

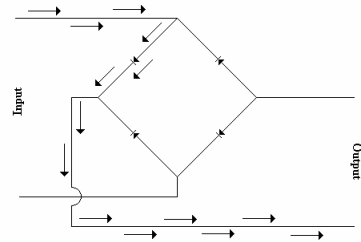
## CHAPTER 29: Molecules and Solids

### Answers to Questions

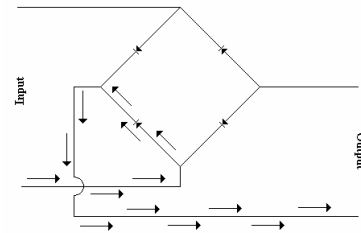
- The bond in an  $\text{N}_2$  molecule is expected to be covalent.
  - The bond in the  $\text{HCl}$  molecule is expected to be ionic.
  - The bond between  $\text{Fe}$  atoms in a solid is expected to be metallic.
- $\text{Ca}$  has 2  $s$  electrons in the outer shell and each  $\text{Cl}$  is only missing 1 electron from its outer shell. These three atoms share their electrons in such a way as to have filled outer shells. Look at Figures 29-4 and 29-5; each of the 2 outer electrons of  $\text{Ca}$  will fit into the “extra electron” position of the 2  $\text{Cl}$  atoms, forming strong ionic bonds.
- No, the  $\text{H}_2$  molecule does not have a permanent dipole moment. The outer electrons are shared equally between the two atoms and they don't leave any unbalanced “polar” ends that are more positively or negatively charged. No, the  $\text{O}_2$  molecule does not have a permanent dipole moment. The outer electrons are shared equally between the two atoms and they don't leave any unbalanced “polar” ends that are more positively or negatively charged. Yes, the  $\text{H}_2\text{O}$  molecule does have a permanent dipole moment. The electrons from the hydrogen atoms tend to spend more time around the 8 positively charged protons of the oxygen atom than the one positively charged proton in each hydrogen atom. This leaves the hydrogen atoms slightly positive and on one side of the molecule, while leaving the oxygen atom slightly negative on the other side of the molecule (see Figure 29-6). This creates a permanent dipole moment.
- The  $\text{H}_3$  atom has three electrons and only two of them can be in the  $1s^2$  state (and only if they have opposite spins, according to the Pauli Exclusion Principle). Accordingly, the third electron cannot be in the  $1s^2$  state, and so it is not held very tightly by the nucleus. This makes  $\text{H}_3$  unstable. On the other hand, the  $\text{H}_3^+$  ion only has two electrons and, if they have opposite spins, the Pauli Exclusion Principle will allow them to both be in the lower energy  $1s^2$  state. This makes  $\text{H}_3^+$  relatively more stable than  $\text{H}_3$ .
- The four categories of energy contained in a molecule are: bond (electrostatic potential) energy, rotational kinetic energy, vibrational kinetic energy, and translational kinetic energy.
- Yes,  $\text{H}_2^+$  should be stable. The two positive nuclei will share the one negative electron. The electron will spend most of its time between the two positive nuclei (basically holding them together).
- The electron configuration of carbon is  $1s^2 2s^2 2p^2$ . The inner two electrons are tightly and closely bound to the nucleus. The four remaining electrons are basically spread around the outside of the atom in four different directions (they repel each other). These four electrons can each form a simple hydrogen-like bond with four atoms that each have only one electron in an  $s$  orbital.
- The freely roaming electrons in a metal are not completely free. They are still attracted to the positive nuclei in the metal, so they would need extra energy from outside the metal to be able to leave the metal. For example, in the photoelectron effect, a photon comes in and strikes an electron to knock it out of the metal. In general, a metal is neutral, so if one electron were to move away from the metal, then the metal would be positively charged and the electron would be attracted back to the metal.
- As you increase the temperature of a metal, the amount of disorder increases and this makes it more difficult for the conduction electrons to move through the metal. Thus, the resistivity increases with

increasing temperature. As you increase the temperature of a semiconductor, the small band gap between the valence band and the conduction band can now be “jumped” by the thermally excited electrons and this means there are more conduction electrons available to move through the semiconductor. Thus, the resistivity decreases with increasing temperature.

10. When the top branch of the Input circuit is at the high voltage (current is flowing in this branch during half of the cycle), then the bottom branch of the Output is at a high voltage. The current follows the path through the bridge in the first diagram.



When the bottom branch of the Input circuit is at the high voltage (current is flowing in this branch during the other half of the cycle), then the bottom branch of the Output is still at a high voltage. The current follows the path through the bridge in the second diagram.



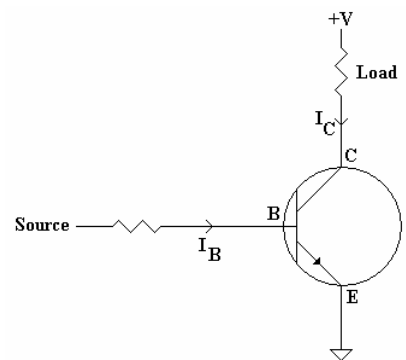
11. Look at Figure 29-28; it takes about 0.6V to get current to flow through the diode in the forward bias direction and it takes about 12 V to get current to flow through the diode in the reverse bias direction. Thus, to get the same current to flow in either direction:

$$V_{\text{forward}} = IR_{\text{forward}} \qquad V_{\text{reverse}} = IR_{\text{reverse}}$$

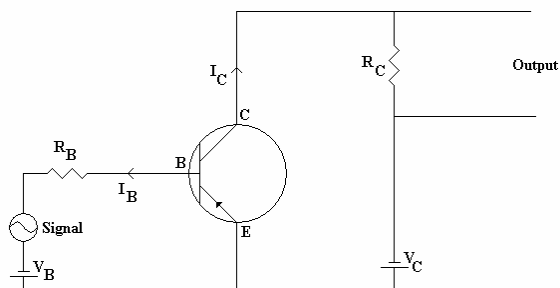
$$R_{\text{reverse}}/R_{\text{forward}} = 12 \text{ V} / 0.6 \text{ V} = 20$$

Thus, reverse bias resistance is approximately 20X larger than the forward bias resistance. This is very approximate based on estimates from reading the graph.

12. Connect the circuit shown in the adjacent diagram. When the source provides no current ( $I_B = 0$ ), which causes the CE resistance to be  $\infty$ , then no load current ( $I_C$ ) flows and the switch is OFF. When the source current is not 0, that causes the CE resistance to go to 0 Ohms. Then, load current flows and the switch is ON.



13. The main difference between *n*-type and *p*-type semiconductors is the type of atom used for the doping impurity. When a semiconductor such as Si or Ge, each atom of which has four electrons to share, is doped with an element that has five electrons to share (such as As or P), then it is an *n*-type semiconductor since an extra electron has been inserted into the lattice. When a semiconductor is doped with an element that has three electrons to share (such as Ga or In), then it is a *p*-type semiconductor since an extra hole (the lack of an electron) has been inserted into the lattice.
14. A *pnp* transistor could operate as an amplifier just like an *npn* transistor (see Figure 29-32), except that the two batteries need to be reversed, since we need to have the holes as the majority carriers (the current goes in the opposite direction as an *npn* transistor). The circuit would look like this:



15. In the circuit shown in Figure 29-32, the base-emitter is forward biased (the current will easily flow from the base to the emitter) and the base-collector is reverse biased (the current will not easily flow from the base to the collector).
16. Look at Figure 29-32; the input signal is amplified by the transistor with the help of the battery,  $E_C$ . When the CE resistance is huge ( $I_B = 0$ ) the voltage output is 0 V, but when  $I_B$  is small, the CE resistance is tiny, which makes  $I_C$  large. Then the output voltage is large, powered by the battery,  $E_C$ .
17. Phosphorus is in the same column of the periodic table as arsenic and each of these atoms have 5 electrons to share when placed in a lattice. Since the phosphorus would be replacing a silicon atom that has 4 electrons to share, there would now be an extra electron in the lattice, making this an *n*-type semiconductor in which the phosphorus atoms are donors.
18. No, diodes and transistors do not obey Ohm's law. These devices are called "non-linear" devices, since the current that flows through them is not linearly proportional to the applied voltage.
19. No, a diode cannot be used to amplify a signal. A diode does let current flow through it in one direction easily (forward biased) and it does not let current flow through it in the other direction (reversed bias), but there is no way to connect a source of power to use it to amplify a signal (which is how a transistor amplifies a signal).

## Solutions to Problems

Note: A factor that appears in the analysis of electron energies is

$$ke^2 = (9.00 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2)(1.60 \times 10^{-19} \text{ C})^2 = 2.30 \times 10^{-28} \text{ J}\cdot\text{m}.$$

1. With the reference level at infinity, the binding energy of the two ions is

$$\begin{aligned} \text{Binding energy} &= -PE = \frac{ke^2}{r} \\ &= \frac{(2.30 \times 10^{-28} \text{ J}\cdot\text{m})}{(0.28 \times 10^{-9} \text{ m})} = 8.21 \times 10^{-19} \text{ J} = \boxed{5.13 \text{ eV}}. \end{aligned}$$

2. With the repulsion of the electron clouds, the binding energy is

$$\text{Binding energy} = -PE - PE_{\text{clouds}};$$

$$4.43\text{eV} = 5.13\text{eV} - PE_{\text{clouds}}, \text{ which gives } PE_{\text{clouds}} = \boxed{0.70\text{eV}}.$$

3. When the electrons are midway between the protons, each electron will have a potential energy due to the two protons:

$$\begin{aligned} PE_{\text{ep}} &= \frac{-(2)(0.33)ke^2}{\left(\frac{r}{2}\right)} = -\frac{(4)(0.33)(2.30 \times 10^{-28} \text{J} \cdot \text{m})}{(0.074 \times 10^{-9} \text{m})(1.60 \times 10^{-19} \text{J/eV})} \\ &= -25.6\text{eV}. \end{aligned}$$

The protons have a potential energy:

$$PE_{\text{pp}} = +\frac{ke^2}{r} = +\frac{(2.30 \times 10^{-28} \text{J} \cdot \text{m})}{(0.074 \times 10^{-9} \text{m})(1.60 \times 10^{-19} \text{J/eV})} = +19.4\text{eV}.$$

When the bond breaks, each hydrogen atom will be in the ground state with an energy  $E_1 = -13.6\text{eV}$ .

Thus the binding energy is

$$\text{Binding energy} = 2E_1 - (2PE_{\text{ep}} + PE_{\text{pp}}) = 2(-13.6\text{eV}) - [2(-25.6\text{eV}) + 19.4\text{eV}] = \boxed{4.6\text{eV}}.$$

4. We convert the units:

$$\begin{aligned} 1\text{kcal/mol} &= \frac{(1\text{kcal/mol})(4186\text{J/kcal})}{(6.02 \times 10^{23} \text{ molecules/mol})(1.60 \times 10^{-19} \text{J/eV})} \\ &= \boxed{0.0435 \text{eV/molecule}}. \end{aligned}$$

For KCl we have

$$(4.43\text{eV/molecule}) \left[ \frac{(1\text{kcal/mol})}{(0.0434\text{eV/molecule})} \right] = \boxed{102 \text{kcal/mol}}.$$

5. The neutral He atom has two electrons in the ground state,  $n=1$ ,  $\ell=0$ ,  $m_\ell=0$ . Thus the two electrons have opposite spins,  $m_s = \pm\frac{1}{2}$ . If we try to form a covalent bond, we see that an electron from one of the atoms will have the same quantum numbers as one of the electrons on the other atom. From the exclusion principle, this is not allowed, so the electrons cannot be shared.

We consider the  $\text{He}_2^+$  molecular ion to be formed from a neutral He atom and an  $\text{He}^+$  ion. If the electron on the ion has a certain spin value, it is possible for one of the electrons on the atom to have the opposite spin. Thus the electron can be in the same spatial region as the electron on the ion, so a bond can be formed.

6. The units of  $\frac{\hbar^2}{I}$  are

$$\frac{(\text{J}\cdot\text{s})^2}{(\text{kg}\cdot\text{m}^2)} = \frac{\text{J}^2}{(\text{kg}\cdot\text{m/s}^2)\text{m}} = \frac{\text{J}^2}{(\text{N}\cdot\text{m})} = \frac{\text{J}^2}{\text{J}} = \text{J}.$$

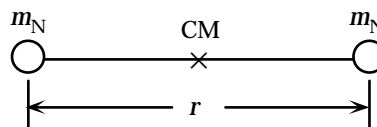
7. The moment of inertia of  $N_2$  about its CM is

$$I = 2m_N \left( \frac{r}{2} \right)^2 = \frac{m_N r^2}{2}.$$

We find the bond length from

$$\frac{\hbar^2}{2I} = \frac{\hbar^2}{m_N r^2}$$

$$= \frac{(1.055 \times 10^{-34} \text{ J}\cdot\text{s})^2}{(14)(1.66 \times 10^{-27} \text{ kg}) r^2}, \text{ which gives } r = \boxed{1.10 \times 10^{-10} \text{ m}.}$$



8. (a) The moment of inertia of  $O_2$  about its CM is

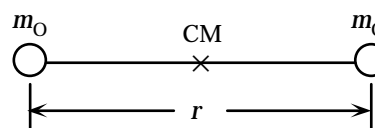
$$I = 2m_O \left( \frac{r}{2} \right)^2 = \frac{m_O r^2}{2}.$$

We find the characteristic rotational energy from

$$\frac{\hbar^2}{2I} = \frac{\hbar^2}{m_O r^2}$$

$$= \frac{(1.055 \times 10^{-34} \text{ J}\cdot\text{s})^2}{(16)(1.66 \times 10^{-27} \text{ kg})(0.121 \times 10^{-9} \text{ m})^2}$$

$$= 2.86 \times 10^{-23} \text{ J} = \boxed{1.79 \times 10^{-4} \text{ eV}.}$$



- (b) The rotational energy is

$$E_{\text{rot}} = L(L+1) \left( \frac{\hbar^2}{2I} \right).$$

Thus the energy of the emitted photon from the  $L = 2$  to  $L = 1$  transition is

$$hf = \Delta E_{\text{rot}} = [(2)(2+1) - (1)(1+1)] \left( \frac{\hbar^2}{2I} \right) = 4 \left( \frac{\hbar^2}{2I} \right) = 4(1.79 \times 10^{-4} \text{ eV}) = \boxed{7.16 \times 10^{-4} \text{ eV}.}$$

The wavelength is

$$\lambda = \frac{c}{f} = \frac{hc}{hf} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(7.16 \times 10^{-4} \text{ eV})} = 1.74 \times 10^{-3} \text{ m} = \boxed{1.74 \text{ mm}.}$$

9. The moment of inertia of  $H_2$  about its CM is

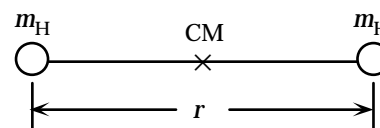
$$I = 2m_H \left( \frac{r}{2} \right)^2 = \frac{m_H r^2}{2}.$$

We find the characteristic rotational energy from

$$\frac{\hbar^2}{2I} = \frac{\hbar^2}{m_H r^2}$$

$$= \frac{(1.055 \times 10^{-34} \text{ J}\cdot\text{s})^2}{(1.67 \times 10^{-27} \text{ kg})(0.074 \times 10^{-9} \text{ m})^2}$$

$$= 1.22 \times 10^{-23} \text{ J} = 7.61 \times 10^{-3} \text{ eV}.$$



The rotational energy is

$$E_{\text{rot}} = L(L+1) \left( \frac{\hbar^2}{2I} \right).$$

Thus the energy of the emitted photon from the  $L$  to  $L-1$  transition is

$$hf = \Delta E_{\text{rot}} = [(L)(L+1) - (L-1)(L)] \left( \frac{\hbar^2}{2I} \right) = 2L \left( \frac{\hbar^2}{2I} \right).$$

(a) For the  $L = 1$  to  $L = 0$  transition, we get

$$hf = 2L \left( \frac{\hbar^2}{2I} \right) = 2(1)(7.61 \times 10^{-3} \text{ eV}) = \boxed{1.52 \times 10^{-2} \text{ eV}}.$$

The wavelength is

$$\lambda = \frac{c}{f} = \frac{hc}{hf} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(1.52 \times 10^{-2} \text{ eV})} = 8.17 \times 10^{-5} \text{ m} = \boxed{0.082 \text{ mm}}.$$

(b) For the  $L = 2$  to  $L = 1$  transition, we get

$$hf = 2L \left( \frac{\hbar^2}{2I} \right) = 2(2)(7.61 \times 10^{-3} \text{ eV}) = \boxed{3.04 \times 10^{-2} \text{ eV}}.$$

The wavelength is

$$\lambda = \frac{c}{f} = \frac{hc}{hf} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(3.04 \times 10^{-2} \text{ eV})} = 4.08 \times 10^{-5} \text{ m} = \boxed{0.041 \text{ mm}}.$$

(c) For the  $L = 3$  to  $L = 2$  transition, we get

$$hf = 2L \left( \frac{\hbar^2}{2I} \right) = 2(3)(7.61 \times 10^{-3} \text{ eV}) = \boxed{4.56 \times 10^{-2} \text{ eV}}.$$

The wavelength is

$$\lambda = \frac{c}{f} = \frac{hc}{hf} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(4.56 \times 10^{-2} \text{ eV})} = 2.72 \times 10^{-5} \text{ m} = \boxed{0.027 \text{ mm}}.$$

10. We find the energies for the transitions from

$$\Delta E = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(10^{-9} \text{ m/nm})\lambda} = \frac{(1.24 \times 10^3 \text{ eV}\cdot\text{nm})}{\lambda}.$$

$$\Delta E_1 = \frac{(1.24 \times 10^3 \text{ eV}\cdot\text{nm})}{(23.1 \times 10^6 \text{ nm})} = 5.38 \times 10^{-5} \text{ eV};$$

$$\Delta E_2 = \frac{(1.24 \times 10^3 \text{ eV}\cdot\text{nm})}{(11.6 \times 10^6 \text{ nm})} = 10.7 \times 10^{-5} \text{ eV};$$

$$\Delta E_3 = \frac{(1.24 \times 10^3 \text{ eV}\cdot\text{nm})}{(7.71 \times 10^6 \text{ nm})} = 16.1 \times 10^{-5} \text{ eV}.$$

The rotational energy is

$$E_{\text{rot}} = L(L+1) \left( \frac{\hbar^2}{2I} \right).$$

Thus the energy of the emitted photon from the  $L$  to  $L - 1$  transition is

$$hf = \Delta E_{\text{rot}} = [(L)(L+1) - (L-1)(L)] \left( \frac{\hbar^2}{2I} \right) = 2L \left( \frac{\hbar^2}{2I} \right).$$

Because  $\Delta E_3 = 3\Delta E_1$ , and  $\Delta E_2 = 2\Delta E_1$ , the three transitions must be from the  $L = 1, 2,$  and  $3$  states.

We find the moment of inertia about the CM from

$$\Delta E_3 = \frac{2(3)(1.055 \times 10^{-34} \text{ J}\cdot\text{s})^2}{2I}, \text{ which gives } I = 1.29 \times 10^{-45} \text{ kg}\cdot\text{m}^2.$$

The positions of the atoms from the CM are

$$r_1 = \frac{[m_{\text{Na}}(0) + m_{\text{Cl}}r]}{(m_{\text{Na}} + m_{\text{Cl}})} \\ = \frac{(35.5 \text{ u})r}{(23.0 \text{ u} + 35.5 \text{ u})} = 0.607r;$$

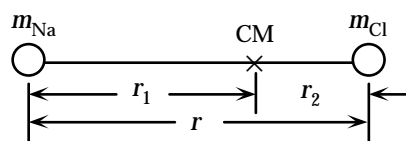
$$r_2 = r - r_1 = 0.393r.$$

We find the bond length from

$$I = m_{\text{Na}}r_1^2 + m_{\text{Cl}}r_2^2;$$

$$1.29 \times 10^{-45} \text{ kg}\cdot\text{m}^2 = [(23.0 \text{ u})(0.607r)^2 + (35.5 \text{ u})(0.393r)^2] (1.66 \times 10^{-27} \text{ kg/u}),$$

which gives  $r = \boxed{2.35 \times 10^{-10} \text{ m}}$ .



11. (a) The curve for  $\text{PE} = \frac{1}{2}kx^2$  is shown in Figure 29–17 as a dotted line. This line crosses the  $\text{PE} = 0$  axis at  $0.120 \text{ nm}$ . If we take the energy to be zero at the lowest point, the energy at the axis is  $4.5 \text{ eV}$ . Thus we have

$$\text{PE} = \frac{1}{2}kx^2;$$

$$(4.5 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV}) = \frac{1}{2}k \left[ (0.120 \text{ nm} - 0.074 \text{ nm})(10^{-9} \text{ m/nm}) \right]^2, \text{ which gives}$$

$$k = \boxed{680 \text{ N/m}}.$$

- (b) For  $\text{H}_2$  the reduced mass is

$$\mu = \frac{m_1 m_2}{(m_1 + m_2)} = \frac{(1 \text{ u})(1 \text{ u})}{(1 \text{ u} + 1 \text{ u})} = 0.50 \text{ u} = 8.3 \times 10^{-28} \text{ kg}.$$

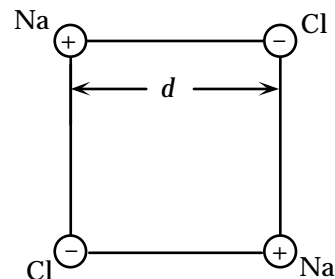
The fundamental wavelength is

$$\lambda = \frac{c}{f} = (2\pi c) \left( \frac{\mu}{k} \right)^{\frac{1}{2}}$$

$$= 2\pi (3.00 \times 10^8 \text{ m/s}) \left[ \frac{(8.3 \times 10^{-28} \text{ kg})}{(680 \text{ N/m})} \right]^{\frac{1}{2}} = 2.1 \times 10^{-6} \text{ m} = \boxed{2.1 \mu\text{m}}.$$

12. From the figure we see that the distance between nearest neighbor Na ions is the diagonal of the cube:

$$D = d\sqrt{2} = (0.24 \text{ nm})\sqrt{2} = \boxed{0.34 \text{ nm.}}$$



13. Because each ion occupies a cell of side  $s$ , a molecule occupies two cells. Thus the density is

$$\rho = \frac{m_{\text{NaCl}}}{2s^3};$$

$$2.165 \times 10^3 \text{ kg/m}^3 = \frac{(58.44 \text{ u})(1.66 \times 10^{-27} \text{ kg/u})}{2s^3}, \text{ which gives } s = 2.83 \times 10^{-10} \text{ m} = \boxed{0.283 \text{ nm.}}$$

14. Because each ion occupies a cell of side  $s$ , a molecule occupies two cells. Thus the density is

$$\rho = \frac{m_{\text{KCl}}}{2s^3};$$

$$1.99 \times 10^3 \text{ kg/m}^3 = \frac{(39.1 \text{ u} + 35.5 \text{ u})(1.66 \times 10^{-27} \text{ kg/u})}{2s^3}, \text{ which gives } s = 3.15 \times 10^{-10} \text{ m} = \boxed{0.315 \text{ nm.}}$$

15. The partially filled shell in Na is the  $3s$  shell, which has 1 electron in it. The partially filled shell in Cl is the  $2p$  shell which has 5 electrons in it. In NaCl the electron from the  $3s$  shell in Na is transferred to the  $2p$  shell in Cl, which results in filled shells for both ions. Thus when many ions are considered, the resulting bands are either completely filled (the valence band) or completely empty (the conduction band). Thus a large energy is required to create a conduction electron by raising an electron from the valence band to the conduction band.

16. The photon with the minimum frequency for conduction must have an energy equal to the energy gap:

$$E_g = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(640 \times 10^{-9} \text{ m})} = \boxed{1.94 \text{ eV.}}$$

17. The photon with the longest wavelength or minimum frequency for conduction must have an energy equal to the energy gap:

$$\lambda = \frac{c}{f} = \frac{hc}{hf} = \frac{hc}{E_g} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(1.1 \text{ eV})} = 1.1 \times 10^{-6} \text{ m} = \boxed{1.1 \mu\text{m.}}$$

18. The energy of the photon must be greater than or equal to the energy gap. Thus the longest wavelength that will excite an electron is

$$\lambda = \frac{c}{f} = \frac{hc}{hf} = \frac{hc}{E_g} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(0.72 \text{ eV})} = 1.7 \times 10^{-6} \text{ m} = 1.7 \mu\text{m.}$$

Thus the wavelength range is  $\boxed{\lambda \leq 1.7 \mu\text{m.}}$



19. The minimum energy provided to an electron must be equal to the energy gap:

$$E_g = 0.72 \text{ eV}.$$

Thus the maximum number of electrons is

$$N = \frac{hf}{E_g} = \frac{(760 \times 10^3 \text{ eV})}{(0.72 \text{ eV})} = \boxed{1.1 \times 10^6}.$$

20. (a) In the  $2s$  shell of an atom,  $\ell = 0$ , so there are two states:  $m_s = \pm \frac{1}{2}$ . When  $N$  atoms form bands, each atom provides 2 states, so the total number of states in the band is  $\boxed{2N}$ .

(b) In the  $2p$  shell of an atom,  $\ell = 1$ , so there are three states from the  $m_\ell$  values:  $m_\ell = 0, \pm 1$ ; each of which has two states from the  $m_s$  values:  $m_s = \pm \frac{1}{2}$ , for a total of 6 states. When  $N$  atoms form bands, each atom provides 6 states, so the total number of states in the band is  $\boxed{6N}$ .

(c) In the  $3p$  shell of an atom,  $\ell = 1$ , so there are three states from the  $m_\ell$  values:  $m_\ell = 0, \pm 1$ ; each of which has two states from the  $m_s$  values:  $m_s = \pm \frac{1}{2}$ , for a total of 6 states. When  $N$  atoms form bands, each atom provides 6 states, so the total number of states in the band is  $\boxed{6N}$ .

(d) In general, for a value of  $\ell$ , there are  $2\ell + 1$  states from the  $m_\ell$  values:  $m_\ell = 0, \pm 1, \dots, \pm \ell$ . For each of these there are two states from the  $m_s$  values:  $m_s = \pm \frac{1}{2}$ , for a total of  $2(2\ell + 1)$  states. When  $N$  atoms form bands, each atom provides  $2(2\ell + 1)$  states, so the total number of states in the band is  $\boxed{2N(2\ell + 1)}$ .

21. If we consider a mole of pure silicon ( $28 \text{ g}$  or  $6.02 \times 10^{23}$  atoms), the number of conduction electrons is

$$N_{\text{Si}} = \left[ \frac{(28 \times 10^{-3} \text{ kg})}{(2330 \text{ kg/m}^3)} \right] (10^{16} \text{ electrons/m}^3) = 1.20 \times 10^{11} \text{ conduction electrons}.$$

The additional conduction electrons provided by the doping is

$$N_{\text{doping}} = \frac{(6.02 \times 10^{23} \text{ atoms})}{10^6} = 6.02 \times 10^{17} \text{ added conduction electrons}.$$

Thus the density of conduction electrons has increased by

$$\frac{N_{\text{doping}}}{N_{\text{Si}}} = \frac{(6.02 \times 10^{17})}{(1.20 \times 10^{11})} = \boxed{5 \times 10^6}.$$

22. The photon will have an energy equal to the energy gap:

$$\lambda = \frac{c}{f} = \frac{hc}{hf} = \frac{hc}{E_g} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(1.4 \text{ eV})} = 8.9 \times 10^{-7} \text{ m} = \boxed{0.89 \mu\text{m}}.$$

23. The photon will have an energy equal to the energy gap:

$$E_g = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(650 \times 10^{-9} \text{ m})} = \boxed{1.91 \text{ eV}}.$$

24. From the current-voltage characteristic, we see that a current of 12 mA means a voltage of 0.68 V across the diode. Thus the battery voltage is

$$V_{\text{battery}} = V_{\text{diode}} + V_R = 0.68 \text{ V} + (12 \times 10^{-3} \text{ A})(960 \Omega) = \boxed{12.2 \text{ V}}$$

25. The battery voltage is

$$V_{\text{battery}} = V_{\text{diode}} + V_R;$$

$$2.0 \text{ V} = V(I) + I(0.100 \text{ k}\Omega), \text{ or } V(I) = 2.0 \text{ V} - I(0.100 \text{ k}\Omega).$$

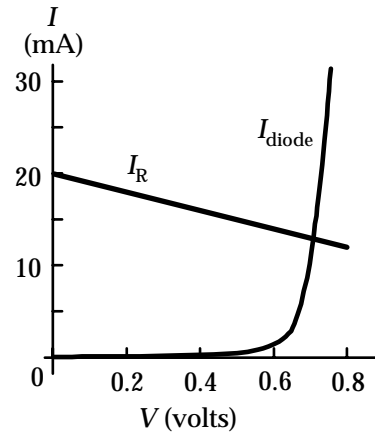
This is a straight line which passes through the points

(20 mA, 0 V) and (12 mA, 0.8 V),

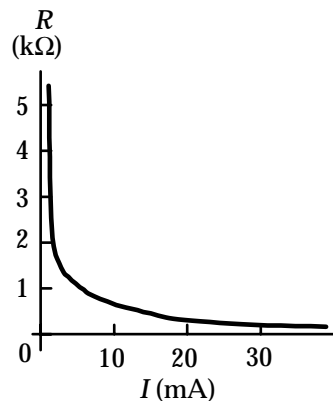
as drawn in the figure. Because  $V(I)$  is represented by both

curves, the intersection will give the current, which we see is

$\boxed{13 \text{ mA}}$ .



- 26.



- $\boxed{27}$ . (a) For a half-wave rectifier without a capacitor, the current is zero for half the time. Thus the average current is

$$I_{\text{av}} = \frac{1}{2} \frac{V_{\text{rms}}}{R} = \frac{1}{2} \frac{(120 \text{ V})}{(25 \text{ k}\Omega)} = \boxed{2.4 \text{ mA}}$$

- (b) For a full-wave rectifier without a capacitor, the current is positive all the time. Thus the average current is

$$I_{\text{av}} = \frac{V_{\text{rms}}}{R} = \frac{(120 \text{ V})}{(25 \text{ k}\Omega)} = \boxed{4.8 \text{ mA}}$$

28. There will be a current in the resistor while the ac voltage varies from 0.6 V to 12.0 V rms. Because the 0.6 V is small, the voltage across the resistor will be almost sinusoidal, so the rms voltage across the resistor will be close to  $12.0 \text{ V} - 0.6 \text{ V} = 11.4 \text{ V}$ .

- (a) For a half-wave rectifier without a capacitor, the current is zero for half the time. If we ignore the short times it takes to reach 0.6 V, this will also be true for the resistor. Thus the average current is

$$I_{\text{av}} = \frac{1}{2} \frac{V_{\text{rms}}}{R} = \frac{1}{2} \frac{(11.4 \text{ V})}{(0.150 \text{ k}\Omega)} = \boxed{38 \text{ mA}}$$

- (b) For a full-wave rectifier without a capacitor, the current is positive all the time. If we ignore the short times it takes to reach 0.6 V, this will also be true for the resistor. Thus the average current is

$$I_{\text{av}} = \frac{V_{\text{rms}}}{R} = \frac{(11.4 \text{ V})}{(0.150 \text{ k}\Omega)} = \boxed{76 \text{ mA}}$$

29. (a) The time constant for the circuit is

$$\tau_1 = RC_1 = (21 \times 10^3 \Omega)(25 \times 10^{-6} \text{ F}) = 0.53 \text{ s}.$$

Because there are two peaks per cycle, the period of the rectified voltage is

$$T = \frac{1}{2f} = \frac{1}{2(60 \text{ Hz})} = 0.0083 \text{ s}.$$

Because  $\tau_1 \gg T$ , the voltage across the capacitor will be essentially constant during a cycle, so the voltage will be the peak voltage. Thus the average current is

$$I_{\text{av}} = \frac{V_0}{R} = \frac{\sqrt{2}(120 \text{ V})}{(21 \text{ k}\Omega)} = \boxed{8.1 \text{ mA (smooth)}}$$

- (b) The time constant for the circuit is

$$\tau_2 = RC_2 = (21 \times 10^3 \Omega)(0.10 \times 10^{-6} \text{ F}) = 0.0021 \text{ s}.$$

Because  $\tau_2 < T$ , the voltage across the capacitor will be rippled, so the average voltage will be close to the rms voltage. Thus the average current is

$$I_{\text{av}} = \frac{V_{\text{rms}}}{R} = \frac{(120 \text{ V})}{(21 \text{ k}\Omega)} = \boxed{5.7 \text{ mA (rippled)}}$$

30. The arrow at the emitter terminal, E, indicates the direction of current  $I_E$ . Because current into the transistor must equal current out of the transistor,

$$I_B + I_C = I_E.$$

31. For an electron confined within  $\Delta x$ , we find the uncertainty in the momentum from

$$\Delta p = \frac{\hbar}{\Delta x},$$

which we take to be the momentum of the particle. The kinetic energy of the electron is

$$\text{KE} = \frac{p^2}{2m} = \frac{\hbar^2}{2m(\Delta x)^2}.$$

When the two electrons are in separated atoms, we get

$$\begin{aligned} \text{KE}_1 &= \frac{2\hbar^2}{2m(\Delta x)^2} \\ &= \frac{2(1.055 \times 10^{-34} \text{ J}\cdot\text{s})^2}{2(9.11 \times 10^{-31} \text{ kg})(0.053 \times 10^{-9} \text{ m})^2} = 4.35 \times 10^{-18} \text{ J} = 27.2 \text{ eV}. \end{aligned}$$

When the electrons are in the molecule, we get

$$\text{KE}_2 = \frac{2\hbar^2}{2m(\Delta x)^2}$$

$$= \frac{2(1.055 \times 10^{-34} \text{ J}\cdot\text{s})^2}{2(9.11 \times 10^{-31} \text{ kg})(0.074 \times 10^{-9} \text{ m})^2} = 2.23 \times 10^{-18} \text{ J} = 14.0 \text{ eV}.$$

Thus the binding energy is

$$KE_1 - KE_2 = 27.2 \text{ eV} - 14.0 \text{ eV} = \boxed{13 \text{ eV}}.$$

32. (a) We find the temperature from

$$KE = \frac{3}{2}kT;$$

$$(4.5 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV}) = \frac{3}{2}(1.38 \times 10^{-23} \text{ J/K})T, \text{ which gives } T = \boxed{3.5 \times 10^4 \text{ K}}.$$

(b) We find the temperature from

$$KE = \frac{3}{2}kT;$$

$$(0.15 \text{ eV})(1.60 \times 10^{-19} \text{ J/eV}) = \frac{3}{2}(1.38 \times 10^{-23} \text{ J/K})T, \text{ which gives } T = \boxed{1.2 \times 10^3 \text{ K}}.$$

33. (a) The potential energy for the point charges is

$$PE = -\frac{ke^2}{r} = -\frac{(2.30 \times 10^{-28} \text{ J}\cdot\text{m})}{(0.27 \times 10^{-9} \text{ m})} = -8.52 \times 10^{-19} \text{ J} = \boxed{-5.3 \text{ eV}}.$$

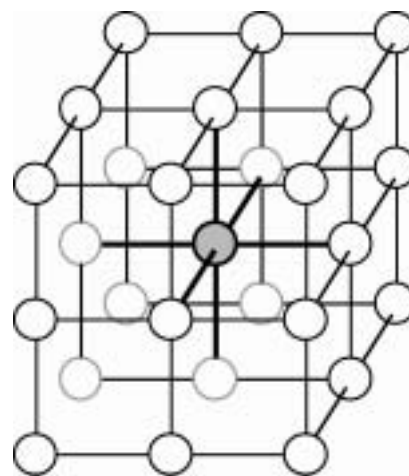
(b) Because the potential energy of the ions is negative, 5.3 eV is released when the ions are brought together. A release of energy means that energy must be provided to return the ions to the state of free atoms. Thus the total binding energy of the KF ions is

$$\text{Binding energy} = 5.3 \text{ eV} + 4.07 \text{ eV} - 4.34 \text{ eV} = \boxed{5.0 \text{ eV}}.$$

34. From the diagram of the cubic lattice, we see that an atom inside the cube is bonded to the six nearest neighbors.

Because each bond is shared by two atoms, the number of bonds per atom is 3. We find the heat of fusion for argon from the energy required to break the bonds:

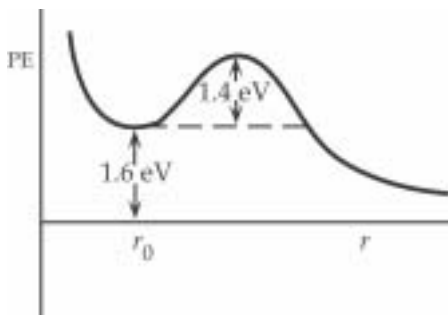
$$\begin{aligned} L_{\text{fusion}} &= \left( \frac{\text{number of bonds}}{\text{atom}} \right) \left( \frac{\text{number of atoms}}{\text{kg}} \right) E_{\text{bond}} \\ &= (3) \left[ \frac{(6.02 \times 10^{23} \text{ atoms/mol})}{(39.95 \times 10^{-3} \text{ kg/mol})} \right] \times \\ &\quad (3.9 \times 10^{-3} \text{ eV})(1.60 \times 10^{-19} \text{ J/eV}) \\ &= \boxed{2.8 \times 10^4 \text{ J/kg}}. \end{aligned}$$



35. An O<sub>2</sub> molecule can be treated as two point masses, 16 u each, and each a distance of 6.05 × 10<sup>-11</sup> m from the molecule's center of mass. Then

$$I = \sum mr^2 = 2 \left[ (16 \text{ u})(1.66 \times 10^{-27} \text{ kg/u}) \right] (6.05 \times 10^{-11} \text{ m})^2 = \boxed{1.94 \times 10^{-46} \text{ kg}\cdot\text{m}^2}.$$

36. Since dissociation energy releases, the binding energy is positive and the diagram is similar to Fig. 29–10:



37. The photon with the minimum frequency for conduction must have an energy equal to the energy gap:

$$E_g = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(226 \times 10^{-9} \text{ m})} = \boxed{5.50 \text{ eV}}$$

38. To use silicon to filter the wavelengths, we want wavelengths below the IR to be able to cause the electron to be raised to the conduction band, so the photon is absorbed in the silicon. We find the shortest wavelength from

$$\lambda = \frac{c}{f} = \frac{hc}{hf} > \frac{hc}{E_g} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(1.14 \text{ eV})} = 1.09 \times 10^{-6} \text{ m} = \boxed{1.09 \mu\text{m}}$$

Because this is in the IR, the shorter wavelengths of visible light will excite the electron, so silicon could be used as a window.

39. In a dielectric, Coulomb's law becomes

$$F = \frac{ke^2}{r^2} = \frac{e^2}{4\pi K \text{Å} r^2}$$

Thus where  $e^2$  appears in an equation, we divide by  $K$ . If the "extra" electron is outside the arsenic ion, the effective  $Z$  will be 1, and we can use the hydrogen results.

- (a) The energy of the electron is

$$E = -\frac{2\pi^2 Z^2 e^4 m k^2}{K^2 h^2 n^2} = -\frac{(13.6 \text{ eV}) Z^2}{K^2 n^2} = -\frac{(13.6 \text{ eV})(1)^2}{(12)^2 (1)^2} = -0.094 \text{ eV}$$

Thus the binding energy is 0.094 eV.

- (b) The radius of the electron orbit is

$$r = \frac{K^2 h^2 n^2}{4\pi^2 Z e^2 m k} = \frac{K^2 n^2 (0.0529 \text{ nm})}{Z} = \frac{(12)(1)^2 (0.0529 \text{ nm})}{(1)^2} = \boxed{0.63 \text{ nm}}$$

Note that this result justifies the assumption that the electron is outside the arsenic ion.

40. The photon with the longest wavelength has the minimum energy, so the energy gap must be

$$E_g = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(1000 \times 10^{-9} \text{ m})} = \boxed{1.24 \text{ eV}}$$

41. The photon with the minimum frequency for absorption must have an energy equal to the energy gap:

$$E_g = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(1.92 \times 10^{-3} \text{ m})} = \boxed{6.47 \times 10^{-4} \text{ eV.}}$$

42. The energy gap is related to photon wavelength by

$$E_g = hf = \frac{hc}{\lambda}.$$

For a green LED,

$$E_g = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(525 \times 10^{-9} \text{ m})} = \boxed{2.37 \text{ eV.}}$$

For a blue LED,

$$E_g = \frac{(6.63 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{(1.60 \times 10^{-19} \text{ J/eV})(465 \times 10^{-9} \text{ m})} = \boxed{2.67 \text{ eV.}}$$

43. (a) The current through the load resistor is

$$I_{\text{load}} = \frac{V_{\text{output}}}{R_{\text{load}}} = \frac{(130 \text{ V})}{(15.0 \text{ k}\Omega)} = 8.67 \text{ mA.}$$

At the minimum supply voltage the current through the diode will be zero, so the current through  $R$  is 8.67 mA, and the voltage across  $R$  is

$$V_{R,\text{min}} = I_{R,\text{min}} R = (8.67 \text{ mA})(1.80 \text{ k}\Omega) = 15.6 \text{ V.}$$

The minimum supply voltage is

$$V_{\text{min}} = V_{R,\text{min}} + V_{\text{output}} = 15.6 \text{ V} + 130 \text{ V} = 146 \text{ V.}$$

At the maximum supply voltage the current through the diode will be 120 mA, so the current through  $R$  is 120 mA + 8.67 mA = 128.7 mA, and the voltage across  $R$  is

$$V_{R,\text{max}} = I_{R,\text{max}} R = (128.7 \text{ mA})(1.80 \text{ k}\Omega) = 232 \text{ V.}$$

The maximum supply voltage is

$$V_{\text{max}} = V_{R,\text{max}} + V_{\text{output}} = 232 \text{ V} + 130 \text{ V} = 362 \text{ V.}$$

Thus the range of supply voltages is  $\boxed{146 \text{ V} \leq V \leq 362 \text{ V.}}$

(b) At a constant supply voltage the voltage across  $R$  is  $200 \text{ V} - 130 \text{ V} = 70 \text{ V}$ , so the current in  $R$  is

$$I_R = \frac{(70 \text{ V})}{(1.80 \text{ k}\Omega)} = 38.9 \text{ mA.}$$

If there is no current through the diode, this current must be in the load resistor, so we have

$$R_{\text{load}} = \frac{(130 \text{ V})}{(38.9 \text{ mA})} = 3.34 \text{ k}\Omega.$$

If  $R_{\text{load}}$  is less than this, there will be a greater current through  $R$ , and thus the voltage across the load will drop and regulation will be lost. If  $R_{\text{load}}$  is greater than 3.34 k $\Omega$ , the current through  $R_{\text{load}}$  will decrease and there will be current through the diode. The current through the diode is 38.9 mA when  $R_{\text{load}}$  is infinite, which is less than the maximum of 120 mA.

Thus the range for load resistance is  $\boxed{3.34 \text{ k}\Omega \leq R_{\text{load}} < \infty.}$