produces a ***p*-type** semiconductor in which positive **holes** carry the current. The energy level of impurity atoms lies slightly below the conduction band in an *n*-type semiconductor, and acts as a **donor** from which electrons readily pass into the conduction band. The energy level of impurity atoms in a *p*-type semiconductor lies slightly above the valence band and acts as an **acceptor** level, since electrons from the valence band easily reach it, leaving holes behind to act as charge carriers.

A semiconductor **diode** consists of a ***pn* junction** and allows current to flow in one direction only; it can be used as a **rectifier** to change ac to dc. Common **transistors** consist of three semiconductor sections, either as ***pnp*** or ***npn***. Transistors can amplify electrical signals and find many other uses. An integrated circuit consists of a tiny semiconductor crystal or **chip** on which many transistors, diodes, resistors, and other circuit elements have been constructed using careful placement of impurities.

Questions

*1. What type of bond would you expect for (*a*) the N_2 molecule, (*b*) the HCl molecule, (*c*) Fe atoms in a solid?

*2. Describe how the molecule $CaCl_2$ could be formed.

*3. Does the H_2 molecule have a permanent dipole moment? Does O_2? Does H_2O? Explain.

*4. Although the molecule H_3 is not stable, the ion H_3^+ is. Explain, using the Pauli exclusion principle.

*5. The energy of a molecule can be divided into four categories. What are they?

*6. Would you expect the molecule H_2^+ to be stable? If so, where would the single electron spend most of its time?

*7. Explain why the carbon atom ($Z = 6$) usually forms four bonds with hydrogen-like atoms.

*8. If conduction electrons are free to roam about in a metal, why don't they leave the metal entirely?

*9. Explain why the resistivity of metals increases with temperature whereas the resistivity of semiconductors may decrease with increasing temperature.

*10. Figure 29–33 shows a "bridge-type" full-wave rectifier. Explain how the current is rectified and how current flows during each half cycle.

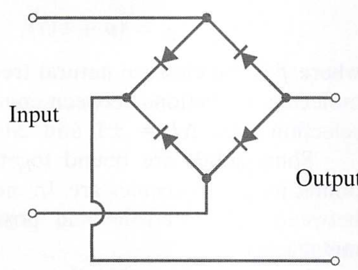

FIGURE 29–33 Question 10.

*11. Compare the resistance of a *pn* junction diode connected in forward bias to its resistance when connected in reverse bias.

*12. Explain how a transistor could be used as a switch.

*13. What is the main difference between *n*-type and *p*-type semiconductors?

*14. Describe how a *pnp* transistor can operate as an amplifier.

*15. In a transistor, the base–emitter junction and the base–collector junction are essentially diodes. Are these junctions reverse-biased or forward-biased in the application shown in Fig. 29–32?

*16. A transistor can amplify an electronic signal, meaning it can increase the power of an input signal. Where does it get the energy to increase the power?

*17. A silicon semiconductor is doped with phosphorus. Will these atoms be donors or acceptors? What type of semiconductor will this be?

*18. Do diodes and transistors obey Ohm's law? Explain.

*19. Can a diode be used to amplify a signal? Explain.

Problems

* 29–1 to 29–3 Molecular Bonds

*1. (I) Estimate the binding energy of a KCl molecule by calculating the electrostatic potential energy when the K^+ and Cl^- ions are at their stable separation of 0.28 nm. Assume each has a charge of magnitude 1.0*e*.

*2. (II) The measured binding energy of KCl is 4.43 eV. From the result of Problem 1, estimate the contribution to the binding energy of the repelling electron clouds at the equilibrium distance $r_0 = 0.28$ nm.

*3. (II) Estimate the binding energy of the H_2 molecule, assuming the two H nuclei are 0.074 nm apart and the two electrons spend 33% of their time midway between them.

*4. (II) Binding energies are often measured experimentally in kcal per mole, and then the binding energy in eV per molecule is calculated from that result. What is the conversion factor in going from kcal per mole to eV per molecule? What is the binding energy of KCl (= 4.43 eV) in kcal per mole?

*5. (III) (*a*) Apply reasoning similar to that in the text for the $S = 0$ and $S = 1$ states in the formation of the H_2 molecule to show why the molecule He_2 is *not* formed. (*b*) Explain why the He_2^+ molecular ion *could* form. (Experiment shows it has a binding energy of 3.1 eV at $r_0 = 0.11$ nm.)

* 29–4 Molecular Spectra

*6. (I) Show that the quantity $\hbar^2/I$ has units of energy.

*7. (II) The so-called "characteristic rotational energy," $\hbar^2/2I$, for N_2 is 2.48×10^{-4} eV. Calculate the N_2 bond length.

*8. (II) (*a*) Calculate the characteristic rotational energy, $\hbar^2/2I$, for the O_2 molecule whose bond length is 0.121 nm. (*b*) What are the energy and wavelength of photons emitted in a $L = 2$ to $L = 1$ transition?

*9. (II) The equilibrium separation of H atoms in the H_2 molecule is 0.074 nm (Fig. 29–8). Calculate the energies and wavelengths of photons for the rotational transitions (*a*) $L = 1$ to $L = 0$, (*b*) $L = 2$ to $L = 1$, and (*c*) $L = 3$ to $L = 2$.

* **10.** (II) Calculate the bond length for the NaCl molecule given that three successive wavelengths for rotational transitions are 23.1 mm, 11.6 mm, and 7.71 mm.

* **11.** (III) (*a*) Use the curve of Fig. 29–17 to estimate the stiffness constant k for the H_2 molecule. (Recall that $\text{PE} = \frac{1}{2}kx^2$.) (*b*) Then estimate the fundamental wavelength for vibrational transitions using the classical formula (Chapter 11), but use only $\frac{1}{2}$ the mass of an H atom (because both H atoms move).

* 29–5 Bonding in Solids

* **12.** (II) The spacing between "nearest neighbor" Na and Cl ions in a NaCl crystal is 0.24 nm. What is the spacing between two nearest neighbor Na ions?

* **13.** (II) Common salt, NaCl, has a density of $2.165\ \text{g/cm}^3$. The molecular weight of NaCl is 58.44. Estimate the distance between nearest neighbor Na and Cl ions. [*Hint*: *each* ion can be considered to have one "cube" or "cell" of side s (our unknown) extending out from it.]

* **14.** (II) Repeat Problem 13 for KCl whose density is $1.99\ \text{g/cm}^3$.

* 29–6 Band Theory of Solids

* **15.** (I) Explain on the basis of energy bands why the sodium chloride crystal is a good insulator. [*Hint*: consider the shells of Na^+ and Cl^- ions.]

* **16.** (I) A semiconductor, bombarded with light of slowly increased frequency, begins to conduct when the wavelength of light is 640 nm. Estimate the size of the energy gap E_g.

* **17.** (II) Calculate the longest-wavelength photon that can cause an electron in silicon $(E_g = 1.1\ \text{eV})$ to jump from the valence band to the conduction band.

* **18.** (II) The energy gap between valence and conduction bands in germanium is 0.72 eV. What range of wavelengths can a photon have to excite an electron from the top of the valence band into the conduction band?

* **19.** (II) The energy gap E_g in germanium is 0.72 eV. When used as a photon detector, roughly how many electrons can be made to jump from the valence to the conduction band by the passage of a 760-keV photon that loses all its energy in this fashion?

* **20.** (III) We saw that there are $2N$ possible electron states in the 3s band of Na, where N is the total number of atoms. How many possible electron states are there in the (*a*) 2s band, (*b*) 2p band, and (*c*) 3p band? (*d*) State a general formula for the total number of possible states in any given electron band.

* 29–7 Semiconductors and Doping

* **21.** (III) Suppose that a silicon semiconductor is doped with phosphorus so that one silicon atom in 10^6 is replaced by a phosphorus atom. Assuming that the "extra" electron in every phosphorus atom is donated to the conduction band, by what factor is the density of conduction electrons increased? The density of silicon is $2330\ \text{kg/m}^3$, and the density of conduction electrons in pure silicon is about $10^{16}\ \text{m}^{-3}$ at room temperature.

* 29–8 Diodes

* **22.** (I) At what wavelength will an LED radiate if made from a material with an energy gap $E_g = 1.4\ \text{eV}$?

* **23.** (I) If an LED emits light of wavelength $\lambda = 650\ \text{nm}$, what is the energy gap (in eV) between valence and conduction bands?

* **24.** (II) A silicon diode, whose current–voltage characteristics are given in Fig. 29–28, is connected in series with a battery and a 960-Ω resistor. What battery voltage is needed to produce a 12-mA current?

* **25.** (II) Suppose that the diode of Fig. 29–28 is connected in series to a 100-Ω resistor and a 2.0-V battery. What current flows in the circuit? [*Hint*: draw a line on Fig. 29–28 representing the current in the resistor as a function of the voltage across the diode. The intersection of this line with the characteristic curve will give the answer.]

* **26.** (II) Sketch the resistance as a function of current, for $V > 0$, for the diode shown in Fig. 29–28.

* **27.** (II) An ac voltage of 120 V rms is to be rectified. Estimate very roughly the average current in the output resistor R (25 kΩ) for (*a*) a half-wave rectifier (Fig. 29–29), and (*b*) a full-wave rectifier (Fig. 29–30) without capacitor.

* **28.** (III) A silicon diode passes significant current only if the forward-bias voltage exceeds about 0.6 V. Make a rough estimate of the average current in the output resistor R of (*a*) a half-wave rectifier (Fig. 29–29), and (*b*) a full-wave rectifier (Fig. 29–30) without a capacitor. Assume that $R = 150\ \Omega$ in each case and that the ac voltage is 12.0 V rms in each case.

* **29.** (III) A 120-V rms 60-Hz voltage is to be rectified with a full-wave rectifier (Fig. 29–30), where $R = 21\ \text{k}\Omega$, and $C = 25\ \mu\text{F}$. (*a*) Make a rough estimate of the average current. (*b*) What happens if $C = 0.10\ \mu\text{F}$? [*Hint*: see Section 19–6.]

* 29–9 Transistors

* **30.** (II) From Fig. 29–32, write an equation for the relationship between the base current (I_B), the collector current (I_C), and the emitter current (I_E, not labeled in the figure).

General Problems

* **31.** Estimate the binding energy of the H_2 molecule by calculating the difference in kinetic energy of the electrons between when they are in separate atoms and when they are in the molecule, using the uncertainty principle. Take Δx for the electrons in the separated atoms to be the radius of the first Bohr orbit, 0.053 nm, and for the molecule take Δx to be the separation of the nuclei, 0.074 nm. [*Hint:* let $p \approx \Delta p_x$.]

* **32.** The average translational kinetic energy of an atom or molecule is about $\overline{\text{KE}} = \frac{3}{2}kT$ (Eq. 13–8), where $k = 1.38 \times 10^{-23}\ \text{J/K}$ is Boltzmann's constant. At what temperature T will $\overline{\text{KE}}$ be on the order of the bond energy (and hence the bond likely to be broken by thermal motion) for (*a*) a covalent bond of binding energy 4.5 eV (say H_2), and (*b*) a "weak" hydrogen bond of binding energy 0.15 eV?

* **33.** In the ionic salt KF, the separation distance between ions is about 0.27 nm. (*a*) Estimate the electrostatic potential energy between the ions assuming them to be point charges (magnitude 1*e*). (*b*) It is known that F releases 4.07 eV of energy when it "grabs" an electron, and 4.34 eV is required to ionize K. Find the binding energy of KF relative to free K and F atoms, neglecting the energy of repulsion.

* **34.** Consider a monoatomic solid with a weakly bound cubic lattice, with each atom connected to six neighbors, each bond having a binding energy of 3.9×10^{-3} eV. When this solid melts, its latent heat of fusion goes directly into breaking the bonds between the atoms. Estimate the latent heat of fusion for this solid, in J/kg. [*Hint*: show that in a simple cubic lattice (Fig. 29–34), there are *three* times as many bonds as there are atoms, when the number of atoms is large.]

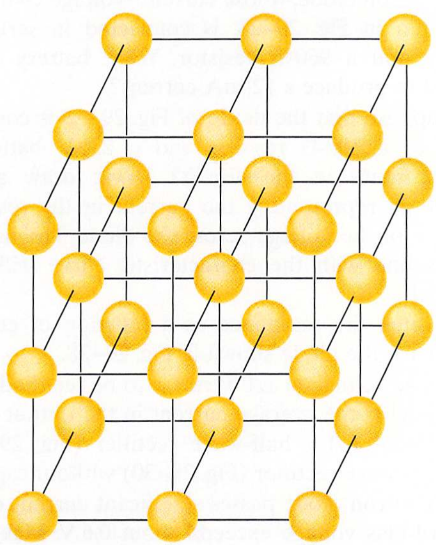

FIGURE 29–34 Problem 34.

* **35.** For O_2 with a bond length of 0.121 nm, what is the moment of inertia about the center of mass?

* **36.** A diatomic molecule is found to have an activation energy of 1.4 eV. When the molecule is disassociated, 1.6 eV of energy is released. Draw a potential energy curve for this molecule.

* **37.** When EM radiation is incident on diamond, it is found that light with wavelengths shorter than 226 nm will cause the diamond to conduct. What is the energy gap between the valence band and the conduction band for diamond?

* **38.** A TV remote control emits IR light. If the detector on the TV set is *not* to react to visible light, could it make use of silicon as a "window" with its energy gap $E_g = 1.14$ eV? What is the shortest-wavelength light that can strike silicon without causing electrons to jump from the valence band to the conduction band?

* **39.** For an arsenic donor atom in a doped silicon semiconductor, assume that the "extra" electron moves in a Bohr orbit about the arsenic ion. For this electron in the ground state, take into account the dielectric constant $K = 12$ of the Si lattice (which represents the weakening of the Coulomb force due to all the other atoms or ions in the lattice), and estimate (*a*) the binding energy, and (*b*) the orbit radius for this extra electron. [*Hint*: substitute $\epsilon = K\epsilon_0$ in Coulomb's law; see Section 17–8.]

* **40.** Most of the Sun's radiation has wavelengths shorter than 1000 nm. For a solar cell to absorb all this, what energy gap ought the material have?

* **41.** For a certain semiconductor, the longest wavelength radiation that can be absorbed is 1.92 mm. What is the energy gap in this semiconductor?

* **42.** Green and blue LEDs became available many years after red LEDs were first developed. Approximately what energy gaps would you expect to find in green (525 nm) and in blue (465 nm) LEDs?

* **43.** A zener diode voltage regulator is shown in Fig. 29–35. Suppose that $R = 1.80\ \text{k}\Omega$ and that the diode breaks down at a reverse voltage of 130 V. (The current increases rapidly at this point, as shown on the far left of Fig. 29–28 at a voltage of −12 V on that diagram.) The diode is rated at a maximum current of 120 mA. (*a*) If $R_{load} = 15.0\ \text{k}\Omega$, over what range of supply voltages will the circuit maintain the output voltage at 130 V? (*b*) If the supply voltage is 200 V, over what range of load resistance will the voltage be regulated?

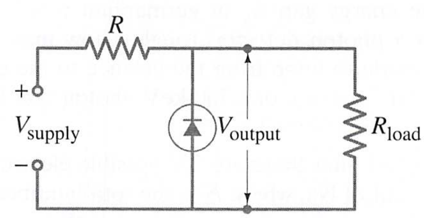

FIGURE 29–35 Problem 43.

Answers to Exercises

A: 1.30 mm, 0.87 mm, 0.65 mm.

B: 0.81 eV.