Ampere’s Law

Ampere’s law is equivalent to the Gauss law in electrostatics which measures the tangential component of magnetic field over any closed surface.

Ampere’s law states that

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 i_{enc} \quad \text{(Ampere's law).}$$

Where μ_0 is the **permeability of free space.**

The line integral in this equation is evaluated around a closed loop called an Amperian loop. The current i on the right side is the net current encircled by the loop.

The loop on the integral sign means that the dot product $\vec{B}.\overrightarrow{ds}$ is to be integrated around a closed loop, called an Amperian loop. The current i_{enc} is the net current encircled by that closed loop. To see the meaning of the scalar product $\vec{B}.\overrightarrow{ds}$ and its integral,let us first apply Ampere’s law to the general situation of Fig 1.

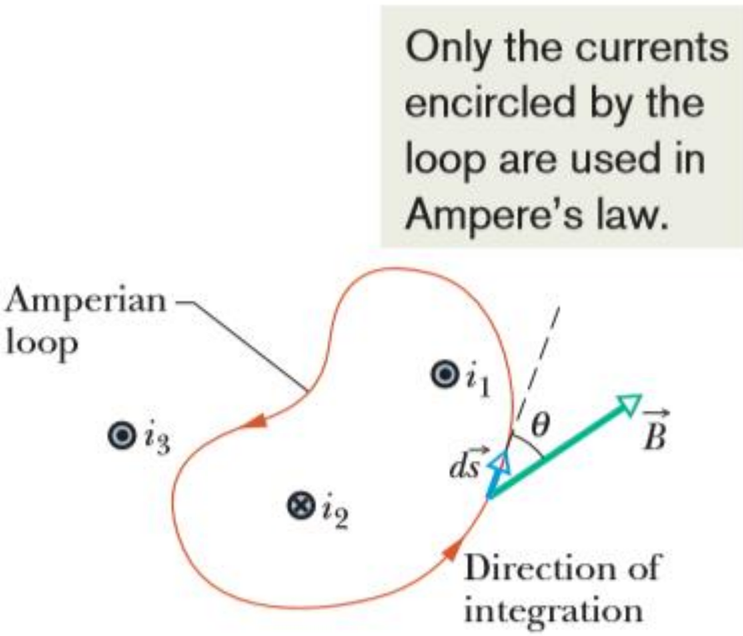


Figure 1. Ampere's law applied to an arbitrary Amperian loop that encircles two long straight wires but excludes a third wire. Note the directions of the currents.

The figure shows cross sections of three long straight wires that carry currents i1, i2, and i3 either directly into or directly out of the page. An arbitrary Amperian loop lying in the plane of the page encircles two of the currents but not the third. The counterclockwise direction marked on the loop indicates the arbitrarily chosen direction of integration. To apply Ampere's law, we mentally divide the loop into differential vector elements $\overrightarrow{\mathrm{ds}}$ that are everywhere directed along the tangent to the loop in the direction of integration. Assume that at the location of the element $\overrightarrow{\mathrm{ds}}$ shown in fig 1. the net magnetic field due to the three currents is $\vec{\mathrm{B}}$. .However,we do not know the orientation of $\vec{\mathrm{B}}$ within the plane. In fig 1. $\vec{\mathrm{B}}$

is arbitrarily drawn at an angle θ to the direction of $\overrightarrow{\mathrm{ds}}$. Thus,Ampere's law can be written as

$$\oint \vec{B} \cdot d\vec{s} = \oint B \cos\theta \, ds = \mu_0 i_{\text{enc}}.$$

Signs. When we can actually perform this integration, we do not need to know the direction $\vec{\mathrm{B}}$ of before integrating. Instead, we arbitrarily assume $\vec{\mathrm{B}}$ to be generally in the direction of integration. Then we use the following curled–straight right-hand rule to assign a plus sign or a minus sign to each of the currents that make up the net encircled current i_{enc}.

Curl your right hand around the Amperian loop,with the fingers pointing in the direction of integration. A current through the loop in the general direction of your outstretched thumb is assigned a plus sign, and a current generally in the opposite direction is assigned a minus sign.

Net Current. With the indicated (figure 2) counterclockwise direction of integration,the net current encircled by the loop is

$$i_{\text{enc}} = i_1 - i_2.$$

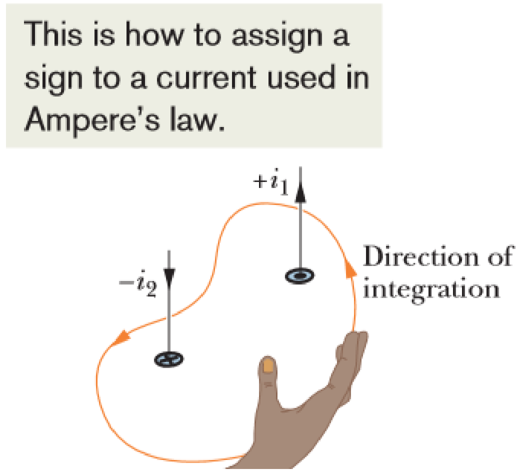


Figure 2

(Current i3 is not encircled by the loop.) We can then rewrite Equation as

$$\oint B \cos\theta\, ds = \mu_0(i_1 - i_2).$$

Magnetic Field Outside a Long Straight Wire with Current:

Figure 3 shows a long straight wire that carries current i directly out of the page.

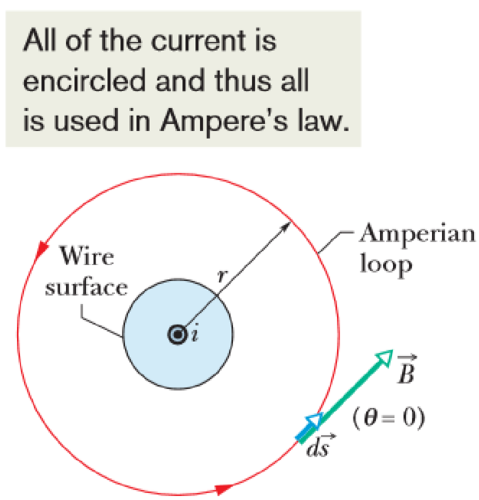


Figure 3. Using Ampere's law to find the magnetic field that a current iproduces outside a long straight wire of circular cross section.The Amperian loop is a concentric circle that lies outside the wire.

the magnetic field $\vec{B}$ produced by the current has the same magnitude at all points that are the same distance rfrom the wire;thatis, the field $\vec{B}$ has cylindrical symmetry about the wire. The magnetic field then has the same magnitude B at every point on the loop.We shall integrate counterclockwise,so that $\overrightarrow{ds}$ has the direction shown in Fig 3.

Now we can write the equation as

$$\oint \vec{B} \cdot d\vec{s} = \oint B \cos \theta \, ds = B \oint ds = B(2\pi r).$$

Note that § ds is the summation of all the line segment lengths ds around the circular loop;that is,it simply gives the circumference 2πr of the loop.

and we then have

$$B(2\pi r) = \mu_0 i$$

$$B = \frac{\mu_0 i}{2\pi r} \quad \text{(outside straight wire).}$$

Magnetic Field Inside a Long Straight Wire with Current:

Figure 4 shows the cross section of a long straight wire of radius R that carries a uniformly distributed current i directly out of the page. Because the current is uniformly distributed over a cross section of the wire, the magnetic field produced by the current must be cylindrically symmetrical.Thus, to find the magnetic field at points inside the wire,we can again use an Amperian loop of radius r,as shown in Fig.4. where now r < R.Symmetry again suggests that $\vec{B}$ is tangent to the loop,as shown;so the left side of Ampere’s law again yields

$$\oint \vec{B} \cdot d\vec{s} = B \oint ds = B(2\pi r).$$

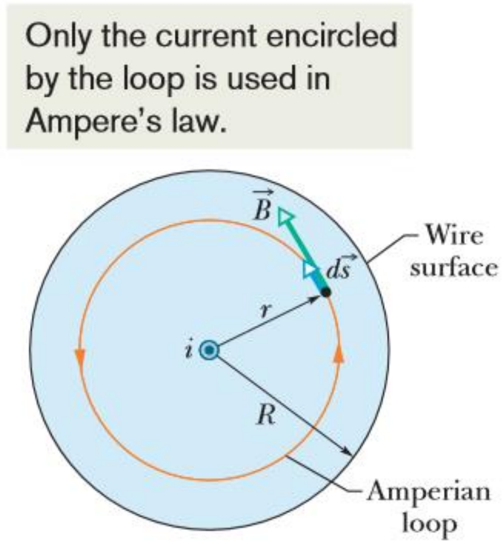


Figure 4. Using Ampere's law to find the magnetic field that a current iproduces inside a long straight wire of circular cross section.The current is uniformly distributed over the cross section of the wire and emerges from the page.An Amperian loop is drawn inside the wire.

Because the current is uniformly distributed,the current i_{enc} encircled by the loop is proportional to the area encircled by the loop;that is

$$i_{\text{enc}} = i\,\frac{\pi r^2}{\pi R^2}.$$

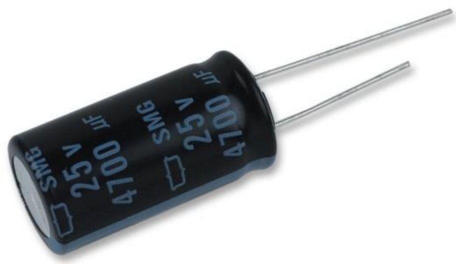
Then Ampere's law gives us

$$B(2\pi r) = \mu_0 i\,\frac{\pi r^2}{\pi R^2}$$

$$B = \left(\frac{\mu_0 i}{2\pi R^2}\right) r \qquad \text{(inside straight wire).}$$

Capacitors

Capacitors are simple passive device that can store an electrical charge on their plates when connected to a voltage source.

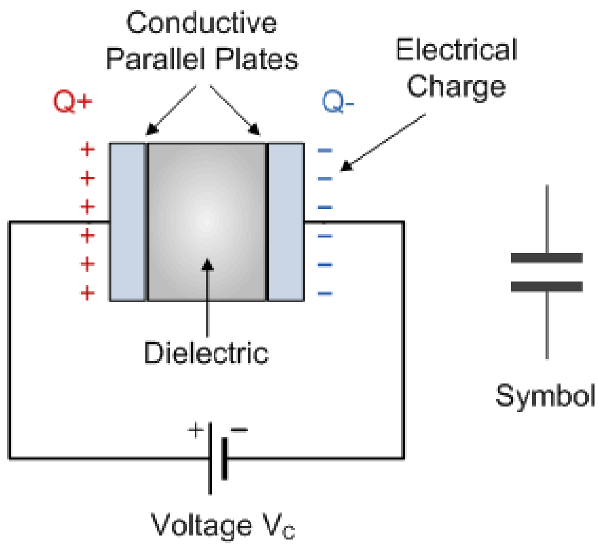


In its basic form, a capacitor consists of two or more parallel conductive (metal) plates which are not connected or touching each other, but are electrically separated either by air or by some form of a good insulating material such as waxed paper, mica, ceramic, plastic or some form of a liquid gel as used in electrolytic capacitors. The insulating layer between a capacitors plates is commonly called the **Dielectric.**

The conductive metal plates of a capacitor can be either square, circular or rectangular, or they can be of a cylindrical or spherical shape with the general shape, size and construction of a parallel plate capacitor depending on its application and voltage rating.

The flow of electrons onto the plates is known as the capacitors **Charging Current** which continues to flow until the voltage across both plates (and hence the capacitor) is equal to the applied voltage Vc. At this point the capacitor is said to be “fully charged” with electrons.

The amount of potential difference present across the capacitor depends upon how much charge was deposited onto the plates by the work being done by the source voltage and also by how much capacitance the capacitor has and this is illustrated below.



The parallel plate capacitor is the simplest form of capacitor. It can be constructed using two metal or metallised foil plates at a distance parallel to each other, with its capacitance value in Farads, being fixed by the surface area of the conductive plates and the distance of separation between them.

Also, because capacitors store the energy of the electrons in the form of an electrical charge on the plates the larger the plates and/or smaller their separation the greater will be the charge that the capacitor holds for any given voltage across its plates. In other words, larger plates, smaller distance, more capacitance.

By applying a voltage to a capacitor and measuring the charge on the plates, the ratio of the charge Q to the voltage V will give the capacitance value of the capacitor and is therefore given as: C = Q/V this equation can also be re-arranged to give the familiar formula for the quantity of charge on the plates as: Q = C x V

Although we have said that the charge is stored on the plates of a capacitor, it is more exact to say that the energy within the charge is stored in an "electrostatic field" between the two plates. When an electric current flows into the capacitor, it charges up, so the electrostatic field becomes much stronger as it stores more energy between the plates.

Likewise, as the current flowing out of the capacitor, discharging it, the potential difference between the two plates decreases and the electrostatic field decreases as the energy moves out of the plates.

The property of a capacitor to store charge on its plates in the form of an electrostatic field is called the **Capacitance** of the capacitor.

The Capacitance of a Capacitor

Capacitance is the electrical property of a capacitor and is the measure of a capacitors ability to store an electrical charge onto its two plates with the unit of capacitance being the **Farad** (abbreviated to F) named after the British physicist Michael Faraday.

Capacitance is defined as being that a capacitor has the capacitance of **One Farad** when a charge of **One Coulomb** is stored on the plates by a voltage of **One volt**. Note that capacitance, C is always positive in value and has no negative units. However, the Farad is a very large unit of measurement to use on its own so sub-multiples of the Farad are generally used such as micro-farads, nano-farads and pico-farads, for example

Standard Units of Capacitance

- Microfarad (μF) 1μF = 1/1,000,000 = 0.000001 = 10^{-6} F
- Nanofarad (nF) 1nF = 1/1,000,000,000 = 0.000000001 = 10^{-9} F
- Picofarad (pF) 1pF = 1/1,000,000,000,000 = 0.000000000001 = 10^{-12} F

Calculating the Capacitance

Our goal here is to calculate the capacitance of a capacitor once we know its geometry. We will consider following steps.

(1) Assume a charge q on the plates; (2) calculate the electric field $\vec{E}$ between the plates in terms of this charge,using Gauss' law;(3)

knowing $\vec{E}$,calculate the potential difference V between the plates; (4) calculate C .

Before we start, we can simplify the calculation of both the electric field and the potential difference by making certain assumptions.We discuss each in turn.

Calculating the Electric Field

To relate the electric field $\vec{E}$, between the plates of a capacitor to the charge q on either plate,we shall use Gauss' law:

$$\varepsilon_0 \oint \vec{E} \cdot d\vec{A} = q.$$

Here q is the charge enclosed by a Gaussian surface and $\oint \vec{E} \cdot d\vec{A}$ is the net electric flux through that surface. In all cases that we shall consider, the Gaussian surface will be such that whenever there is an electric flux through it, $\vec{E}$ will have a uniform magnitude E and the vectors $\vec{E}$ and $d\vec{A}$ will be parallel.

$$q=\varepsilon_{\circ}EA$$

in which A is the area of that part of the Gaussian surface through which there is a flux

.

Calculating the Potential Difference

the potential difference between the plates of a capacitor is related to the field $\vec{E}$ by

$$V_f - V_i = -\int_i^f \vec{E} \cdot d\vec{s},$$

in which the integral is to be evaluated along any path that starts on one plate and ends on the other. We shall always choose a path that follows an electric field line, from the negative plate to the positive plate. For this path, the vectors $\vec{E}$ and $d\vec{s}$ will have opposite directions; so the dot product $\vec{E} \cdot d\vec{s}$ will be equal to –Eds.

$$V = \int_-^+ E\, ds$$

in which the - and + remind us that our path of integration starts on the negative plate and ends on the positive plate.

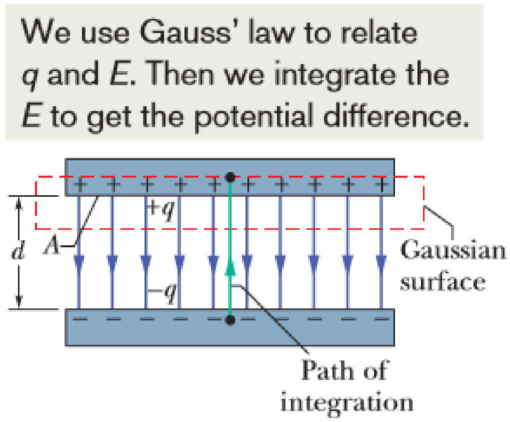


Figure (1)

Capacitance of a Parallel Plate Capacitor

We assume, as figure (1) suggests, that the plates of our parallel-plate capacitor are so large and so close together that we can neglect the fringing of the electric field at the edges of the plates, taking electric field to be constant throughout the region between the plates.

We draw a Gaussian surface that encloses just the charge q on the positive plate.

$$q = \varepsilon_0 E A,$$

Where A is the area of plate.

And potential difference is given as

$$V = \int_{-}^{+} E\, ds = E \int_{0}^{d} ds = Ed.$$

E can be placed outside the integral because it is a constant, the second integral then is simply the plate separation d.

If we now substitute q from above equations into the relation q= CV,we find

$$C = \frac{\varepsilon_0 A}{d} \quad \text{(parallel-plate capacitor).}$$

Thus, the capacitance does indeed depend only on geometrical factors namely, the plate area A and the plate separation d. Note that C increases as we increase area A or decrease separation d.

Capacitance Example No1

A capacitor is constructed from two conductive metal plates 30cm x 50cm which are spaced 6mm apart from each other, and uses dry air as its only dielectric material. Calculate the capacitance of the capacitor.

$$\text{Using:} \quad C = \varepsilon_O \frac{A}{d}$$

$$\text{where:} \ \varepsilon_O = 8.84 \times 10^{-12}$$

$$A = 0.3 \times 0.5\, m^2 \quad \text{and} \quad d = 6 \times 10^{-3}\, m$$

$$C = \frac{8.84 \times 10^{-12} \times (0.3 \times 0.5)}{6 \times 10^{-3}} = 0.221 nF$$

Then the value of the capacitor consisting of two plates separated by air is calculated as 221pF or 0.221nF

A Cylindrical Capacitor

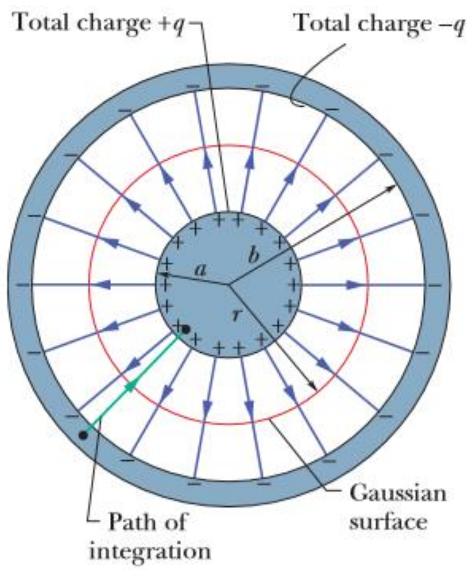


Figure (2)

Figure (2) shows, in cross section, a cylindrical capacitor of length L formed by two coaxial cylinders of radii a and b. We assume that L >b so that we can neglect the fringing of the electric field that occurs at the ends of the cylinders. Each plate contains a charge of magnitude q. As a Gaussian surface,we choose a cylinder of length L and radius r,closed by end caps and placed as is shown in Figure (2).

q is given as

$$q = \varepsilon_0 EA = \varepsilon_0 E(2\pi rL),$$

in which 2πrL is the area of the curved part of the Gaussian surface. There is no flux through the end caps. Solving for E yields

$$E = \frac{q}{2\pi\varepsilon_0 L r}.$$

And potential difference is given as

$$V = \int_{-}^{+} E\, ds = -\frac{q}{2\pi\varepsilon_0 L}\int_{b}^{a}\frac{dr}{r} = \frac{q}{2\pi\varepsilon_0 L}\ln\left(\frac{b}{a}\right),$$

where we have used the fact that here ds= - dr (we integrated radially inward).

From the relation C= q/V, we then have

$$C = 2\pi\varepsilon_0 \frac{L}{\ln(b/a)} \quad \text{(cylindrical capacitor).}$$

We see that the capacitance of a cylindrical capacitor, like that of a parallel-plate capacitor, depends only on geometrical factors, in this case the length L and the two radii b and a.

A Spherical Capacitor

Figure (2) can also serve as a central cross section of a capacitor that consists of two concentric spherical shells, of radii a and b. As a Gaussian surface we draw a sphere of radius r concentric with the two shells.

$$q = \varepsilon_0 E A = \varepsilon_0 E(4\pi r^2),$$

In which $4\pi r^2$ is the area of spherical Gaussian surface. We solve this equation for E obtaining

$$E = \frac{1}{4\pi\varepsilon_0}\frac{q}{r^2},$$

And potential difference is

$$V = \int_{-}^{+} E\,ds = -\frac{q}{4\pi\varepsilon_0}\int_b^a \frac{dr}{r^2} = \frac{q}{4\pi\varepsilon_0}\left(\frac{1}{a} - \frac{1}{b}\right) = \frac{q}{4\pi\varepsilon_0}\frac{b-a}{ab},$$

where again we have substituted -dr for ds.

$$C = 4\pi\varepsilon_0 \frac{ab}{b-a} \quad \text{(spherical capacitor).}$$

Capacitors in Parallel and in Series

When there is a combination of capacitors in a circuit,we can sometimes replace that combination with an equivalent capacitor that is, a single capacitor that has the same capacitance as the actual combination of capacitors. With such a replacement, we can simplify the circuit, affording easier solutions for unknown quantities of the circuit. Here we discuss two basic combinations of capacitors that allow such a replacement.

Capacitors in Parallel

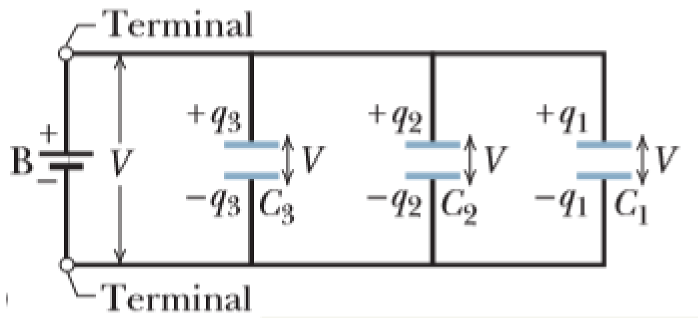


Figure (3)

Figure (3) shows an electric circuit in which three capacitors are connected in parallel to battery B. This description has little to do with how the capacitor plates are drawn. Rather, "in parallel" means that the capacitors are directly wired together at one plate and directly wired together at the other plate, and that the same potential difference V is applied across the two groups of wired-together plates. Thus, each capacitor has the same potential difference V, which produces charge on the capacitor.

In general, When a potential difference V is applied across several capacitors connected in parallel, that potential difference V is applied across each capacitor. The total charge q stored on the capacitors is the sum of the charges stored on all the capacitors.

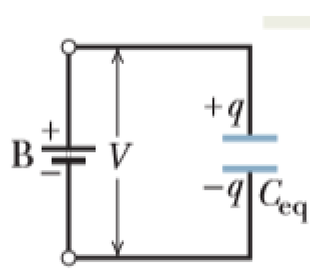


Figure (4)

Figure (4) shows the equivalent capacitor (with equivalent capacitance Ceq) that has replaced the three capacitors (with actual capacitances C1,C2,and C3) of Figure (3).

To derive an expression for Ceq in Fig (4),we first find the charge on each actual capacitor:

$$q_1 = C_1V, \quad q_2 = C_2V, \quad \text{and} \quad q_3 = C_3V.$$

The total charge on the parallel combination of Fig (3) is then

$$q = q_1 + q_2 + q_3 = (C_1 + C_2 + C_3)V.$$

The equivalent capacitance, with the same total charge q and applied potential difference V as the combination, is then

$$C_{eq} = \frac{q}{V} = C_1 + C_2 + C_3,$$

a result that we can easily extend to any number n of capacitors, as

$$C_{eq} = \sum_{j=1}^{n} C_j \quad (n \text{ capacitors in parallel}).$$

Thus, to find the equivalent capacitance of a parallel combination, we simply add the individual capacitances.

Capacitors in Series

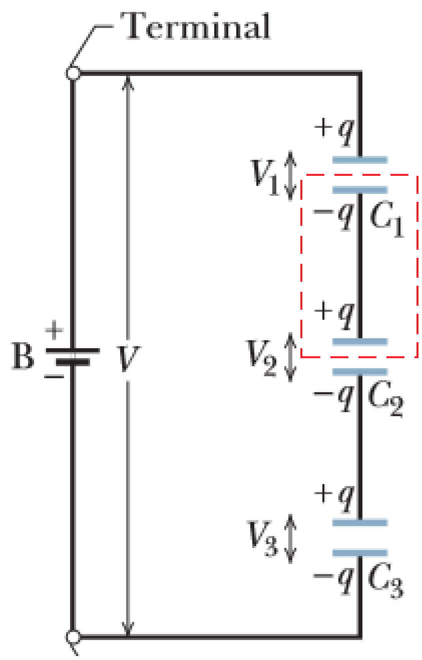


Figure (5)

Figure (5) shows three capacitors connected in series to battery B. This description has little to do with how the capacitors are drawn. Rather, "in series" means that the capacitors are wired serially, one after the other, and that a potential difference V is applied across the two ends of the series. The potential differences that then exist across the capacitors in the series produce identical charges q on them.

When a potential difference V is applied across several capacitors connected in series, the capacitors have identical charge q. The sum of the potential differences across all the capacitors is equal to the applied potential difference V.

We can explain how the capacitors end up with identical charge by following a chain reaction of events, in which the charging of each capacitor causes the charging of the next capacitor. We start with capacitor 3 and work upward to capacitor 1.When the battery is first connected to the series of capacitors, it produces charge –q on the bottom plate of capacitor 3.That charge then repels negative charge from the top plate of capacitor 3 (leaving it with charge +q).The repelled negative charge moves to the bottom plate of capacitor 2 (giving it charge -q).That charge on the bottom plate of capacitor 2 then repels negative charge from the top plate of capacitor 2 (leaving it with charge +q) to the bottom plate of capacitor 1 (giving it charge -q). Finally, the charge on the bottom plate of capacitor 1 helps move negative charge from the top plate of capacitor 1 to the battery, leaving that top plate with charge +q.

Here are two important points about capacitors in series:

1. When charge is shifted from one capacitor to another in a series of capacitors, it can move along only one route, such as from capacitor 3 to capacitor 2.If there are additional routes, the capacitors are not in series.

2. The battery directly produces charges on only the two plates to which it is connected (the bottom plate of capacitor 3 and the top plate of capacitor 1). Charges that are produced on the other plates are due merely to the shifting of charge already there. When we analyze a circuit of capacitors in series, we can simplify it with this mental replacement:

Capacitors that are connected in series can be replaced with an equivalent capacitor that has the same charge q and the same total potential difference V as the actual series capacitors.

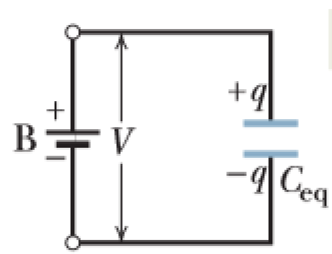


Figure (6)

To derive an expression for Ceq in Fig. (6),we first find the potential difference of each actual capacitor:

$$V_1 = \frac{q}{C_1}, \quad V_2 = \frac{q}{C_2}, \quad \text{and} \quad V_3 = \frac{q}{C_3}.$$

The total potential difference V due to the battery is the sum

$$V = V_1 + V_2 + V_3 = q\left(\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}\right).$$

The equivalent capacitance is then

$$C_{eq} = \frac{q}{V} = \frac{1}{1/C_1 + 1/C_2 + 1/C_3},$$

or

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}.$$

We can easily extend this to any number n of capacitors as

$$\frac{1}{C_{eq}} = \sum_{j=1}^{n} \frac{1}{C_j} \quad (n \text{ capacitors in series}).$$

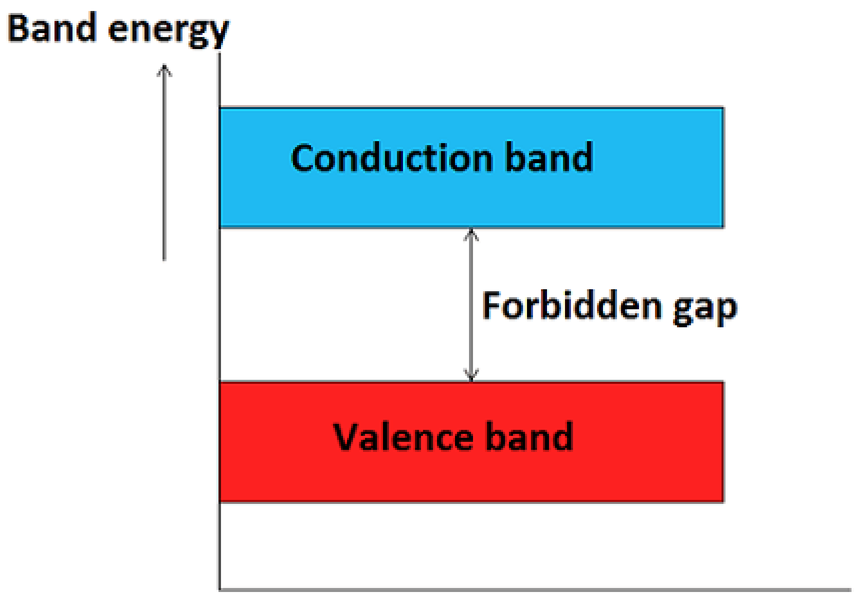
Energy band theory in solids

In a single isolated atom, the electrons in each orbit have definite energy associated with it. But in case of solids all the atoms are close to each other, so the energy levels of outermost orbit electrons are affected by the neighboring atoms.When two single or isolated atoms are bring close to each other then the outermost orbit electrons of two atoms are interact or shared with each other. i.e, the electrons in the outermost orbit of one atom experience a attractive force from the nearest or neighboring atomic nucleus. Due to this the energies of the electrons will not be in same level, the energy levels of electrons are changed to a value which is higher or lower than that of the original energy level of the electron.The electrons in same orbit exhibits different energy levels. The grouping of this different energy levels is called energy band.However, the energy levels of inner orbit electrons are not much affected by the presence of neighboring atoms.

Important energy bands in solids

There are number of energy bands in solids but three of them are very important. These three energy bands are important to understand the behavior of solids. These energy bands are

- Valence band
- Conduction band
- Forbidden band or forbidden gap



- **Valence band**

The energy band which is formed by grouping the range of energy levels of the valence electrons or outermost orbit electrons is called as valence band. Valence band is present below the conduction band as shown in figure. Electrons in the valence band have lower energy than the electrons in conduction band. The electrons present in the valence band are loosely bound to the nucleus of atom.

- **Conduction band**

The energy band which is formed by grouping the range of energy levels of the free electrons is called as conduction band.Generally, the conduction band is empty but when external energy is applied the electrons in the valence band jumps in to the conduction band and becomes free electrons. Electrons in the conduction band have higher energy than the electrons in valence band. The conduction band electrons are not bound to the nucleus of atom.

- **Forbidden gap**

The energy gap which is present between the valence band and conduction band by separating these two energy bands is called as forbidden band or forbidden gap.

In solids, electrons cannot stay in forbidden gap because there is no allowed energy state in this region. Forbidden gap is the major factor for determining the electrical conductivity of a solid. The classification of materials as insulators, conductors and semiconductors is mainly depends on forbidden gap.

The energy associated with forbidden band is called energy gap and it is measured in unit electron volt (eV).

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

The applied external energy in the form of heat or light must be equal to to the forbidden gap in order to push an electron from valence band to the conduction band.

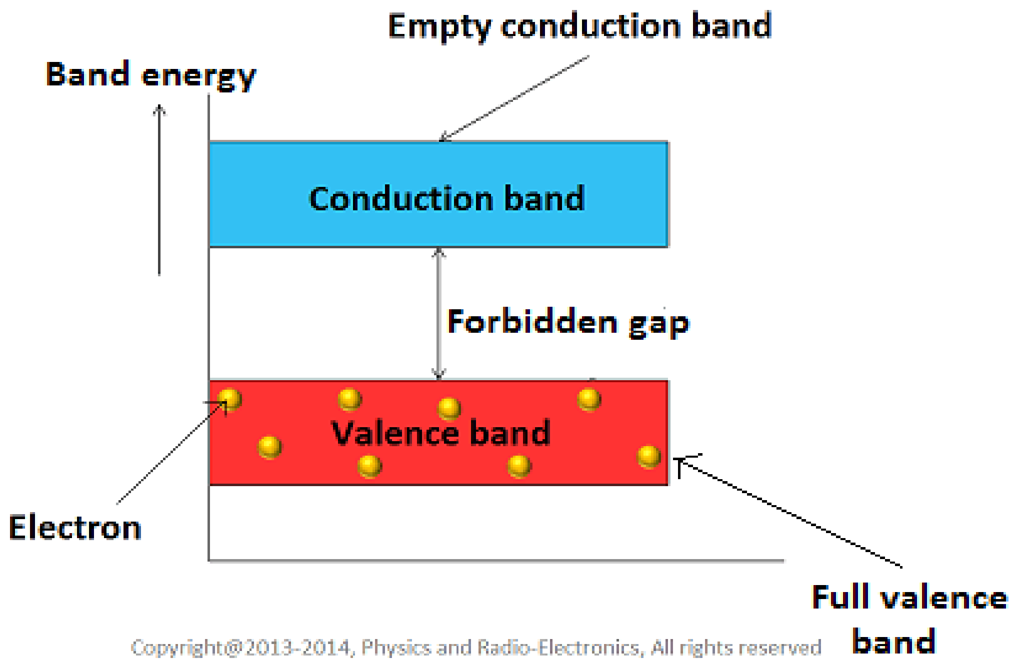
Classification of materials based on forbidden gap

Forbidden gap plays a major role for determining the electrical conductivity of material. Based on the forbidden gap materials are classified in to three types, they are

- Insulators
- Conductors
- semiconductors

- **Insulators**

The materials which does not allow the flow of electric current through them are called as insulators. Insulators are also called as poor conductors of electricity.



Normally, in insulators the valence band is fully occupied with electrons due to sharing of outer most orbit electrons with the neighboring atoms. Where as conduction band is empty, I.e, no electrons are present in conduction band.

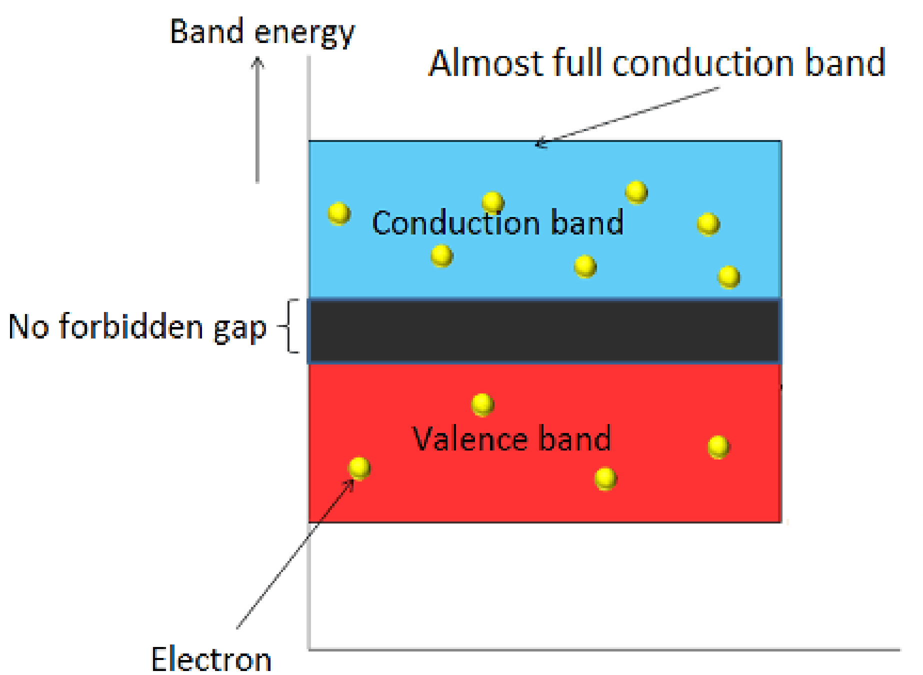
The forbidden gap between the valence band and conduction band is very large in insulators. The energy gap of insulator is approximately equal to 15 electron volts (eV).

The electrons in valence band cannot move because they are locked up between the atoms. In order move the valence band electrons in to conduction band large amount of external energy is applied which is equal to the forbidden gap. But in insulators, this is practically impossible to move the valence band electrons in to conduction band.

Rubber, wood, diamond, plastic are some examples of insulators. Insulators such as plastics are used for coating of electrical wires. These insulators prevent the flow of electricity to unwanted points and protect us from electric shocks.

- **Conductors**

The materials which easily allow the flow of electric current through them are called as conductors. Metals such as copper, silver, iron, aluminum etc. are good conductors of electricity.



In a conductor, valence band and conduction band overlap each other as shown in figure. Therefore, there is no forbidden gap in a conductor.

A small amount of applied external energy provides enough energy for the valence band electrons to move in to conduction band. Therefore, more number of valence band electrons can easily moves in to the conduction band.

When valence band electrons moves to conduction band they becomes free electrons. The electrons present in the conduction band are not attached to the nucleus of a atom.

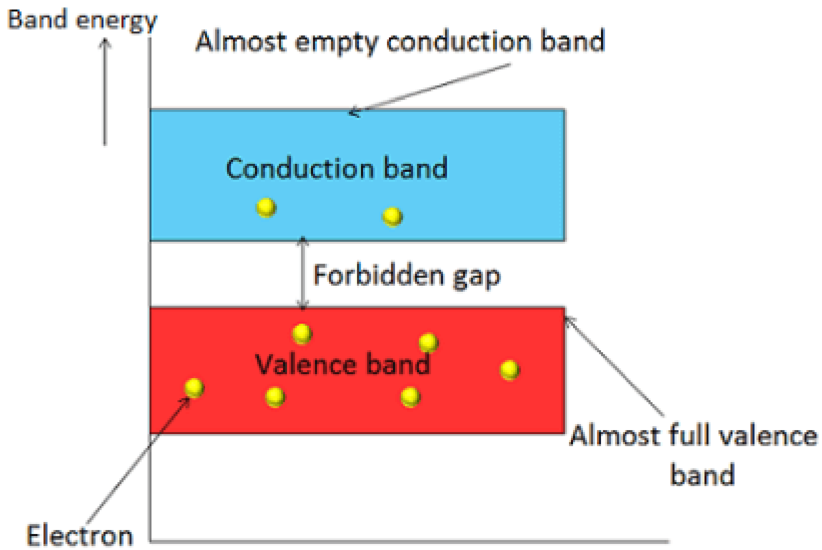
In conductors, large number of electrons are present in conduction band at room temperature, I.e, conduction band is almost full with electrons. Where as valence band is partially occupied with electrons. The electrons present in the conduction band moves freely by carrying the electric current from one point to other.

- **Semiconductors**

The material which has electrical conductivity between that of a conductor and an insulator is called as semiconductor. Silicon, germanium and graphite are some examples of semiconductors.

In semiconductors, the forbidden gap between valence band and conduction band is very small. It has a forbidden gap of about 1 electron volt (eV).

At low temperature, the valence band is completely occupied with electrons and conduction band is empty because the electrons in the valence band does not have enough energy to move in to conduction band. Therefore, semiconductor behaves as an insulator at low temperature.



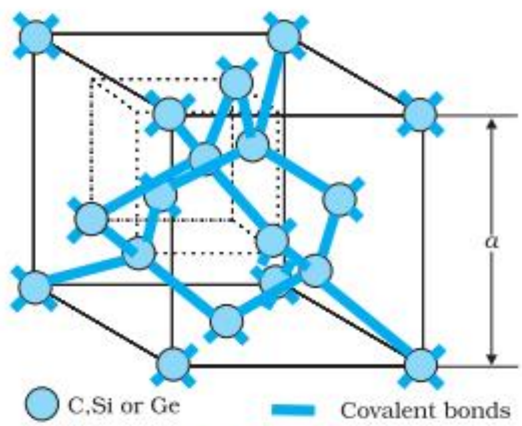
However, at room temperature some of the electrons in valence band gains enough energy in the form of heat and moves in to conduction band.

When the temperature is goes on increasing, the number of valence band electrons moving in to conduction band is also increases. This shows that electrical conductivity of the semiconductor increases with increase in temperature. I.e. a semiconductor has negative temperature co-efficient of resistance. The resistance of semiconductor decreases with increase in temperature.

Intrinsic Semiconductor

An Intrinsic Semiconductor is the purest form of a semiconductor, elemental, without any impurities. Naturally available elements like silicon and germanium are best examples of an Intrinsic Semiconductor.

The Lattice Structure of Elements

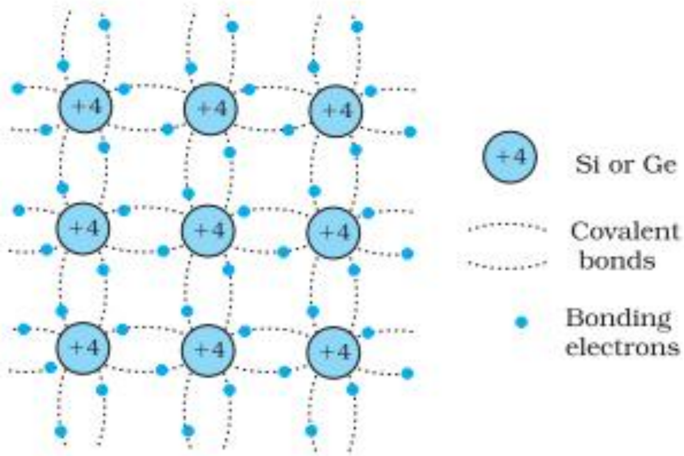


Three-dimensional diamond-like crystal structure for Carbon, Silicon or Germanium with respective lattice spacing a equal to 3.56, 5.43 and 5.66 Å.

They are also called diamond-like structures. In such structures, every atom is surrounded by four neighbouring atoms. Now, both Si and Ge have four valence electrons and in the crystalline structure, each atom shares one of its valence electrons with each of its four neighbours.

Also, it takes one electron from each of its neighbours. This shared pair of electron is called a Covalent bond or a Valence bond. This is how the

Si or Ge structure looks in two-dimensions with emphasis on the covalent bond:



Schematic two-dimensional representation of Si or Ge structure showing covalent bonds at low temperature (all bonds intact). +4 symbol indicates inner cores of Si or Ge.

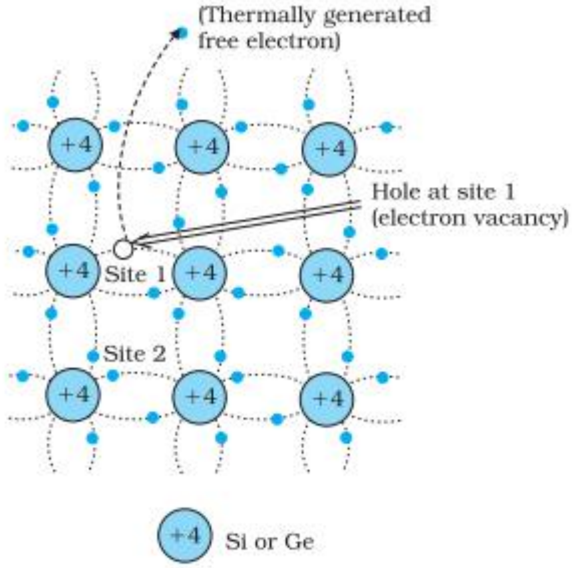
Also, the above image shows the structure with all bonds intact. This is possible only at low temperatures. As the temperature increases and more energy becomes available to the valence electrons, they break away leading to an increase in conductivity of the element.

Now, the thermal energy ionizes only a few atoms. This ionization creates a vacancy in the bond. When an electron, having charge –q, gets excited due to the thermal energy, it breaks free from the bond. This leaves a vacancy there with effective charge +q. This vacancy with an effective positive electronic charge is a hole.

The hole also behaves like a free particle but with a positive charge. In intrinsic semiconductors, the number of free electrons is equal to the number of holes and is called the intrinsic carrier concentration.

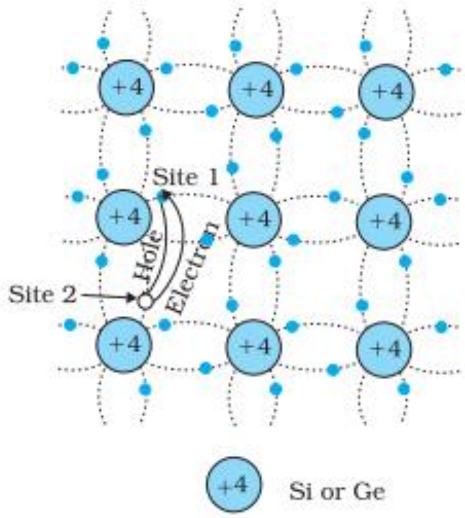
Intrinsic Semiconductor – The Movement of Holes

Another interesting property of semiconductors is that like the electrons, the holes move too. Consider the following image:



Schematic model of generation of hole at site 1 and conduction electron due to thermal energy at moderate temperatures.

In the image above, you can see that an electron, after being excited due to thermal energy breaks itself away from the bond, generating a free electron. (Site1) A vacancy is created at the site from where the electron releases itself. Now, imagine that an electron from Site 2, as shown in the image, jumps to the hole or vacancy created in Site 1. The hole will now have moved from Site1 to Site2 as shown in the image below:



Simplified representation of possible thermal motion of a hole. The electron from the lower left hand covalent bond (site 2) goes to the earlier hole site1, leaving a hole at its site indicating an apparent movement of the hole from site 1 to site 2.

It is important to observe that the electron freed from Site 1 is not involved in the movement of the hole. It moves independently like a conduction electron contributing to electron current (I_e) under an applied electric field. Also, movement of the hole is actually a movement of bound electrons.

Under an electric field, these holes move towards the negative potential generating hole current (I_h). Hence, the total current (I) is:

$I = I_e + I_h$

Another important thing to remember is that apart from the process of the generation of free electrons and holes, a process of recombination takes place simultaneously. In this process, the electrons recombine with the holes. In the state of equilibrium, the rate of generation is equal to the rate of recombination.

Extrinsic semiconductors

Semiconductors can be broadly classified into Intrinsic and Extrinsic Semiconductors. Intrinsic Semiconductors start conducting at temperatures above the room temperature, developing important electronic devices using these can pose a problem. This led to a need for improving the conductivity of intrinsic semiconductors.

After some experiments, scientists observed an increase in the conductivity of a Semiconductor when a small amount of impurity was added to it. These materials are Extrinsic Semiconductors or impurity Semiconductors. Another term for these materials is 'Doped Semiconductor'. The impurities are dopants and the process – Doping.

An important condition to doping is that the amount of impurity added should not change the lattice structure of the Semiconductor. To achieve this the size of the dopant and Semiconductor atoms should be the same.

Types of Dopants in Extrinsic Semiconductors

Crystals of Silicon and Germanium are doped using two types of dopants:

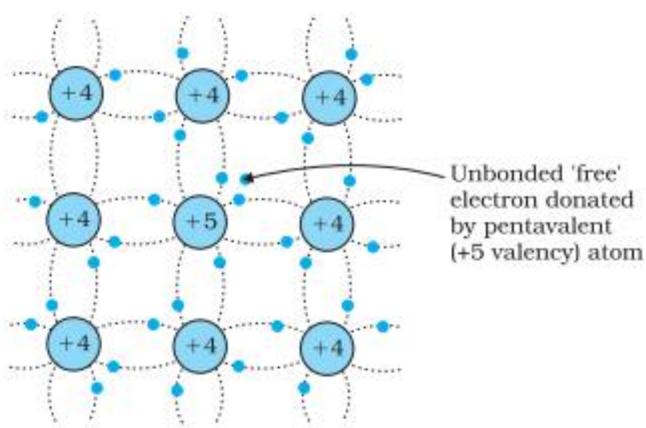
1. Pentavalent (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.
2. Trivalent (valency 3); like Indium (In), Boron (B), Aluminium (Al), etc.

The reason behind using these dopants is to have similarly sized atoms as the pure semiconductor. Both Si and Ge belong to the fourth group in the periodic table. Hence, the choice of dopants is from the third and fifth group. This ensures that size of the atoms is not much different from the fourth group. Hence, the trivalent and pentavalent choices. These dopants give rise to two types of semiconductors:

1. n-type
2. p-type

n-type semiconductor

An n-type semiconductor is created when pure semiconductors, like Si and Ge, are doped with pentavalent elements.



As can be seen in the image above, when a pentavalent atom takes the place of a Si atom, four of its electrons bond with four neighbouring Si atoms. However, the fifth electron remains loosely bound to the parent atom. Hence, the ionization energy required to set this electron free is very small. Thereby, this electron can move in the lattice even at room temperature.

To give you a better perspective, the ionization energy required for silicon at room temperature is around 1.1 eV. On the other hand, by adding a pentavalent impurity, this energy drops to around 0.05 eV.

It is important to remember that the number of electrons made available by the dopant atoms is independent of the ambient temperature and primarily depends on the doping level. Also, as the temperature rises, the Si atoms free some electrons and generate some holes. But, the number of these holes is very small. Hence, at any given point in time, the number of free electrons is much higher than the number of holes. Also, due to recombination, the number of holes reduce further.

In a nutshell, when a semiconductor is doped with a pentavalent atom, electrons are the majority charge carriers. On the other hand, the holes are the minority charge carriers. Therefore, such extrinsic semiconductors are called n-type semiconductors. In an n-type semiconductor,

Number of free electrons (n_e) >> Number of holes (n_h)

p-type semiconductor

A p-type semiconductor is created when trivalent elements are used to dope pure semiconductors, like Si and Ge. As can be seen in the image above, when a trivalent atom takes the place of a Si atom, three of its electrons bond with three neighbouring Si atoms. However, there is no electron to bond with the fourth Si atom.

This leads to a hole or a vacancy between the trivalent and the fourth silicon atom. This hole initiates a jump of an electron from the outer orbit of the atom in the neighbourhood to fill the vacancy. This creates a hole at the site from where the electron jumps. In simple words, a hole is now available for conduction.

It is important to remember that the number of holes made available by the dopant atoms is independent of the ambient temperature and primarily depends on the doping level. Also, as the temperature rises, the Si atoms free some electrons and generate some holes. But, the number of these electrons is very small. Hence, at any given point in time, the number of holes is much higher than the number of free electrons. Also, due to recombination, the number of free electrons reduce further.

In a nutshell, when a semiconductor is doped with a trivalent atom, holes are the majority charge carriers. On the other hand, the free electrons are the minority charge carriers. Therefore, such extrinsic semiconductors are called p-type semiconductors. In a p-type semiconductor,

Number of holes (n_h) >> Number of free electrons (n_e)

Faraday's Law

Two Experiments

Let us examine two simple experiments to prepare for our discussion of Faraday's law of induction.

First Experiment : Figure 1 shows a conducting loop connected to a sensitive ammeter.

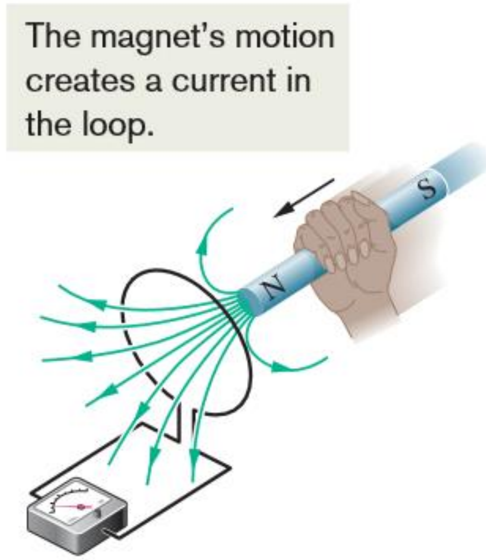


Figure 1

Because there is no battery or other source of emf included, there is no current in the circuit.However,if we move a bar magnet toward the loop, a current suddenly appears in the circuit.The current disappears when the magnet stops. If we then move the magnet away,a current again suddenly appears,but now in the opposite direction. If we experimented for a while, we would discover the following:

1. A current appears only if there is relative motion between the loop and the magnet (one must move relative to the other); the current disappears when the relative motion between them ceases.

2. Faster motion produces a greater current.

3. If moving the magnet's north pole toward the loop causes, say, clockwise current, then moving the north pole away causes counterclockwise current. Moving the south pole toward or away from the loop also causes currents, but in the reversed directions.

The current produced in the loop is called an induced current; the work done per unit charge to produce that current (to move the conduction electrons that constitute the current) is called an induced emf;and the process of producing the current and emf is called induction.

Second Experiment. For this experiment we use the apparatus of Figure 2, with the two conducting loops close to each other but not touching.

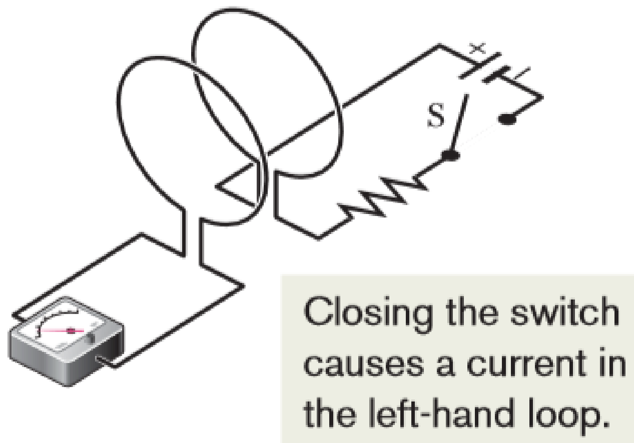


Figure 2

If we close switch S, to turn on a current in the right-hand loop, the meter suddenly and briefly registers a current—an induced current—in the left-hand loop. If we then open the switch, another sudden and brief induced current appears in the left-hand loop,but in the opposite direction.We get an induced current (and thus an induced emf) only when the current in the right-hand loop is changing (either turning on or turning off) and not when it is constant (even if it is large). The induced emf and induced current in these experiments are apparently caused when something changes.

Faraday's Law of Induction

Faraday realized that an emf and a current can be induced in a loop, as in our two experiments,by changing the amount of magnetic field passing through the loop. Faraday's law of induction,stated in terms of our experiments,is this:

An emf is induced in the loop at the left (in Figs 1 and 2) when the number of magnetic field lines that pass through the loop is changing.

The actual number of field lines passing through the loop does not matter; the values of the induced emf and induced current are determined by the rate at which that number changes.

In our first experiment (Fig.1), the magnetic field lines spread out from the north pole of the magnet. Thus,as we move the north pole closer to the loop, the number of field lines passing through the loop increases.That increase apparently causes conduction electrons in the loop to move (the induced current) and provides energy (the induced emf) for their motion.When the magnet stops moving,the number of field lines through the loop no longer changes and the induced current and induced emf disappear. In our second experiment (Fig.2), when the switch is open (no current), there are no field lines.However,when we turn on the current in the right-hand loop,the increasing current builds up a magnetic field around that loop and at the left-hand loop.While the field builds,the number of magnetic field lines through the left-hand loop increases.As in the first experiment,the increase in field lines through that loop apparently induces a current and an emf there. When the current in the right-hand loop reaches a final, steady value, the number of field lines through the left-hand loop no longer changes,and the induced current and induced emf disappear.

A Quantitative Treatment

To put Faraday's law to work,we need a way to calculate the amount of magnetic field that passes through a loop .

Here we define a magnetic flux: Suppose a loop enclosing an area A is placed in a magnetic field $\vec{B}$.Then the magnetic flux through the loop is

$$\Phi_B = \int \vec{B} \cdot d\vec{A} \quad \text{(magnetic flux through area } A\text{)}.$$

Special Case. As a special case of above Eq. ,suppose that the loop lies in a plane and that the magnetic field is perpendicular to the plane of the loop. Then we can write the dot product in above equation as B dA cos 0°= B dA. If the magnetic field is also uniform, then B can be brought out in front of the integral sign.Thus, equation reduces to

$$\Phi_B = BA \quad (\vec{B} \perp \text{area } A, \vec{B} \text{ uniform}).$$

the SI unit for magnetic flux is the tesla–square meter,which is called the weber(abbreviated Wb)

$$1 \text{ weber} = 1 \text{ Wb} = 1 \text{ T} \cdot \text{m}^2.$$

Faraday's Law. With the notion of magnetic flux,we can state Faraday's law in a more quantitative and useful way:

The magnitude of the emf Ɛ induced in a conducting loop is equal to the rate at which the magnetic flux ΦB through that loop changes with time.

Faraday's law is formally written as

$$\mathscr{E} = -\frac{d\Phi_B}{dt} \quad \text{(Faraday's law)},$$

with the minus sign indicating the opposition that induced emf tends to exert on flux change.

If we change the magnetic flux through a coil of N turns, an induced emf appears in every turn and the total emf induced in the coil is the sum of these individual induced emfs. If the coil is tightly wound (closely packed), so that the same magnetic flux ΦB passes through all the turns,the total emf induced in the coil is

$$\mathscr{E} = -N\frac{d\Phi_B}{dt} \quad \text{(coil of } N \text{ turns)}.$$

Here are the general means by which we can change the magnetic flux through a coil:

1. Change the magnitude B of the magnetic field within the coil.

2. Change either the total area of the coil or the portion of that area that lies within the magnetic field (for example,by expanding the coil or sliding it into or out of the field).

3. Change the angle between the direction of the magnetic field and the plane of the coil.

Inductance

If we establish a current i in the windings (turns) of the solenoid we are taking as our inductor, the current produces a magnetic flux Φ_B through the central region of the inductor.The inductance of the inductor is then defined in terms of that flux as

$$L = \frac{N\Phi_B}{i} \quad \text{(inductance defined)},$$

in which N is the number of turns. The windings of the inductor are said to be linked by the shared flux and the product $N\Phi_B$ is called the magnetic flux linkage. The inductance L is thus a measure of the flux linkage produced by the inductor per unit of current.

The SI unit of Inductance is Henry (H)

$$1 \text{ henry} = 1 \text{ H} = 1 \text{ T} \cdot \text{m}^2/\text{A}.$$

Inductance of a Solenoid

Consider a long solenoid of cross-sectional area A. we must calculate the flux linkage set up by a given current in the solenoid windings. Consider a length l near the middle of this solenoid. The flux linkage there is

$$N\Phi_B = (nl)(BA),$$

in which n is the number of turns per unit length of the solenoid and B is the magnitude of the magnetic field within the solenoid.

The magnitude B is given as

$$B = \mu_0 i n,$$

And Inductance will be

$$L = \frac{N\Phi_B}{i} = \frac{(nl)(BA)}{i} = \frac{(nl)(\mu_0 in)(A)}{i}$$
$$= \mu_0 n^2 l A.$$

Thus,the inductance per unit length near the center of a long solenoid is

$$\boxed{\frac{L}{l} = \mu_0 n^2 A \quad \text{(solenoid).}}$$

And

$$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{T \cdot m/A}$$
$$= 4\pi \times 10^{-7}\,\mathrm{H/m}.$$

Example # 1 Calculate the inductance of the solenoid if it contains 300 turns, its length is 25.0 cm, and its cross-sectional area is 4.00 cm.

Solution

$$L = (4\pi \times 10^{-7}\,\mathrm{T \cdot m/A})\,\frac{300^2}{25.0 \times 10^{-2}\,\mathrm{m}}\,(4.00 \times 10^{-4}\,\mathrm{m^2})$$
$$= 1.81 \times 10^{-4}\,\mathrm{T \cdot m^2/A} = \boxed{0.181\,\mathrm{mH}}$$

Self induction

If two coils are near each other, a current I in one coil produces a magnetic flux Φ_B through the second coil.We have seen that if we change this flux by changing the current, an induced emf appears in the second coil according to Faraday's law. An induced emf appears in the first coil as well. An induced emf appears in any coil in which the current is changing. This process is called **self-induction**, and the emf that appears is called a **self-induced emf**.

For any inductor

$$N\Phi_B = Li.$$

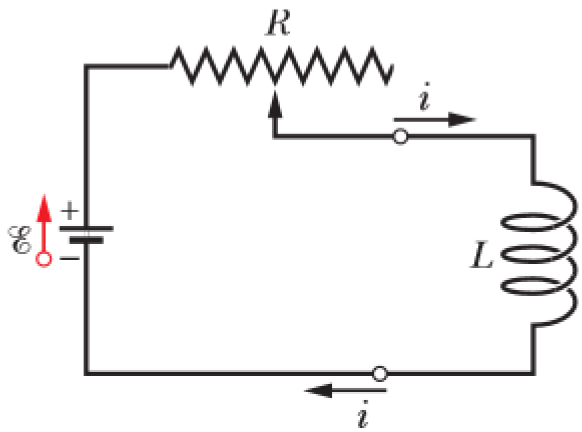
Faraday's law tells us that

$$\mathscr{E}_L = -\frac{d(N\Phi_B)}{dt}.$$

By combining both equations we can write as

$$\mathscr{E}_L = -L\frac{di}{dt} \quad \text{(self-induced emf)}.$$

Thus, in any inductor (such as a coil, a solenoid, or a toroid) a self-induced emf appears whenever the current changes with time. The magnitude of the current has no influence on the magnitude of the induced emf, only the rate of change of the current counts.



If the current in a coil is changed by varying the contact position on a variable resistor, a self-induced emf will appear in the coil while the current is changing.

Mutual Induction

If two coils are close together,a steady current i in one coil will set up a magnetic flux Φ through the other coil (linking the other coil).If we change I with time, an emf given by Faraday's law appears in the second coil; we called this process induction. We could better have called it mutual induction, to suggest the mutual interaction of the two coils and to distinguish it from self-induction, in which only one coil is involved.

Let us look a little more quantitatively at mutual induction. Figure 1 shows two circular close-packed coils near each other. .With the variable resistor set at a particular resistance R, the battery produces a steady current i_1 in coil 1.This current creates a magnetic field represented by the lines of $\overrightarrow{B_1}$ in the figure. Coil 2 is connected to a sensitive meter but contains no battery; a magnetic flux Φ_{21}. (the flux through coil 2 associated with the current in coil 1) links the N_2turns of coil 2.

We define the mutual inductance M_{21} of coil 2 with respect to coil 1 as

$$M_{21} = \frac{N_2 \Phi_{21}}{i_1},$$

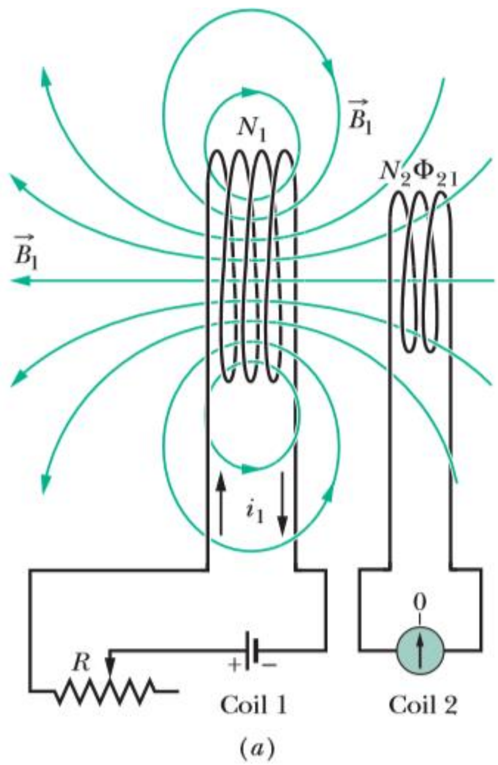


Figure 1

which has the same form as the definition of inductance.

$$L = N\Phi/i,$$

Where

$$M_{21} i_1 = N_2 \Phi_{21}.$$

If we cause i_1 to vary with time by varying R,we have

$$M_{21} \frac{di_1}{dt} = N_2 \frac{d\Phi_{21}}{dt}.$$

The right side of this equation is, according to Faraday's law, just the magnitude of the emf appearing in coil 2 due to the changing current in coil 1.Thus,with a minus sign to indicate direction,

$$\mathcal{E}_2 = -M_{21}\frac{di_1}{dt},$$

Interchange. Let us now interchange the roles of coils 1 and 2,as in Figure 2.

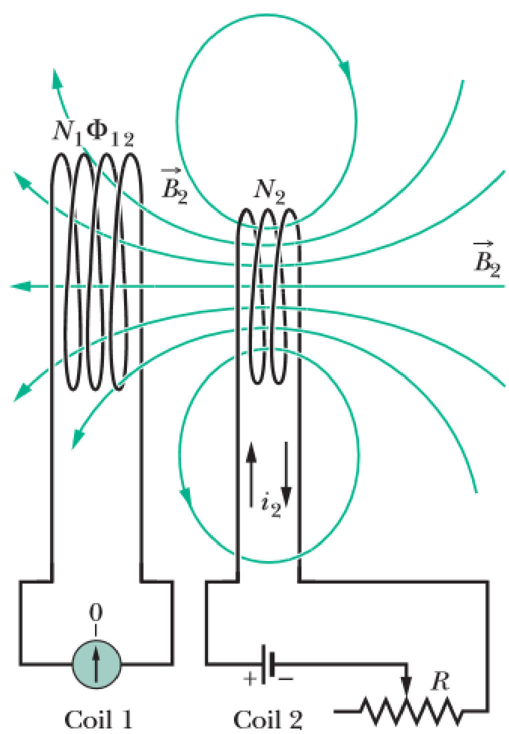


Figure 2

that is, we set up a current i_2 in coil 2 by means of a battery, and this produces a magnetic flux that links coil 1.If we change i_2 with time by varying R, we then have, by the argument given above,

$$\mathcal{E}_1 = -M_{12}\frac{di_2}{dt}.$$

Thus,we see that the emf induced in either coil is proportional to the rate of change of current in the other coil. The proportionality constants M_{21} and M_{12} seem to be different. However, they turn out to be the same

Thus,we have

$$M_{21} = M_{12} = M,$$

So

$$\mathcal{E}_2 = -M \frac{di_1}{dt}$$

And

$$\mathcal{E}_1 = -M \frac{di_2}{dt}.$$

Introduction to Magnetic Fields

We have seen that a charged object produces an electric field $\vec{E}$at all points in space. In a r similar manner, a bar magnet is a source of a magnetic field $\vec{B}$. This can be readily demonstrated by moving a compass near the magnet. The compass needle will line up along the direction of the magnetic field produced by the magnet, as depicted in Figure 1

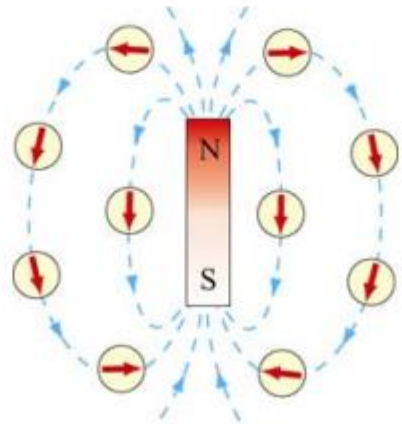


Figure 1. Magnetic field produced by a bar magnet

Notice that the bar magnet consists of two poles, which are designated as the north (N) and the south (S). Magnetic fields are strongest at the poles. The magnetic field lines leave from the north pole and enter the south pole. When holding two bar magnets close to each other, the like poles will repel each other while the opposite poles attract.

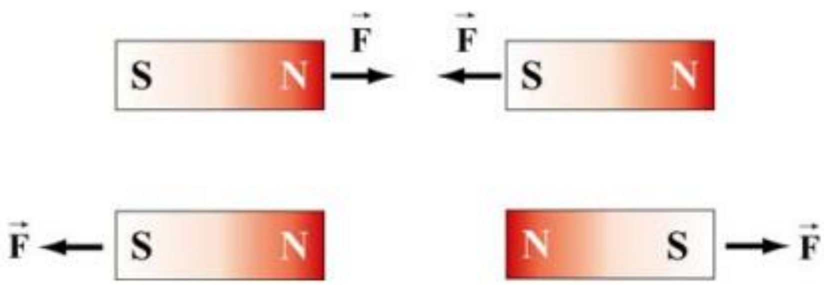


Figure 2. Magnets attracting and repelling

Unlike electric charges which can be isolated, the two magnetic poles always come in a pair. When you break the bar magnet, two new bar magnets are obtained, each with a north pole and a south pole (Figure 3). In other words, magnetic “monopoles” do not exist in isolation.

Figure 3. Magnetic monopoles do not exist in isolation

The Definition of a Magnetic Field

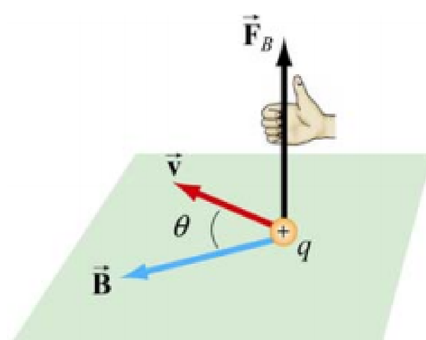
To define the magnetic field at a point, consider a particle of charge q and moving at a velocity v . Experimentally we have the following observations:

(1) The magnitude of the magnetic force $\vec{\mathbf{F}}_B$ exerted on the charged particle is proportional to both v and q.

(2) The magnitude and direction of $\vec{\mathbf{F}}_B$ depends on $\vec{\mathbf{v}}$ and $\vec{\mathbf{B}}$.

(3) The magnetic force $\vec{\mathbf{F}}_B$ vanishes when $\vec{\mathbf{v}}$ is parallel to $\vec{\mathbf{B}}$. However, when $\vec{\mathbf{v}}$ makes an angle θ with $\vec{\mathbf{B}}$, the direction of $\vec{\mathbf{F}}_B$ is perpendicular to the plane formed by $\vec{\mathbf{v}}$ and $\vec{\mathbf{B}}$, and the magnitude of $\vec{\mathbf{F}}_B$ is proportional to $\sin\theta$.

(4) When the sign of the charge of the particle is switched from positive to negative (or vice versa), the direction of the magnetic force also reverses.



The above observations can be summarized with the following equation:

$$\vec{\mathbf{F}}_B = q\vec{\mathbf{v}} \times \vec{\mathbf{B}}$$

The above expression can be taken as the working definition of the magnetic field at a point in space. The magnitude of magnetic force is given by

$$F_B = |q| vB \sin\theta$$

The SI unit of magnetic field is the tesla (T):

$$1 \text{ tesla} = 1 \text{ T} = 1 \frac{\text{Newton}}{(\text{Coulomb})(\text{meter/second})} = 1 \frac{\text{N}}{\text{C} \cdot \text{m/s}}$$