PRACTICAL

INDUSTRIAL ELECTRONICS

IDC TECHNOLOGIES PTY LTD

SPECIALIST ENGINEERING, CONSULTING AND TRAINING SERVICES FOR INDUSTRY

IDC TECHNOLOGIES

Technology Training that Works

Practical

Industrial Electronics

Lubomir Dimitrov

MSc. PEng. Grad IE Aust.

Web Site: http://www/idc-online.com

E-mail: idc@idc-online.com

IDC
TECHBOOKS

Technical Information that Works

Table of Contents

Basic Concepts

Chapter 1

Basic Concepts

1.1 Atomic Structure

When you have completed study of this section you should be able to:

- **Describe atomic structure**
- **Define nucleus, electron, proton and neutron**
- **Define atomic number**
- **Define energy levels (shells)**
- **Identify valence electrons**
- **Describe ionization**

1.1.1 Atoms

The smallest particle of an element that retains the characteristics of that element is called an **atom**. Each element has a different atomic structure. The most common model of atomic structure is the classical Bohr model of an atom. According to it, the atoms have a planetary type of structure. This is illustrated in Figure 1.1. The **nucleus** consists of uncharged particles called **neutrons** and positively charged particles called **protons**. Negatively charged particles called **electrons** orbit around the nucleus.

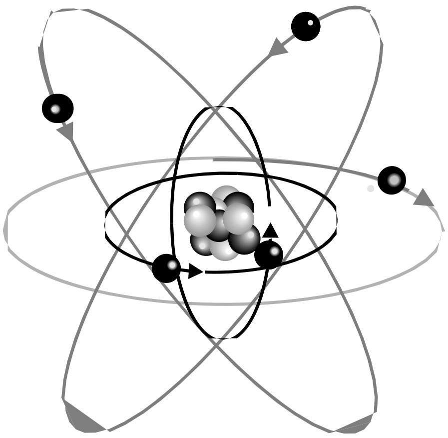

Figure 1.1
The Bohr Model of an Atom

Each of the known 109 elements has a different atomic structure. Every atom has a certain number of electrons and protons that distinguish it from the atoms of other elements. For example, the simplest atom is that of hydrogen. It consists from one electron and one proton, as shown in Figure 1.2 (a). As another example, the nucleus of the helium atom, shown in Figure 1.2 (b) consists from two protons and two neutrons. Two electrons orbit around the nucleus.

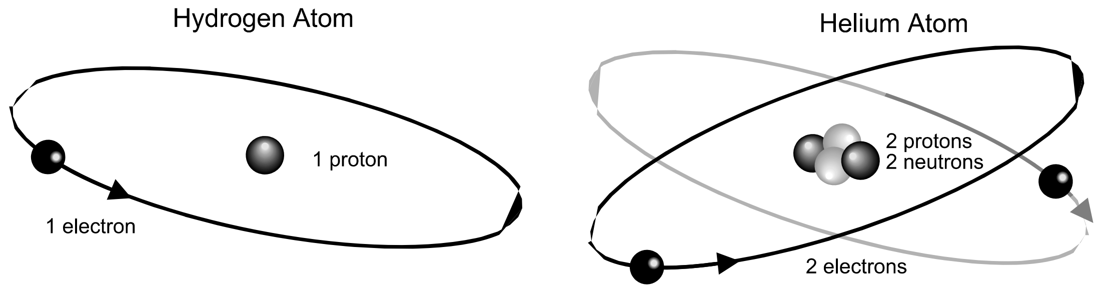

Figure 1.2
The Two Simplest Atoms

1.1.2 Atomic Number

According to their **atomic number,** all elements are arranged in a periodic table. The atomic number equals the number of protons in the nucleus. In an electrically balanced (or neutral) atom, the number of electrons equals the number of protons. For example, hydrogen has an atomic number of 1, and helium has an atomic number of 2. When the atoms of a certain element are in their normal (or neutral) state, they have the same number of electrons and protons. The negative charges cancel the positive charges, and the atom has a net charge of zero.

1.1.3 Electron Shells

Electrons orbit around the nucleus of an atom at distances that are precisely defined and grouped into energy bands called **shells**. Only distinct values of electron energies exist within the atomic structures. Therefore, the electrons orbit only at distinct (discrete) distances from the nucleus. Each one of these discrete distances (orbits) from the nucleus corresponds to a certain energy level. Electrons near the nucleus have less energy then those in most distant orbits. A given atom has a fixed number of shells. The shells are designated K, L, M, N and so on with K being closest to the nucleus. The energy band concept is illustrated in Figure 1.3.

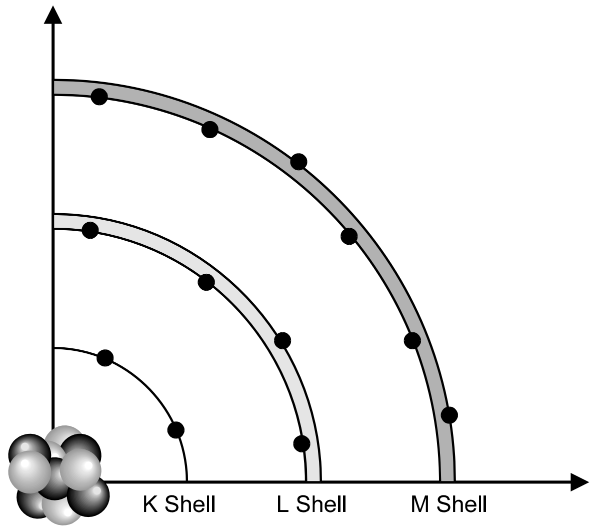

Figure 1.3
Electron Shells

The maximum number of electrons in each shell is fixed and can be derived from the formula:

$$N_e = 2\,n^2$$

where:

n is the number of the shell.

Therefore the maximum number of electrons that can exist in the first innermost shell (K) is 2, the second (L) – 8, the third (M) – 18 and so on.

1.1.4 Valence

The force of attraction between the electrons and nucleus decreases when the distance between them increases. Therefore, the electrons in the outermost shell have the highest energy levels and are relatively loosely bound to the atom.

The outermost shell or energy level that contains electrons is known as the **valence level** of that atom. The number of electrons in the outer level is known as the **valence number** of that atom and the electrons in this level are called **valence electrons**. If an electron is dislodged from an atom, the balance of the atom is upset. With more protons than electrons, the atom becomes positively charged. The energy required to free an electron may be obtained from an external source of heat or voltage.

1.1.5 Ionization

The relatively loosely bound to the atom valence electrons can easily jump to the higher energy levels, even when a minimal amount of external energy is absorbed. When a valence electron absorbs a sufficient amount of energy and dislodges from the atom, it becomes a **free electron**.

The process of **losing** a valence electron is called **ionization,** and the atom with one or more disassociated electrons is called a **positive ion**. At the same time, the opposite process may occur. Free electrons may join positive ions, which turns them back into neutral atoms. This process is called **recombination**.

For example, a neutral hydrogen atom, which consists of one positively charged proton and one negatively charged electron is designated with the letter **H**. If this atom loses its valence electron, it becomes a positive ion and is designated as $\mathbf{H^+}$. On the other hand, if the disassociated free electron joins the outer shell of another hydrogen atom, the atom becomes negatively charged and it is called a negative ion, designated $\mathbf{H^-}$.

1.1.6 Summary

The atom is the smallest item of matter. All substances are made up of atoms. The atom consists of a nucleus, with electrons orbiting around it. The nucleus consists of protons and neutrons. Protons have a positive charge, electrons have a negative charge and neutrons have no charge. A balanced atom contains an equal number of protons and electrons. The number of protons in the nucleus equals the atomic number of the element. Electrons orbit the nucleus in defined energy levels or shells. The outermost energy level of an atom is called valence shell. Electrons in the valance shell are called valence electrons. The process of dislodging valence electrons is called ionization.

1.1.7 Section Quiz

1. Describe what a proton, neutron and electron is.
2. What is the physical relationship between them?
3. Is it true that the electrons in shell L have more energy, compared to those in shell M?
4. An atom has 77 orbiting electrons. Is it true that its net charge is zero?
5. Describe the process of ionization.

1.2 Conductors, Insulators and Semiconductors

When you have completed study of this section you should be able to:

- **Describe the atomic structure of conductors, insulators and semiconductors**
- **List some of them**
- **Discuss the difference between them**
- **Explain how covalent bonds are formed in a crystal structure**
- **Define doping**
- **Explain what n-type and p-type semiconductors are**

1.2.1 Conductors

To simplify the theory, it can be assumed that the **electric current** is made up of many free electrons, moving in the same direction. According to the availability of free electrons, all materials can be divided into conductors and insulators.

Conductors are materials that easily conduct electrical current. Materials, consisting of atoms with a low valence number (1,2 and 3) make very good conductors of electricity. Because of their low valence, very little energy is required to dislodge the outer electrons from their orbits.

The best conductors are characterized by atoms with one valence electron only, such as copper (Cu), silver (Ag) and aluminum (Al). Other metals, such as gold (Au) and platinum (Pt) may have even better conducting properties, but due to their high cost are used only in some specific applications. Other conductors used in electronics are brass, tin-foil and solder.

Most metals have their atoms arranged in a **crystal structure**. This is made up of positively charged ions that are oscillating from specified stationary positions. Many free electrons are moving randomly between the ions and are constantly colliding with them. The electrons also repel from each other. This concept is illustrated in Figure 1.4.

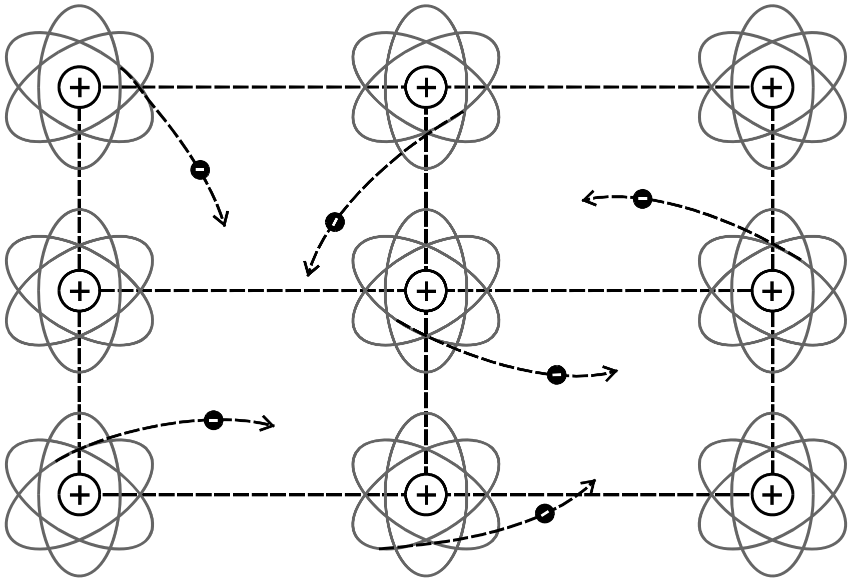

Figure1.4
Conductor Structure

1.2.2 Insulators

An **insulator** is a material that under normal conditions does not conduct electrical current. Atoms of insulating materials consist of at least 5 valence electrons. Valence electrons are tightly bound to the atoms and they have to absorb a considerable amount of energy in order to leave their orbits. The more valence electrons in an atom, the more energy is needed to dislodge them.

Most good insulators do not consist of single-elements. Usually they are compounds, and contain only a very limited number of free electrons. However, if an extremely high voltage is applied to the insulator, it will be forced into the conductive state, and will then break down and fail. This breakdown causes many of the component failures. Figure 1.5 shows energy diagrams for insulators, semiconductors and conductors, which helps understand this process.

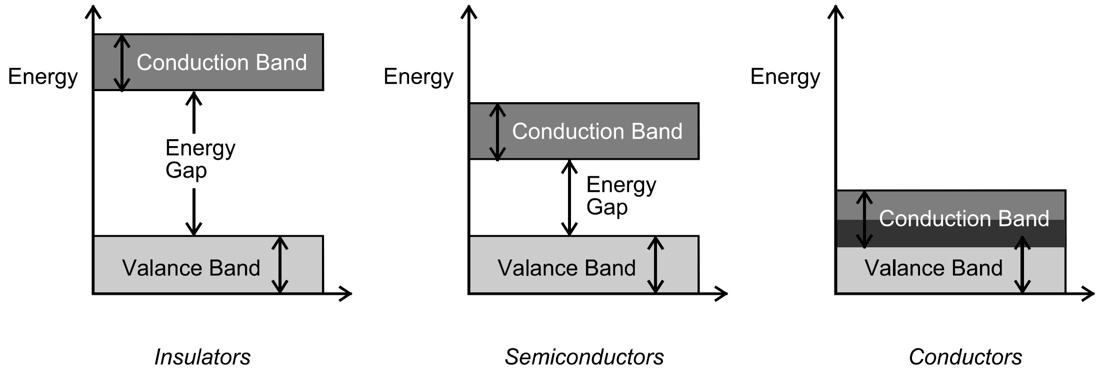

Figure 1.5
Energy Diagrams for Insulators, Semiconductors and Conductors

Remember that each electron is confined to a certain energy band or shell (see Section 1.1.3). For example, when a valence electron acquires sufficient additional energy from an external source to overcome the energy gap, it can jump from the valence band to the conduction band, becoming a free electron. It is important to remember that an electron can jump from one band to another, for example from K to L or from L to M, but it cannot orbit at an energy level, situated between two distinct bands.

The energy required for the electron to leave the band (the shell), where it is orbiting, and to jump into the next one is called **energy gap**. Insulators are characterized by very wide energy gaps. For this reason, valence electrons jump into the conductor band only when extremely high voltages are applied across the material, in which case a breakdown occurs. The wider the energy gap, the better quality of the insulator. Some commonly used insulators in electronics are plastic, ceramics, mica, wood, neon, argon and glass.

In contrast, conductors have a very narrow energy gap and their valence band and conduction band even overlap. This means that the valence electrons do not need any external energy to become free electrons. In fact, even under normal conditions most of their electrons are disassociated from their atoms and *are* free electrons.

1.2.3 Semiconductors

The semiconductors are materials, with conductive properties somewhere between conductors and insulators. Strictly speaking, they are neither good conductors, nor good insulators. Their valence number is always 4. The most popular semiconductors are silicon and germanium. Gallium arsenide is also common.

Both silicon and germanium atoms have four valence electrons. However the silicon atom has 14 electrons, while the germanium atom has 32. Therefore, the germanium valence electrons are at higher energy levels, which makes them unstable at high temperatures. For this reason, silicon is the most widely used material in diodes, transistors, integrated circuits and other semiconductor devices.

The atoms of semiconductors are arranged in fixed pattern called a **crystal**. Each atom in this structure shares its four valence electrons with another four adjacent atoms. This holds the atoms together, and forms the basis of the **crystal structure**. When two atoms share common valence electrons they form a **covalent bond** between them. The semiconductors have four valence electrons. Therefore, each atom forms four covalent bonds with the neighboring atoms. Each neighboring atom is in turn bonded with another four atoms and forms another four covalent bonds and so on. This is illustrated in Figure1.6.

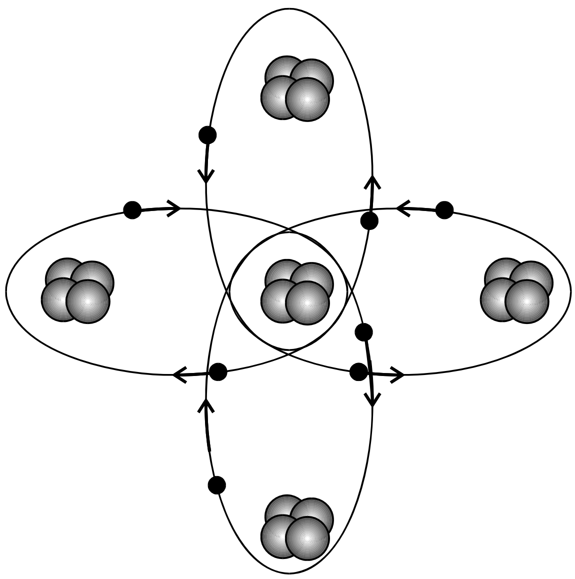

Figure 1.6
Bonding Diagram

Normally 14 electrons orbit around the silicon nucleus, and only 4 of these are in the valence shell. The electrons in the inner shells are tightly bonded to the atom. These electrons do not play any part in the electrical conductivity of the crystal. For this reason, only four valence electrons and four protons are shown in the figures.

A crystal that contains no impurities is called an **intrinsic crystal**. The covalent bonding in an intrinsic silicon crystal at 0°K (absolute zero) is shown in Figure 1.7. At this temperature all valence electrons are in the valence shell. In this case, even if a voltage is applied to the semiconductor, there is no current, as there are no free electrons. Therefore, semiconductors behave as ideal insulators at 0°K.

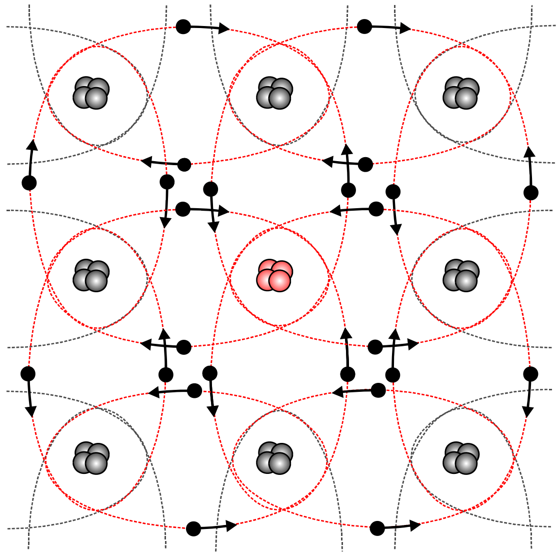

Figure 1.7
Covalent Bonding in an Intrinsic Silicon Crystal at 0°K

However, at room temperature some of the electrons will overcome the energy gap and will jump into the conduction band, becoming free electrons. They move randomly in the crystal structure. If a voltage is applied, they are attracted to the positive end, thus creating an **electron current**.

At the same time, when an electron is freed from the valence band, it leaves a vacancy. This vacancy is called a **hole** and has a positive charge. An intrinsic crystal has an equal number of free electrons and holes. A valence electron may jump from its atom to fill a hole in an adjacent atom with little change in its energy level. In this case, the electron will leave a hole in the atom, where it was previously situated. Effectively the hole is moving from one location to another and this is called a **hole current**. Figure.1.8 illustrates this process.

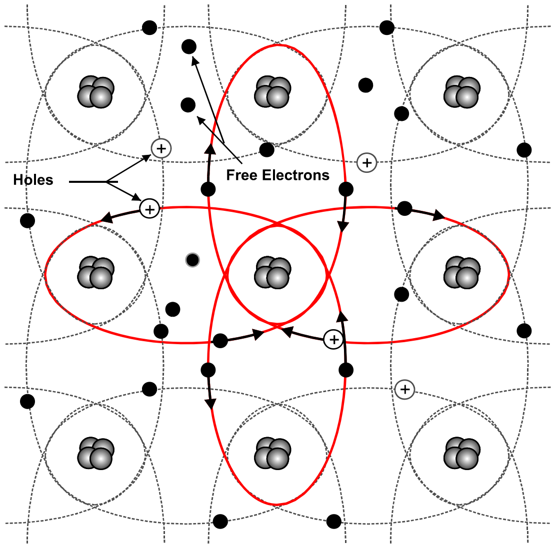

Figure 1.8
Intrinsic Silicon Crystal at Room Temperature

The conductivity of semiconductors can be drastically increased through doping. **Doping** is the process of controlled addition of impurities to the intrinsic semiconductive crystal. The conductivity of semiconductors could be increased hundreds and thousands of times even with minimal impurities added.

The impurity atoms could be **pentavalent** or **trivalent**. For example, if an atom with five valence electrons (a pentavalent atom) is added to intrinsic silicon, four of its valence electrons will form covalent bonds with the adjacent silicon atoms and one electron will remain free. Thus, the doping process creates an additional free electron, without leaving a hole. The material produced in this way is called **n-type** material, as most of its carriers are electrons. This is illustrated in Figure 1.9. Most commonly used pentavalent impurity atoms are those of arsenic (As), bismuth (Bi) and phosphorus (P).

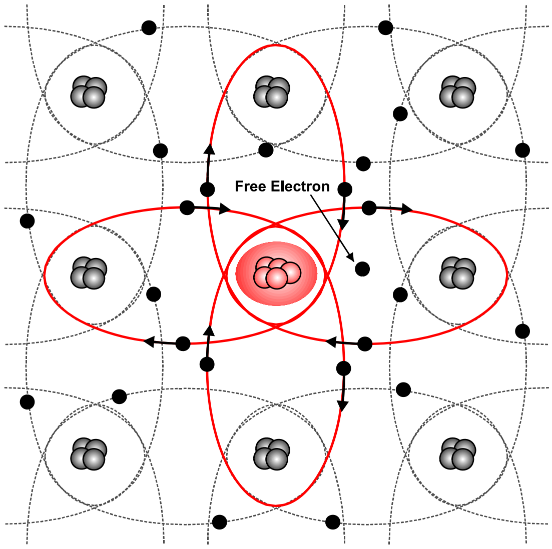

Figure 1.9
N-type Semiconductor

Similarly, if an atom with three valence electrons is added to intrinsic silicon, all of them will form covalent bonds with the adjacent silicon atoms. Since four electrons are required, a hole will appear in the semiconductor crystal. Thus, the doping process will create an additional hole, without leaving a free electron. Such a material is called **p-type,** as most of its carriers are holes. To create p-type semiconductors typically aluminum (Al), indium (In), boron (B) and gallium (Ga) are used. A p-type semiconductor is shown in Figure. 1.10.

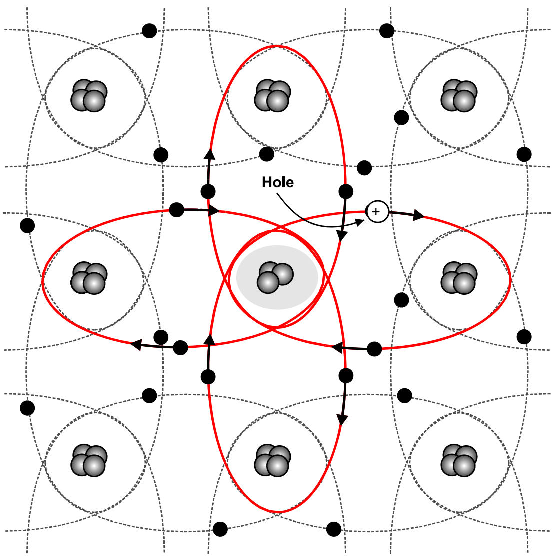

Figure 1.10
P-type Semiconductor

1.2.4 Summary

There are three types of materials: conductors, semiconductors and insulators. Materials with 1,2 or 3 valence electrons are conductors. Materials with 4 valence electrons are semiconductors. Materials with more than 5 valence electrons are insulators. The atoms of the semiconductors are arranged in a crystal structure. When two adjacent atoms share a common pair of valence electrons, they form a covalent bond. Doping is the process of controlled addition of impurities to intrinsic semiconductive crystals. The addition of pentavalent impurity atoms produces n-type semiconductors. The addition of trivalent impurity atoms produces p-type semiconductors.

1.2.5 Quiz

1. What is the basic difference between insulators and conductors?
2. How many valence electrons does a semiconductor have?
3. List the most common conductors and insulators.
4. Which is the most widely used semiconductor material?
5. Is it true that at 0°K semiconductors behave as ideal conductors?
6. What is the name of the process that dramatically increases the conductivity of the semiconductors?

1.3 Current, Voltage, Resistance, Power

When you have completed study of this section you should be able to:

- **Explain the terms current, voltage, resistance and power**
- **Define the relationships between them**
- **List conditions that are necessary for continuous current flow**

1.3.1 Electromotive Force and Current Flow

The structure of conductors resembles a net of positively charged ions, linked together as shown in Figure 1.11. A large number of free electrons move randomly between the ions. In their movement they are constantly colliding with each other and with the ions. The speed of electrons and the number of collisions are proportional to the ambient temperature.

Current only flows if a voltage is applied to the conductor. The voltage source is referred to as the **electromotive force (emf)**. This word comes from the combination of words "electron" and "motion". This force makes the electrons move in a certain direction. Electromotive force is created between two points, when one of them has more positively charged particles, and the other has more negatively charged particles.

As you can see in Figure 1.11 when the electromotive force is applied to the conductor, all electrons start moving in the same direction following the direction of the emf. At this stage, they still collide with each other, but their energy is also passed as impulses in the same direction in which they are moving. The energy is distributed at a very high speed, close to that of the speed of light. Thus, the **current flow** in the conductor is a complex process, involving electrons moving in one direction and simultaneously transferring their energy through impulses in the same direction.

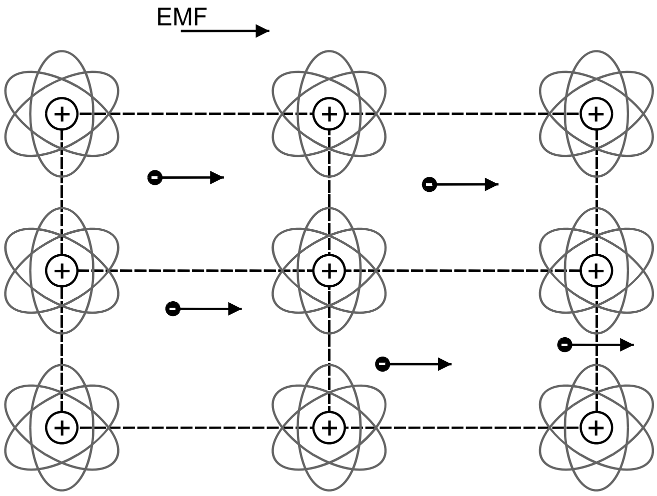

Figure 1.11
Conductor with Current Flow

When electricity was initially discovered, it was decided that the direction of the current flow is from the positive terminal to the negative terminal of the voltage source. This belief was wide spread for many years, until the electron was discovered. Then it was realized, that all theories were wrong, and that the electrons actually flow from the negative terminal to the positive terminal of the voltage source. It was then too late to change all books, which have been written at that time. Moreover, the actual direction of the current is not so important, as long as we accept that the current *has* a direction and we are *consistent* in using one or the other direction.

The current flowing from the positive to the negative terminal is referred to as a **conventional current flow**. At the same time we have to keep in mind that actually electrons flow in the opposite direction, forming an **electrons current flow.**

1.3.2 Current, Voltage and Power Relationships

As was discussed in an earlier section, all electrons can start moving in a certain direction only if there is a potential difference, applied between the two ends of a conductor. In other words the electrical current is the effect, caused from an external source of emf. The emf source converts one type of energy into another, namely its internal energy into that of electrical. This creates at its terminals a potential difference. Because electrons are negatively charged particles, they are attracted to the positively charged terminal of the external emf source. This brings them into motion, orientated towards the positive terminal. The current then starts flowing.

However, the current will flow only if the emf expends some energy. When energy is expended, work is done. The following formula describes this relationship:

$$\mathbf{V} = \frac{\mathbf{W}}{\mathbf{Q}}$$

where:

V is the emf in volts (V),
W is the work done in joules (J),
Q is the charge in coulombs (C).

In other words, the electromotive force will be equal to the work done by the external voltage source in order to transfer a certain quantity of charge via the conductor. Most countries in the world use the **international system of units (SI)**. In this manual only SI units are used. According to SI, if an external voltage source of 1volt emf, transfers 1 coulomb of charge, 1 joule of work has been done.

As was mentioned earlier, the electron current flows from the negative side of the voltage source, through the circuit and back to the positive side of the voltage source. This means that directions of the emf inside the voltage source and actual electron flow will be the same. The conventional current flow, however, has an opposite direction. Unless it is specifically written otherwise, it is a common practice to analyze electronic circuits, with regard the *conventional* current flow. This manual is no exception. Figure 1.12 depicts a simple electrical circuit. The direction of the conventional current flow is shown with an arrow.

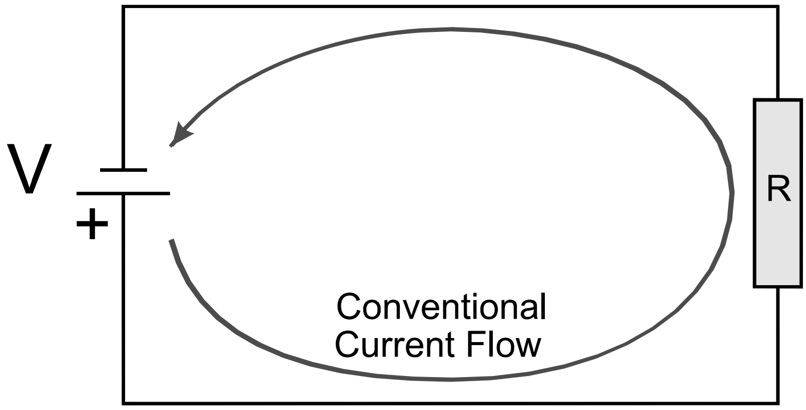

Figure 1.12
Simple Electrical Circuit

Electric current can flow continuously in the circuit if two conditions are satisfied:

- **External source of emf must be available.**

  This source creates on its terminals a differential potential. In order to do this it has to transform some other type of energy into electrical. This other type of energy can be a mechanical rotation, a chemical reaction, a thermal energy or a source of light. For example batteries use a chemical reaction, based on the process called *electrolytic dissociation* to produce an emf.

- **The electrical circuit must be closed.**

  This means that the electrical current that starts flowing from one of the terminals of the voltage source and goes all the way round the continuous circuit must come back to its other terminal. As it is shown in Figure 1.13, if for some reason the circuit is broken at any given point along its way, the current flow will cease.

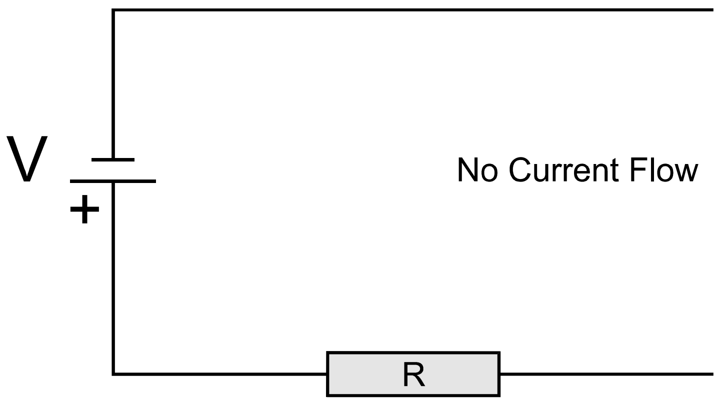

Figure 1.13
Open Electrical Circuit

It becomes clear that the two basic components necessary to maintain continuous current flow are an external source of emf and a closed circuit. However, in order to make use of the electrical energy, an additional component is included in the circuit, and this is the **load**. The load could be for example a bulb, an electrical motor, a speaker and so on. With some thought you can contribute considerably to this list. For example, in Figure 1.12, a resistor is connected as a load.

1.3.3 Resistance and Power

In an electrical circuit, the energy is constantly changing from one form to another. For example chemical energy in the battery is changed into potential electrical energy. Then in the load it is changed again, for example into mechanical energy. Some of it is lost in the conducting wires and dissipated as heat. All this is done according to the law of conservation of energy.

All materials, (including conductors) resist the current flow. Obviously, conductors offer much less resistance to the current flow, compared to insulators or semiconductors. The quality that describes how much the material counteracts the electrical current flowing through it, is called **electrical resistance**. It is measured in **Ohms (Ω).** If a potential difference of 1 V produces current of 1 A, the resistance of the load is 1 Ω.

The resistance of materials depends on their specific properties, called **resistivity**. This parameter represents the electrical resistance of a certain amount of the given substance (namely one cubic centimeter). It is measured in **Ohm.m**. The electrical properties of different materials can be easily compared by their resistivity. For example, the resistivity of copper is 1.75 x 10^{-8} Ω m, while the resistivity of nickel is 1.25 x 10^{-7} Ω m. Thus, a conductor, made of nickel, exhibits nearly ten times higher resistance to the current, compared to an identical conductor, made of copper. The resistivity of materials will be discussed further in Chapter 2.

The electrical resistance of metals depends also on the ambient temperature. Higher temperature will increase the energy of positively charged ions. This will increase their rate of oscillation. Therefore, when moving forward, the free electrons will collide more frequently into the ions, losing in this way more of their energy. Consequently, a higher ambient temperature will increase the conductor's resistance.

And finally the electrical resistance of a conductor depends on its dimensions. The longer and thinner the conductor, the higher its resistance.

Electrical power is equal to the work done for a certain time and it can be expressed with the formula:

$$\mathbf{P = \frac{W}{t}}$$

where:

P is the electrical power in watts (W)
W is the work done in joules (J)
t is the time in seconds (s)

The electrical power is one of the most important parameters of the circuits, as it shows how quickly the energy is transformed from one form to another. A potential difference of 1 V and a current flow of 1 A result in 1 W power consumption.

1.3.4 Summary

The current flow in the conductor is a complex process, involving electrons moving in one direction and simultaneously transferring their energy through impulses. Current can flow continuously in a circuit only if an external electromotive force is applied and the circuit is closed. The direction of the conventional current flow is from the positive to the negative side of the voltage source. The actual electron current flow is in the opposite direction. In a closed circuit, the energy is constantly changing from one form to another. Power is the rate at which work is done.

1.3.5 Quiz

1. What happens with the electrons when an emf is applied to a conductor?
2. What is the difference between resistance and resistivity?
3. A charge of 2 C is moved through a circuit with an emf of 12 V. How much work is done?
4. Is it true that semiconductors increase their conductivity at higher temperatures?
5. It takes 10 s for an emf of 6 V to drive a charge of 6 C. How much power was expended?

1.4 Direct and Alternating Current

When you have completed study of this section you should be able to:

- **Define direct and alternating current**
- **Recognize primary and secondary cells**
- **Describe the basic structure of a battery**
- **Describe the period and frequency of an ac waveform**
- **Describe sine wave values**

1.4.1 Direct Current

An electric current can be either direct or alternating. If the voltage source is a constant polarity supply then the current always flows in one direction. For this reason it is called **dc (direct current)**. The voltage from such a source is called a **dc voltage**. It can be produced from batteries and dc generators. Batteries are much more common and will be discussed here.

A battery is a device that creates a potential difference between its two terminals by means of a chemical reaction. Each battery consists of one or more units, called **cells**. The cell contains electrolytes that take part in the chemical reaction. Most people simply classify batteries into wet and dry. Strictly speaking **dry batteries** do not exist, for the simple reason that if the electrolytes were totally dry they could not operate! However, electrolytes may be in a jelly form, or semi-solid, which makes the battery appear to be dry.

Batteries are made from either primary or secondary cells. Primary cells use a non-reversible chemical process and once their chemicals are used up, they are discarded. Every "dry" primary battery has two structures called electrodes. They are made from different kinds of chemically active materials. An electrolyte placed between them promotes a chemical reaction, known as electrolytic dissociation. The result of the electrolytic dissociation is that one of the electrodes, called an anode becomes negatively charged, and the other one, called a cathode becomes positively charged. The construction of the dry cell is shown in Figure. 1.14.

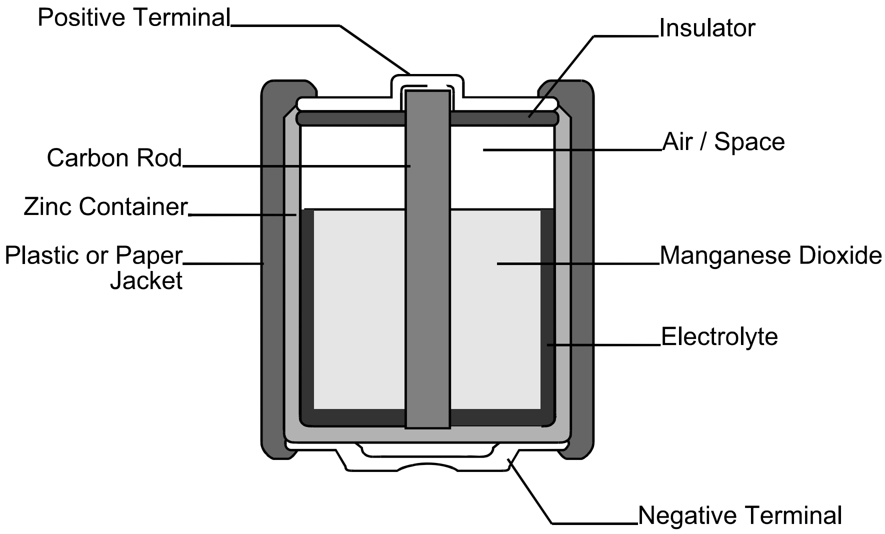

Figure 1.14
Structure of a Dry Cell

Depending on what material the anode and the cathode are made from, dry batteries are classified into three main groups:

- **Carbon/zinc cells**. These are primarily used as general-purpose batteries in radios, torches, toys etc. A carbon rode in the center of the cell functions as a cathode. A sheet of porous material, soaked in the electrolyte separates the anode and the cathode from each other. The electrolyte is a paste, comprising zinc chloride, ammonium chloride and water.
- **Alkaline cells**. The construction of alkaline cells is similar to that of the carbon/zinc cells. The basic difference is that the electrolyte is made from a strong alkaline solution, called *potassium hydroxide*. This compound conducts electricity better, than that of the carbon/zinc cells. This feature enables the alkaline cell to deliver sustained higher level of current more efficiently. For this reason, alkaline batteries are an ideal source of energy for portable TVs, cassette players and electrical toys that require high level of current. They are more economical than the carbon/zinc batteries and last up to eight times longer.
- **Mercury cells**. They have a cathode of mercuric oxide, an anode of zinc and an electrolyte of potassium hydroxide. They produce voltage of 1.4 V, instead of 1.5 V as with the other type of cells. The advantage of the mercury cell is that their voltage remains stable, while that of the other primary cells declines, during use. This feature makes them suitable for use in sensitive devices, such as scientific instruments or hearing aids.

Secondary cells have a chemical structure, which can change between two states. Passing a current through a secondary cell in the opposite direction to its normal discharge current reconstitutes the electrolyte back to its original form. The most common types of secondary batteries are:

- **Lead/acid storage batteries.** They comprise of a hard rubber or plastic container that holds three or six cells. Each cell has two sets of electrodes. The frames of the electrodes, called grids are made from antimony-lead alloy. The electrolyte is sulfuric acid and water. Lead/acid batteries are widely used to produce current in cars and trucks. They also provide emergency electricity for vital facilities, such as hospitals or sewage-treatment plants.
- **Nickel/cadmium (NiCd) storage batteries.** They operate on the same principle as the lead/acid batteries. The main difference is that the electrolyte is a solution of potassium hydroxide and that the anode and the cathode are made respectively from cadmium and nickel oxide. The chemical composition of nickel/cadmium batteries allows them to be sealed. This prevents the corrosive solution from leaking and makes these batteries suitable for use in portable electronic equipment and many other applications. Nicad batteries are reliable, inexpensive and can deliver plenty of electrical current. On average, they can be re-charged about 1,000 times. Their main drawback is that they suffer from an effect called the **memory effect**. It occurs when the battery is not fully discharged every time when it is used. Then the battery "forgets" its full capacity rate, and "remembers" only the capacity rate, for which it was lastly used. For example if a Nicad battery is repeatedly used only at 20% of its maximum capacity, then it is unable to deliver its maximum capacity current over the rated time. When the 20% discharge point is reached, its voltage drops sharply. This makes 80% of battery's capacity unusable. The process of draining over 50% of the rated capacity from the battery, and then recharging it in a normal way is called **deep cycling** and is used to overcome the memory effect. Another disadvantage of Nicad batteries is that they discharge internally at the rate of 15% per month.
- **Nickel Metal Hydride (NiMH) storage batteries**. These batteries were first introduced to the market in 1991. They also can be re-charged about 1,000 times, but are much lighter than Nicad batteries and are capable of storing larger charge. NiMH batteries also suffer from the memory effect and discharge internally at the rate of 25% per month.
- **Lithium-ion (Li-ion) storage batteries**. They were first introduced to the market in 1994. These are the most powerful of all. They can be re-charged over 1,200 times, do not suffer from memory effect, and their rate of internal discharging is only 8% per month. Li-ion batteries are

four times more expensive than Nicad batteries and twice as expensive than NiMH batteries. At present, their main application is as a backup power supply for portable computers.

A constant-voltage charger or a constant-current charger may be used to charge batteries. For alkaline batteries, a constant-current charger is preferred, as it is more effective in correcting the memory effect. There are three main methods to charge a battery:

- **Fast charge** is used for emergencies only. It lasts about 1 hour. The battery is charged at its full rate. For example, a battery rated at 20 ampere/hours will be charged at 20 amperes for 1 hour.
- **Normal charge** is used for most cases and lasts 5 hours. For example, the same battery, mentioned above will be charged at 4 amperes for 5 hours.
- **Slow rate** is done for 10 hours. Therefore, the same battery, mentioned at the previous two examples will be charged at 2 amperes for 10 hours.

1.4.2 Alternating Current

The direct current flows in one direction only. Conversely, alternating current (ac) constantly reverses its direction. The same rule applies for the ac voltage. To generate and to transmit ac is much easier and cheaper than dc. Furthermore, it is much easier to transform ac into dc, than vice versa. For these reasons, dc voltages are more widely used. The domestic supply voltage in most countries, including Australia is 240 volts ac. Some other countries use mains of 220 V or 110 V, but it is always an ac.

To learn more about the alternating current first we have to know more about the sine wave, as this is the basic waveform, from which all other waveforms can be derived. It is known that if a magnetic flux cuts a conductor, an emf is induced in it. Figure 1.15 illustrates a conductor, which is rotating in a homogenous magnetic field at a constant speed.

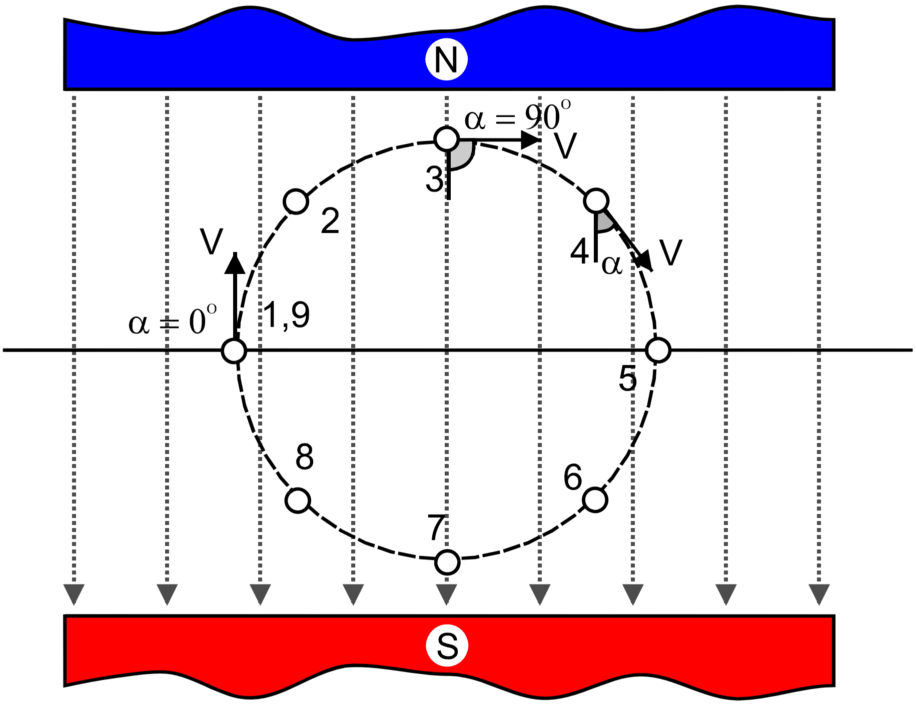

Figure 1.15
Generating Sine emf

Because the magnetic flux cuts the conductor, an emf is induced in it. Its magnitude is:

$$\mathbf{e = B\,l\,v}$$

where:

e is the emf, induced across the conductor,
B is the flux density,
l is the conductor's length,
v is the conductor's speed.

On the other hand:

$$\mathbf{v = v_r \sin \alpha}$$

where:

v_r is conductor's speed of rotation,
sin α is the angle between the speed (v) and the magnetic flux (B).

Substituting this expression in the original formula gives us the equation for the sine wave:

$$\mathbf{e = B\,l\;v_r\;\sin\alpha}$$

The conductor is rotated with a constant speed, and the angle α is changing gradually from 0° to 360°. In fact, the angle α is the only parameter in the formula that is changing with time. The flux density, the conductor's length and the speed of rotation remain constant. For this reason the induced emf is also changing constantly and gradually, following the changes in the angle α. It is not difficult to see that the emf reaches its peak value when α = 90° (at positions 3 and 7) and has a value of zero when α = 0° (at positions 1, 5 and 9). Every time the conductor crosses the "neutral line" (the line connecting positions 1 and 5), the direction of induced emf is changed. In Figure 1.16, the values of the emf for one full rotation are plotted on a diagram against the time.

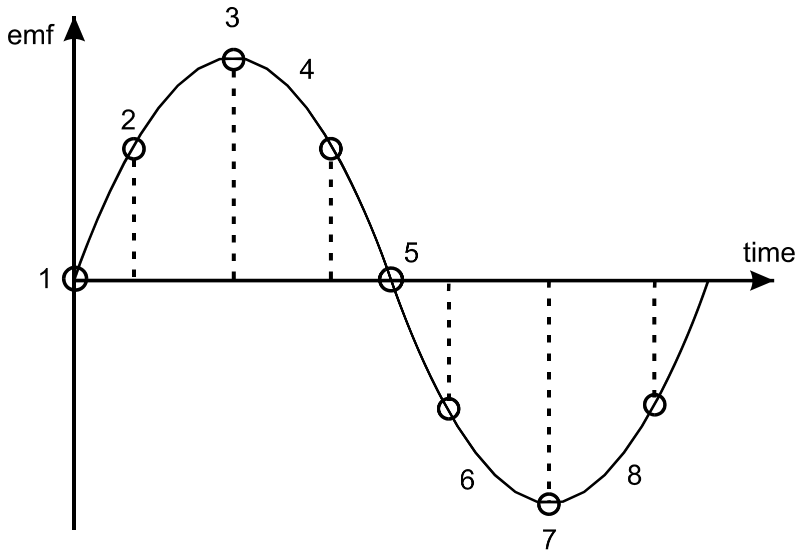

Figure 1.16
Sine Wave

In practice, it is better to use not one but two conductors, connected in series and forming a **loop**. This is illustrated in Figure 1.17. When the loop is in a horizontal position the motion of each conductor in this instant is parallel to the direction of the magnetic field. Therefore no flux lines are being cut by both conductors, and no emf is induced in them. The total emf in the loop is zero volts, and no current flows through it.

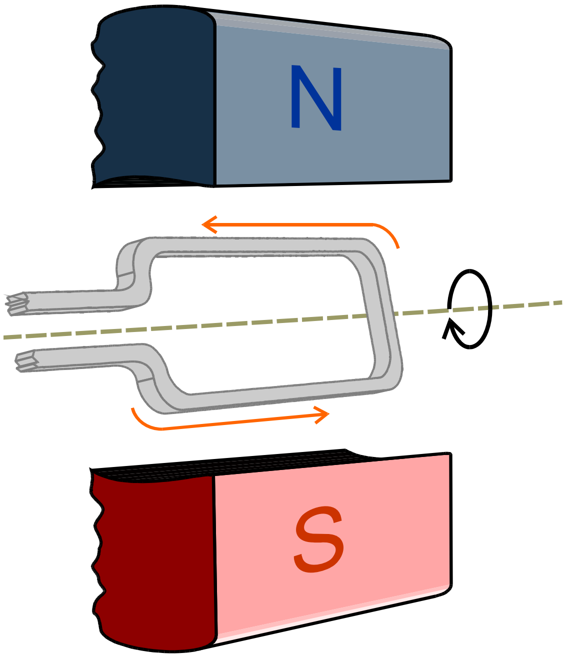

Figure 1.17
Generating Sine emf in a Loop

As the loop starts rotating, it starts cutting some flux lines. An emf is being induced in both conductors. However, because they are influenced by opposite poles (one is closer to the north pole, and the other is closer to the south pole), the emf induced in them are with opposite polarities. The loop represents two conductors, connected in series. When two conductors are connected in series, the total induced emf is the *sum* of the electromotive forces induced in each one of them. This can be expressed with the formula:

$$\mathbf{e_L = 2\,B\,l\,v_r \sin\alpha}$$

where:

e_L is the total emf, induced in the loop.

In continuing its rotation, the loop reaches the vertical position. At this instant, the motion of the conductors is perpendicular to the magnetic field. Therefore each conductor cuts a maximum number of flux lines. The emf, induced in each conductor reaches its maximum value. The total emf at this instant reaches its maximum value, and subsequently the current in the loop is also in its maximum.

From here onwards, the total emf decreases in the same manner, until the loop reaches the horizontal position. In this instant, the current stops flowing. The loop continues its rotation and the emf is induced again. This time the conductor that was previously closer to the north pole is now closer to the south pole. The opposite is true for the other conductor. This means that the total emf now has a reversed polarity and the resulting current will flow in the opposite direction through the loop.

This reversed polarity emf reaches its peak value, when the loop comes again into a vertical position. After that, it decreases and becomes zero, when the loop reaches again a horizontal position. This process can be constantly repeated, and results in producing an emf, with a waveform, called a **sine wave** (Figure 1.16).

1.4.3 Period and Frequency of Sine Waves

From the processes, described in the previous section, it becomes clear that the value and the direction of the alternating current are changing continuously. Here are some characteristics that describe these changes:

- **A period** is the smallest interval of time taken for the sine wave to complete one full cycle. When the cycle is completed, the sine wave begins to repeat the quantities of the current in the same sequence. For example, let us take the maximum positive value of the sine wave as a starting point. The smallest time taken for the sine wave to revert back to the maximum positive value, is called the **period** of this sine wave. After that, the sine wave begins to repeat the same values in the same sequence. A period is designated with the letter **T**, and is measured in seconds. Figure 1.18 shows a waveform with a period of 20 ms.

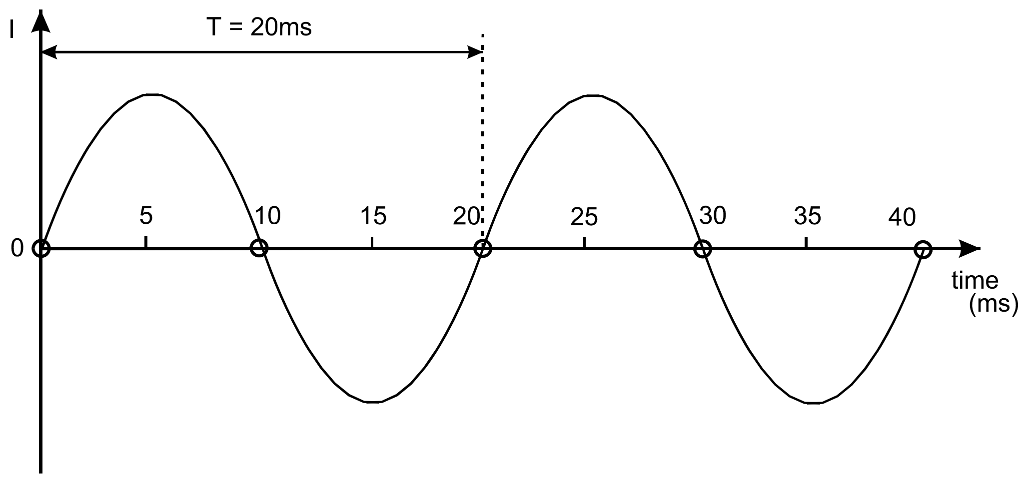

Figure 1.18
A Period of a Sine Wave

- **The frequency** is designated with the letter **f** and depends on the number of periods, contained in one second. Their reciprocal relationship can be described with the formula:

$$\mathbf{f = \frac{1}{T}}$$

where:

f is the frequency of the sine wave,
T is the period of the sine wave.

Frequency shows the number of full cycles that occur in one second. The unit of frequency is cycles per second or more commonly known as Hertz (Hz). If a sine wave makes only one full cycle per second its frequency is 1 Hz.

It is not difficult to calculate, using the formula above, that the sine wave in Figure. 1.18 has a frequency of 50 Hz. This is the frequency of the mains voltage in most countries around the world, including Australia. In the USA the standard is 60 Hz.

1.4.4 Sine Wave Values

The period and the frequency of a sine wave are related to time. The voltage and current measurements are also important. They are measured on the vertical graph and can be expressed in a number of ways:

- **Peak value.** The peak value of a sine wave is the maximum value that the current or the voltage reaches with respect to zero. The polarity is not important, because the negative and the positive peak should have identical values. Peak values are designated V_p and I_p for peak voltage and peak current respectively. Figure 1.19 shows peak values.

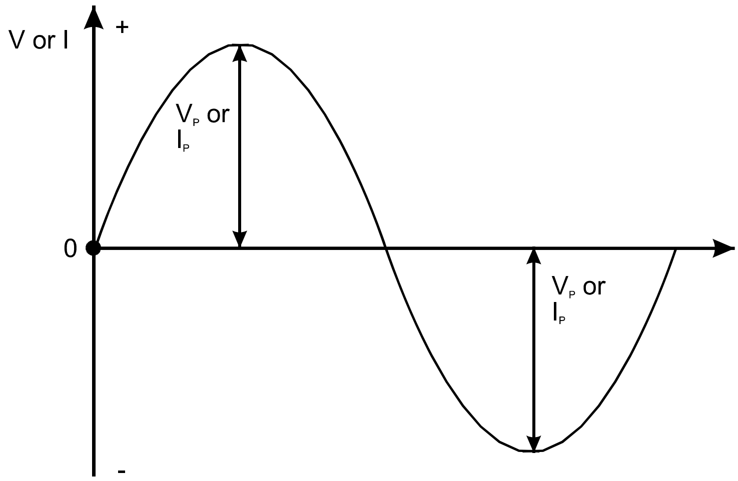

Figure 1.19
Peak Values

- **Peak–to-peak value.** This is the voltage or the current, measured between the positive and negative peak of the waveform. Obviously, the peak-to-peak value is two times greater than the peak value. The peak-to-peak value is shown in Figure 1.20. These values are most commonly used when taking measurements with oscilloscopes. This is discussed further in Section 6.3.7.

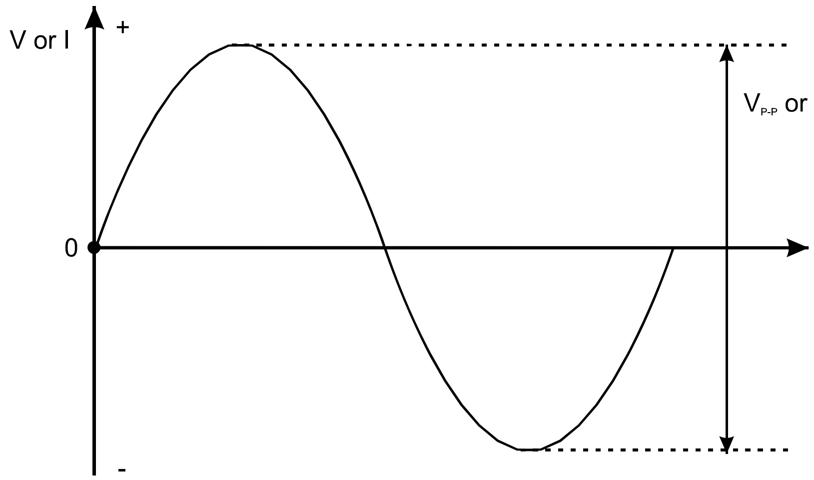

Figure 1.20
Peak-to-Peak Values

- **Average value.** Normally the average value of a sine wave is zero. During the first half-period the electrical current transfers electrical charges in one direction through the conductor. Then, during the second half-period the current transfers the same amount of charges in the opposite direction. Therefore, the net charge transferred is zero. For this reason, the average value of a sine wave is calculated for a half-period (half-cycle) only. The polarity of the half-cycle is not important and the average value could be calculated for either one of the half-cycles. Figure 1.21 shows the average value graphically.

The area enclosed from the positive half-period represents the amount of electrical charges transferred through the conductor for this half-period. Let us assume that the area enclosed from the positive half-period is equal to the area of the rectangular ABCD (see Figure 1.21). The area enclosed from the rectangular ABCD represents the same amount of electrical charges, transferred for the same time, through the same conductor, but as if a direct current with a magnitude, equal to AB flows through it. The energy dissipated, and the work done from the alternating current will be equivalent to the energy dissipated and the work done from the direct current.

Therefore, the average value of a sine wave is equal to the value of a direct current, which for the time of a *half-period* transfers through the conductor the same amount of charge as the alternating current. Through mathematical calculations that go beyond the scope of this manual, it is possible to prove that the relationship between the peak value and the average value is as follows:

$$I_{av} = \frac{2Ip}{\pi} = 0.637Ip$$

$$V_{av} = \frac{2Ip}{\pi} = 0.637Vp$$

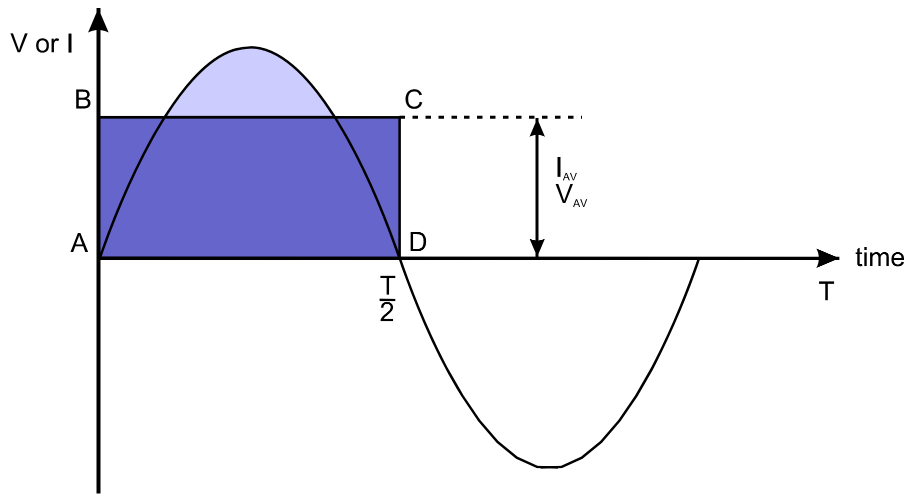

Figure 1.21
Average Value

- **Root-mean-square value (rms).** An alternating current flowing through the load (for example a heater or a stove) has a heating effect. The produced amount of heat does not depend on the current's direction. Let's assume that the amount of heat, produced from an alternating current for 1 second is equal to Q. It is possible to find out a source of a direct current, producing the same amount of heat, equal to Q for the same time. Therefore, the root-mean-square value can be defined as equal to the value of the direct current, producing the same amount of heat, in the same load, for the same time, as an alternating current. The formula describing the relationship between the rms and the peak value is given below:

$$I = \frac{Ip}{\sqrt{2}} = 0.707Ip$$

$$V = \frac{Vp}{\sqrt{2}} = 0.707Vp$$

These formulae can be proved mathematically, but this will not be developed here. The rms is the value read from the voltmeters or the ammeters, as you will see in Chapter 6. In electronics, all specified values are given in root-mean-square values, unless specifically written otherwise.

1.4.5 Summary

An electric current can be either direct (dc) or alternating (dc). The direct current flows all the time in one direction only. The alternating current constantly reverses its direction. A battery is the most common source of direct current. Batteries are made from either primary or secondary cells. Primary cells are discarded, once their chemicals are used up. Secondary cells can be charged and used repeatedly. The basic waveform of an alternating current is the sine wave. A cycle of a sine wave is a sequence of values in a certain order, after which the sine wave begins to repeat them in the same order. The period of a sine wave is the smallest interval of time, taken for the wave to complete one full cycle. The frequency of a sine wave is the number of full cycles that occur for one second. The sine wave values are described with peak, peak-to-peak, average and root-mean-square (rms) values. In electronics, all specified values are rms, unless specifically written otherwise.

1.4.6 Quiz

1. What is the main difference between a direct and an alternating current?
2. What is the name of the process that creates a potential difference in the battery?
3. What type of dry battery produces the most stable voltage over time?
4. What is the memory effect and how can it be overcome?
5. Describe three methods for a full constant-current charge.
6. What formula describes the sine wave?
7. What has to be done in order to generate a sine wave with a higher frequency?
8. What is the peak value of the voltage for the domestic power supply in Australia?

1.5 Units and Abbreviations

Every science has its own unique language. Electronics is no exception. In this manual, some of the most common definitions and abbreviations are given in the text, where they appear first. To learn more definitions and abbreviations you should consider buying an electronic dictionary. They are available in most specialized bookshops and in most cases are excellent value for money.

Most countries in the world, including Australia, use the international system of units, called *Systeme International d'Unites*, known simply as SI. This system is discussed in details in Section 6.1.1. The common electric terms, according to SI have the following symbols and units:

Item	Symbol	Unit	Symbol
Current	*I*	*Ampere*	*A*
Voltage	*V*	*Volts*	*V*
Charge	*Q*	*Coulomb*	*C*
Energy	*W*	*Joule*	*J*
Power	*P*	*Watt*	*W*
Resistance	*R*	*Ohm*	*Ω*
Resistivity	*ρ*	*Ohm.Meter*	*Ω.m*
Reactance	*X*	*Ohm*	*Ω*
Inductance	*L*	*Henry*	*H*
Capacitance	*C*	*Farad*	*F*
Frequency	*f*	*Hertz*	*Hz*
Time	*t*	*Second*	*s*

Table 1.1
Common Electronic Units

IDC TECHNOLOGIES PTY LTD

AUSTRALIA
West Coast Office
982 Wellington Street, West Perth, WA 6005
PO Box 1093, West Perth, WA 6872
Telephone: (08) 9321 1702 • Facsimile: (08) 9321 2891

East Coast Office
PO Box 1750, North Sydney, NSW 2060
Telephone: (02) 9957 2706 • Facsimile: (02) 9955 4468

CANADA
103-8080 Anderson Road, Richmond, B.C. V6Y 1S4
Telephone: (1 604) 244 9221 • Facsimile: (1 604) 278 6260
Toll Free: 1-800-324-4244

NEW ZEALAND
Parkview Towers, 28 Davies Avenue, Manukau City
PO Box 76-142, Manukau City
Telephone: (09) 263 4759 • Facsimile: (09) 262 2304

IRELAND
PO Box 6078, Dublin 1
Telephone: (01) 473 3190 • Facsimile: (01) 473 3191

SINGAPORE
100 Eu Tong Sen Street, #04-11 Pearl's Centre, Singapore 059812
Telephone: (65) 224 6298 • Facsimile: (65) 224 7922

SOUTH AFRICA
13 Adele Road, Willowild 2196
PO Box 785640, Sandton 2146
Telephone: (011) 789 6257 • Facsimile: (011) 789 6499
Toll Free: (0800) 114 160

UNITED KINGDOM
46 Central Road, Worcester Park, Surrey KT4 8HY
Telephone: (0181) 335 4014 • Facsimile: (0181) 335 4120

UNITED STATES
7101 Highway 71 West #200, Austin TX 78735
Telephone: (1 512) 288 8525 • Facsimile: (1 512) 288 8521
Toll Free: 1-800-324-4244

Web Site: http://www.idc-online.com
E-mail: idc@idc-online.com