CLASS 3

Extrinsic semiconductor, important parameters of the semiconductor, charge density and Fermi-Dirac function.
References: Floyd, Boylestad and Neaman.

EXTRINSIC SEMICONDUCTOR

- If trivalent (3 valence electrons) or pentavalent (5 valence electrons) atoms are added to the intrinsic Si and Ge, extrinsic/ doped/ impure semiconductors will be formed.
- The impurity atoms are divided into 2:

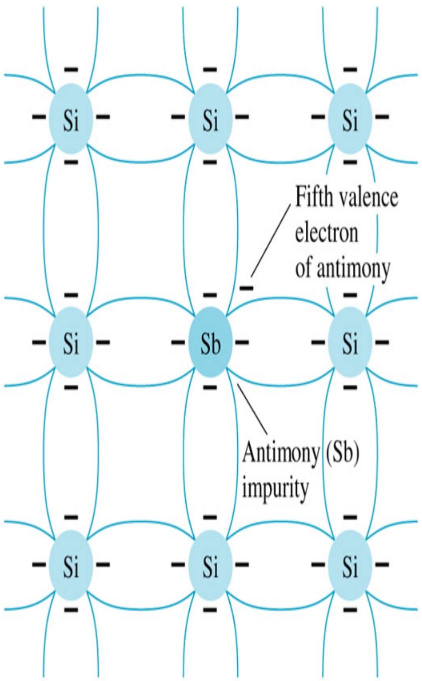
1. donor impurities
2. acceptor impurities

Intrinsic semiconductor doped with the donor impurities is called extrinsic-n semiconductor.

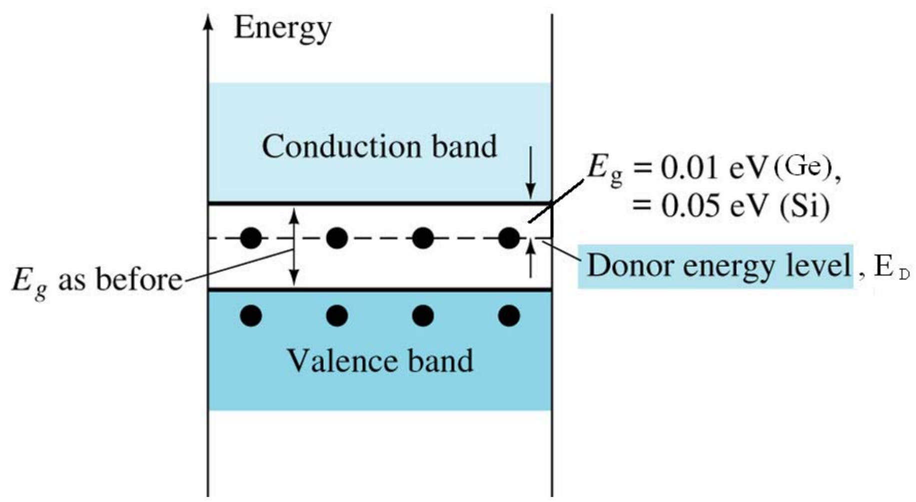
Intrinsic semiconductor doped with the acceptor impurities is called extrinsic-p semiconductor.

Extrinsic-n

- If the doping material has 5 valence electrons, the n-semiconductor formed will have its crystal structure as shown here.
- The impurity atoms will replace some of the Si atoms in the crystal . 4 out of its 5 valence electrons will be covalently bonded with the neighbouring Si atoms and the 5th will be quite free. The 5th electron will be the current carrier.



- When the donor impurities are added to the semiconductor, the energy levels are as shown in the diagram.
- For the Ge, the distance of the new donor energy level, E_D, is just 0.01 eV (0.05 eV for Si) below the conductance band.
- At room temperature, almost all of the donor atoms' 5^{th} electron are in the conduction band.
- If the intrinsic semiconductor is doped with an n-type impurity, not only will the no. of electrons increases but the no. of holes will also be reduced. This is due to the increase of the no. of electron and hole recombination in the valence band.



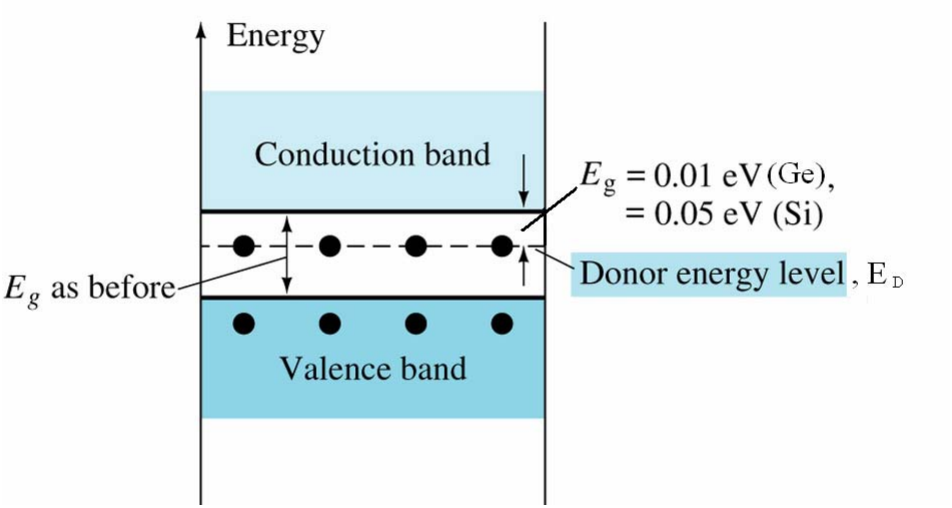
The energy required to separate the 5th electron from its atom is

1. 0.01 eV for the Ge
2. 0.05 eV for the Si.

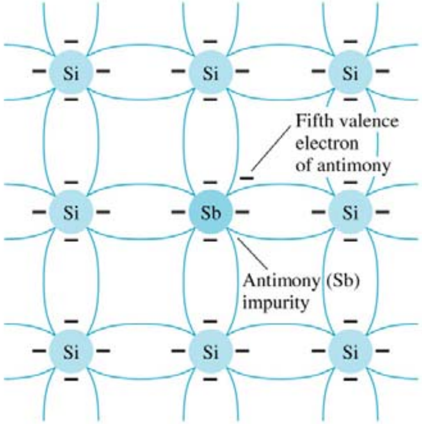
Two of the pentavalent impurities normally used are:

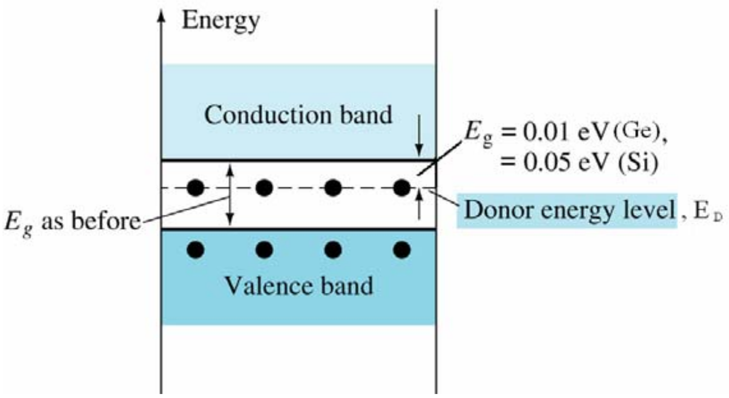
1. antimony phosphorus
2. arsenic

These impurities donate the extra electron carrier and therefore are known as donor or n-type impurities.

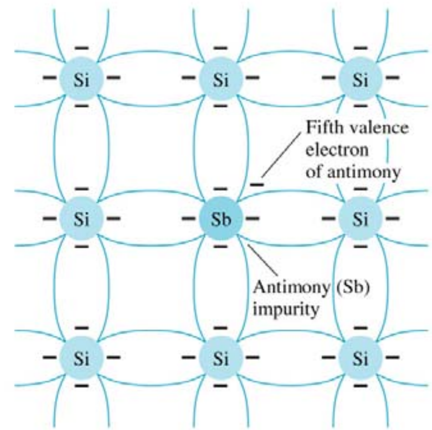


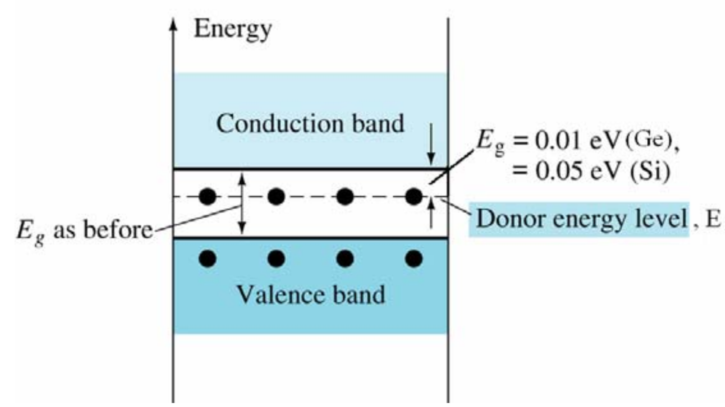
- The total no. of free electrons in the n-semiconductor = 5^{th} electron from the donor impurity atoms + thermally generated free electrons
- 5^{th} electron from the donor impurity atoms >> thermally generated free electrons
- Hence, the total no. of electrons in the n-semiconductor ≈ 5^{th} electron from the donor impurity atoms.





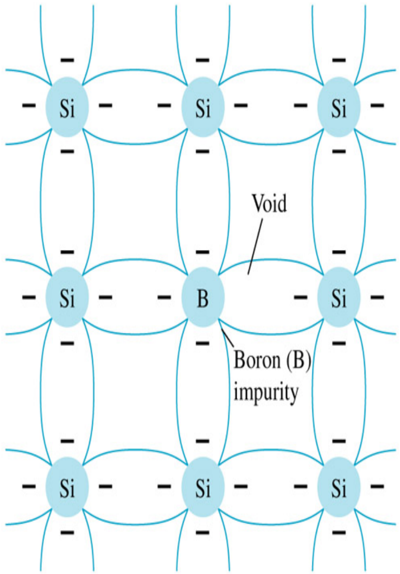
- Since the Sb has lost 1electron (the 5th electron), it becomes a +ve ion. These +ve ions are fixed (through covalent bonding). They are not mobile and are not current carriers. The no. of +ve ions = the no. of donor atoms.
- The 5th electrons are the <u>majority carriers</u>. The no. of carriers = the no. of donor atoms.
- With additional energy (ex: from heat), electrons in the valence band will have enough energy to overcome the forbidden band and become free. Holes left in the valence band become the <u>minority carriers</u> of the extrinsic-n semiconductor. If T↑, holes ↑.



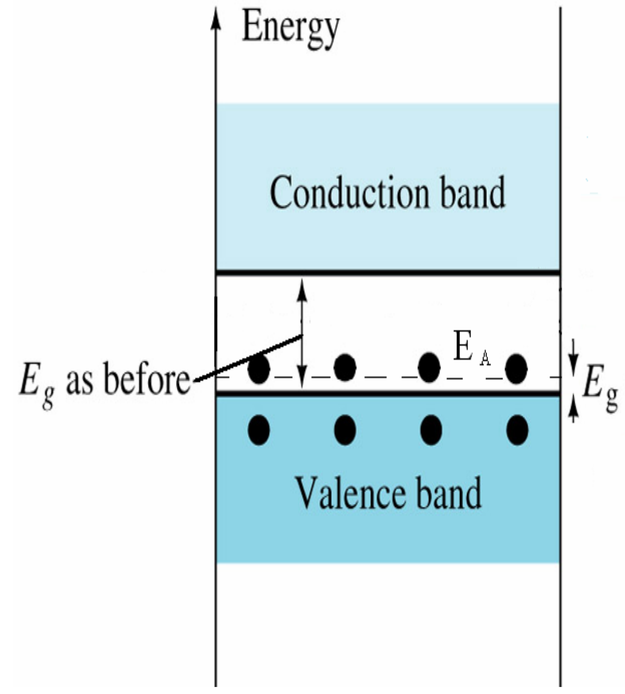


Extrinsic-p

- If a trivalent impurity (ex. boron, gallium and indium) is added to the intrinsic semiconductor, only 3 of the Si covalent bond will be filled. An empty space which forms a hole will be in the 4^{th} bond. The crystal diagram of extrinsic-p semiconductor is as shown.
- This type of impurity generates +ve carriers in the form of holes. The holes can easily accept electrons. Hence, this impurity is known as acceptor or p-type impurity.



- When the acceptor impurities are added to the semiconductor, the energy levels are as shown in the diagram.
- A new acceptor energy level, E_A, is found in the forbidden band just above the valence band.
- Only a small amount of energy is required by the electrons to leave the valence band and be at the new energy level. At room temperature, a lot of the valence electrons are at E_A leaving holes in the valence band.
- Holes in the valence band are the majority carriers in the extrinsic –p semiconductor.

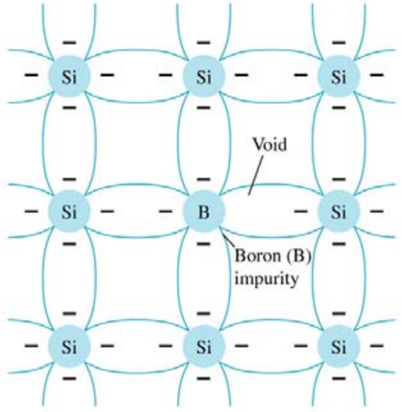


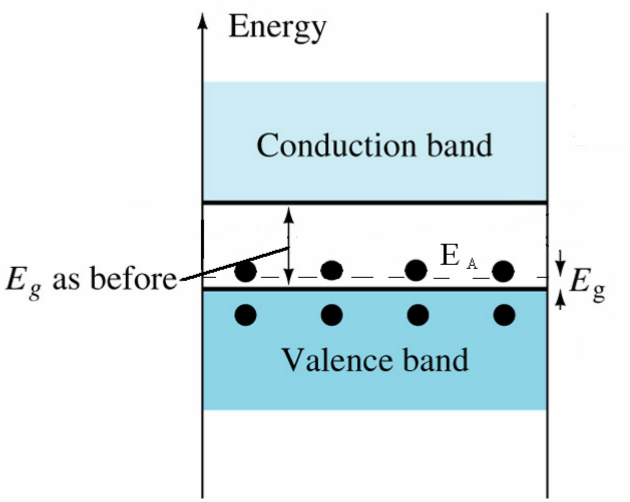
Three of the trivalent impurities normally used are

1. boron
2. gallium
3. indium

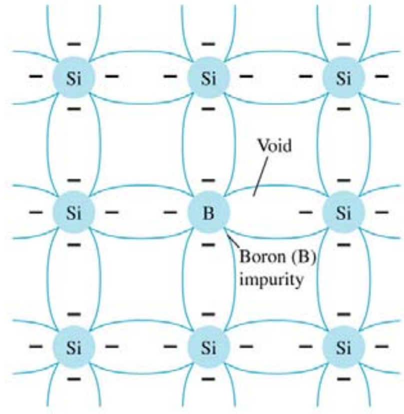
The holes in the impurity atoms easily accept electrons and therefore these impurities are known as acceptor or p-type impurities.

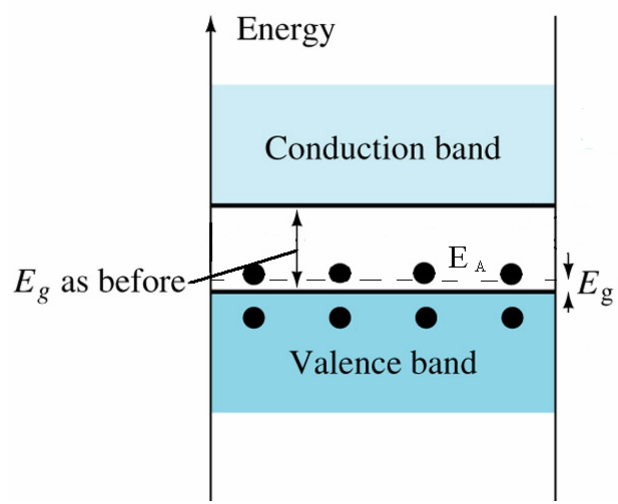
- The total no. of holes in the p-semiconductor = holes from the acceptor impurity atoms + thermally generated holes.
- holes from the acceptor impurity atoms >> thermally generated holes.
- Hence, the total no. of holes in the p-semiconductor ≈ holes from the acceptor impurity atoms.





- Since the B has 1 hole which easily accepts an electron, it becomes a -ve ion. These -ve ions are fixed (through covalent bonding). They are not mobile and are not current carriers. The no. of -ve ions = the no. of acceptor atoms.
- The holes are the majority carriers. The no. of carriers = the no. of acceptor atoms.
- With additional energy (ex: from heat), electrons in the valence band will have enough energy to overcome the forbidden band and become free. These electrons in the conduction band become the minority carriers of the extrinsic-p semiconductor. If T↑, electrons↑.





- If impurities are added at the rate of 1 to every 10^8 part, the conductivity of the Ge will increase by 12 times.
- Doping an intrinsic semiconductor will not only increase its conductivity, but will also create a conductor whose electrical carriers are hole or electron domain.
- In an n-type semiconductor, electrons are called majority carriers and holes are known as the minority carriers.
- In a p-type semiconductor, holes are called majority carriers and electrons are known as the minority carriers.

Summary

- <u>Intrinsic semiconductor:</u>

1. pure; consisted of Ge or Si atoms only
2. conductivity (the ability to flow current) is quite poor
3. insulator at 0°K, conductor at room temperature.
4. $np = n_i^2$, $n = p = n_i$

- <u>Extrinsic semiconductor:</u>

1. Impurity atoms (doping atoms) are added to the intrinsic semiconductor
2. Conductivity is much better than the intrinsic semiconductor.
3. $np = n_i^2$ but $n \neq p$

Important parameters of the semiconductor

- <u>Mobility, μ</u>

  The carriers' ability to move in the crystal.

  Mobility of the hole = μ_p

  Mobility of the electron = μ_n

  Unit for mobility = m^2/Vs

- <u>Conductivity, σ</u>

  Material's ability to allow current to flow through it.

  If the material is highly resistive towards the flow of current, the material is said to have high resistivity, ρ (in Ωm), or low conductivity, σ (in 1/(Ωm)).Ex: insulator.

  $\boxed{\sigma = ne\mu_n + pe\mu_p}$

  where n = electron density ($/m^3$)

  p = hole density ($/m^3$)

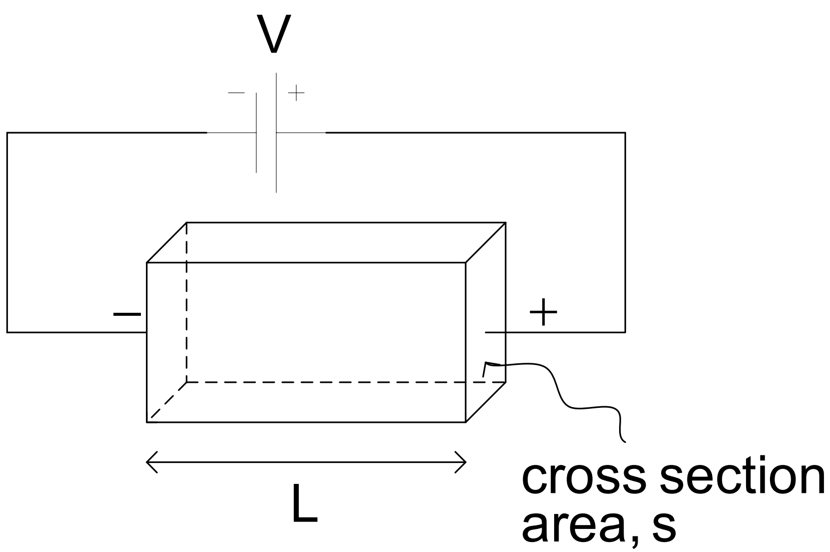
  e = 1.6×10^{-19} Coulomb

  $\boxed{\rho = 1/\sigma = 1/(ne\mu_n + pe\mu_p)}$

  Resistance of the material (in Ω),

  $\boxed{R = \rho L/s}$

  where L and s are the length and cross section area of the semiconductor in m and m^2, respectively.



E=V/L

- Drift velocity, u

  Semiconductors have 2 current carriers, i.e. holes and electrons

  When a constant electric field, E (in V/m), is set across a semiconductor, there will be a force that will accelerate the carriers.

  The electron's velocity will increase with time if there is no collision with the surrounding ions. Collisions with the ions will cause the carriers to lose energy. The increase in velocity and the lost of energy will occur over and over again. Throughout this process, the electron will gain an average drift velocity.

  Drift velocity for hole in (m/s) = $u_p = \mu_p E$

  Drift velocity for electron in (m/s) = $u_n = \mu_n E$

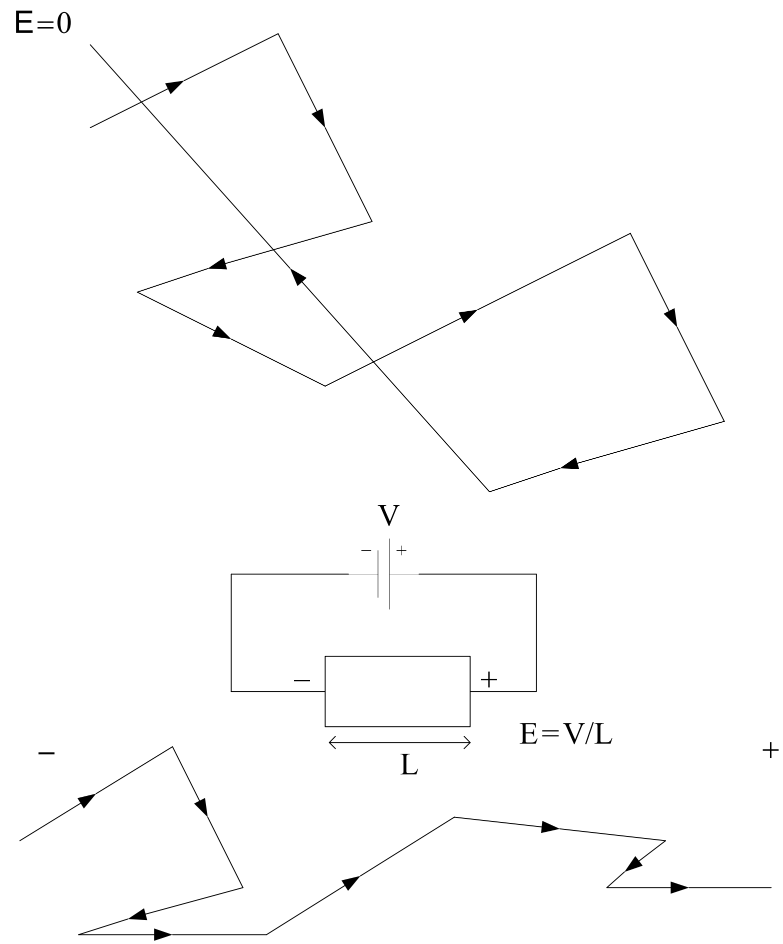
- <u>Mean free path</u>

  Free electrons can collide with other atoms. The average distance between collisions is called the mean free path.

  Electrons movement:

  0 electric field – movement of the electrons are random

  Finite electric field – electrons move in one direction i.e. towards the more positive potential or away from the more negative potential.



- <u>Carrier charge lifetime</u>

  In an intrinsic semiconductor,

  no. of holes = no. of electrons

  Thermal effect will always generate new electron-hole pairs whereas the existing electron-hole pairs might be lost due to the recombination process. In average, a hole (electron) will exist for a mean lifetime of $\tau_p(\tau_n)$ second before recombination. The carrier lifetime is in the range of nanosecond to hundreds of microsecond.