Q1 Crystalline solids form lattices which are body center cubic (BCC), face centered cubic (FCC), and diamond cubic. The diamond cubic arrangement is shown in Fig. 1 (or Fig. 6a page 11 of Notes).

(a) How many neighbors one Si atoms has? Circle one: 2 4 3 1

(b) Draw a 3-D sketch of Si atom and its neighbors.

See a section of Fig. 2a shown below. Imagine the filled circle as Si atom which has four neighbor atoms. Ignore two vertical lines and two horizontal lines.

(c) What do we call this arrangement?

(d) What is the bonding in Si diamond lattice (Circle one)  
- Covalent  
- Ionic  
- Both

Fig. 1a Si lattice (all atoms same) top;  
(b) GaAs lattice (Ga and As atoms) open and dark circles.

Q.2 The atomic number of sodium (Na) is 11 and its electron distribution is given in Fig. 3 [page 14/Fig. 9 Notes]. There is one electron in the outer shell 3s.

(a) Circle one: The outer 3s shell of sodium is

Fig. 3. Energy levels and electrons in one sodium atom.  

(b) In a solid chain of sodium atoms, the outer electrons (1 per each atom) are shared between neighbors. The discrete energy levels in a single sodium atom become energy bands (in which energy levels are very close to each other) as shown in 4 [Notes Fig. 11]. Will sodium chain behave like at room temperature? Circle one  
- Metal  
- Semiconductor  
- Insulator

(c) Based on information in part (b), can we conclude that solid Na will conduct electricity via electron flow in a when an electric voltage or field is applied. Circle one  
- Yes  
- No
Q.3 Si atom has 14 electrons as its atomic number is 14. The electron distribution (shown on page 17) is:
2 electrons in first 1s level (spin up and down; shell n=1),
2 electrons in 2s,
6 in 2p, (2s and 2p combination forms shell #2 (n=2) with 8 electrons.
2 are accommodated in 3s
2 in 3p (this leaves 3rd shell partially filled having 4 electrons as it can accommodate 8).

(a) Based on this information, will Si behave like a metal or semiconductor? Circle one.

(b) We know that Si is a semiconductor. Explain how 4N outer electrons in N atoms of Si solid are arranged when a solid is formed to result in a semiconductor.

In a Si solid, 3s and 3p orbitals form sp3 hybridization. This results in the formation of two bands. These bands have 8N states (2N states from 3s levels and 6N states from 3p levels). 4N states belong to lower or valence band and 4N states belong to the upper or conduction band.

Since N Si atoms have 4N outer electrons, these 4N electrons completely fill the lower or valence band (at 0°FK).

HINT: This is explained by invoking sp3 hybridization? (Hint: see Fig. 15 page 19). That is, 3s electron orbital and 3p orbitals get combined/hybridized. Their 8N states divide into two energy bands as shown in Fig. 17. Four outer electrons of each Si atom contribute 4N electrons in a solid comprising of N Si atoms. These 4N electrons fill the lower energy band. The upper energy band remains empty.

c) What do we call the energy band that is filled first? Circle one Conduction band Valence band

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Q.4 (a) In Fig. 5 the upper band which is identified by “4N states 0 electrons” is called

\[ \text{Conduction band} \quad \text{Valence band} \]

(b) Do all semiconductors have an energy gap \( E_g \) as shown in Fig 5. Circle one.

\[ \text{True} \quad \text{False} \]

(c) Generally at 0°FK, the lower of the two energy bands is completely filled up with electrons and upper band is empty. Does this make Si an insulator semiconductor metal

\[ \text{True} \quad \text{False} \]

(d) At finite temperature \( T \), some electrons statistically (though the probability is very small) leave the lower or valence band and make transition to the upper or conduction band. Will Si conduct electricity Circle one.

\[ \text{YES} \quad \text{NO} \]

(e) When few electrons from a fully filled valence band make transition to the upper band (conduction band), they leave behind unfilled energy states. What do we call these states?

\[ \text{holes} \quad \text{acceptors} \]

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Fig. 5 [Fig.17 page 19]
Formation of energy bands from discrete levels when Si atoms are far apart. When Si crystal or solid is formed, atoms get closer and their electrons start interacting (like shown in Figs. 11/12 notes.) Two bands are shown at the location of double headed arrow.
Q. 5 (a) Do electrons in the valence band conduct electricity? **Circle one**
   - Yes
   - No

(b) Can there be holes in the top or conduction band? **Circle one**
   - Yes
   - No

(c) Semiconductors have both electrons and holes that enable current conduction.
   - True
   - False

Q. 6a. In a pure (intrinsic) Si, there are equal number of electrons and holes. **Circle one**
   - Yes
   - No

Q. 6b. The number of electrons and holes goes up as the operating temperature T of Si raised. **Circle one**
   - True
   - False

Q7. (a) **What** is the charge of a hole (circle one)
   - $+q$
   - $-q$

   $q = 1.6 \times 10^{-19}$ Coulombs.

Q. 7(b) When electron concentrations in the conduction band and hole concentrations in the conduction band are in equal numbers (that is, $n = p = n_i$) the semiconductor is known as intrinsic semiconductor. Does the value of $n_i$ depend on energy gap $E_g$?
   - YES
   - [n$_i$ is proportional to $\exp(-E_g/kT)$, increase in T reduces the magnitude of exponent term]

Q. 8 Carrier concentration of an intrinsic semiconductor can be changed by adding impurity atoms which donate (electrons to the conduction band) or accept electrons from the valence band. They are called donors ($N_A$) and acceptors ($N_D$), respectively. The impurity atom concentration is usually fraction of Si atoms per unit volume.

(a) If a Si atom is replaced by boron which has 3 outer electrons, does it behave as a donor or acceptor.

8(b) What happens if Si atoms are substituted by Phosphorus atoms, does it behave as a donor or acceptor.

8(c) **What** determines if the donor atom will donate the electrons or not?
   - The location of donor level with respect to the conduction band edge. The difference is $E_D$ or ionization energy of a donor atom.

Q. 9 Semiconductors have more donors (or no acceptors) are called n-type semiconductors as they have more electrons in the conduction band, and semiconductors having more acceptor atoms behave as p-type as they have more holes. Unlike metals, semiconductors consist of both electrons and holes.

The product of electron ($n$) and hole ($p$) concentration, under equilibrium, is constant $np=n_i^2$.

(a) **Find** electron concentration in the p- region ($n_{p_0}$) and hole concentration in the n-region ($p_{n_0}$) of a p'-n diode shown in Fig. 6. Here, subscript p refers to the p-region, primary character n refers to n-Si, subscript 'o' is for equilibrium.

**Given** $n_i$ in Si at room temperature (T=300K) = $1.5 \times 10^{16}$ cm$^{-3}$; the product of hole concentration $p$ and electron concentration $n$ outside the junction is constant $pn = (n_i)^2$ **Assume all donors and acceptors are ionized at 300K**.

Electron concentration in p-Si: $n_{p_0} = n_i^2/p_{n_0}$ and $p_{p_0} = (1.5 \times 10^{16})^2/10^{20} = 2.25 \times 10^{17}$ cm$^{-3}$

Hole concentration in n-Si: $p_{n_0} = n_i^2/n_{p_0}$ and $n_{p_0} = -N_A$, $p_{n_0} = (1.5 \times 10^{16})^2/10^{17} - 2.25 \times 10^{20}/10^{17} = 2.25 \times 10^2$ cm$^{-3}$

(b) Plot the hole and electron concentrations in the p, n regions, and in the junction region for the p'-n Si diode of Fig. 6. (Concentration of holes in p-region and electrons in n-region are shown)
Q.10. (a) Show that the solution of Schrodinger equation 1 (pages 20-21) \( \psi \) is expressed by Eq. 3. This is obtained by solving in an infinite well for the boundary conditions \( \psi(x=L)=0 \) and \( \psi(x=0)=0 \).

\[
\frac{d\psi}{dx} = i k_x (A e^{-k_x x} + B e^{k_x x}), \quad \frac{d^2\psi}{dx^2} = -k_x^2 (A e^{-k_x x} + B e^{k_x x}) = -k_x^2 \psi \tag{1}
\]

(b) Find three energy levels from Eq. 2 using three energy levels \( n=1, 2, 3 \). HINT: find \( k_x \) from Eq. 3 via boundary conditions.

\[
\psi = A e^{-ik_x x} + B e^{ik_x x} \tag{2}
\]

\[
\psi = A e^{-ik_x x} + B e^{ik_x x} \tag{3}
\]

HINT: This question reviews your partial differential equation background.

\[
E_{\text{PS}} \text{ can be rewritten as } \psi = A \left( \cos(k_x x) + \frac{\sin(k_x x)}{k_x} \right) + B \left[ \cos(k_x x) - \frac{\sin(k_x x)}{k_x} \right]
\]

\[
\frac{\hbar}{2\pi} = \frac{h}{2\pi}
\]

\[
E_1 = \frac{h^2 k_x^2}{8m} \frac{1}{2}
\]

\[
E_2 = \frac{h^2 k_x^2}{8m} \frac{1}{2}
\]

\[
E_3 = \frac{h^2 k_x^2}{8m} \frac{1}{2}
\]

\[
\text{at } x=L, \quad 4(L)=0 = D \sin(k_x L); \quad 4(L)=0 \quad \text{if } D = \frac{A-B}{2}
\]

\[
\text{at } x=0, \quad 4(0)=0 \quad 0 = C + D \times 0
\]

\[
C = A + B
\]

\[
\text{at } x=L, \quad 4(L)=0 = D \sin(k_x L); \quad 4(L)=0 \quad \text{if } D = \frac{A-B}{2}
\]

\[
E = \frac{h^2 k_x^2}{8m} \frac{1}{2}
\]

\[
\sin(k_x L) = n \pi \quad \text{or } k_x = \frac{n \pi}{L}, \quad n = 1, 2, 3, 4, \ldots
\]

\[
\text{Holes}
\]

\[
\text{Electrons}
\]