



Vellore – 632014, Tamil Nadu, India
SCHOOL OF ELECTRICAL ENGINEERING
WINTER SEMESTER 2023-2024

CAT-1 Answer Key

SLOT: C2+TC2

Programme Name & Branch : B.Tech (BEE & BEI)	Course Code : BEEE201L
Course Name : Electronic Materials	Exam Date : 13-02-2024
Faculty Members : Dr. Mallikarjuna Golla	Max. Marks : 50

Q. No	Answers
1.	1) <u>Ans</u> a) Number of atoms = $(6 \times \frac{1}{2}) + (8 \times \frac{1}{8})$ (1 mark) $= 3 + 1 = 4$ (4 atoms per unit cell) b) From the figure using Pythagoras theorem (3 marks) $(4R)^2 = a^2 + a^2$ $16R^2 = 2a^2$ $R = \frac{a}{2\sqrt{2}}$ (or) $a = 2\sqrt{2} R$ (c) APF = $\frac{(\text{No. of atoms in unit cell}) \times (\text{Volume of atom})}{\text{Volume of unit cell}}$ (3 marks) $= \frac{4 \times \frac{4}{3}\pi R^3}{a^3} = \frac{\frac{16}{3}\pi R^3}{(2\sqrt{2}R)^3} = \frac{\frac{16}{3}\pi}{3(2\sqrt{2})^3}$ $= 0.74$ (d) Mass density (ρ) = $\frac{Z \cdot M}{N_A \cdot a^3}$ (3 marks) Given 107.9 g/mol, $R = 0.144 \times 10^{-9} \text{ m}$ $a = 2\sqrt{2} R = 2\sqrt{2} \times 0.144 \times 10^{-9} = 4.07 \times 10^{-10} \text{ m}$ $\rho = \frac{(\frac{4}{a^3}) \times (107.9)}{6.022 \times 10^{23}} \frac{\text{m}^3 \cdot \text{g/mol}}{\text{mol}^{-1}} = 1063059 \text{ g/m}^3$ $= 10.630 \text{ g/cm}^3$

2. Classification of Defects:
- (a) Based on Dimensionality
1. Zero Dimensional or Point Defects: Vacancies and Impurities.
 2. One dimensional or Line defects : Edge and Screw Dislocation.
 3. Two dimensional or Surface defects: Free Surface, Grain boundary, Twin boundary, stacking fault.

Real crystal are finite crystal has a boundary line and that boundary has an external surface or free surface.

Above the absolute zero temperature, all crystals have atomic vacancies or atoms missing from lattice sites in the crystal structure. The vacancies exist as a requirement of thermal equilibrium and are called thermodynamic defects. Vacancies introduce disorder into the crystal by upsetting the perfect periodicity of atomic arrangements.

1. Zero Dimensional or Point Defects: Vacancies and Impurities

At some instant, there may be **one atom with sufficient energy to break its bonds and jump to an adjoining site on the surface**, as depicted in Figure 1.45. **This leaves a vacancy behind**, just below the surface. This vacancy can then diffuse into the bulk of the crystal, because a neighboring atom can diffuse into it.

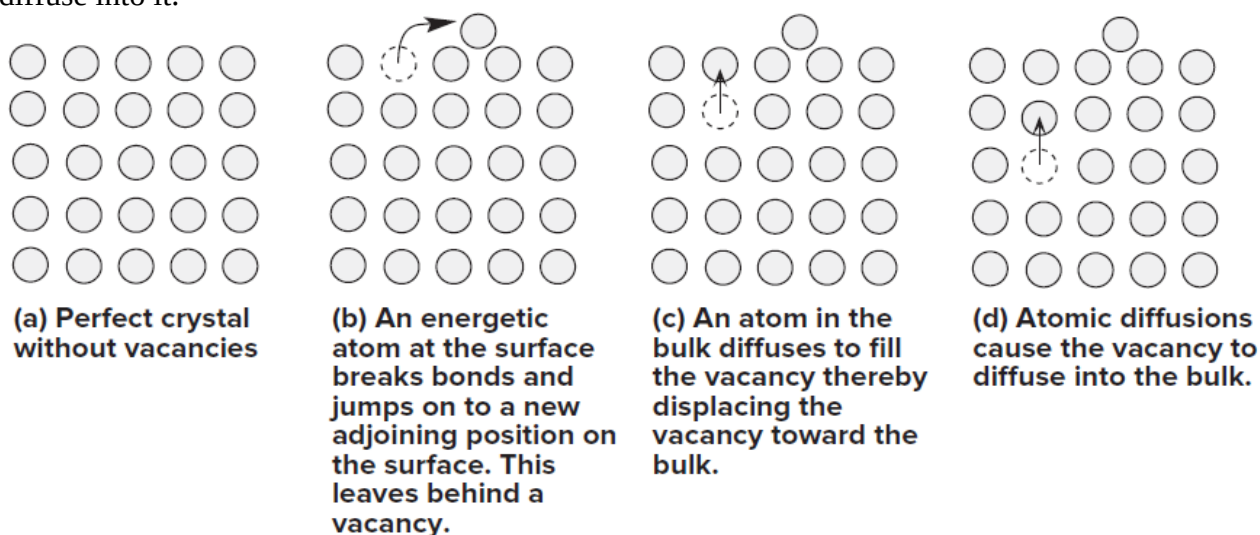
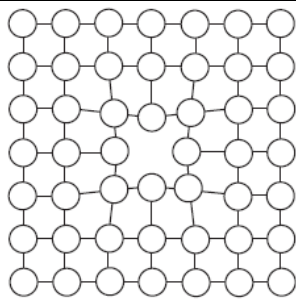
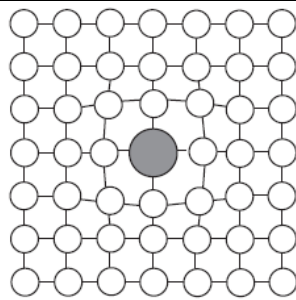


Figure 1.45 Generation of a vacancy by the diffusion of an atom to the surface and the subsequent diffusion of the vacancy into the bulk.

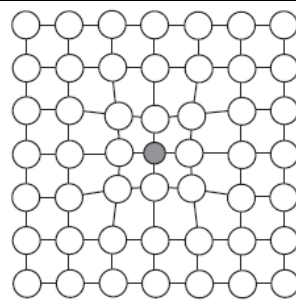
Vacancies are only one type of **point defect** in a crystal structure. Point defects generally involve lattice changes or distortions of a few atomic distances, as depicted in Figure 1.46a. The crystal structure may contain impurities, either naturally or as a consequence of intentional addition, as in the case of silicon crystals grown for microelectronics. If the impurity atom substitutes directly for the host atom, the result is called a **substitutional impurity** and the resulting crystal structure is that of a **substitutional solid solution**, as shown in Figure 1.46b and c. When a Si crystal is “doped” with small amounts of arsenic (As) atoms, the As atoms substitute directly for the Si atoms in the Si crystal; that is, the arsenic atoms are substitutional impurities. The impurity atom can also place itself in an interstitial site, that is, in a void between.



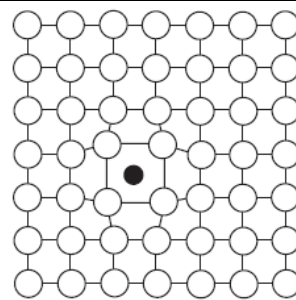
(a) A vacancy in the crystal.



(b) A substitutional impurity in the crystal. The impurity atom is larger than the host atom.



(c) A substitutional impurity in the crystal. The impurity atom is smaller than the host atom.



(d) An interstitial impurity in the crystal. The impurity occupies an empty space between host atoms.

2.
(b)

2) b)
Ans

$$F(E) = \frac{1}{1 + e^{\left(\frac{E - E_F}{kT}\right)}} \Rightarrow \text{probability of filling}$$

probability of empty $1 - F(E) = 1 - \frac{1}{1 + e^{\left(\frac{E - E_F}{kT}\right)}}$

$$\Rightarrow 0.1 = 1 - \frac{1}{1 + e^{\left(\frac{E - E_F}{kT}\right)}}$$

$$\Rightarrow \frac{1}{1 + e^{\left(\frac{E - E_F}{kT}\right)}} = 1 - 0.1 = 0.9$$

$$\Rightarrow 1 + e^{\left(\frac{E - E_F}{kT}\right)} = \frac{1}{0.9}$$

$$\Rightarrow e^{\left(\frac{E - E_F}{kT}\right)} = \frac{1}{0.9} - 1 = \frac{0.1}{0.9} = \frac{1}{9}$$

$$\Rightarrow \frac{E - E_F}{kT} = \ln(0.9)$$

$$\Rightarrow T = \frac{E - E_F}{k \times \ln(0.9)} = \frac{(4.75 - 5.25) \text{ eV}}{1.38 \times 10^{-23} \text{ J/K} \times \ln(0.9)}$$

$$T = \frac{(0.5 \times 1.6 \times 10^{-19}) \text{ J}}{1.38 \times 10^{-23} \text{ J/K} \times 2.198}$$

$$T = 2637.44 \text{ K}$$

3.
(a)

Figure 5.11a. Because B has only three valence electrons, when it shares them with four neighboring Si atoms, one of the bonds has a missing electron, which of course is a hole. A nearby electron can tunnel into this hole and displace the hole further away from the boron atom. As the hole moves away, it gets attracted by the negative charge left behind on the boron atom and therefore takes an orbit around the B^- ion, as shown in Figure 5.11b. The binding energy of this hole to the B^- ion can be calculated using the hydrogenic atom analogy as in the n -type Si case. This binding energy turns out to be very small, ~ 0.05 eV, so at room temperature the thermal vibrations of the lattice can free the hole away from the B^- site. A free hole, we

recall, exists in the VB. The escape of the hole from the B^- site involves the B atom *accepting* an electron from a neighboring Si–Si bond (from the VB), which effectively results in the hole being displaced away and its eventual escape to freedom in the VB. The B atom introduced into the Si crystal therefore acts as an electron acceptor and, because of this, it is called an **acceptor impurity**. The electron accepted by the B atom comes from a nearby bond. On the energy band diagram, an electron leaves the VB and gets accepted by a B atom, which becomes negatively charged. This process leaves a hole in the VB that is free to wander away, as illustrated in Figure 5.12.

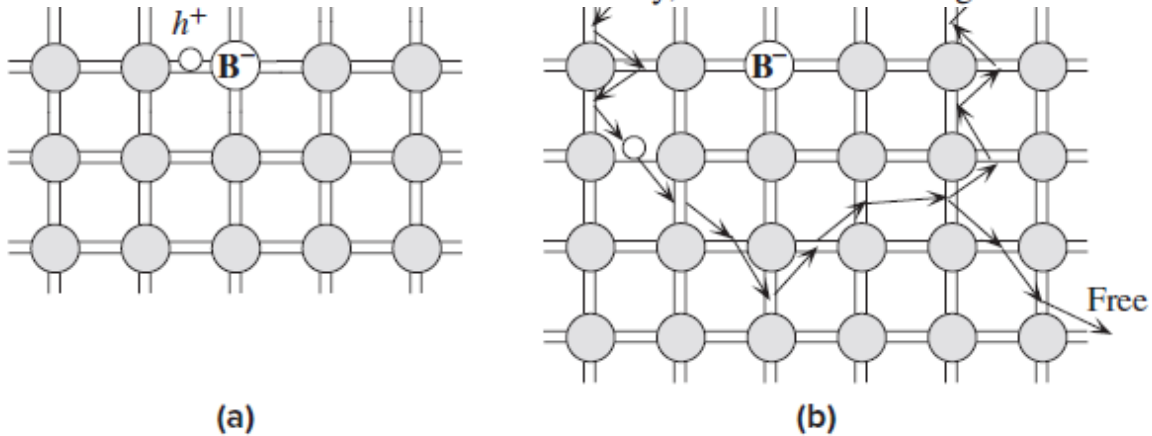
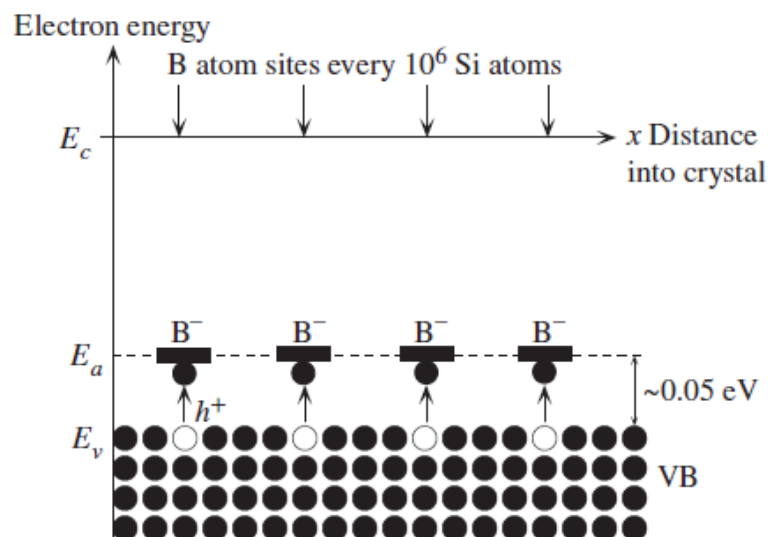


Figure 5.11 Boron-doped Si crystal.

B has only three valence electrons. When it substitutes for a Si atom, one of its bonds has an electron missing and therefore a hole, as shown in (a). The hole orbits around the B^- site by the tunneling of electrons from neighboring bonds, as shown in (b). Eventually, thermally vibrating Si atoms provide enough energy to free the hole from the B^- site into the VB, as shown.

Figure 5.12 Energy band diagram for a p -type Si doped with 1 ppm B. There are acceptor energy levels E_a just above E_v around B^- sites. These acceptor levels accept electrons from the VB and therefore create holes in the VB.



It is apparent that doping a silicon crystal with a trivalent impurity results in a p -type material. We have many more holes than electrons for electrical conduction since the negatively charged B atoms are immobile and hence cannot contribute to the conductivity. If the concentration of acceptor impurities N_a in the crystal is much greater than the intrinsic concentration n_i , then at room temperature all the acceptors would have been ionized and thus $p \approx N_a$. The electron concentration is then determined by the mass action law, $n = n_i^2/N_a$, which is much smaller than p , and consequently the conductivity is simply given by $\sigma = eN_a\mu_h$.

3.
(b)

3) b) For intrinsic semiconductor

Ans

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{kT}\right)$$

$$= 3.2 \times 10^{24} \times 1.5 \times 10^{24} \exp\left(\frac{-0.8}{0.0259}\right)$$

$$n_i^2 = 1.848 \times 10^{35}$$

$$n_i = 4.299 \times 10^{17} / \text{cm}^3$$

For intrinsic semiconductor,

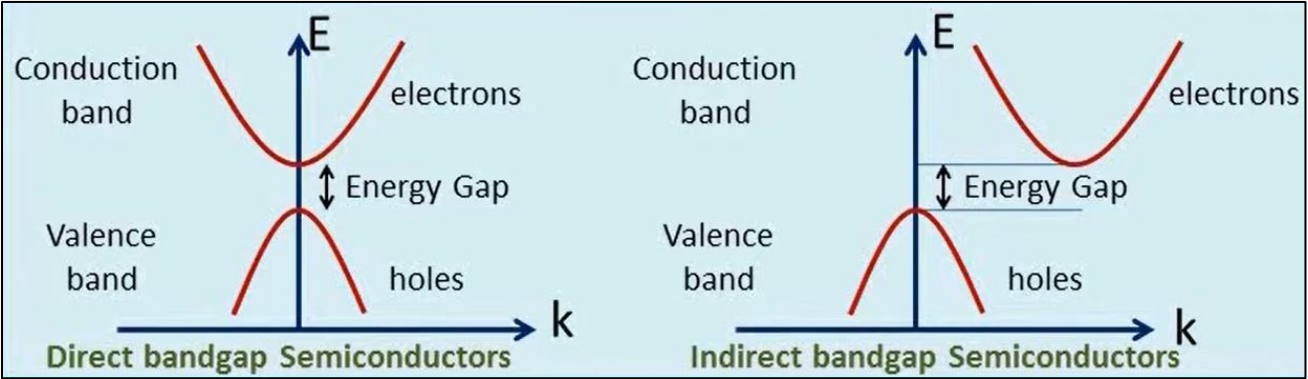
$$n_i = n = p$$

$$\text{conductivity } (\sigma) = en\mu_e + ep\mu_h$$

$$= en_i(\mu_e + \mu_h)$$

$$= 1.6 \times 10^{-19} \times 4.299 \times 10^{17} (1500 + 500)$$

$$\sigma = 137.57 \text{ } \Omega^{-1}\text{-cm}^{-1}$$

4. (a)	The energy of an electron is given by $E = \frac{p^2}{2m} = \frac{h^2 k^2}{2m}$ Where p is momentum, m is mass of electron, h is planks constant and k is propagation constant. Thus $E \propto k^2$ which is an equation of parabola. The graph of E vs k is shown below  <table border="1" data-bbox="183 696 1497 1205"> <tbody> <tr> <td>Maximum of VB and minimum of CB occur at same momentum values</td><td>Maximum value of VB and minimum of CB occur at two different momentum values.</td></tr> <tr> <td>The minimum of CB and maximum of VB occurring at same propagation constant (k).</td><td>The minimum of CB and maximum of VB occurring at different propagation constant (k).</td></tr> <tr> <td>Electron making transition from CB to VB, need not undergo any change in its momentum. When electron fall from CB to VB, it disappear with hole (recombination of electron and hole) and their pair release the energy in the form of Light. i.e Photon of light.</td><td>In order to make transition from minimum point in CB to maximum point in VB, the electron requires some momentum. First it will go to some defect state and then fall directly on the VB. When ever it has some deflection, it radiates the energy in the form heat in the lattice itself.</td></tr> <tr> <td>The compound semiconductor such as GaAs, GaN, GaSb, InP, InAs are direct gap semiconductor.</td><td>All elemental semiconductor such as Si, Ge, SiC, GaP are indirect gap semiconductor.</td></tr> <tr> <td>These direct gap semiconductors are used in LED and Lasers etc.</td><td>These indirect gap semiconductors are used in diodes and solar panels etc.</td></tr> </tbody> </table>	Maximum of VB and minimum of CB occur at same momentum values	Maximum value of VB and minimum of CB occur at two different momentum values.	The minimum of CB and maximum of VB occurring at same propagation constant (k).	The minimum of CB and maximum of VB occurring at different propagation constant (k).	Electron making transition from CB to VB, need not undergo any change in its momentum. When electron fall from CB to VB, it disappear with hole (recombination of electron and hole) and their pair release the energy in the form of Light. i.e Photon of light.	In order to make transition from minimum point in CB to maximum point in VB, the electron requires some momentum. First it will go to some defect state and then fall directly on the VB. When ever it has some deflection, it radiates the energy in the form heat in the lattice itself.	The compound semiconductor such as GaAs, GaN, GaSb, InP, InAs are direct gap semiconductor.	All elemental semiconductor such as Si, Ge, SiC, GaP are indirect gap semiconductor.	These direct gap semiconductors are used in LED and Lasers etc.	These indirect gap semiconductors are used in diodes and solar panels etc.
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4. (b)	Piezo-resistivity is an electromechanical phenomenon in which the electrical resistivity of a material changes reversibly with strain. Stress – Force per unit area Strain – Deflection per unit length/area Applications: Variety of Sensors such as Force, strain, pressure and bio-medical instruments. The change in the resistivity may be due to a change in the concentration of carriers or due to a change in the drift mobility of the carriers, both of which can be modified by a strain in the crystal. Typically, in an extrinsic or doped semiconductor, the concentration of carriers does not change as significantly as the drift mobility; the piezoresistivity is then associated with the change in the mobility.										

5.

$$5) \underline{A8} \quad N_A = \frac{100 \times 4.22 \times 10^{22}}{10^8}$$

condition $N_A \gg n_i$

$$p = N_A = 4.22 \times 10^{16}$$

At equilibrium $np = n_i^2$

$$n = \frac{n_i^2}{p} = \frac{(2 \times 10^{15})^2}{4.22 \times 10^{16}} = 0.9479 \times 10^{10} \text{ cm}^{-3}$$

$$n_i = 0.9479 \times 10^{10} \text{ cm}^{-3}$$

conductivity $(\sigma) = e n \mu_e + e p \mu_h$

Intrinsic semiconductor (without doping)

$$\begin{aligned} \sigma &= e n_i (\mu_e + \mu_h) \\ &= 1.6 \times 10^{-19} \times 2 \times 10^{13} (4000 + 2000) \\ &= 0.0192 \text{ } \Omega^{-1} \text{ cm}^{-1} \end{aligned}$$

$$R = \frac{\rho l}{A} = \frac{4}{1.0192 \times 4^2} = \underline{\underline{13.021 \text{ } \Omega}}$$

Extrinsic semiconductor (with doping)

$$\begin{aligned} \sigma &= e p \mu_h \quad (\text{since } p \gg n_i) \\ &= 1.6 \times 10^{-19} \times 4.22 \times 10^{16} \times 2000 \\ &= 13.504 \text{ } \Omega^{-1} \text{ cm}^{-1} \end{aligned}$$

$$R = \frac{\rho l}{A} = \frac{4}{13.504 \times 4^2} = \underline{\underline{0.0185 \text{ } \Omega}}$$