Chapter 15

Semiconductor Electronics: Materials, Devices And Simple Circuits

SEMICONDUCTOR BASICS

Electronic instruments serve diverse purposes in fields ranging from telecommunication and entertainment to computers and nuclear physics. While their origins trace back to the era of vacuum tubes, today's advancements in electronics owe much to semiconductor devices.

Semiconductor devices offer numerous advantages over their predecessors. They are compact, consume less power, have longer lifespans, and operate more efficiently. Moreover, they are cost-effective. These traits have spurred the widespread adoption of semiconductor devices, replacing vacuum tubes in almost every application. Take computers, for instance: early vacuum tube-based models were massive, requiring entire rooms and limited to basic calculations. In contrast, contemporary personal computers (PCs) are much smaller yet immensely powerful, thanks to semiconductor technology's strides.

In subsequent sections, we will explore the foundational principles of semiconductors. This understanding will lay the groundwork for comprehending the functioning of various semiconductor devices. We will delve into specific devices like diodes and transistors, elucidating their workings and practical applications.

Materials in the solid state are classified based on their electrical conductivity, typically characterized by their resistivity (ρ) or conductivity (σ), where resistivity is the inverse of conductivity ($\rho = 1/\sigma$).

(i) Metals: Metals demonstrate exceptionally low resistivity, indicating high conductivity. Their resistivity (ρ) typically falls within the range of $10^{(-2)}$-$10^{(-8)}$ Ω.m, corresponding to conductivity (σ) values of approximately 10^2-10^8 S.m$^{(-1)}$.

(ii) Semiconductors: Semiconductors exhibit resistivity or conductivity values intermediate between metals and insulators. Their resistivity (ρ) generally ranges from $10^{(-5)}$-10^6 Ω.m, with conductivity (σ) around 10^5-$10^{(-6)}$ S.m$^{(-1)}$.

(iii) Insulators: Insulators possess high resistivity, indicating low conductivity. Their resistivity (ρ) typically lies within the range of 10^{11}-10^{19} Ω.m, corresponding to conductivity (σ) values of approximately $10^{(-11)}$-$10^{(-19)}$ S.m$^{(-1)}$.

Properties And Examples

While the provided resistivity and conductivity values offer approximations to gauge magnitude, they may vary beyond the specified ranges. However, it's important to note that relative resistivity values aren't the sole criteria for distinguishing between metals, insulators, and semiconductors. Other factors will become apparent as we delve further into this topic.

This chapter primarily focuses on semiconductor examination, which can be categorized as follows:

(i) Elemental Semiconductors: Notably Silicon (Si) and Germanium (Ge).

(ii) Compound Semiconductors, including:

Inorganic Compounds: Such as Cadmium Sulfide (CdS), Gallium Arsenide (GaAs), Cadmium Selenide (CdSe), Indium Phosphide (InP), among others.

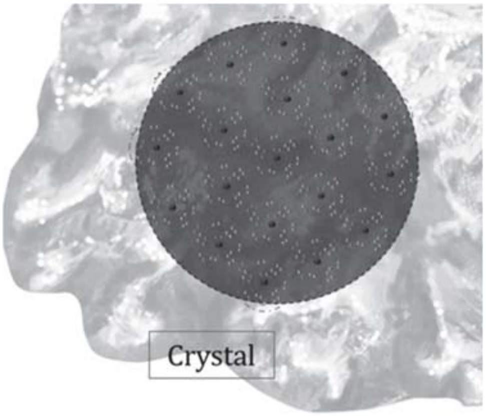
Organic Compounds: Examples include Anthracene, doped phthalocyanines, etc.

Organic Polymers: Like Polypyrene, polyaniline, polythiophene, etc.

While conventional semiconductor devices predominantly utilize elemental and inorganic compound semiconductors like Si or Ge, advancements since 1990 have introduced semiconductor devices incorporating organic semiconductors and semiconducting polymers. This heralds the advent of futuristic technologies such as polymer electronics and molecular electronics.

Band Theory of Solids

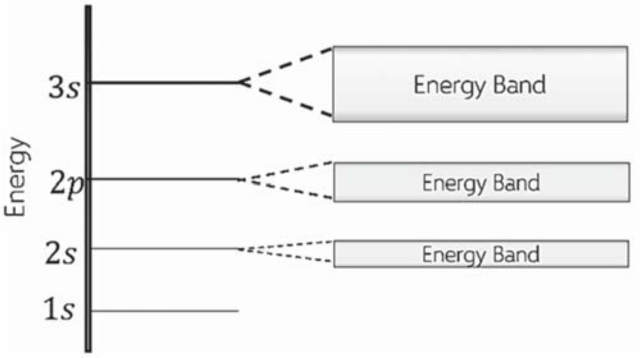
Within the confines of an individual atom, each electron possesses a specific energy level dictated by its quantum state. Furthermore, electrons sharing identical quantum states exhibit uniform energy levels across all isolated atoms.



When arranged in a crystalline structure, atoms are brought into close proximity, typically within a range of 2 to 3 angstroms. In this configuration, electrons undergo novel interactions due to the altered spatial arrangement and the collective influence of neighboring atoms.

1. Interacting with the electrons of adjacent atoms.
2. Interacting with the nuclei of neighboring atoms.

$Na_{11} = 1s^2\ 2s^2 2p^6\ 3s^1$



The N states corresponding to the angular momentum quantum number l = 0, initially exhibiting identical energy levels within individual isolated atoms, undergo dispersion and amalgamation to give rise to a continuous energy band.

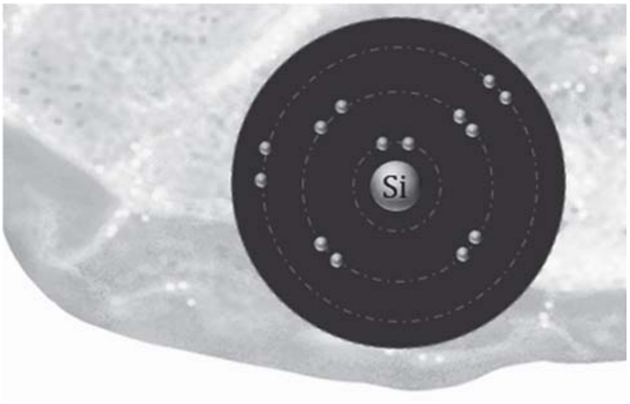
When considering a collection of N isolated sodium (Na) atoms, each possessing three $3s^1$ electrons, all N electrons within the $3s^1$ orbital share identical energy levels. Consequently, their energy distribution can be represented as a singular line, as depicted earlier.

However, upon bringing these isolated atoms together within a crystal lattice, the interactions between neighboring atoms disrupt this uniformity.

As a result, each electron's energy level deviates, leading to the formation of an energy band.
Of note, the width of this energy band is most pronounced for the valence electrons, such as the 3s electrons in sodium (Na).

Silicon Semiconductor

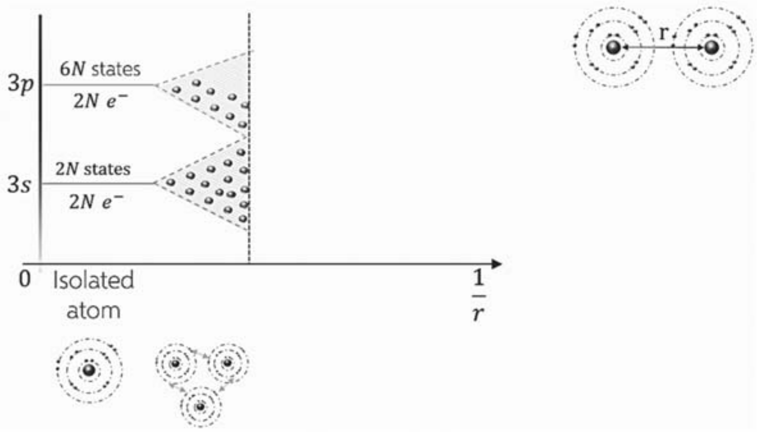
Silicon is a semiconductor material widely used in electronic devices due to its unique electrical properties. In its pure form, silicon is a crystalline solid with four valence electrons, making it part of Group 14 in the periodic table. Each silicon atom forms covalent bonds with four neighboring silicon atoms, creating a stable crystal lattice structure known as a silicon crystal.
The electronic structure of silicon contributes to its semiconductor properties. Silicon has a band gap, which is the energy difference between the valence band (where electrons are bound to atoms) and the conduction band (where electrons can move freely). In pure silicon at absolute zero temperature, the valence band is fully occupied with electrons, and the conduction band is empty, creating an energy gap between them.
However, at higher temperatures or when subjected to external influences such as doping, silicon can conduct electricity. Doping involves intentionally introducing impurities into the silicon crystal to alter its electrical properties.
For example, adding a small amount of a Group 15 element like phosphorus (n-type doping) introduces extra electrons into the crystal structure, creating excess negative charge carriers (electrons). Conversely, adding a Group 13 element like boron (p-type doping) creates "holes" or deficiencies of electrons in the crystal lattice, which behave like positive charge carriers.
Semiconductor devices, such as diodes and transistors, exploit the unique properties of silicon to control the flow of electricity. Silicon's abundance, stability, and controllable conductivity make it a cornerstone material in modern electronics.
Let's examine a silicon (Si) crystal composed of a substantial number, denoted as N, of silicon atoms. The magnitude of N is approximately on the order of 10^23, illustrating the immense quantity of atoms constituting the crystal structure.

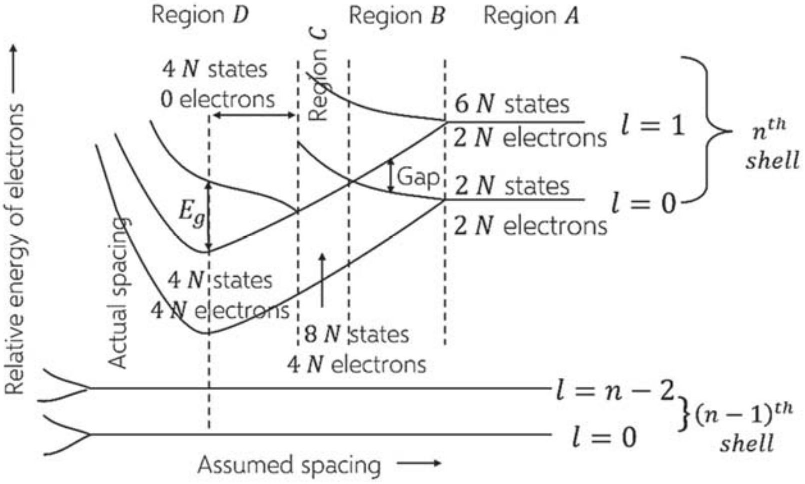


$$Si_{14} = 1s^2\ \ 2s^2 2p^6\ \ 3s^2 3p^2$$

$$\boxed{\uparrow\downarrow}\qquad \boxed{\uparrow}\ \ \boxed{\uparrow}\ \ \boxed{}$$

Each silicon (Si) atom possesses four electrons within its outer orbit. Consequently, in a silicon crystal comprised of N atoms, the total number of electrons occupying the outer orbit amounts to 4N.
Moreover, each silicon atom's outer energy level comprises eight states, characterized by two in the s sublevel and six in the p sublevel.
Extending this to the silicon crystal with N atoms, the total available outer energy levels amount to 8N, consisting of 2N states in the s sublevel and 6N states in the p sublevel.
Electrons fill 4N positions. There are 4N empty positions. At absolute zero temperature





In region A, where atoms are in an isolated state, all 6N states associated with p-orbitals exhibit identical energy levels. Only 2N of these states are occupied by electrons. Similarly, all 2N states corresponding to s-orbitals share the same energy level and are fully occupied by electrons.

Moving to region B, where atoms are brought closer together compared to region A, the energy levels start to split. The 6N states occupied by 2N electrons and the 2N states occupied by 2N electrons can now have energies distributed across the energy band, resulting in the formation of a noticeable gap between two energy bands.

In region C, further compression of atoms leads to the intermixing of energy levels. Some of the 6N states shift below the energy level of the 2N states.

Continuing to region D, where atoms are brought even closer, approximately within a range of 2 to 3 angstroms, the 8N states split evenly into two energy bands. An energy gap (Eg) emerges between the lowest energy level of the upper band (known as the Conduction band) and the highest energy level of the lower band (referred to as the Valence band).

At absolute zero temperature (0 K), all 4N electrons occupy the energy band with lower energy (the Valence band), while the energy band with higher energy (the Conduction band) remains unoccupied.

The Valence Band (VB)

The lower band is entirely filled with electrons, including those from the valence shell.

The Conduction Band (CB)

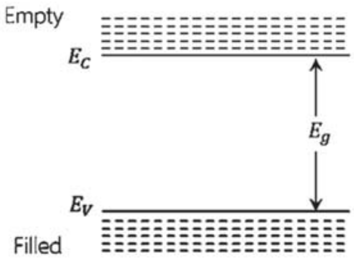
The region of energy levels situated above the valence band is referred to as the "Conduction band." Electrons occupying this band, particularly those from the outermost orbitals, play a crucial role in facilitating electrical conductivity within the material.

The Forbidden Energy Gap (FEG)

The Fermi energy level (FEG) is determined by subtracting the maximum product of the valence band energy (V) and magnetic field strength (B) from the minimum product of the conduction band energy (C) and magnetic field strength (B).

Additionally, the band gap energy (E_g) is calculated by subtracting the energy of the valence band (E_v) from the energy of the conduction band (E_c).

Certainly, here's more detailed rephrased version:

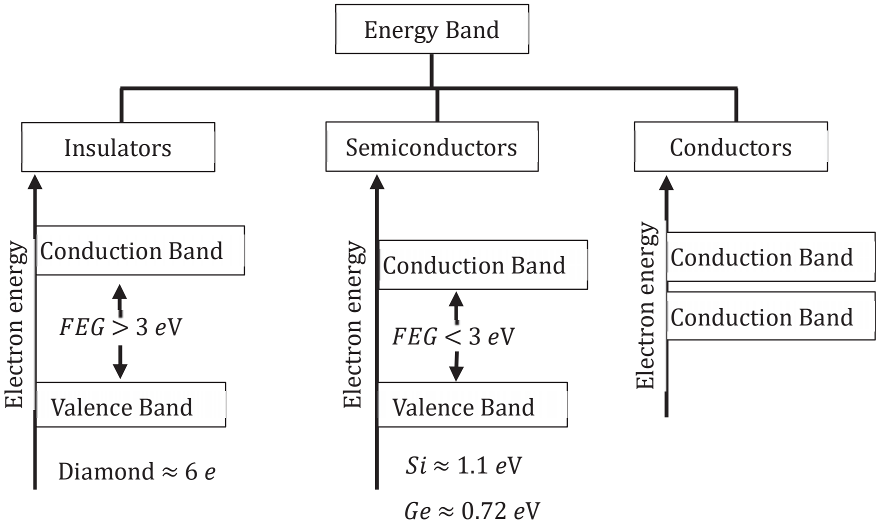


a) When electrons occupy the valence band, it indicates that they are involved in bonding within the material. These electrons are tightly bound to the atoms or molecules, contributing to the stability of the substance. However, when external energy is supplied to the material, it provides the necessary force to overcome the bonding forces holding the electrons in place. As a result, some electrons gain sufficient energy to break free from their bonds and transition to the conduction band. In this state, these electrons are no longer confined to specific atoms or molecules and are free to move throughout the material, contributing to its electrical conductivity.

b) When an external energy input equal to the band gap energy (E_g) is supplied to a material, it prompts a specific phenomenon: electrons from the valence band gain sufficient energy to overcome the band gap and transition into the conduction band. This transition leaves behind a localized region of positive charge, known as a hole, within the valence band. The hole represents the absence of an electron in its usual position within the valence band structure. Both the movement of electrons to the conduction band and the creation of holes in the valence band significantly influence the material's electrical and optical properties, playing a crucial role in its behavior as a semiconductor or insulator.

Energy Band

The term "energy band" typically refers to the distribution of allowed energy levels for electrons in a solid material. In solid-state physics, electrons in a crystalline solid are governed by quantum mechanics and are confined to specific energy levels within the solid's electronic structure.



The energy gap that separates the valence and conduction bands in a material is commonly referred to as the "forbidden energy gap." This term is used because within this region, electrons are prohibited from occupying energy states. In other words, electrons cannot exist within this gap unless they acquire sufficient energy from an external source to transition from the valence band to the conduction band. This constraint arises due to the quantum mechanical nature of electron behavior within the crystalline lattice of the material.

The forbidden energy gap plays a fundamental role in determining the electrical and optical properties of the material, as it influences its conductivity and ability to absorb or emit photons of specific energies.

Intrinsic Semiconductor

A semiconductor lacking any impurities is termed an intrinsic semiconductor. Ideally, an intrinsic semiconductor crystal would consist solely of atoms of that particular semiconductor. However, attaining such absolute purity is practically unfeasible. Nonetheless, if the impurity concentration falls below 1 in 10^8 parts of the semiconductor, it qualifies as intrinsic.

To elucidate the characteristics of intrinsic semiconductors, we'll consider the examples of silicon and germanium. Both silicon and germanium are classified under Group IV of the periodic table and exhibit tetravalent properties.

Their electronic configurations are as follows:

Silicon (Si) has an atomic number of 14, and its electronic configuration is represented as follows:

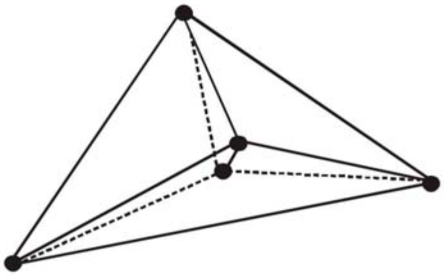
$$(14) = 1s^2 2s^2 2p^6 3s^2 3p^2$$

Germanium (Ge) has an atomic number of 32, and its electronic configuration is represented as follows:

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

These electronic configurations describe how electrons are distributed across the energy levels and orbitals of silicon and germanium atoms.

Both silicon and germanium possess a crystalline structure where each atom resides within a tetrahedral arrangement formed by its four nearest neighboring atoms. This arrangement is depicted in the provided figure. Within this structure, each atom shares its four valence electrons with its immediate neighbors on a one-to-one basis, resulting in the formation of four covalent bonds for each atom.

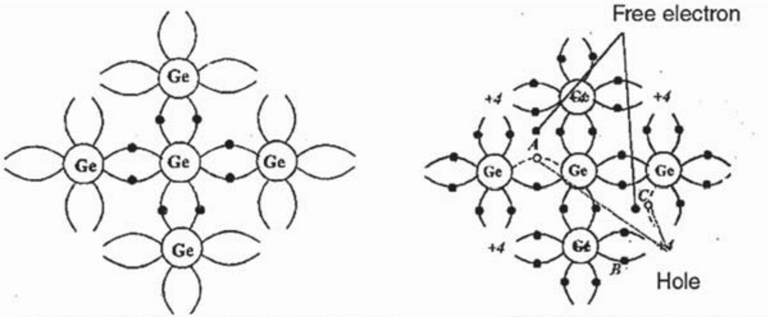


To enhance clarity, the figure illustrates a two-dimensional representation of the crystal structure, focusing specifically on the covalent bonds within the structure. While the figure is shown for germanium, the same structure applies to silicon as well.

At a temperature of absolute zero (0 Kelvin or 0 K), all the valence electrons are fully occupied in bonding, resulting in the crystal exhibiting properties of a perfect insulator. At this temperature, there are no free electrons available for electrical conduction.

However, as the temperature rises, some valence electrons gain sufficient thermal energy to overcome the bonding forces and break away from their respective atoms. These freed electrons then begin to move randomly within the crystal lattice. When an external electric field is applied to the material, these mobile electrons experience a net drift, contributing to the flow of electric current.

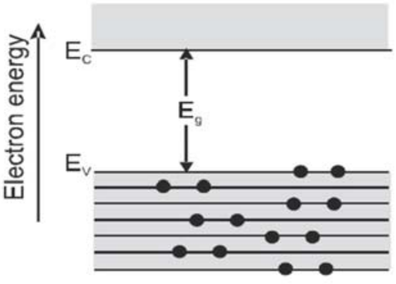
In essence, the conductivity of the crystal increases with higher temperatures because more electrons gain the energy necessary to participate in electrical conduction, thus enhancing the material's ability to conduct electricity.



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

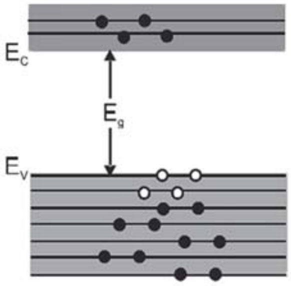
Formation of electron hole pair

When an electron transitions out of a band within a semiconductor, it leads to the formation of an empty space in the crystal lattice, termed a "hole." This vacancy, arising from the electron's departure, effectively carries a positive charge equal in magnitude to that of an electron. As we will explore further, these holes play a pivotal role in facilitating the conduction of electrical current in semiconductors.



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

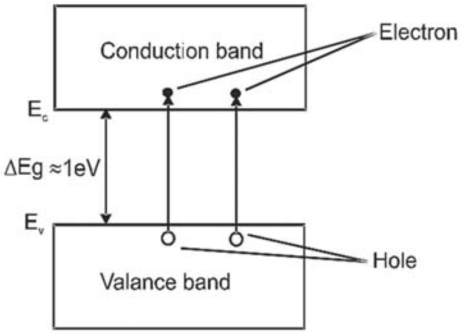
When a covalent bond is broken, it initiates the creation of an electron-hole pair. At typical room temperature conditions (approximately 300 Kelvin), the crystal lattice contains a multitude of electron-hole pairs. The mechanism behind the generation of electron-hole pairs is illustrated in the accompanying figure.



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

Let's delve into a scenario where thermal energy facilitates the liberation of an electron from a covalent bond, taking place at site A within the crystal lattice. This liberation generates a hole at this specific location. Subsequently, an electron from a neighboring atom's covalent bond, situated at site B, may relocate to occupy the newly vacated site A, thereby restoring the bond at A while simultaneously creating a hole at B. This transition involves relatively low energy compared to the process of generating an electron-hole pair, as the electron merely shifts from one bond to another. In this scenario, all electrons within the bonding state possess, on average, comparable energy levels.

The accompanying figure illustrates this phenomenon: as electrons continue to jump between adjacent sites, holes are continually generated and migrate throughout the lattice. Effectively, these vacancies or holes exhibit mobility within the semiconductor material. Consequently, in a semiconductor, both electrons and holes serve as charge carriers, actively participating in the conduction of electric current.



In an intrinsic semiconductor, there is an equilibrium between the number of electrons and holes generated due to thermal processes. If n_e represents the electron concentration and n_h represents the hole concentration, then n_i (the concentration of intrinsic charge carriers) can be expressed as:

$$n_i = n_e = n_h$$

Moreover, the multiplication of the electron and hole concentrations, denoted as $n_e \times n_h$, equals the square of the intrinsic charge carriers' concentration n_i:

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

Here are the key points about intrinsic semiconductors, rephrased in detail:

1) An intrinsic semiconductor refers to a semiconductor in its pure form, characterized by the presence of thermally generated current carriers.

2) These semiconductors are distinguished by atoms having four electrons in their outermost orbit, with bonding occurring through covalent bonds.
3) Both free electrons and holes serve as charge carriers, with the concentration of electrons (n_e) in the conduction band being equal to the concentration of holes (n_h) in the valence band.
4) Electrons exhibit a greater drift velocity (v_e) compared to holes (v_h).
5) The Fermi energy level in pure semiconductors is positioned at the midpoint between the conduction and valence bands.
6) Impurity levels in pure semiconductors must remain below 1 in 10^8 parts of the semiconductor.
7) In an intrinsic semiconductor, the initial electron density n_e (0) in the conduction band equals the initial hole density n_h (0) in the valence band, both of which are equal to the density of intrinsic carriers (n_i).
8) The fraction (f) of electrons transitioning from the valence band to the conduction band is given by $f \propto e^{-E_g/kT}$, where E_g represents the Fermi energy, k is Boltzmann's constant, and T is the absolute temperature.
9) Due to the limited number of charge carriers at room temperature, intrinsic semiconductors typically exhibit low conductivity and have restricted practical applications.
10) The number of electrons (n) transitioning from the valence band to the conduction band is given by $n=AT^{3/2}e^{-E_g/2kT}$, where A is a positive constant.
11) The overall charge of a pure semiconductor is neutral.

Electrical Conductivity of Intrinsic Semiconductor:

At typical room temperature, a semiconductor comprises electrons occupying the conduction band and holes occupying the valence band. When exposed to an external electric field, electrons migrate in a direction opposite to that of the field, while holes move in alignment with the field's direction. This movement collectively adds to the overall current flow, which constitutes the combined contributions of electron and hole currents.

The aggregate current (denoted as i) is represented as the accumulation of the electron current (i_e) and the hole current (i_h):

$$i = i_e + i_h$$

This indicates that the electrically conductive properties of an intrinsic semiconductor are impacted by the movement of both electrons and holes when subjected to an external electric field. The actions of electrons and holes collectively influence the semiconductor's overall conductivity, thereby constituting a fundamental component of its electrical characteristics.

Hole Current ($\mathbf{i_h}$):

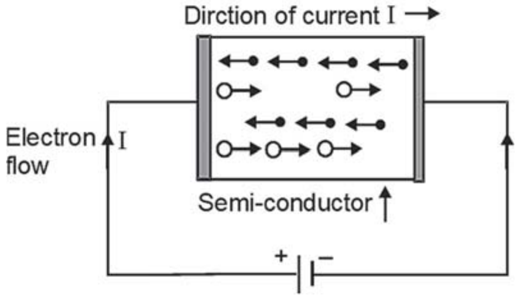
The movement of electrons within the covalent bonding sites situated in the valence band induces a corresponding motion of holes in the opposite direction. As electrons transition from one position to another within the valence band, the hole moves inversely to the electron's movement. It's crucial to emphasize that the original liberated electron does not directly partake in the motion of the hole.

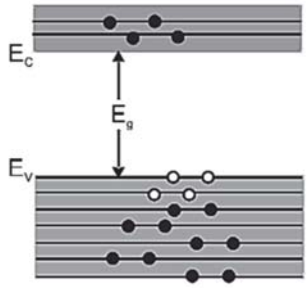
The concept of hole motion is introduced as a convenient method to depict the actual movement of bonded electrons within the valence band. The progression of holes provides a helpful abstraction for comprehending the behavior of electrons within the valence band of a semiconductor.

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

Conduction electrons, also referred to as free electrons, exhibit autonomous movement when subjected to an electric field, thus contributing to the electron current within the material. It's essential to highlight that in addition to the generation of conduction electrons and holes, there is a simultaneous occurrence of recombination. Recombination involves the bonding of electrons with holes, and at a state of equilibrium, the rate of charge carrier generation is offset by the rate of recombination.

Recombination typically occurs when an electron collides with a hole within the semiconductor material. This dynamic interaction between generation and recombination is vital for maintaining equilibrium in the semiconductor, ensuring a consistent number of charge carriers over time.





Let's examine a semiconductor block characterized by a length λ and a cross-sectional area A, with electron concentration n_e and hole concentration n_h. Upon applying an electric field E across the ends of the semiconductor, the magnitude of the electric field is expressed as:

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

In response to this electric field, electrons and holes undergo drift motions in opposite directions, giving rise to currents i_e and i_h, respectively, oriented in the direction of the electric field. The cumulative current passing through the semiconductor is the aggregate of these individual currents:

$$i = i_e + i_h$$

If v_e represents the drift velocity of electrons within the conduction band, and v_h signifies the drift velocity of holes within the valence band, then:

$$i_e = n_e e A v_e$$

$$i_h = n_h e A v_h$$

In this context, e denotes the magnitude of the electron charge. Hence, the total current (i) can be formulated as:

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

This equation demonstrates how the combined impacts of electron and hole drift velocities respond to the externally applied electric field across the semiconductor.

Let's examine the resistance R of the semiconductor block, with ρ denoting the resistivity of the material.

Here, $\rho = \frac{RA}{\lambda}$ (equation iii). Dividing equation (i) by equation (iii) results in:

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

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

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

Now, let's introduce the mobility μ, which is defined as the drift velocity per unit electric field and is expressed in square meters per volt-second (m^2/V-s). The mobilities of electrons and holes are specified as follows:

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

By incorporating μ_e and μ_h into equation (iv), we obtain:

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

The electrical conductivity σ is the inverse of resistivity ρ. Hence, the electrical conductivity of the semiconductor is expressed as:

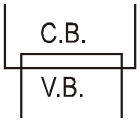
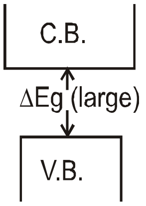
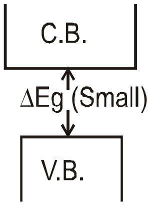
$$\sigma = en_i(\mu_e + \mu_h)$$

Here, n_i denotes the intrinsic carrier concentration, specifically in intrinsic semiconductors,

$$n_e = n_h = n_i.$$

This equation demonstrates that the electrical conductivity of a semiconductor depends on the concentrations (number densities) of electrons and holes, along with their individual mobilities. It's noteworthy that the electron mobility exceeds the hole mobility.

With increasing temperature, both electron (n_e) and hole (n_h) concentrations elevate as more covalent bonds are disrupted. Although the mobilities (μ_e and μ_h) experience a slight decrease with temperature rise, this reduction is offset by the significant increase in n_e and n_h. Consequently, the semiconductor's conductivity undergoes an augmentation, leading to a decrease in resistivity with increasing temperature.

Properties	**Conductors**	**Insulators**	**Semiconductors**
Electrical conductivity	10^2 to 10^8 $\mho$/m	10^{-8} $\mho$/m	10^{-5} to 10^0 $\mho$/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

Extrinsic Semiconductors

The conductivity of an intrinsic semiconductor is contingent upon temperature, and typically remains low at room temperature. Consequently, developing significant electronic devices using these semiconductors proves challenging. To bolster their conductivity, impurities are introduced.

By infusing a minute quantity, typically a few parts per million (ppm), of a suitable impurity into the pristine semiconductor, its conductivity experiences a substantial enhancement. These materials are known as extrinsic semiconductors or impurity semiconductors.

The deliberate introduction of a desired impurity is termed doping, with the impurity atoms referred to as dopants. This process yields a material termed a doped semiconductor. It's imperative that the dopant does not distort the original pristine semiconductor lattice, and occupies only a fraction of the original semiconductor atom sites in the crystal. This necessitates the dopant and semiconductor atoms to have closely matching sizes.

There exist two categories of dopants utilized for doping tetravalent Si or Ge:

(i) Pentavalent dopants (valency 5), such as Arsenic (As), Antimony (Sb), Phosphorous (P), among others.

(ii) Trivalent dopants (valency 3), including Indium (In), Boron (B), Aluminium (Al), and similar elements.

The selection of a dopant relies on the intended effect and the particular semiconductor material under consideration. The dopant element is chosen from neighboring groups in the Periodic table, ensuring that the dopant atom's size closely matches that of Si or Ge. Intriguingly, the utilization of pentavalent and trivalent dopants in Si or Ge yields two distinct semiconductor types, each possessing unique characteristics.

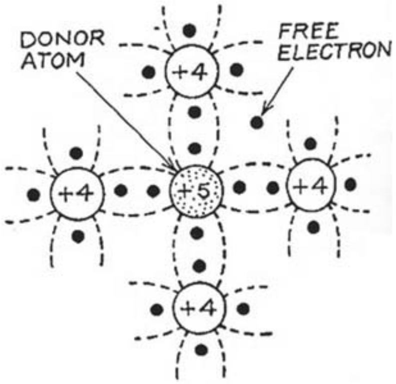
Extrinsic semiconductor is of two types: n–type and p–type.

(a) n–type semiconductor:

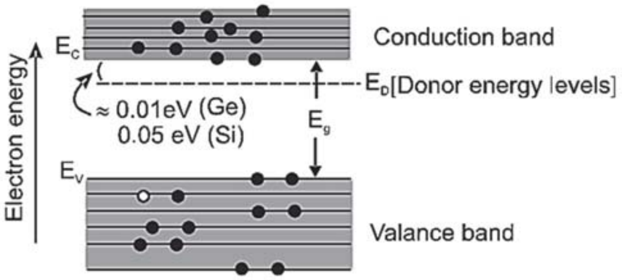
When a pentavalent impurity atom, such as antimony, phosphorus, or arsenic, is inserted into a germanium (Ge) or silicon (Si) crystal, it occupies the position of a Ge (or Si) atom within the crystal lattice. Four out of the five valence electrons of the impurity atom establish covalent bonds, with each valence electron pairing up with one of the valence electrons from four neighboring Ge (or Si) atoms. Consequently, the inclusion of a pentavalent impurity to pure Ge (or Si) leads to a rise in the number of free electrons, thereby augmenting the conductivity of the crystal.

The impure Ge (or Si) crystal is designated as an 'n-type' semiconductor due to its surplus of 'negative' charge carriers, which are electrons. In this context, the impurity atoms are labeled 'donor' atoms since they supply or donate conducting electrons to the crystal, consequently shaping its electrical characteristics.

The fifth valence electrons of the impurity atoms occupy distinct energy levels situated slightly below the conduction band. These energy levels are known as 'donor levels' and are positioned approximately 0.01 eV below the conduction band in germanium (Ge) and 0.05 eV below in silicon (Si). As a result, at room temperature, the "fifth" electrons associated with nearly all donor atoms experience thermal excitation from the donor levels to the conduction band. Upon reaching the conduction band, these electrons serve as charge carriers when subjected to an external electric field.



In typical circumstances, the predominant source of electrons in the conduction band is the donor levels, with only a minor portion arising from the valence band. Consequently, the primary charge carriers accountable for conduction are the electrons provided by the donor atoms. Because of the restrained excitation from the valence band, the quantity of holes within this band remains minimal.



As a result, the contribution to current from the holes is restricted. In an n-type semiconductor, electrons are regarded as the 'majority carriers,' whereas holes are classified as the 'minority carriers.'

The provided illustration depicts an n-type semiconductor at temperatures exceeding 0 Kelvin. Within this semiconductor, there exists one electron-hole pair thermally generated in the conduction band, along with nine conduction electrons derived from donor atoms.

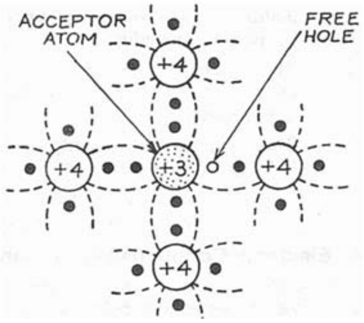
Here are some significant details about P-Type Semiconductors:

These semiconductors are produced by introducing a small quantity of trivalent impurity into a pristine semiconductor sample, such as germanium (Ge).

1) Majority Charge Carriers: Holes
   - Minority Charge Carriers: Electrons
2) Concentration Relationship:
   - $n_e \gg n_h$
   - $i_e \gg i_h$
3) Conductivity σ:
   - $\sigma = n_e \mu_e e$
4) Donor Energy Level:
   - Positioned just below the conduction band.
5) Electron and Hole Concentration: In a doped semiconductor, the electron concentration (n_e) and the hole concentration (n_h) are not equivalent (unlike in an intrinsic semiconductor). This relationship can be expressed as $n_e \cdot n_h = n_i^2$, where n_i is the intrinsic concentration. In an n-type semiconductor, the concentration of electrons in the conduction band is nearly equivalent to the concentration of donor atoms (N_d) and is significantly greater than the concentration of holes in the valence band, i.e., $n_e \approx N_d \gg n_h$.
6) Impurity Atom:
   - Referred to as the donor atom, it falls under the V group of the periodic table.
7) Net Charge:
   - The overall charge on an n-type crystal is neutral.
8) Immobile Charge:
   - Carries a positive charge.

(b) p–type semiconductor:

When a trivalent impurity atom, such as boron, Aluminium, gallium, or indium, is added to a germanium (Ge) or silicon (Si) crystal, it replaces one of the Ge (or Si) atoms within the crystal lattice. The three valence electrons of the impurity atom form covalent bonds with one valence electron each from the adjacent Ge (or Si) atoms. As a result, a void is created, leading to the formation of a 'p-type' semiconductor. This designation stems from its excess of positive 'acceptor' atoms, which generate holes capable of accepting electrons.

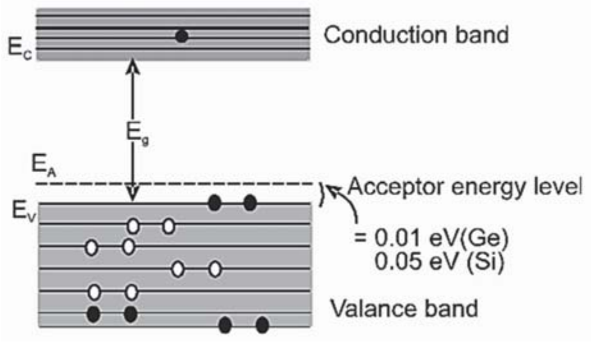


The impurity atoms occupy distinct vacant energy levels situated just above the uppermost portion of the valence band, known as 'acceptor levels'.

At room temperature, electrons undergo easy excitation from the valence band to the acceptor levels. The resultant holes formed in the valence band serve as the primary charge carriers in the crystal when an electric field is applied.

In a p-type semiconductor, the predominant carriers are the holes, while the scant electrons that are thermally excited from the valence band to the conduction band are regarded as 'minority carriers'.

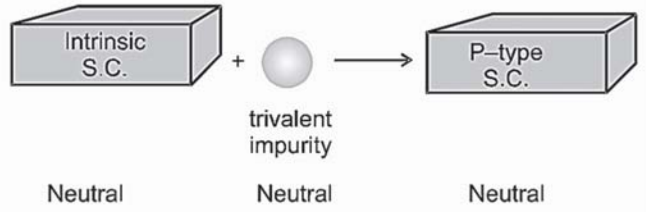
The accompanying figure illustrates the distribution of electrons and holes in a p-type semiconductor at temperatures exceeding 0 Kelvin. It showcases one electron-hole pair thermally generated and seven holes attributable to acceptor atoms.



Some important facts about P-Type Semiconductor:

P-Type Semiconductors are fashioned by introducing a minute quantity of trivalent impurity into a pristine semiconductor specimen, such as Ge. Below are some crucial attributes:

1) Majority Charge Carriers: Holes dominate as the primary charge carriers, while electrons are classified as minority carriers.
2) Concentration Disparity: The concentration of holes (n_h) greatly surpasses the concentration of electrons (n_e), resulting in a noticeable disparity.
3) Conductivity: The conductivity (σ) is approximately linked to the concentration of holes (n_h) and their mobility (μ_h).
4) Electrically Neutral: Despite the surplus of positive charge carriers (holes), a p-type semiconductor maintains electrical neutrality.
5) Acceptor Impurity: The trivalent impurity, belonging to the III group in the periodic table, is recognized as an acceptor impurity.
6) Acceptor Energy Level: The energy levels attributed to the acceptor impurity are positioned just above the valence band.
7) Electron and Hole Concentration: In a p-type semiconductor, the hole concentration in the valence band is almost equivalent to the concentration of acceptor atoms (Na), significantly outnumbering electrons in the conduction band. Thus, $n_h = N_a \gg n_e$.
8) Zero Net Charge: The overall charge of a p-type crystal is neutral.
9) Immobile Charge: The immobile charge in a p-type semiconductor is negative.



	Instrinsic Semiconductor	Extrinsic Semiconductor
1	It is a pure, natural semiconductor, such as pure Ge and pure Si.	It is prepared by adding a small quantity of impurity to a pure semiconductor, such as n-and p-type semiconductors.
2	In this scenario, the concentration of electrons and holes is identical.	In this case, the two concentrations are disparate. N-type semiconductors exhibit a surplus of electrons, while p-type semiconductors showcase an excess of holes.
3	Its electrical conductivity is exceedingly minimal.	Its electrical conductivity is notably elevated.
4	Its conductivity remains uncontrollable.	Its conductivity can be controlled by adjusting the quantity of the impurity added.
5	Its conductivity experiences an exponential rise with temperature.	Its conductivity escalates with temperature as well, albeit not in an exponential manner.

Distinction between n–type and p–type semiconductor:

	n-type semiconductor	p-type semiconductor
1	It's an extrinsic semiconductor acquired by incorporating a pentavalent impurity into a pristine intrinsic semiconductor.	It's also an extrinsic semiconductor achieved by introducing a trivalent impurity into a pristine intrinsic semiconductor.
2	The introduced impurity atoms supply additional free electrons to the crystal lattice and are referred to as donor atoms.	The impurity atoms introduced generate holes within the crystal lattice and are termed acceptor atoms since these holes accept electrons.
3	The electrons dominate as majority carriers, while the holes are in the minority.	The holes prevail as majority carriers, while the electrons constitute the minority carriers.
4	The concentration of electrons surpasses that of holes significantly ($n_e >> n_n$).	The concentration of holes exceeds that of electrons significantly ($n_h >> n_e$).

Ex. Doping transforms a silicon sample into a p-type semiconductor, where roughly one indium atom is inserted for every 5×10^7 silicon atoms. With a silicon specimen having an atomic number density of 5×10^{28} atoms/m^3, calculate the quantity of acceptor atoms in silicon per cubic centimeter.

Sol. Introducing a single indium atom into a silicon semiconductor generates one acceptor atom in the p-type semiconductor. With one indium atom doped for every 5×10^7 silicon atoms, the acceptor atom's number density in silicon can be computed as $(5\times10^{28})/(5\times10^7)$, resulting in 10^{21} atoms/m^3 or 10^{15} atoms/cm^3.

Ex. At 300 K, intrinsic silicon showcases identical concentrations of electrons n_e and holes n_h at 1.5×10^{16} m^{-3}. Following doping with indium, the hole concentration n_h escalates to 4.5×10^{22} m^{-3}. Calculate the new electron concentration n_e in the doped silicon.

Sol.

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

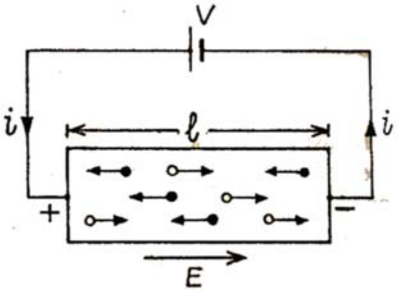
$$n_h = 4.5 \times 10^{22}\, m^{-3}$$

So,

$$n_e = 5.0 \times 10^{9}\, m^{-3}$$

(c) **Electrical conductivity of extrinsic semiconductors:**

At standard temperature, a semiconductor harbors electrons within the conduction band and holes within the valence band. When an external electric field is imposed, electrons migrate counter to the field, while holes travel in alignment with the field, inducing a current in the corresponding direction. Contemplating a semiconductor block characterized by length (l), cross-sectional area (A), electron concentration (n_e), and hole concentration (n_h), the introduction of a potential difference (V) across the semiconductor initiates an electric field E ($E = \frac{V}{l}$).



Under the influence of the electric field (E), electrons and holes undergo drift in opposing directions, generating currents denoted as i_e and i_h, respectively. The cumulative current passing through the semiconductor (i) is the aggregation of the electron and hole currents:

$$i = i_e + i_h$$

When expressed in terms of drift velocities (v_e and v_h), i_e and i_h can be articulated as:

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

In this context, e represents the magnitude of the electron charge. The resistance (R) and resistivity (ρ) of the semiconductor block are linked through $\rho = \frac{RA}{l}$. By dividing the equation representing the electric field (E) by the expression for current (i),

we derive: $$\frac{E}{\rho} = \frac{v}{RA} = \frac{i}{A}$$

Given V = iR (Ohm's law), substituting the value of $\frac{i}{A}$ into the equation yields:

$$\frac{1}{\rho} = e\left(\frac{n_e v_e}{E} + \frac{n_h v_h}{E}\right)$$

By introducing the mobility (μ), defined as the drift velocity per unit field, for electrons ($\mu_e = \frac{v_e}{E}$) and holes ($\mu_h = \frac{v_h}{E}$), the equation can be formulated as:

$$\frac{1}{\rho} = e(n_e\mu_e + n_h\mu_h)$$

The electrical conductivity (σ), which is the inverse of resistivity (ρ), is represented as:

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

This equation highlights that the electrical conductivity of a semiconductor relies on the concentrations of electrons and holes, as well as their mobilities. Notably, electron mobility exceeds that of holes. As temperature rises, both electron and hole concentrations increase due to the breaking of more covalent bonds. Although electron and hole mobilities decrease slightly with temperature, this decline is counteracted by the significant increase in concentrations. Consequently, semiconductor conductivity rises overall (or resistivity decreases) with temperature elevation.

Questions

Que.1. Calculate the electric field necessary to impart, on average, 1 electron volt of energy to a conduction electron in a copper block, where the mean free path of conduction electrons is approximately 4×10^{-8} m.

Sol. Consider the electric field as E. The force exerted on an electron is eE. As the electron traverses a distance d, the work done on it is eEd. which equals the energy imparted to the electron. Given that the electron travels an average distance of 4×10^{-8} m before a collision, the Energy transferred is eE (4×10^{-8} m). To attain 1 electron volt of energy from the electric field,

$$eE\,(4 \times 10^{-8}\ \text{m}) = 1\ \text{eV} \quad \text{or} \quad E = 2.5 \times 10^{7}\ \text{V/m}.$$

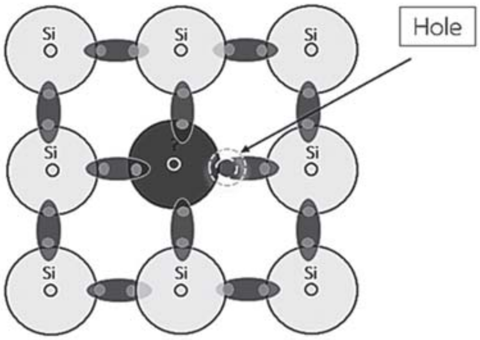
Que.2. If the predominant charge carriers in a semiconductor are holes, then the potential impurity that could be added is:

(A) Gallium (B) Arsenic (C) None of these (D) Both 1 and 2

Sol.

Holes serve as the primary charge carriers for a p-type semiconductor, which is established by introducing a trivalent atom into Si. Since Gallium (Ga) is a trivalent atom, its addition will indeed yield a p-type semiconductor.

Therefore, option (A) is accurate.



Que.3. As a copper piece and a germanium piece are cooled from room temperature to 77 K, the resistance of

(A) copper decreases and germanium increases
(B) copper increases and germanium decrease
(C) each of them increases
(D) each of them decreases

Solution.

Copper functions as a conductor, while germanium acts as a semiconductor. When cooled, the resistance of copper decreases and that of germanium increases.

Therefore, option (A) copper decreases and germanium increases.