SEMICONDUCTOR ELECTRONICS

EXTRINSIC SEMICONDUCTOR

EXTRINSIC SEMICONDUCTORS:

The conductivity of an intrinsic semiconductor is temperature-dependent, and at room temperature, its conductivity is quite low. Consequently, it is challenging to develop significant electronic devices using these semiconductors. To enhance their conductivity, impurities are introduced. By adding a small amount, typically a few parts per million (ppm), of a suitable impurity to the pure semiconductor, the conductivity is significantly increased. These materials are referred to as extrinsic semiconductors or impurity semiconductors. The intentional addition of a desirable impurity is termed doping, and the impurity atoms are known as dopants, resulting in a material known as a doped semiconductor. It is crucial that the dopant does not distort the original pure semiconductor lattice and occupies only a few of the original semiconductor atom sites in the crystal. This requires the sizes of the dopant and semiconductor atoms to be nearly the same.

There are two types of dopants used for doping tetravalent Si or Ge:

(i) Pentavalent dopants (valency 5), such as Arsenic (As), Antimony (Sb), Phosphorous (P), etc.
(ii) Trivalent dopants (valency 3), like Indium (In), Boron (B), Aluminium (Al), etc.

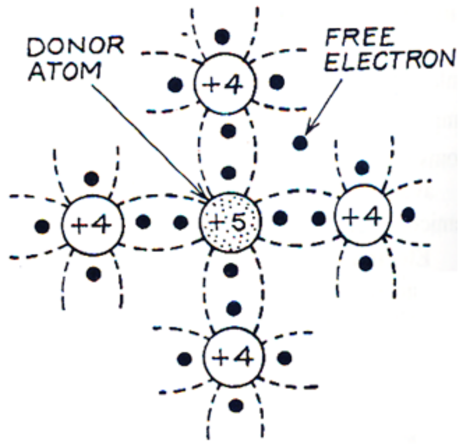
The choice of dopant depends on the desired effect and the specific semiconductor material. The dopant element is selected from nearby groups in the Periodic table, ensuring that the size of the dopant atom is approximately the same as that of Si or Ge. Intriguingly, the use of pentavalent and trivalent dopants in Si or Ge results in two distinct types of semiconductors, each with its own characteristics.

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

(a) n–type semiconductor:

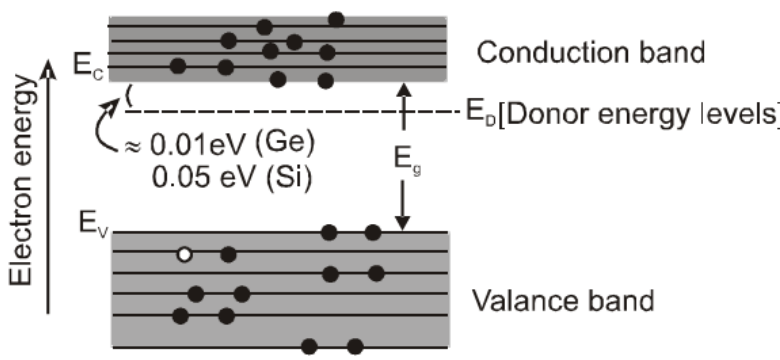
When a pentavalent impurity atom, such as antimony, phosphorus, or arsenic, is introduced into a germanium (Ge) or silicon (Si) crystal, it takes the place of a Ge (or Si) atom within the crystal lattice. Four of the five valence electrons of the impurity atom form covalent bonds, with each valence electron pairing up with one of the valence electrons of four neighboring Ge (or Si) atoms. Consequently, the addition of a pentavalent impurity to pure Ge (or Si) results in an increase in the number of free electrons, thereby enhancing the conductivity of the crystal.

The impure Ge (or Si) crystal is referred to as an 'n-type' semiconductor due to its excess of 'negative' charge carriers, which are electrons. The impurity atoms in this context are termed 'donor' atoms because they contribute or donate conducting electrons to the crystal, further influencing its electrical properties.



The fifth valence electrons of the impurity atoms occupy specific energy levels located just below the conduction band. These energy levels are termed 'donor levels' and are positioned approximately 0.01 eV below the conduction band in the case of germanium (Ge) and 0.05 eV below in the case of silicon (Si). Consequently, at room temperature, the "fifth" electrons associated with almost all donor atoms undergo thermal excitation from the donor levels to the conduction band. Once in the conduction band, these electrons function as charge carriers when subjected to an external electric field.

Under normal conditions, the majority of electrons in the conduction band originate from the donor levels, with only a small fraction coming from the valence band. As a result, the primary charge carriers responsible for conduction are the electrons supplied by the donor atoms. Due to the limited excitation from the valence band, the number of holes in this band is minimal.



The current contribution from the holes is consequently limited. In an n-type semiconductor, electrons constitute the 'majority carriers,' while holes are considered the 'minority carriers.'

The accompanying figure illustrates an n-type semiconductor at temperatures above 0 K. In this semiconductor, one thermally generated electron-hole pair is present in the conduction band, accompanied by nine conduction electrons originating from donor atoms.

Some important facts about P-Type Semiconductor

These are obtained by introducing a small amount of trivalent impurity into a pure 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:

- Lies just below the conduction band.

5. Electron and Hole Concentration:

- In a doped semiconductor, the electron concentration (n_e) and the hole concentration (n_e) are not equal (unlike in an intrinsic semiconductor). It can be expressed as $n_e\ n_h = \ n_i{}^2$, where n_i is the intrinsic concentration. In an n-type semiconductor, the concentration of electrons in the conduction band is nearly equal to the concentration of donor atoms (N_d) and is very large compared to the concentration of holes in the valence band, i.e., $n_e \approx N_d \gg n_h$

6. Impurity Atom:

- Called donor atom, belonging to the V group of the periodic table.

7. Net Charge:

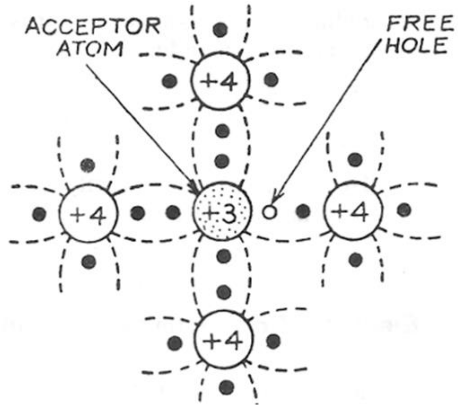
- The net charge on an n-type crystal is zero.

8. Immobile Charge:

- Positive charge.

(b) p–type semiconductor:

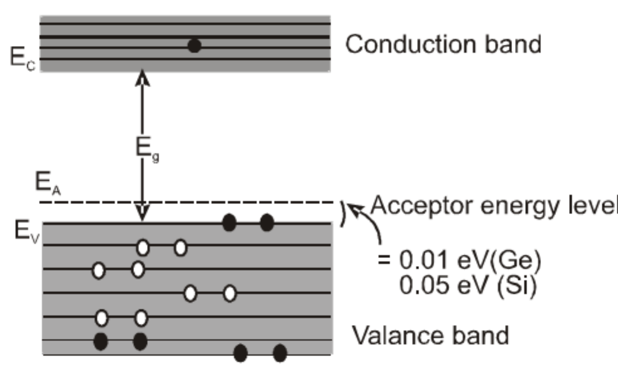
When a trivalent impurity atom such as boron, Aluminium, gallium, or indium is introduced into a germanium (Ge) or silicon (Si) crystal, it substitutes one of the Ge (or Si) atoms in the crystal lattice. The three valence electrons of the impurity atom form covalent bonds with one valence electron each from the surrounding Ge (or Si) atoms. Consequently, an empty space is created, giving rise to a 'p–type' semiconductor. This designation arises from its surplus of positive 'acceptor' atoms that generate holes capable of accepting electrons.



The impurity atoms occupy vacant discrete energy levels just above the top of the valence band. These are called 'acceptor levels'. At room temperature, electrons are easily excited from the valence band into the acceptor levels. The corresponding holes created in the valence band are the main charge–carriers in the crystal when an electric field is applied.

In a p–type semiconductor, the holes are the 'majority carriers', and the few electrons that are thermally excited from the valence band into the conduction band are considered 'minority carriers'.

The adjacent figure illustrates the concentration of electrons and holes for a p-type semiconductor at temperatures greater than 0 K. It depicts one thermally generated electron-hole pair and seven holes due to acceptor atoms.



Some important facts about P-Type Semiconductor:

P-Type Semiconductors are created by introducing a small amount of trivalent impurity into a pure semiconductor sample, such as Ge. Here are some key characteristics:

1. Majority Charge Carriers: Holes are the majority charge carriers, while electrons are considered minority carriers.

2. Concentration Imbalance: The concentration of holes (n_h) is significantly greater than the concentration of electrons (n_e), resulting in a notable imbalance.

3. Conductivity: The conductivity (σ) is approximately proportional to the concentration of holes (n_h) and their mobility (μ_h).

4. Electrically Neutral: Despite having an excess of positive charge carriers (holes), a p-type semiconductor remains electrically neutral.

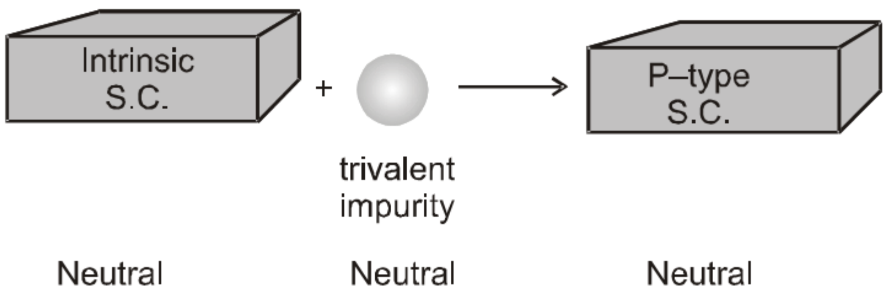
5. Acceptor Impurity: The trivalent impurity, which is part of the III group in the periodic table, is referred to as an acceptor impurity.

6. Acceptor Energy Level: The energy levels associated with the acceptor impurity lie just above the valence band.

7. Electron and Hole Concentration: In a p-type semiconductor, the concentration of holes in the valence band is nearly equal to the concentration of acceptor atoms (Na), and this concentration is significantly larger than that of electrons in the conduction band. Therefore, $n_h = N_a \gg n_e$.

8. Zero Net Charge: The overall charge on 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.	1	It is prepared by adding a small quantity of impurity to a pure semiconductor, such as n-and p-type semiconductors.
2	In it the concentration of electrons and holes are equal.	2	In it the two concentrations are unequal. There is an excess of electrons in n-type semiconductors and an excess of holes in p-type semiconductors.
3	Its electrical conducitivity is very low.	3	Its electrical conductivity is siginifcantly high.
4	Its conductivity cannot be controlled.	4	Its conductivity can be controlled by adjusting the quantity of the impurity added.
5	Its conductivity increases exponentially with temperature.	5	Its conductivity also increases with temperature, but not exponentially.

Distinction between n–type and p–type semiconductor:

	n-type semiconductor		p-type semiconductor
1	It is an extrinsic semiconductor obtained by adding a pentavalent impurity to a pure intrinsic semiconductor.	1	It is also an extrinsic semiconductor obtained by adding a trivalent impurity to a pure intrinsic semiconductor.
2	The impurity atoms added provides extra free electrons to the crystal lattice and are called donor atoms.	2	The impurity atoms added create holes in the crystal lattice and are called acceptor atoms because the created holes accept electrons.
3	The electrons are majority carriers and the holes are minority carriers.	3	The holes are majority carriers and the electrons are minority carriers.
4	The electrons concentration is much more than the hole concentration ($n_e >> n_h$).	4	The hole concentration is much more than the electron concentration ($n_h >> n_e$).

Example.

A silicon specimen is rendered a p-type semiconductor through the process of doping, where approximately one indium atom is introduced for every 5×10^7 silicon atoms. Given that the number density of atoms in the silicon specimen is 5×10^{28} atoms$/m^3$, determine the number of acceptor atoms present in silicon per cubic centimeter.

Solution.

The introduction of one indium atom into a silicon semiconductor results in the creation of one acceptor atom in the p-type semiconductor. Given that one indium atom is doped for every 5×10^7 silicon atoms, the number density of acceptor atoms in silicon can be calculated as $\frac{5\times10^{28}}{5\times10^7}$, which equals 10^{21} atoms$/m^3$ or 10^{15} atoms$/cm^3$.

Example.

At 300 K, intrinsic silicon exhibits equivalent concentrations of electrons (n_e) and holes (n_h) at $1.5 \times 10^{16}\ m^{-3}$. Upon doping with indium, the hole concentration (n_h) is enhanced to $4.5 \times 10^{22}\ m^{-3}$. Determine the new electron concentration (n_e) in the doped silicon.

Solution.

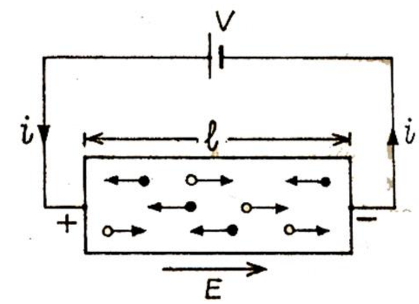
$n_e\, n_h = {n_i}^2$

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

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

(c) Electrical conductivity of extrinsic semiconductors:

At room temperature, a semiconductor contains electrons in the conduction band and holes in the valence band. Upon the application of an external electric field, electrons move opposite to the field, while holes move in the direction of the field, resulting in a current in the same direction. Considering a semiconductor block with length (l), cross-sectional area (A), and electron concentration (n_e) and hole concentration (n_h), a potential difference (V) across the semiconductor creates an electric field E ($E = \frac{V}{l}$).



Under the electric field (E), electrons and holes drift in opposite directions, contributing to currents i_e and i_e, respectively. The total current through the semiconductor (i) is the sum of the electron and hole currents:

$$i = i_e + i_h$$

Expressing (i_e) and (i_h) in terms of drift velocities (v_e) and (v_h), we get:

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

Here, e is the magnitude of the electron charge. The resistance (R) and resistivity (ρ) of the semiconductor block are related by $\rho = \frac{RA}{l}$. Dividing the equation representing the electric field (E) by the expression for current(i), we obtain:

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

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

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

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

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

The electrical conductivity (σ), the reciprocal of resistivity (ρ), is given by:

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

This expression demonstrates that the electrical conductivity of a semiconductor depends on the concentrations of electrons and holes, as well as their mobilities. The mobility of electrons is higher than that of holes. With an increase in temperature, both electron and hole concentrations rise due to the breakage of more covalent bonds. Although electron and hole mobilities slightly decrease with temperature, this decrease is compensated by the substantial increase in concentrations, resulting in an overall increase in semiconductor conductivity (or decrease in resistivity) with temperature rise.

Example.

In a copper block, the mean free path of conduction electrons is approximately $4 \times 10^{-8} m$. Determine the electric field required to provide, on average, 1 electron volt of energy to a conduction electron.

Solution.

Let the electric field be E. The force on an electron is eE. As the electron moves through a distance d, the work done on it is eEd. This is equal to the energy transferred to the electron. As the electron travels an average distance of 4×10^{-8} m before a collision, the Energy transferred is eE (4×10^{-8} m). To get 1 eV energy from the electric field,

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