9.E: Condensed Matter Physics (Exercises)

Conceptual Questions

9.1 Types of Molecular Bonds

1. What is the main difference between an **ionic bond,** a **covalent bond**, and a **van der Waals bond**?

2. For the following cases, what type of bonding is expected?

(a) KCl molecule;

(b) N_2 molecule.

3. Describe three steps to ionic bonding.

4. What prevents a positive and negative ion from having a zero separation?

5. For the H_2 molecule, why must the spins the electron spins be antiparallel?

9.2 Molecular Spectra

6. Does the absorption spectrum of the diatomic molecule HCl depend on the isotope of chlorine contained in the molecule? Explain your reasoning.

7. Rank the energy spacing (ΔE) of the following transitions from least to greatest: an electron energy transition in an atom (atomic energy), the rotational energy of a molecule, or the vibrational energy of a molecule?

8. Explain key features of a vibrational-rotation energy spectrum of the diatomic molecule.

9.3 Bonding in Crystalline Solids

9. Why is the equilibrium separation distance between K^+ and Cl^- different for a diatomic molecule than for solid KCl?

10. Describe the difference between a face-centered cubic structure (FCC) and a body-centered cubic structure (BCC).

11. In sodium chloride, how many Cl^- atoms are "nearest neighbors" of Na^+? How many Na+Na+ atoms are "nearest neighbors" of Cl^-?

12. In cesium iodide, how many Cl^- atoms are "nearest neighbors" of Cs^+? How many Cs^+ atoms are "nearest neighbors" of Cl^-?

13. The NaCl crystal structure is FCC. The equilibrium spacing is $r_0 = 0.282 nm$. If each ion occupies a cubic volume of r_0^3, estimate the distance between "nearest neighbor" Na^+ ions (center-to-center)?

9.4 Free Electron Model of Metals

14. Why does the Fermi energy (E_F) increase with the number of electrons in a metal?

15. If the electron number density (**N/V**) of a metal increases by a factor 8, what happens to the Fermi energy (E_F)?

16. Why does the horizontal line in the graph in Figure 9.12 suddenly stop at the Fermi energy?

17. Why does the graph in Figure 9.12 increase gradually from the origin?

18. Why are the sharp transitions at the Fermi energy "smoothed out" by increasing the temperature?

9.5 Band Theory of Solids

19. What are the two main approaches used to determine the energy levels of electrons in a crystal?

20. Describe two features of energy levels for an electron in a crystal.

21. How does the number of energy levels in a band correspond to the number, **N**, of atoms.

22. Why are some materials very good conductors and others very poor conductors?

23. Why are some materials semiconductors?

24. Why does the resistance of a semiconductor decrease as the temperature increases?

9.6 Semiconductors and Doping

25. What kind of semiconductor is produced if germanium is doped with

(a) arsenic, and

(b) gallium?

26. What kind of semiconductor is produced if silicon is doped with

(a) phosphorus, and

(b) indium?

27. What is the Hall effect and what is it used for?

28. For an **n**-type semiconductor, how do impurity atoms alter the energy structure of the solid?

29. For a **p**-type semiconductor, how do impurity atoms alter the energy structure of the solid?

9.7 Semiconductor Devices

30. When **p-** and **n-**type materials are joined, why is a uniform electric field generated near the junction?

31. When **p-** and **n-**type materials are joined, why does the depletion layer not grow indefinitely?

32. How do you know if a diode is in the **forward biased** configuration?

33. Why does the reverse bias configuration lead to a very small current?

34. What happens in the extreme case that where the **n-** and **p-**type materials are heavily doped?

35. Explain how an audio amplifier works, using the transistor concept.

9.8 Superconductivity

36. Describe two main features of a superconductor.

37. How does BCS theory explain superconductivity?

38. What is the Meissner effect?

39. What impact does an increasing magnetic field have on the critical temperature of a semiconductor?

Problems

9.1 Types of Molecular Bonds

40. The electron configuration of carbon is $1s^2 2s^2 2p^2$. Given this electron configuration, what other element might exhibit the same type of hybridization as carbon?

41. Potassium chloride (KCl) is a molecule formed by an ionic bond. At equilibrium separation the atoms are $r_0 = 0.279 nm$ apart. Determine the electrostatic potential energy of the atoms.

42. The electron affinity of Cl is 3.89 eV and the ionization energy of K is 4.34 eV. Use the preceding problem to find the dissociation energy. (Neglect the energy of repulsion.)

43. The measured energy dissociated energy of KCl is 4.43 eV. Use the results of the preceding problem to determine the energy of repulsion of the ions due to the exclusion principle.

9.2 Molecular Spectra

44. In a physics lab, you measure the vibrational-rotational spectrum of HCl. The estimated separation between absorption peaks is $\Delta f \approx 5.5 \times 10^{11} Hz$. The central frequency of the band is $f_0 = 9.0 \times 10^{13} Hz$.

(a) What is the moment of inertia (I)?

(b) What is the energy of vibration for the molecule?

45. For the preceding problem, find the equilibrium separation of the H and Cl atoms. Compare this with the actual value.

46. The separation between oxygen atoms in an O_2 molecule is about 0.121 nm. Determine the characteristic energy of rotation in eV.

47. The characteristic energy of the N_2 molecule is $2.48 \times 10^{-4} eV$. Determine the separation distance between the nitrogen atoms

48. The characteristic energy for KCl is $1.4 \times 10^{-5} eV$.

(a) Determine μ for the KCl molecule.

(b) Find the separation distance between the K and Cl atoms.

49. A diatomic F_2 molecule is in the $l=1$ state.

(a) What is the energy of the molecule?

(b) How much energy is radiated in a transition from a $l=2$ to a $l=1$ state?

50. In a physics lab, you measure the vibrational-rotational spectrum of potassium bromide (KBr). The estimated separation between absorption peaks is $\Delta f \approx 5.35 \times 10^{10} Hz$. The central frequency of the band is $f_0 = 8.75 \times 10^{12} Hz$.

(a) What is the moment of inertia (**I**)?

(b) What is the energy of vibration for the molecule?

9.3 Bonding in Crystalline Solids

51. The CsI crystal structure is BCC. The equilibrium spacing is approximately $r_0 = 0.46 nm$. If Cs^+ ion occupies a cubic volume of r_0^3, what is the distance of this ion to its "nearest neighbor" I^+ ion?

52. The potential energy of a crystal is $-8.10 eV$/ion pair. Find the dissociation energy for four moles of the crystal.

53. The measured density of a NaF crystal is $2.558 g/cm^3$. What is the equilibrium separate distance of Na^+ and Fl^- ions?

54. What value of the repulsion constant, **n**, gives the measured dissociation energy of 221 kcal/mole for NaF?

55. Determine the dissociation energy of 12 moles of sodium chloride (NaCl). (**Hint:** the repulsion constant n is approximately 8.)

56. The measured density of a KCl crystal is $1.984 g/cm^3$. What is the equilibrium separation distance of K^+ and Cl^- ions?

57. What value of the repulsion constant, **n**, gives the measured dissociation energy of 171 kcal/mol for KCl?

58. The measured density of a CsCl crystal is $3.988 g/cm^3$. What is the equilibrium separate distance of Cs^+ and Cl^- ions?

9.4 Free Electron Model of Metals

59. What is the difference in energy between the $n_x = n_y = n_z = 4$ state and the state with the next higher energy? What is the percentage change in the energy between the $n_x = n_y = n_z = 4$ state and the state with the next higher energy?

(b) Compare these with the difference in energy and the percentage change in the energy between the $n_x = n_y = n_z = 400$ state and the state with the next higher energy.

60. An electron is confined to a metal cube of $l = 0.8 cm$ on each side. Determine the density of states at

(a) $E = 0.80 eV$;

(b) $E = 2.2 eV$; and

(c) $E = 5.0 eV$.

61. What value of energy corresponds to a density of states of $1.10 \times 10^{24} eV^{-1}$?

62. Compare the density of states at 2.5 eV and 0.25 eV.

63. Consider a cube of copper with edges 1.50 mm long. Estimate the number of electron quantum states in this cube whose energies are in the range 3.75 to 3.77 eV.

64. If there is one free electron per atom of copper, what is the electron number density of this metal?

65. Determine the Fermi energy and temperature for copper at $T = 0 K$.

9.5 Band Theory of Solids

66. For a one-dimensional crystal, write the lattice spacing (a) in terms of the electron wavelength.

67. What is the main difference between an insulator and a semiconductor?

68. What is the longest wavelength for a photon that can excite a valence electron into the conduction band across an energy gap of 0.80 eV?

69. A valence electron in a crystal absorbs a photon of wavelength, $\lambda = 0.300nm$. This is just enough energy to allow the electron to jump from the valence band to the conduction band. What is the size of the energy gap?

9.6 Semiconductors and Doping

70. An experiment is performed to demonstrate the Hall effect. A thin rectangular strip of semiconductor with width 10 cm and length 30 cm is attached to a battery and immersed in a 1.50-**T** field perpendicular to its surface. This produced a Hall voltage of 12 V. What is the drift velocity of the charge carriers?

71. Suppose that the cross-sectional area of the strip (the area of the face perpendicular to the electric current) presented to the in the preceding problem is $1mm^2$ and the current is independently measured to be 2 mA. What is the number density of the charge carriers?

72. A current-carrying copper wire with cross-section $\sigma = 2mm^2$ has a drift velocity of 0.02 cm/s. Find the total current running through the wire.

73. The Hall effect is demonstrated in the laboratory. A thin rectangular strip of semiconductor with width 5 cm and cross-sectional area $2mm^2$ is attached to a battery and immersed in a field perpendicular to its surface. The Hall voltage reads 12.5 V and the measured drift velocity is 50 m/s. What is the magnetic field?

9.7 Semiconductor Devices

74. Show that for **V** less than zero, $I_net \approx -I_0$.

75. A **p-n** diode has a reverse saturation current $1.44 \times 10^{-8} A$. It is forward biased so that it has a current of $6.78 \times 10^{-1} A$ moving through it. What bias voltage is being applied if the temperature is 300 K?

76. The collector current of a transistor is 3.4 A for a base current of 4.2 mA. What is the current gain?

77. Applying the positive end of a battery to the p-side and the negative end to the **n**-side of a **p-n** junction, the measured current is $8.76 \times 10^{-1} A$. Reversing this polarity give a reverse saturation current of $4.41 \times 10^{-8} A$. What is the temperature if the bias voltage is 1.2 V?

78. The base current of a transistor is 4.4 A, and its current gain 1126. What is the collector current?

9.8 Superconductivity

79. At what temperature, in terms of T_C, is the critical field of a superconductor one-half its value at $T = 0K$?

80. What is the critical magnetic field for lead at $T = 2.8K$?

81. A Pb wire wound in a tight solenoid of diameter of 4.0 mm is cooled to a temperature of 5.0 K. The wire is connected in series with a $50 - \Omega$ resistor and a variable source of emf. As the emf is increased, what value does it have when the superconductivity of the wire is destroyed?

82. A tightly wound solenoid at 4.0 K is 50 cm long and is constructed from Nb wire of radius 1.5 mm. What maximum current can the solenoid carry if the wire is to remain superconducting?

Additional Problems

83. Potassium fluoride (KF) is a molecule formed by an ionic bond. At equilibrium separation the atoms are $r_0 = 0.255nm$ apart. Determine the electrostatic potential energy of the atoms. The electron affinity of F is 3.40 eV and the ionization energy of K is 4.34 eV. Determine dissociation energy. (Neglect the energy of repulsion.)

84. For the preceding problem, sketch the potential energy versus separation graph for the bonding of K^+ and Fl^- ions.

(a) Label the graph with the energy required to transfer an electron from K to Fl.

(b) Label the graph with the dissociation energy.

85. The separation between hydrogen atoms in a H_2 molecule is about 0.075 nm. Determine the characteristic energy of rotation in eV.

86. The characteristic energy of the Cl_2 molecule is $2.95 \times 10^{-5} eV$. Determine the separation distance between the nitrogen atoms.

87. Determine the lowest three rotational energy levels of H_2.

88. A carbon atom can hybridize in the sp^2 configuration.

(a) What is the angle between the hybrid orbitals?

89. List five main characteristics of ionic crystals that result from their high dissociation energy.

90. Why is bonding in H_2^+ favorable? Express your answer in terms of the symmetry of the electron wave function.

91. Astronomers claim to find evidence of He_2 from light spectra of a distant star. Do you believe them?

92. Show that the moment of inertia of a diatomic molecule is $I = \mu r_0^2$, where μ is the reduced mass, and r_0 is the distance between the masses.

93. Show that the average energy of an electron in a one-dimensional metal is related to the Fermi energy by $\bar{E} = \frac{1}{2} E_F$.

94. Measurements of a superconductor's critical magnetic field (in **T**) at various temperatures (in K) are given below. Use a line of best fit to determine $B_c(0)$. Assume $T_c = 9.3K$.

Table 9.6

T (in K)	$B_c(T)$
3.0	0.18
4.0	0.16
5.0	0.14
6.0	0.12
7.0	0.09
8.0	0.05
9.0	0.01

95. Estimate the fraction of Si atoms that must be replaced by As atoms in order to form an impurity band.

96. Transition in the rotation spectrum are observed at ordinary room temperature ($T = 300K$). According to your lab partner, a peak in the spectrum corresponds to a transition from the $l = 4$ to the $l = 1$ state. Is this possible? If so, determine the momentum of inertia of the molecule.

97. Determine the Fermi energies for

(a) Mg,

(b) Na, and

(c) Zn.

98. Find the average energy of an electron in a Zn wire.

99. What value of the repulsion constant, **n**, gives the measured dissociation energy of 158 kcal/mol for CsCl?

100. A physical model of a diamond suggests a BCC packing structure. Why is this not possible?

Challenge Problems

101. For an electron in a three-dimensional metal, show that the average energy is given by $\bar{E} = \frac{1}{N}\int_0^{E_F} Eg(E)dE = \frac{3}{5}E_F$, Where **N** is the total number electrons in the metal.