentration must be added to the sample to change its resistivity to 0.25 $\Omega \cdot$cm? (b) What concentration of donors would have to be added to the original sample to change the resistivity to 0.25 $\Omega \cdot$cm? Would the resulting material be classified as $n$- or $p$-type silicon?

*2.46. A silicon wafer has a doping concentration of $1 \times 10^{16}$ phosphorus atoms/cm$^3$. (a) Determine the conductivity of the wafer. (b) What concentration of boron atoms must be added to the wafer to make the conductivity equal to 4.0 $(\Omega \cdot \text{cm})^{-1}$?

*2.47. A silicon wafer has a background concentration of $1 \times 10^{16}$ boron atoms/cm$^3$. (a) Determine the conductivity of the wafer. (b) What concentration of phosphorus atoms must be added to the wafer to make the conductivity equal to 5.5 $(\Omega \cdot \text{cm})^{-1}$?

## 2.8 Diffusion Currents

2.48. Make a table of the values of thermal voltage $V_T$ for $T$ = 50 K, 75 K, 100 K, 150 K, 200 K, 250 K, 300 K, 350 K, and 400 K.

2.49. The electron concentration in a region of silicon is shown in Fig. P2.49. If the electron mobility is 350 cm$^2$/V $\cdot$ s and the width $W_B = 0.5$ μm, determine the electron diffusion current density. Assume room temperature.

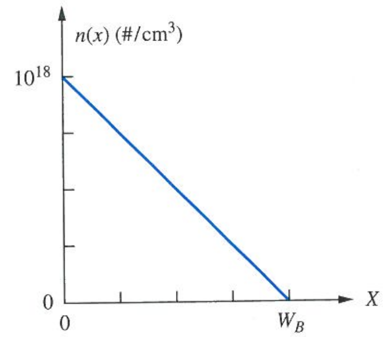


Figure P2.49

2.50. Suppose the hole concentration in silicon sample is described mathematically by

$$p(x) = 10^5 + 10^{19} \exp\left(-\frac{x}{L_p}\right) \text{ holes/cm}^3, x \geq 0$$

in which $L_p$ is known as the diffusion length for holes and is equal to 2.0 μm. Find the diffusion current density for holes as a function of distance for $x \geq 0$ if $D_p$ = 15 cm$^2$/s. What is the diffusion current at $x = 0$ if the cross-sectional area is 10 μm$^2$?

## 2.9 Total Current

*2.51. A 5-μm-long block of $p$-type silicon has an acceptor doping profile given by $N_A(x) = 10^{14} + 10^{18} \exp(-10^4 x)$, where $x$ is measured in cm. Use Eq. (2.17) to demonstrate that the material must have a nonzero internal electric field $E$. What is the value of $E$ at $x = 0$ and $x = 5$ μm? (*Hint:* In thermal equilibrium, the total electron and total hole currents must each be zero.)

2.52. Figure P2.52 gives the electron and hole concentrations in a 2-μm-wide region of silicon. In addition, there is a constant electric field of 20 V/cm present in the sample. What is the total current density at $x = 0$? What are the individual drift and diffusion components of the hole and electron current

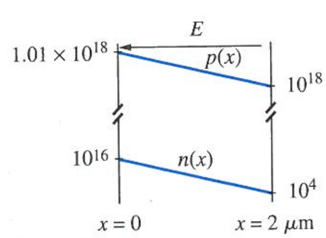


Figure P2.52

densities at $x = 1.0\ \mu m$? Assume that the electron and hole mobilities are 350 and 150 $cm^2/V \cdot s$, respectively.

## 2.10 Energy Band Model

2.53. Draw a figure similar to Fig. 2.15 for the case $N_A > N_D$ in which there are two acceptor atoms for each donor atom.

*2.54. Electron–hole pairs can be created by means other than the thermal activation process as described in Figs. 2.3 and 2.12. For example, energy may be added to electrons through optical means by shining light on the sample. If enough optical energy is absorbed, electrons can jump the energy bandgap, creating electron–hole pairs. What is the maximum wavelength of light that we should expect silicon to be able to absorb? (*Hint:* Remember from physics that energy $E$ is related to wavelength $\lambda$ by $E = hc/\lambda$ in which Planck's constant $h = 6.626 \times 10^{-34}$ J · s and the velocity of light $c = 3 \times 10^{10}$ cm/s.)

## 2.11 Overview of Integrated Circuit Fabrication

2.55. Draw the cross section for a $pn$ diode similar to that in Fig. 2.17(h) if the fabrication process utilizes a $p$-type substrate in place of the $n$-type substrate depicted in Fig. 2.17.

2.56. To ensure that a good ohmic contact is formed between aluminum and $n$-type silicon, an additional doping step is added to the diode in Fig. 2.17(h) to place an $n+$ region beneath the left-hand contact as in Fig. P2.56. Where might this step go in the process flow in Fig. 2.17? Draw a top and side view of a mask that could be used in the process.

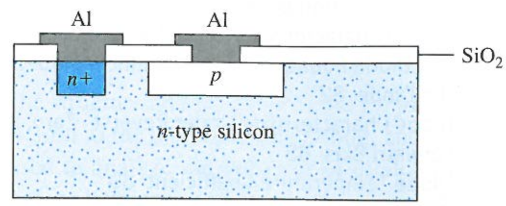


**Figure P2.56**

## Miscellaneous

*2.57. Single crystal silicon consists of three-dimensional arrays of the basic unit cell in Fig. 2.1(a). (a) How many atoms are in each unit cell? (b) What is volume of the unit cell in $cm^3$? (c) Show that the atomic density of silicon is $5 \times 10^{22}$ atoms/$cm^3$. (d) The density of silicon is 2.33 $g/cm^3$. What is the mass of one unit cell? (e) Based on your calculations here, what is the mass of a proton? Assume that protons and neutrons have the same mass and that electrons are much much lighter. Is your answer reasonable? Explain.