SEMICONDUCTOR ELECTRONICS

INTRINSIC SEMICONDUCTOR

INTRINSIC SEMICONDUCTORS:

A semiconductor that is devoid of impurities is referred to as an intrinsic semiconductor. Ideally, an intrinsic semiconductor crystal should exclusively consist of atoms of that specific semiconductor. However, achieving such absolute purity in practice is impractical. Nevertheless, if the impurity content is less than 1 in 10^8 parts of the semiconductor, it can be considered as intrinsic.

To illustrate the properties of intrinsic semiconductors, we will use the examples of silicon and germanium. Both silicon and germanium belong to Group IV of the periodic table and are tetravalent. Their electronic configurations are as follows:

- Silicon (Si) with an atomic number of 14:

  $Si(14) = 1s^2 2s^2 2p^6 3s^2 3p^2$

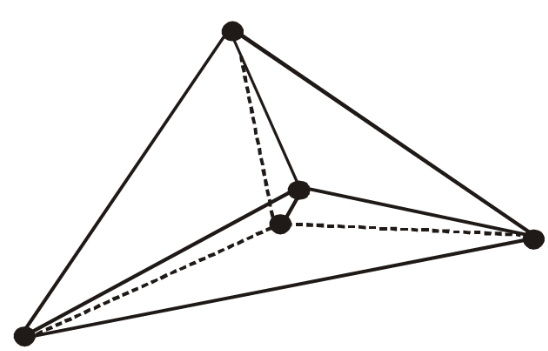
- Germanium (Ge) with an atomic number of 32:

  $Ge\ (32) = 1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$

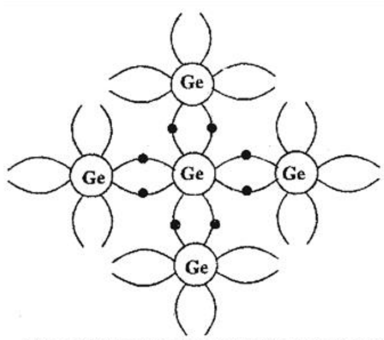
These electronic configurations depict the distribution of electrons in the respective energy levels and orbitals of silicon and germanium atoms.

Both silicon and germanium exhibit a crystalline structure wherein each atom within the crystal is situated inside a tetrahedron formed by the four closest atoms to it. The figure illustrates one of these tetrahedral units. In this arrangement, each atom shares its four valence electrons with its immediate neighbors on a one-to-one basis, resulting in each atom participating in four covalent bonds.

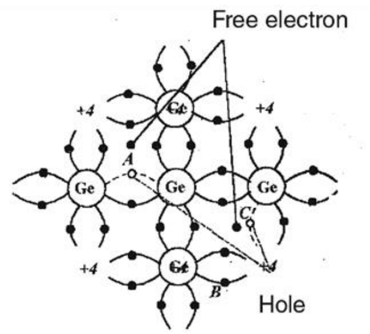
For clarity, a two-dimensional representation of the crystal structure for germanium is presented in the figure, which can also be applied to silicon. This representation focuses specifically on the covalent bonds within the structure.



At a temperature of 0 Kelvin (0 K), all the valence electrons are actively engaged in bonding, rendering the crystal a perfect insulator. In this state, there are no free electrons available for conduction. However, as the temperature increases, some valence electrons acquire enough energy to break away from the bonds, allowing them to move randomly within the crystal lattice. When an external electric field is applied, these electrons experience a drift, leading to the conduction of electricity. In essence, the conductivity of the crystal increases with higher temperatures as some electrons gain the energy needed to participate in electrical conduction.

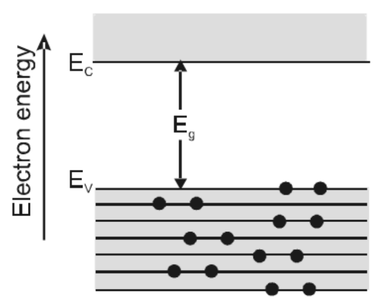


Two dimensional representation of the crystal structure of germanium at 0 K



Formation of electron hole pair

When an electron escapes from a band within a semiconductor, it results in the creation of a vacancy in the crystal lattice, known as a "hole." This vacancy, caused by the absence of an electron, essentially represents a positive charge of the same magnitude as that of an electron. As elaborated later, holes play a significant role in the conduction of semiconductors.



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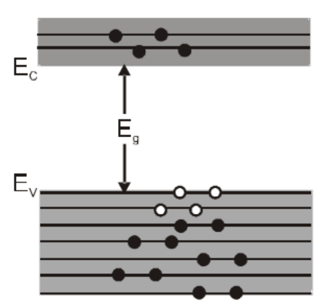
An intrinsic semiconductor at T = 0 K behaves like insulator.

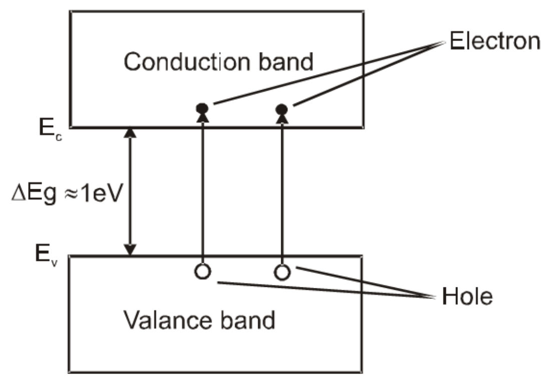
When a covalent bond is disrupted, it leads to the generation of an electron-hole pair. At room temperature (300 K), numerous electron-hole pairs are present in the crystal lattice. The process of electron-hole pair generation is elucidated in the figure.



At T > 0 K four thermally generated electron-hole pairs. The filled circles (.) represent electrons and empty fields (O) represent holes.

Consider a scenario where, due to thermal energy, an electron is liberated from the covalent bond at site A, creating a hole at this location. Subsequently, an electron from the covalent bond of a neighboring atom at site B may jump to the vacant site A, completing the bond at A but leaving a hole at B. In this process, the energy involved is relatively small compared to what is required for the generation of an electron-hole pair. This is because the electron is transitioning from one bond to another, and all electrons in the bonding state have, on average, the same energy.

As depicted in the figure, when an electron jumps from C to B, a hole is created at C, and this process continues. Effectively, such a vacancy or hole can be considered mobile. Consequently, in a semiconductor, both electrons and holes function as charge carriers, actively contributing to electric conduction.



The intrinsic semiconductor exhibits equality in the number of electrons and holes generated through thermal processes. If ne represents the electron concentration and n_h represents the whole concentration, then n_i (intrinsic charge carriers' concentration) is given by:

$$n_i = n_e = n_h$$

Furthermore, the product of the electron and hole concentrations, $n_e\, n_h$ is equal to the square of the intrinsic charge carriers' concentration (n_i):

$$n_e\, n_h = n_i^2$$

Key points to note about intrinsic semiconductors:

1. A pure semiconductor is termed an intrinsic semiconductor, characterized by thermally generated current carriers.

2. These semiconductors have four electrons in the outermost orbit of the atom, and atoms are interconnected by covalent bonds.

3. Both free electrons and holes function as charge carriers, with n_e (in the conduction band) equal to n_h (in the valence band).

4. The drift velocity of electrons (v_e) is greater than that of holes (v_h).

5. The Fermi energy level in pure semiconductors lies at the center of the conduction band and valence band.

6. Impurity in a pure semiconductor must be less than 1 in 10^8 parts of the semiconductor.

7. In an intrinsic semiconductor, $n_e(0) = n_h(0) = n_i$, where ne(0) is the electron density in the conduction band, $n_h(0)$ is the hole density in the valence band, and n_i is the density of intrinsic carriers.

8. The fraction of electrons from the valence band present in the conduction band is given by $f \propto e^{-\frac{E_g}{kT}}$, where E_g is the Fermi energy, k is Boltzmann's constant, and T is the absolute temperature.

9. Due to the low number of charge carriers at room temperature, intrinsic semiconductors exhibit low conductivity and limited practical applications.

10. The number of electrons reaching from the valence band to the conduction band, n, is given by $n = AT^{\frac{3}{2}}\, e^{-\frac{E_g}{2kT}}$, where A is a positive constant.

11. The net charge of a pure semiconductor is zero.

(a) Electrical Conductivity of Intrinsic Semiconductor:

At room temperature, a semiconductor consists of electrons in the conduction band and holes in the valence band. When subjected to an external electric field, electrons move in the opposite direction of the field, and holes move in the direction of the field. This motion contributes to the total current, which is the sum of the electron and hole currents.

The total current (i) is expressed as the sum of the electron current (i_e) and the whole current(i_h):

$i = i_e + i_h$

This implies that the electrical conductivity of an intrinsic semiconductor is influenced by both the movement of electrons and holes in response to an applied electric field. The behavior of electrons and holes contributes to the overall conductivity of the semiconductor, forming an essential aspect of its electrical properties.

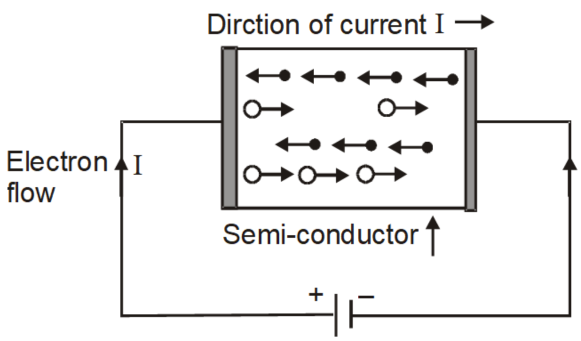
Hole Current (i_h):

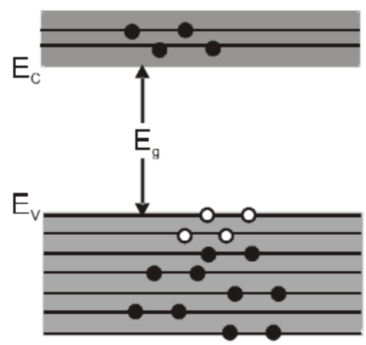
The movement of electrons within the covalent bond sites in the valence band results in the motion of holes in the opposite direction. When electrons jump from one position to another within the valence band, the whole moves in the opposite direction to the electron jump. It is essential to note that the original electron that was set free is not directly involved in the motion of the hole.

The concept of whole motion is introduced as a convenient way to describe the actual movement of the bonded electrons within the valence band. The motion of holes serves as a useful abstraction to understand the behavior of electrons in the valence band of a semiconductor.

Electron Current ($\mathbf{i}_e$):

Conduction electrons, which are free electrons, move independently under the influence of an electric field, contributing to the electron current. It is important to highlight that, in addition to the generation of conduction electrons and holes, there is a simultaneous process of recombination. Recombination involves the electrons combining with the holes, and at equilibrium, the rate of generation is balanced by the rate of recombination of charge carriers. Recombination typically occurs when an electron collides with a hole within the semiconductor material. This dynamic process of generation and recombination is crucial for maintaining equilibrium in the semiconductor, ensuring that the number of charge carriers remains constant over time.





Let's consider a semiconductor block with a length λ, a cross-sectional area A, and electron concentration n_e and whole concentration n_h. When an electric field E is applied across the ends of the semiconductor, the electric field is given by:

$$E = \frac{V}{\ell}$$

Under this electric field, electrons and holes drift in opposite directions, resulting in currents i_e and i_h, respectively, in the direction of the electric field. The total current flowing through the semiconductor is the sum of these individual currents:

$$i = i_e + i_h$$

If v_e is the drift velocity of electrons in the conduction band and v_h is the drift velocity of holes in the valence band, then:

$$i_e = n_e e A v_e$$

$$i_h = n_h e A v_h$$

Here, e represents the magnitude of the electron charge. Therefore, the total current (i) can be expressed as:

$$i = eA(n_e v_e + n_h v_h)$$

This equation illustrates the combined effect of electron and hole drift velocities in response to the applied electric field across the semiconductor.

Consider the resistance R of the semiconductor block and ρ as the resistivity of the material, then $\rho = \frac{RA}{\lambda}$ (equation iii). Dividing equation (i) by equation (iii) yields:

$$\frac{V}{i} = R$$

Substituting the value of $\frac{i}{A}$ from equation (ii) into this equation, we obtain:

$$R = \frac{e}{\sigma}$$

Now, let's introduce the mobility μ, defined as the drift velocity per unit field and expressed in $\text{meter}^2/(\text{volt} - \text{second})$. The mobilities of electrons and holes are given by:

$\mu_e = \frac{ve}{E}$ And $\mu_h = \frac{vh}{E}$

Introducing μ_e and μ_h into equation (iv), we get:

$$\sigma = e(ne\mu_e + n_h\mu_h)$$

The electrical conductivity σ is the reciprocal of resistivity ρ. Therefore, the electrical conductivity of the semiconductor is given by:

$$\sigma = e(ne\mu_e + n_h\mu_h)$$

Simplifying further, we find:

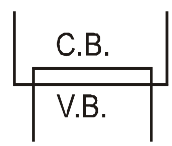
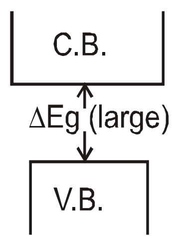
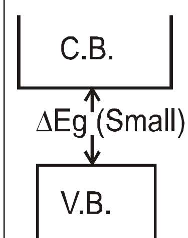
$$\sigma = en_i(\mu_e + \mu_h)$$

Where n_i is the intrinsic carrier concentration, and in intrinsic semiconductors, $n_e = n_h = n_i$.

This expression reveals that the electrical conductivity of a semiconductor relies on the concentrations (number densities) of electrons and holes, as well as their respective mobilities. Notably, the electron mobility is greater than the hole mobility.

As the temperature increases, both electron (n_e) and hole (n_h) concentrations rise due to the breakage of more covalent bonds.

Although the mobilities (μ_e) and (μ_h) slightly decrease with an increase in temperature, this decrease is counteracted by the substantial increase in n_e and n_h. Consequently, the conductivity of a semiconductor experiences an increase, or conversely, the resistivity decreases with a rise in temperature.

Properties	Conductors	Insulators	Semiconductors
Electrical conductivity	10^2 to 10^8 ℧/m	10^{-8} ℧/m	10^{-5} to 10^0 ℧/m
Resistivity	10^{-2} to 10^{-8} Ω-m (negligible)	10^8 Ω-m	10^5 to 10^0 Ω-m
Band Structure			
Energy gap (E_g)	Zero or very small	Very large : for diamond it is 6 eV	Ge → 0.7 eV Si → 1.1 eV GaAs → 1.3 eV GaF_2 → 2.8 eV
Current carriers	Free electrons	—	Free electrons and holes
Condition of V.B. and C.B. at ordinary temperature	V.B. and C.B. are completely filled or C.B is some what empty	V.B – Completely .field C.B.–Completely unfilled	V.B– some what empty C.B.- some what filled
Temperature co-efficient of resistance	Positive	Zero	Negative
Effect of temperature on conductivity	Decreases	—	Increases
Effect of temperature on resistance	Increases	—	Decreases
Examples	Cu, Ag, Au, Na, Pt, Hg etc.	Wood, plastic, mica diamond, glass etc.	Ge, Si GaAs etc,
Electron density	$10^{29}/m^3$	—	Ge ~ $10^{19}/m^3$ Si ~ 10^{16} / m^3