9.A: Condensed Matter Physics (Answers)

Check Your Understanding

9.1. It corresponds to a repulsive force between core electrons in the ions.

9.2. the moment of inertia

9.3. more difficult

9.4. It decreases.

9.5. The forward bias current is much larger. To a good approximation, diodes permit current flow in only one direction.

9.6. a low temperature and low magnetic field

Conceptual Questions

1. An ionic bond is formed by the attraction of a positive and negative ion. A covalent bond is formed by the sharing of one or more electrons between atoms. A van der Waals bond is formed by the attraction of two electrically polarized molecules.

3. 1. An electron is removed from one atom. The resulting atom is a positive ion.

2. An electron is absorbed from another atom. The result atom is a negative ion.

3. The positive and negative ions are attracted together until an equilibrium separation is reached.

5. Bonding is associated with a spatial function that is symmetric under exchange of the two electrons. In this state, the electron density is largest between the atoms. The total function must be antisymmetric (since electrons are fermions), so the spin function must be antisymmetric. In this state, the spins of the electrons are antiparallel.

7. rotational energy, vibrational energy, and atomic energy

9. Each ion is in the field of multiple ions of the other opposite charge.

11. 6, 6

13. 0.399 nm

15. increases by a factor of $\sqrt[3]{8^2} = 4$

17. For larger energies, the number of accessible states increases.

19. (1) Solve Schrödinger’s equation for the allowed states and energies. (2) Determine energy levels for the case of a very large lattice spacing and then determine the energy levels as this spacing is reduced.

21. For **N** atoms spaced far apart, there are **N** different wave functions, all with the same energy (similar to the case of an electron in the double well of H^2). As the atoms are pushed together, the energies of these **N** different wave functions are split. By the exclusion principle, each electron must each have a unique set of quantum numbers, so the **N** atoms bringing **N** electrons together must have at least **N** states.

23. For a semiconductor, there is a relatively large energy gap between the lowest completely filled band and the next available unfilled band. Typically, a number of electrons traverse the gap and therefore the electrical conductivity is small. The properties of a semiconductor are sensitivity to temperature: As the temperature is increased, thermal excitations promote charge carriers from the valence band across the gap and into the conduction band.

25. a. Germanium has four valence electrons. If germanium doped with arsenic (five valence electrons), four are used in bonding and one electron will be left for conduction. This produces an n-type material. b. If germanium is doped with **gallium** (three valence electrons), all three electrons are used in bonding, leaving one hole for conduction. This results in a p-type material.

27. The Hall effect is the production of a potential difference due to motion of a conductor through an external magnetic field. This effect can be used to determine the drift velocity of the charge carriers (electrons or hole). If the current density is measured, this effect can also determine the number of charge carriers per unit volume.

29. It produces new unfilled energy levels just above the filled valence band. These levels accept electrons from the valence band.

31. The electric field produced by the uncovered ions reduces further diffusion. In equilibrium, the diffusion and drift currents cancel so the net current is zero. Therefore, the resistance of the depletion region is large.

33. The positive terminal is applied to the n-side, which uncovers more ions near the junction (widens the depletion layer), increases the junction voltage difference, and therefore reduces the diffusion of holes across the junction.

35. Sound moves a diaphragm in and out, which varies the input or base current of the transistor circuit. The transistor amplifies this signal (**p-n-p** semiconductor). The output or collector current drives a speaker.

37. BSC theory explains superconductivity in terms of the interactions between electron pairs (Cooper pairs). One electron in a pair interacts with the lattice, which interacts with the second electron. The combine electron-lattice-electron interaction binds the electron pair together in a way that overcomes their mutual repulsion.

39. As the magnitude of the magnetic field is increased, the critical temperature decreases.

Problems

41. $U = -5.16eV$

43. $-4.43eV = -4.69eV + U_{ex}, U_{ex} = 0.26eV$

45. The measured value is 0.484 nm, and the actual value is close to 0.127 nm. The laboratory results are the same order of magnitude, but a factor 4 high.

47. 0.110 nm

49. a. $E = 2.2 \times 10^{-4} eV$;

b. $\Delta E = 4.4 \times 10^{-4} eV$

51. 0.65 nm

53. $r_0 = 0.240nm$

55. 2196 kcal

57. 11.5

59. a. 4;

b. 4.2×10^{-4} ; for very large values of the quantum numbers, the spacing between adjacent energy levels is very small (“in the continuum”). This is consistent with the expectation that for large quantum numbers, quantum and classical mechanics give approximately the same predictions.

61. 10.0 eV

63. 4.55×10^{9}

65. Fermi energy, $E_F = 7.03eV$, Temperature, $T_F = 8.2 \times 10^{4} K$

67. For an insulator, the energy gap between the valence band and the conduction band is larger than for a semiconductor.

69. 4.13 keV

71. $n = 1.56 \times 10^{19} holes/m^3$

73. 5 T

75. $V_b = 0.458V$

77. $T = 829K$

79. $T = 0.707T_c$

81. 61 kV

Additional Problems

83. $U_{coul} = -5.65eV$

$E_{form} = -4.71eV$,

$E_{diss} = 4.71eV$

85. $E_{0r} = 7.43 \times 10^{-3}eV$

87. $E_{0r} = 7.43 \times 10^{-3}eV; l = 0; E_r = 0eV$ (no rotation);

$l = 1; E_r = 1.49 \times 10^{-2}eV; l = 2; E_r = 4.46 \times 10^{-2}eV$

89.

1. They are fairly hard and stable.
2. They vaporize at relatively high temperatures (1000 to 2000 K).
3. They are transparent to visible radiation, because photons in the visible portion of the spectrum are not energetic enough to excite an electron from its ground state to an excited state.
4. They are poor electrical conductors because they contain effectively no free electrons.
5. They are usually soluble in water, because the water molecule has a large dipole moment whose electric field is strong enough to break the electrostatic bonds between the ions.

91. No, He atoms do not contain valence electrons that can be shared in the formation of a chemical bond.

93. $\sum_1^{N/2} n^2 = \frac{1}{3}(\frac{N}{2})^3$, so $\bar{E} = \frac{1}{3}E_F$

95. An impurity band will be formed when the density of the donor atoms is high enough that the orbits of the extra electrons overlap. We saw earlier that the orbital radius is about 50 Angstroms, so the maximum distance between the impurities for a band to form is 100 Angstroms. Thus if we use 1 Angstrom as the interatomic distance between the Si atoms, we find that 1 out of 100 atoms along a linear chain must be a donor atom. And in a three-dimensional crystal, roughly 1 out of 10^6 atoms must be replaced by a donor atom in order for an impurity band to form.

97. a. $E_F = 7.11eV$;

b. $E_F = 3.24eV$;

c. $E_F = 9.46eV$

99. $9.15 \approx 9$

Challenge Problems

101. In three dimensions, the energy of an electron is given by:

$E = R^2 E_1$, where $R^2 = n_1^2 + n_2^2 + n_3^2$. Each allowed energy state corresponds to node in **N** space (n_1, n_2, n_3). The number of particles corresponds to the number of states (nodes) in the first octant, within a sphere of radius, **R**. This number is given by: $N = 2(\frac{1}{8})(\frac{4}{3})\pi R^3$, where the factor 2 accounts for two states of spin. The density of states is found by differentiating this expression by energy:

$g(E) = \frac{\pi V}{2}(\frac{8m_e}{h^2})^{3/2}E^{1/2}$. Integrating gives: $\bar{E} = \frac{3}{5}E_F$