Lecture 15

Hall Effect in Semiconductors

When a current-carrying **semiconductor or metal** is kept in a magnetic field, the charge carriers of the **semiconductor** experience a force in a direction perpendicular to both the magnetic field and the current. At equilibrium, a voltage appears at the **semiconductor** edges.

Hall Effect was discovered by Edwin Hall in 1879. The voltage or electric field produced due to the application of magnetic field is also referred to as Hall voltage or Hall field. We know that the p-type semiconductor and n-type semiconductor are the two types of semiconductors. In the n-type semiconductor, free electrons are the majority carriers and holes are the minority carriers. That means most of the current in the n-type semiconductor is conducted by free electrons.

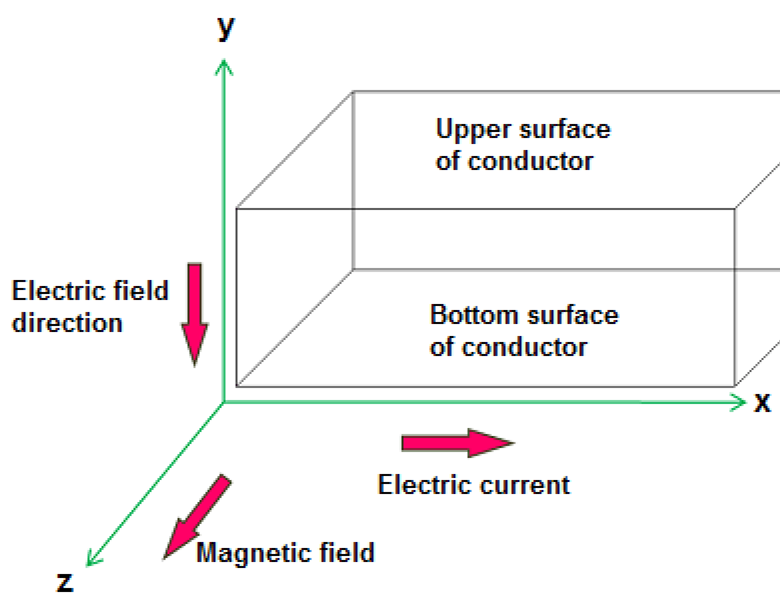
In the p-type semiconductor, holes are the majority carriers and free electrons are the minority carriers. That means most of the current in the p-type semiconductor is conducted by holes. Now we get an idea about the p-type and n-type semiconductors. But how can we identify whether the semiconductor is p-type or n-type.

Free electrons and holes are the very small particles. So we can't see them directly with our eyes. But by using Hall Effect we can easily identify whether the semiconductor is a p-type or n-type. When a voltage is applied to a conductor or semiconductor, electric current starts flowing through it. In conductors, the electric current is conducted by free electrons whereas in semiconductors, electric current is conducted by both free electrons and holes.

The free electrons in a semiconductor or conductor always try to flow in a straight path. However, because of the continuous collisions with the atoms, free electrons slightly change their direction. But if the applied voltage is strong enough, the free electrons forcefully follow the straight path. This happens only if no other forces are applied to it in other direction.

If we apply the force in other direction by using the magnetic field, the free electrons in the conductor or semiconductor change their direction.

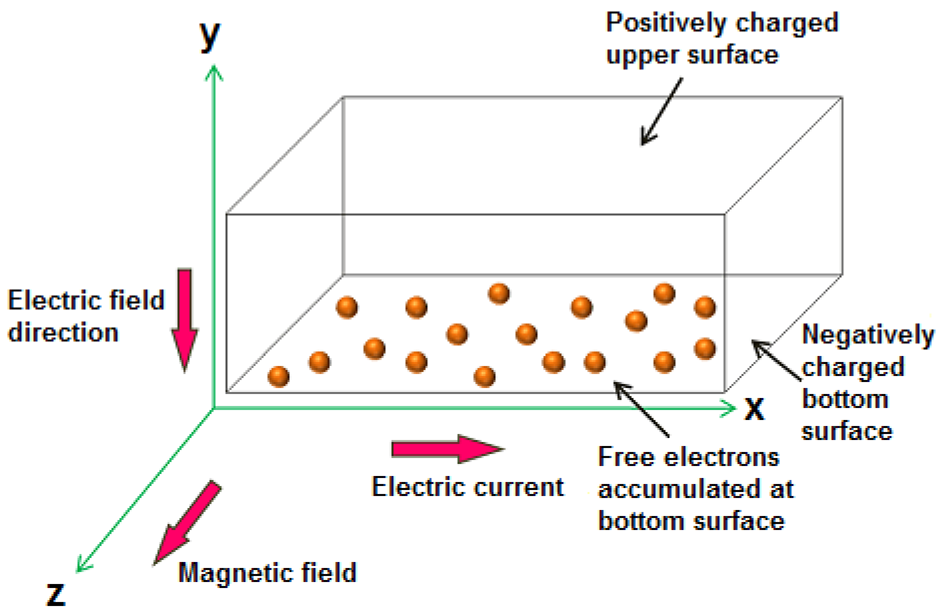
Consider a material, either a semiconductor or conductor as shown in the below figure. When a voltage is applied, electric current starts flowing in the positive x-direction (from left to right).



If a magnetic field is applied to this current carrying conductor or semiconductor in a direction perpendicular to that of the flow of current (that is z-direction), an electric field is produced in it that exerts force in the negative y direction (downwards). This phenomenon is known as Hall Effect. Hall Effect was named after American Physicist Edwin Hall, who discovered the phenomenon in 1879.

Hall Effect in conductor

The electric field produced in the material pushes the charge carriers downwards. If the material is a conductor, the electric field pushes the free electrons downwards (that is in negative y-direction). As a result, a large number of charge carriers (free electrons) are accumulated at the bottom surface of the conductor.



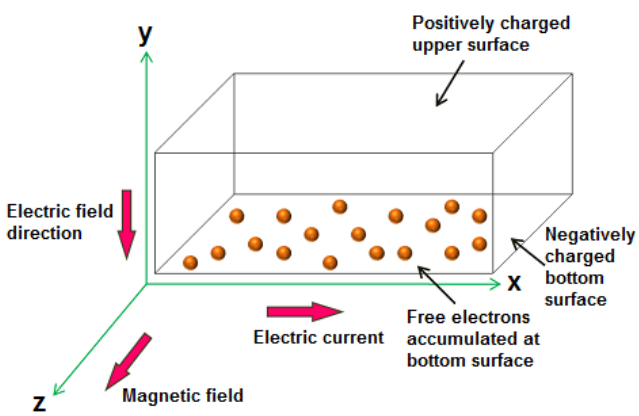
Hall Effect in conductor

Because of this large accumulation of negative charges (free electrons) at the bottom surface and deficiency of negative charges (free electrons) at the upper surface, the bottom surface is negatively charged and the upper surface is positively charged.

As a result, an electrical difference or potential difference develops between the upper surface and bottom surface of the conductor. This potential difference is known as Hall voltage. In a conductor, the electric field is produced due to the negatively charged free electrons. So the hall voltage produced in the conductor is negative.

Hall Effect in n-type semiconductor

If the magnetic field is applied to an n-type semiconductor, both free electrons and holes are pushed down towards the bottom surface of the n-type semiconductor. Since the holes are negligible in n-type semiconductor, so free electrons are mostly accumulated at the bottom surface of the n-type semiconductor.



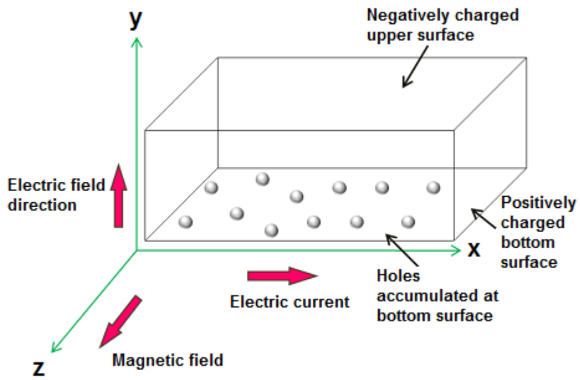
Hall Effect in N-type semiconductor

This produces a negative charge on the bottom surface with an equal amount of positive charge on the upper surface. So in n-type semiconductor, the bottom surface is negatively charged and the upper surface is positively charged.

As a result, the potential difference is developed between the upper and bottom surface of the n-type semiconductor. In the n-type semiconductor, the electric field is primarily produced due to the negatively charged free electrons. So the hall voltage produced in the n-type semiconductor is negative.

Hall Effect in p-type semiconductor

If the magnetic field is applied to a p-type semiconductor, the majority carriers (holes) and the minority carriers (free electrons) are pushed down towards the bottom surface of the p-type semiconductor. In the p-type semiconductor, free electrons are negligible. So holes are mostly accumulated at the bottom surface of the p-type semiconductor.



Hall Effect in P-type semiconductor

So in the p-type semiconductor, the bottom surface is positively charged and the upper surface is negatively charged.

As a result, the potential difference is developed between the upper and bottom surface of the p-type semiconductor. In the p-type semiconductor, the electric field is primarily produced due to the positively charged holes. So the hall voltage produced in the p-type semiconductor is positive. This leads to the fact that the produced electric field is having a direction in the positive y-direction.

Hall Effect helps to determine the type of a material

We can easily identify whether a semiconductor is p-type or n-type by using Hall Effect. If the voltage produced is positive then the material is said to be p-type and if the voltage produced is negative then the material is said to be n-type.

The Hall voltage is directly proportional to the current flowing through the material, and the magnetic field strength, and it is inversely proportional to the number of mobile charges in the material, and the thickness of the material. So in order to produce a large Hall voltage we need to use a thin material with few mobile charges per unit volume.

As the holes are the majority carriers in p type semiconductor the current is given by :

$$\mathbf{I = n_h A e \ v_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where n_h = density of holes

A = w × d = cross sectional area of the specimen

v_d = drift velocity of the holes.

The current density is

$$\mathbf{J = I/A = n_h A e \ v_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

The magnetic field is applied transversely to the crystal surface in z direction. Hence the holes experience a magnetic force in a downward direction

$$\boldsymbol{F_m = e\, v_d\, B} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{(3)}$$

As a result of this the holes are accumulated on the bottom surface of the specimen.

Due to this a corresponding equivalent negative charge is left on the top surface.

The separation of charge set up a transverse electric field across the specimen given by,

$E_H = V_H/d$ ……………………………..(4)

Where V_H is called the HALL VOLTAGE and E_H the HALL FIELD.

In equilibrium condition the force due to the magnetic field B and the force due to the electric field E_H acting on the charges are balanced.

$eE_H = ev_dB$

$E_H = v_dB$ ……………………………(5)

Using equation (4) in the equation (5)

$V_H = v_d B d$ ………………………….(6)

From equation (1) and (2), the drift velocity of holes is found as

$v_d = I/(en_hA) = J/(en_h)$ ……………………..(7)

Hence hall voltage can be written as

$V_H = IBd/(en_hA) = (JBd)/(en_h)$

An important parameter is the hall coefficient defined as the hall field per unit current density per unit magnetic induction.

$R_H = E_H/(JB)$…………………………………..(9)

Where R_H = Hall coefficient = $1/en_h$, Which is positive for p-type and negative for n-type.

Applications of Hall Effect

- Hall Effect is used to find whether a semiconductor is N-type or P-type.
- Hall Effect is used to find carrier concentration.
- Hall Effect is used to calculate the mobility of charge carriers (free electrons and holes).
- Hall Effect is used to measure conductivity.
- Hall Effect is used to measure a.c. power and the strength of magnetic field.
- Hall Effect is used in an instrument called Hall Effect multiplier which gives the output proportional to the product of two input signals.