# CHAPTER 23

# Electronics

## INTRODUCTION 23.1

It was seen in the previous chapter that electricity is very important in modern society. Electronics is a relatively new branch of general electrical studies, which makes use of small-scale components and circuits. The development of electronics in the latter half of the twentieth century has led to many of our modern consumer electrical products and technology. Unlike the general use of electricity that dates back well over 150 years, modern electronics has expanded only since the invention of simple semiconductor devices in the early 1950s. The improvement in understanding of solid state physical devices has made possible micro-miniaturisation and very fast electronic circuit operations. These features are the basis of modern computer technology and the real start of what has been termed the 'information age'.

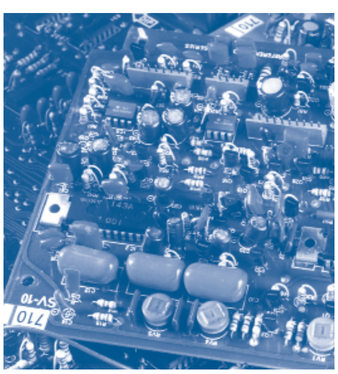
Electronic engineering today involves the use of many thousands of specialised components and circuits that have all developed from the early discoveries in semiconductor solid state physics. In this chapter we will look specifically at a set of basic electronic circuit components and their behaviour. It is from this basic set of components that electronic systems can be developed. This will be further discussed in Chapter 24. At the completion of this chapter, you will be able to answer questions like the following:

- Why do we have portable batteries but still need household electricity supplies?
- What is the difference between DC and AC voltages and currents?
- Is colour-blindness a problem for people working in electronics?
- How can some electronic devices be made so small that they can hardly be seen?
- Are electronic circuits, especially those of larger devices like TV sets and computers, really as complex as they look?

## MEASUREMENT AND TEST INSTRUMENTS 23.2

### Multimeters

**Photo 23.1**
Electronic circuit boards.



In the previous chapter, the basic electric measurement meters called the voltmeter and the ammeter were introduced. These instruments are most often used in fixed circuit applications or as stand-alone instruments to give a continuous voltage and current reading. In practical electronics a more versatile and portable measurement instrument is required. This is the **multimeter**. Its readout can be an analog needle over a scale or, more usually, a digital display readout. (See Photo 22.4 on page 483.) Modern multimeters provide numerous measurement quantities over a wide range of values, such as DC/AC voltage, DC/AC current, resistance and conductivity testing, frequency, diode conductance and capacitance. Unlike the older analog models which required the correct range of the quantity to be selected via a selector switch, newer digital models are often **auto-ranging**, which means that the input circuitry automatically senses the correct measurement range and produces an output that matches this range. For example, without altering the instrument, apart from selecting AC voltage, a technician is able to measure millivolts AC in a radio circuit, through to household domestic 240 volt AC mains.

It is always important to be aware of the measurement being made with a multimeter and check both the quantity being measured and the approximate range of the values before making any connection to a circuit. In any unknown measurement exercise it is good protection policy to select the instrument's highest scale setting and then adjust downward until an appropriate instrument scale reading is achieved. It is also often necessary on some multimeter models to adjust the input probe connectors on the face of the instrument and move them to different sockets when changing from low values to high values. The manual that comes with the multimeter will explain this. Recall also from the previous chapter that any measurement instrument should affect the circuit under test as little as possible. Especially with analog multimeters, this means that the instrument's **sensitivity range** should be as high as possible, with a value of 20 kΩ/V being regarded as the most useful in professional electronic measurement. Digital multimeters have the advantage that their sensitivity range is already very high due to the electronic integrated circuit components that comprise the internal circuitry.

When using a multimeter to measure either DC or AC voltage, the probes should be placed in parallel or across the component in the circuit in exactly the same way as a conventional voltmeter. When using a multimeter to measure either DC or AC current, the probes will need to be placed in series with the component, as with a conventional ammeter. This may necessitate disconnecting one end of the component from the circuit and using the multimeter probes to remake the connection. When using a multimeter to measure resistance, it is often necessary, especially on analog models, to re-zero the meter. This means shorting the probes together and using the 'ohms adjust' knob to make sure that the needle of the multimeter actually reads zero resistance. There is a variety of different multimeters and it is always important to read the manual properly and take care in operating the instrument.

**Photo 23.2**
CBL2 data-logger.

## Data-loggers and sensors

You may be lucky enough to have the use of a set of measurement instruments that could make the automatic measurement of electrical and other physics quantities very easy. This is the laboratory **data-logger**; when coupled with electronic or other sensors and connected to a graphics calculator, this allows not only the recording of data over time intervals from milliseconds to months, but also the analysis of that data almost immediately. Common sensors such as current and voltage probes allow normal electrical circuit quantities to be logged, but a range of non-electrical attachments such as accelerometers, pressure sensors, temperature probes and rotation sensors allow an even greater range of physics measurements in your experiments. Photo 23.2 (a) shows an example of the Texas instruments CBL2 data-logger connected to the TI-83 Plus graphics calculator and sensors.

**Photo 23.3**
Power supplies.


## Power supplies

A bench-top **power supply** is needed for electronic testing as it supplies the necessary DC/AC operating voltages for the components and circuit under test. Quite often these power supply units in the laboratory are referred to as power packs or rectifiers. How they are constructed will be further discussed in Section 23.6 and Chapter 31. One of the most important considerations in the use of bench-top power supplies is to avoid the voltage connector leads, the positive, negative or the AC leads, coming into contact and short-circuiting. Not only will this usually produce dangerous sparking, but the power supply itself may be damaged. The short circuit created will generally exceed the maximum current rating for which the power supply is designed and internal damage may occur if the unit is not fuse-protected or does not contain some form of current overload circuit-breaker. It is also important that you check that the voltage settings on the power supply are as low as possible before turning the instrument on. In general, changes made to any electrical circuit should only be made with its power supply connections turned off. This avoids very high voltage transient spikes from causing possible damage to the circuit components under test.

# Cathode ray oscilloscope

**Figure 23.1**
Cathode ray tube assembly.

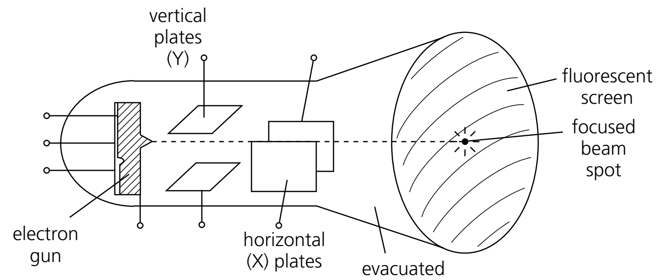
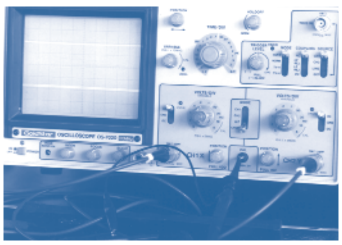
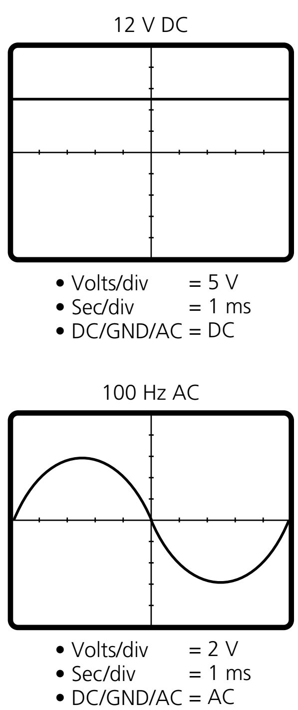



**Photo 23.4**
A dual beam oscilloscope.



Invented in 1897 by a German physicist, Karl Ferdinand Braun, the **cathode ray oscilloscope** (CRO) is an instrument used widely in electric and electronic circuits to display and make measurements on voltage waveforms. The CRO uses a very fast electron beam striking the face of a **cathode ray tube** (CRT), which is being deflected by rapidly changing magnetic and electric fields. The moving electron beam passes over the calibrated scale on the face of the CRT and allows measurements of voltage wave shape, amplitude and frequency. As well, it allows a simple visual inspection of the way the voltage may vary under different circuit settings. Within the evacuated cathode ray tube, an electron gun emits a narrow beam of electrons, which travel down the tube and strike a fluorescent screen at the front. Light is emitted and a bright spot is formed on the screen. (See Figure 23.1 and Photo 23.4.) This electron beam passes through a set of vertical deflection plates carrying a voltage proportional to the input voltage being measured. This can be expanded by the use of the 'vertical gain' control. At the same time the beam passes through a set of horizontal deflection plates across which is placed a regularly changing **timebase voltage**. The timebase voltage can be selected by a control on the front of the CRO and allows the user to set the time the beam takes to sweep from one side of the screen to the other. This is called the **sweep time** and can vary from microseconds to seconds. The combination of **vertical amplifier gain** and timebase produces a moving spot that perfectly matches the input voltage being tested, with vertical scale divisions representing voltage amplitude and horizontal divisions representing time. Figure 23.2 represents a typical CRO tracing for a constant DC voltage of 12 V as well as a 100 Hz sine wave AC voltage if the timebase is set to one millisecond.

**Figure 23.2**
CRO tracings.




Some of the common controls on a typical oscilloscope instrument are:

- Intensity and Focus — these controls allow the brightness of the electron beam as well as the spot sharpness to be adjusted on the screen.
- Channels A and B — these are the connector points for the input probes. Each probe usually has a ground clip as well as the test clip, so that the input signal can be measured with respect to the ground or zero potential. On dual-beam or dual-trace oscilloscopes, two separate voltage signals can be connected and displayed on the respective A and B inputs.
- Horizontal and Vertical positions — these controls allow the overall positioning of the spot or trace to be adjusted. For convenience, especially on dual-beam oscilloscopes, two separate voltage waveforms may need to be adjusted horizontally or vertically so that they can be more easily compared. There are separate controls for each channel.
- Volts/div — this stands for volts per 1 cm division in the vertical direction. This is the vertical amplifier gain control and allows the complete input waveform to be displayed no matter what its amplitude might be.
- Sec/div — this stands for seconds per 1 cm division in the horizontal direction. This is the timebase horizontal deflection adjustment. The selector switch will set the time interval representing each horizontal division.
- Trigger level — this setting determines the point at which the beam begins its sweep across the screen. It allows synchronisation of the sweep timebase waveform and the input test waveform so that the signal trace is stable on the screen and does not drift about. The trigger may be either an internal instrument signal or an external signal.
- DC/GND/AC — this selector switch is set to the type of input waveform being measured. For example, if set to AC, any DC component of the input test voltage signal will not cause extra vertical deflection.

## AC waveform analysis

Consider Figure 23.3, which illustrates the voltage waveform as seen on an oscilloscope connected across resistor R. In the DC case the voltage waveform is easily described as a single fixed voltage; however, in the AC case there exist several alternatives in describing the magnitude of the voltage. Note that in the AC case, the frequency of the waveform would almost certainly be 50 Hz as supplied by any standard power supply.

Whereas direct current (DC) only flows in one direction, alternating current (AC) reverses direction at a given frequency as determined by the alternating voltage. Often the AC voltage can be mathematically described as a sinusoidal voltage (sine wave) represented by the expression:

$$V = V_0 \sin\omega t = V_0 \sin(2\pi f)t$$

where $V$ = instantaneous voltage; $V_0$ = voltage maximum; $f$ = frequency; $t$ = time.

Let us look carefully at the methods of describing the AC waveform magnitude or amplitude. It is obvious that the average of all instantaneous voltage points over one complete AC cycle will be zero volts, as the positive area equals the negative area if the waveform is perfectly symmetrical about the zero axis. One method called the **peak voltage**, $V_P$, is to read the scaled vertical amplifier from the zero axis up to the top of the sine wave. In Figure 23.3, if the vertical amplifier was set at 5 volts/div then the reading would be $V_P$ = 10 V. A second method is to record the **peak to peak voltage**, $V_{PP}$, off the vertical amplifier scale from the top of a crest to the bottom of a trough. Thus $V_{PP} = 2V_P$ = 20 V. The most common method is to employ the reading known as the **root mean square voltage**, $V_{RMS}$.

It can be shown mathematically that:

$$V_{RMS} = \frac{V_P}{\sqrt{2}} = 0.7\ V_P$$

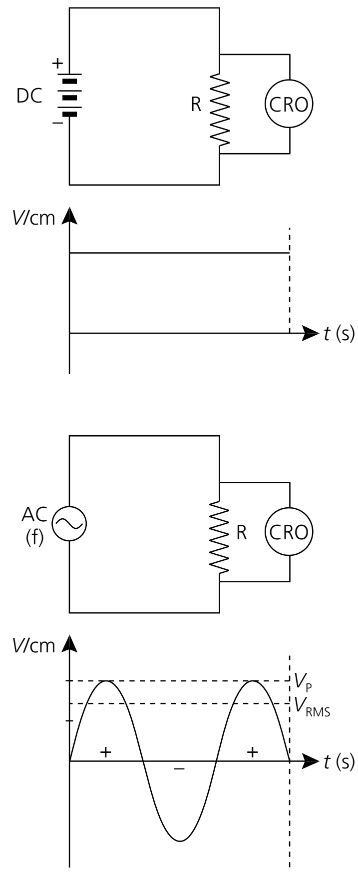
In the AC waveform of Figure 23.3:

$$V_{RMS} = \frac{10}{\sqrt{2}} = 7.07\ V$$

The reason why the $V_{RMS}$ method is most often used to describe AC voltages is that the average power dissipated in a resistor by any RMS voltage over one complete cycle will be identical to the power dissipated in the same resistor by an equivalent DC voltage. In terms of resistive electrical power dissipation, $V_{RMS}$ (AC) = $V_{DC}$ and thus a method of direct comparison is obtained.

An AC voltmeter or multimeter set to read AC voltage will usually display its output directly on an RMS scale. An oscilloscope will most conveniently display the waveform as a measured $V_P$ or $V_{PP}$ value. In some electronic circuits, the actual voltages present at particular points as viewed on an oscilloscope will often contain both DC and AC components. In these instances, the oscilloscope can be used to measure the DC offset voltage as well as the RMS ripple voltage.

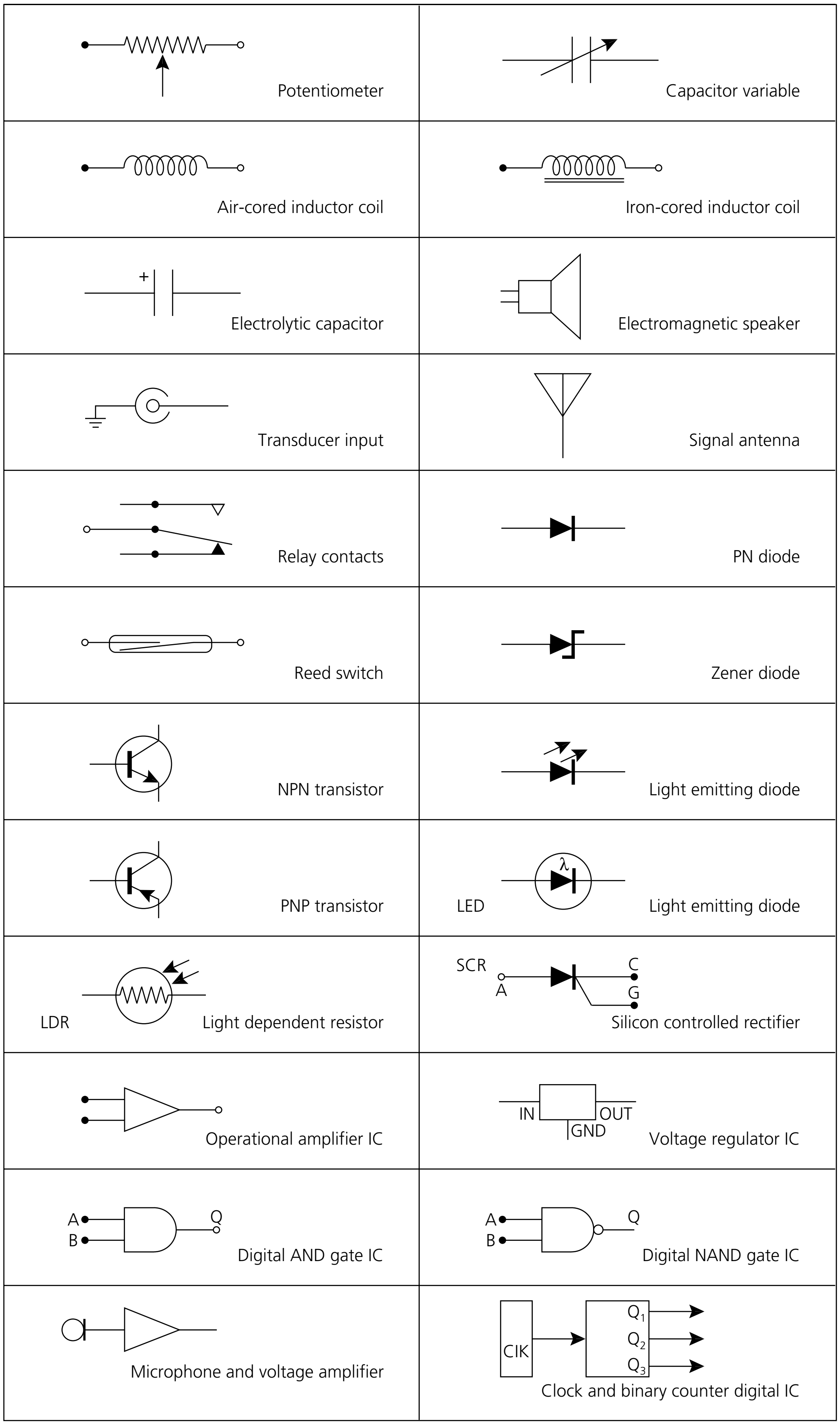
**Figure 23.3**
AC waveform analysis.




## Circuit symbols

Recall that in the previous chapter in Figure 22.19, several electric circuit symbols were introduced. At this point it would be appropriate to introduce a further set of specific electric circuit symbols for devices that will be met from this point onward. Any table such as this can never be complete and reference to other textbooks and electronics magazines will build up your knowledge and ability to recognise a large number of electronic circuit symbols. (See Figure 23.4.)

**Figure 23.4**
Electronic circuit symbols.



## 23.3 RESISTORS IN ELECTRONICS

At this point it would be useful to revise the basic properties of resistance, as described in Section 22.4. In this chapter we will look closely at the practical **electronic resistor** component and its uses. Resistors are simple devices used to control the flow of electric current as well as act in voltage divider networks. Resistors are generally of two types: fixed and variable. They differ considerably in physical size due to the total electrical power they are required to dissipate in a circuit. A resistor dissipates energy when a current flows through it and the resistor consequently heats up. It must be able to lose this heat energy to the air or cooling elements without being damaged. The rate of energy dissipation, or its power rating, is determined by its physical size and shape. The greater the resistor's surface area, the greater is its **power rating**. Commonly in electronics, manufacturers mass-produce resistors that are able to dissipate one-quarter watt ($\frac{1}{4}$ W) and ($\frac{1}{2}$ W), (1 W) or (5 W). Resistors made from wire-wound elements are able to dissipate even greater power. When used in electronic circuits, the power rating of a resistor must exceed its actual operating power dissipation, otherwise physical burn-out will occur — a possible cause of electrical fires in poorly designed electronic devices.

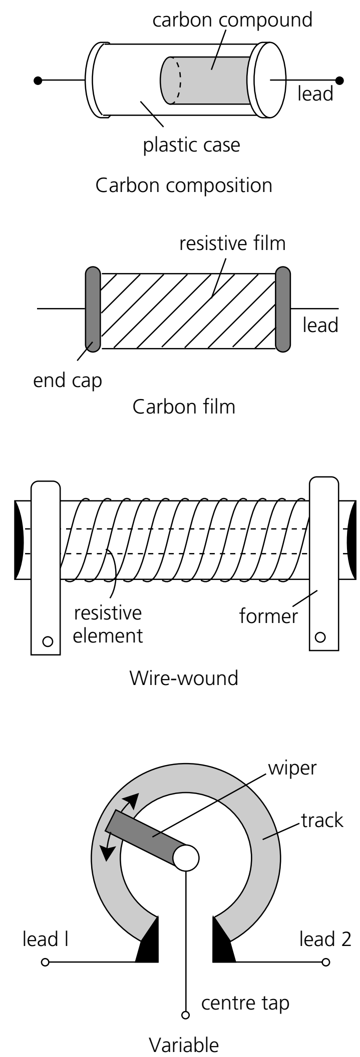



**Figure 23.5**
Resistor types.

### Example

In a simple DC circuit, with a voltage supply of 9 V, what value series resistor will limit the current flow to 90 mA? What is this resistor's power rating in the circuit and what would be the best resistor type to purchase for the circuit construction?

### Solution

Given $V = 9$ V, $I = 90 \times 10^{-3}$ A, and using:

$$V = I \times R$$
$$9 = 90 \times 10^{-3} \times R$$
$$R = 100\ \Omega \text{ as the value of the resistor}$$

Power rating $P = V \times I$, $P = 9 \times 90 \times 10^{-3} = 0.81$ W.
Hence the best resistor would be a 100 Ω, 1 W type.

## Fixed resistors

In electronics, resistors are usually made of some form of carbon mixture. The simplest type of resistor is the **carbon composition** resistor, made of finely divided graphite carbon mixed with a powdered insulating medium such as crushed clay in a defined proportion. This mixture is pressed into a plastic case with two connector leads embedded into the mixture and supported by the case (Figure 23.5). A more recent construction is the **carbon film** resistor in which a graphite carbon film is deposited on the outside of a ceramic rod. A spiral pattern is wound around the rod so that the effective length of the resistor film is often considerably longer than the rod itself. Special metal end caps are welded to the connector leads and pressed over the ends of the rod to complete the electrical path. **Metal film** resistors are similar to carbon film except that the resistive element is made from a metal oxide such as tin oxide. The advantage is that closer tolerance to the stated resistor value in ohms can be maintained, and the oxide film has a much longer lifetime than carbon film; however, they are more expensive to make. A **wire-wound** resistor can be made in which a resistive wire element (nichrome) is wound around a small core called a 'former'. The main advantage with this type is the higher power rating that can be achieved especially if the former is hollow and air- or fluid-cooled. Generally, manufacturers use an outer coating of paint or epoxy compound over the resistor in order to print onto the component the descriptive **colour code** or simple ohmic value, power rating and tolerance percentage. Electronics technicians become quite expert at recognising resistor values directly from their printed colour codes.

## Variable resistors

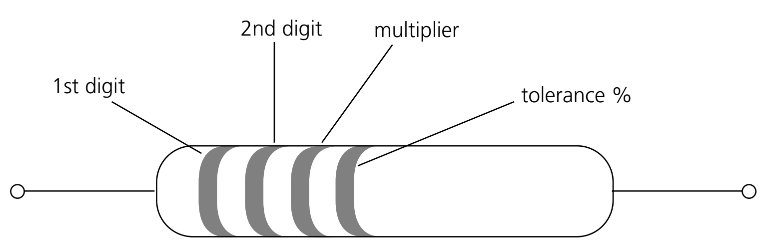
Not all electronic resistors are fixed in value; a host of different types of variable resistors are manufactured. A **variable resistor** is generally a two-terminal device that is used in circuits to vary the electric current flowing; however, three terminal devices called **potentiometers**, or pots, are also common and these are generally used to vary voltage or potential in applications such as volume controls on radios and rheostats in light dimmers. The term 'pot' is now generally used in electronics to describe any variable resistor, no matter what its primary function. The resistive element of these devices usually is either a carbon deposit on an insulating surface, or a resistive wire wound around a suitable former. A moving arm or **wiper** is drawn across the resistive element and connects to a metal contact, with the total resistance of the device changing from zero ohms at one end to the maximum ohms value at the other end.

Often the resistive element design follows a **linear** relationship, where the resistance is proportional to how far the wiper arm has moved, called an A-type pot. In other cases the resistance change is **logarithmic** in nature. This is called a C-type pot and is most often used as a volume control in an audio amplifier as it matches the human ear's logarithmic response to sound volume changes.

## Preferred resistance values and colour codes

All resistors have three basic parameters: wattage, resistance and tolerance or accuracy. Physical size and type determine the wattage. Some manufacturers use a cream body colour for carbon film resistors and a blue or green body for metal film types. Manufacturers use a standardised band colour code printed on smaller resistors where physical lettering is not

**Figure 23.6**
Resistor colour code.




Black - 0
Brown - 1
Red - 2
Orange - 3
Yellow - 4
Green - 5
Blue - 6
Violet - 7
Grey - 8
White - 9

Gold - 5%
Silver - 10%
None - 20%

*Example*
Red Red Green Silver
is
2.2 M $\Omega \pm$ 10%

possible. The resistor colour code illustrated in Figure 23.6 and in the centre colour pages is one of the best known in electronics and with a little practice in reading the code it is easily committed to memory. The coloured bars always start closer to one end of the resistor and this is the bar that is used first in order to deduce the value in ohms of the resistor. If ever there is any doubt about the resistor colour code, then a multimeter should be used to determine a resistor's actual ohmic value.

The bands of the colour code as marked on a resistor give both the ohmic value and its tolerance as follows:

- Band 1 — first figure of ohmic value.
- Band 2 — second figure of ohmic value.
- Band 3 — multiplier for the first two figures.
- Band 4 — tolerance band colours, where brown is 1%, red is 2%, gold is 5%, silver is 10%, and none represents 20%.

Note that some resistors have a five band colour code and in this case the first three bands give the first three digits in the value, the fourth in the multiplier and the fifth is the tolerance.

Because it would be impractical to manufacture every possible value of resistance, there exists a **preferred value** set of resistors used in circuit construction. The most common preferred value range is known as the E12 series (12 values per 100). An E24 series also exists (24 values per 100). These preferred value sets apply to each of nine decade ranges or multipliers from $\times 10^{-2}$ to $\times 10^{6}$ (Table 23.1).

### Table 23.1 RESISTOR PREFERRED VALUE SERIES

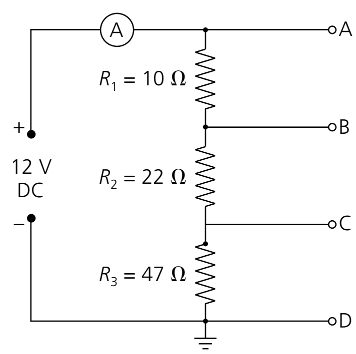
| E12 SERIES (Ω) | | | E24 SERIES (Ω) | | | |
|---|---|---|---|---|---|---|
| 10 | 33 | | 10 | 18 | 33 | 56 |
| 12 | 39 | | 11 | 20 | 36 | 62 |
| 15 | 47 | | 12 | 22 | 39 | 68 |
| 18 | 56 | | 13 | 24 | 43 | 75 |
| 22 | 68 | | 15 | 27 | 47 | 82 |
| 27 | 82 | | 16 | 30 | 51 | 91 |
| *Decades* | | 100–1000 | | | | |
| 0.01–0.1 | | 1000–10 000 | | | | |
| 0.1–1 | | 10 000–100 000 | | | | |
| 1–10 | | 100 000–1 000 000 | | | | |
| 10–100 | | 1 000 000–10 000 000 | | | | |

Thus, any manufactured resistor must begin with a number from the E12 or E24 series and be a multiple from $10^{-2}$ or $10^{6}$. It should be noted at this point that in some resistor applications in electronics, critical values of resistance are not important, as a circuit will often perform quite successfully with anything up to about 20% tolerance in resistor values.

## Resistors as voltage dividers

Recall that the total resistance in series of several resistors is the sum of each individual resistance. If the circuit of Figure 23.7 is set up, the respective voltage drops across each resistor in the series chain can be used as a separate voltage supply. That is, the 12 volt DC supply can be split into three separate voltages, $V_{AB}$, $V_{BC}$, $V_{CD}$. Ohm's law can be used to calculate the respective voltages and maximum currents that can be supplied using such a **voltage divider** circuit. Any electronic device, such as a small motor, connected to any output of the divider cannot draw a very large current compared with that flowing around the divider circuit, otherwise the effect on the voltage divider will be quite large. The general rule is that as the current drawn from a voltage divider circuit increases, the output voltage decreases. Refer to the following example.

**Figure 23.7**
Voltage divider circuit.



### Example

Consider the circuit shown in Figure 23.7. Calculate:

**(a)** the current drawn from the 12 V supply as registered on the ammeter;
**(b)** the value of the voltages $V_{AB}$, $V_{BC}$, $V_{CD}$;
**(c)** the most appropriate connection points for a 3 V, 10 mA motor.

### Solution

Total circuit resistance = $R_1 + R_2 + R_3 = 79\ \Omega$.

**(a)** To calculate the ammeter current, use:

$$I = \frac{V}{R_{tot}} = \frac{12}{79} = 150\ \text{mA}$$

**(b)** To calculate the respective voltages, use:

- Voltage $V_{AB} = I \times R_1 = 150\ \text{mA} \times 10\ \Omega = 1.5$ V.
- Voltage $V_{BC} = I \times R_2 = 150\ \text{mA} \times 22\ \Omega = 3.3$ V.
- Voltage $V_{CD} = I \times R_3 = 150\ \text{mA} \times 47\ \Omega = 7.0$ V.

**(c)** As the required 10 mA maximum is considerably less that the 150 mA flowing through the divider network, the motor will not load the circuit and the most appropriate connection points to operate the motor are voltage $V_{BC}$.

In order to produce a continuously variable voltage divider it is necessary to substitute a potentiometer for the fixed resistor chain. **Volume controls** on a radio or TV work this way, with the potentiometer being a 10 kΩ or 20 kΩ type. The movable wiper of the pot produces a continuously variable output voltage from zero to the maximum available at the divider input. These devices are usually controlling very small voltages and currents present within a radio receiver or small amplifier.

## EI Activity 23.1 TEACHER RESISTANCE

Obtain from your teacher numerous examples of different resistors. Use the colour code to determine their nominal resistance value, or read it directly and compare this with the actual value as determined by a multimeter set to read resistance. Be careful to correctly set the multimeter to its correct range and check that it is zoroed properly by shorting its measurement probes and checking for zero ohms. Use the 'ohms adjust' control if necessary.

## Questions

1. List four different types of electronic test instruments and explain their functions.
2. If the waveform being observed on an oscilloscope is too small and the peaks too close together, explain the adjustments necessary to redisplay the waveform with greater clarity.
3. Convert 15.6 $V_{RMS}$ to a peak to peak value.
4. A resistor of value 470 Ω is required to control a current of 250 mA. What minimum power rating is appropriate? What is its colour code markings?

## CAPACITORS, INDUCTORS AND RELAYS 23.4

Resistors dissipate energy in the form of heat and hence they cannot store energy. Two components that are capable of storing energy in electrical circuits are the **capacitor**, which stores energy in an electric field, and the **inductor**, which stores energy in a magnetic field.

## Capacitors and DC

A capacitor can be likened to a very fast storage tank for electric charges. It consists basically of two conducting plates separated by an insulating material called the **dielectric**. This assembly is often housed in a protective outer coating with either the plates held flat as in a disc, or with the metal foil plates and dielectric rolled up to form a cylinder. In both cases, either via markings or colour coding, the outer casing holds information such as capacitance value, tolerance and working voltage. Connecting leads allow the flow of current to and from the capacitor's plates (Figure 23.8 and Photo 23.5).

According to literature, the first capacitor, called a Leyden jar, was discovered almost simultaneously by Dean von Kleist of the cathedral of Camin in Germany in October 1745, and Peter von Muschenbrock, professor in the University of Leyden, in January 1746. As described by them, it was a glass jar or vial with inner and outer electrodes made of various substances — water, mercury, metal foil, etc. The modern miniature glass dielectric capacitor differs in form and structure from the 250-year-old Leyden jar, but the principle of operation is the same.

If a DC voltage is applied to a capacitor, an electric current will carry charge to the plates, so that one plate becomes positively charged and the other is left negatively charged. When a capacitor is fully charged, several conditions exist:

- There is equal and opposite charge on the plates.
- The voltage across the plates equals the supply voltage, $V_s$.
- An electric field exists within the dielectric.
- Any further flow of direct current (DC) is blocked.

The **capacitance**, $C$, of this system is defined as the amount of charge in coulombs, $Q$, stored on each plate when the potential difference voltage, $V$, across the plates is 1 V. Capacitance $C = \frac{Q}{V}$ is in coulombs per volt; 1 C V$^{-1}$ = 1 farad (F). The unit called the farad is named after Michael Faraday (1791–1867), the great British physicist who was the first to develop the idea of electric and magnetic fields.

Typical capacitors in electronics have values ranging from one microfarad (1 μF) to one thousand microfarads (1000 μF). The capacitance of any capacitor is dependent on the type of dielectric material it contains and, because the dielectric material is usually very thin, all capacitors have a maximum **working voltage** rating. **Capacitor leakage** refers to the amount of charge that is lost during capacitor operation when a voltage is applied across its terminals. Generally with modern electronic capacitors, leakage is not an important factor in circuit design.

Using calculus, it is possible to calculate, in joules, the total energy, $W$, stored in a fully charged capacitor. If $Q$ is the charge stored on each capacitor plate, $C$ is the capacitance and $V$ is the working voltage across the plates, then:

$$W = \frac{QV}{2} = \frac{CV^2}{2} = \frac{Q^2}{2C}$$

Generally capacitors are used in one of three ways in electronic circuits.

- In conjunction with resistors, they can be used in timing circuits, making use of the length of time it takes for a particular voltage across the capacitor plates to appear.
- To bypass or filter rapidly changing AC frequencies and block the flow of DC.
- To eliminate voltage fluctuations arising from the conversion of AC voltage to DC voltage.

These last two applications are further discussed in Sections 23.5, 23.6 and Chapter 31.

## Types of capacitors

Different types of capacitors vary widely in their electrical characteristics. Let's look at the most common types.

**Figure 23.8**
Capacitors: dielectric **(a)**; symbols **(b)**; uncharged **(c)**; charged **(d)**.

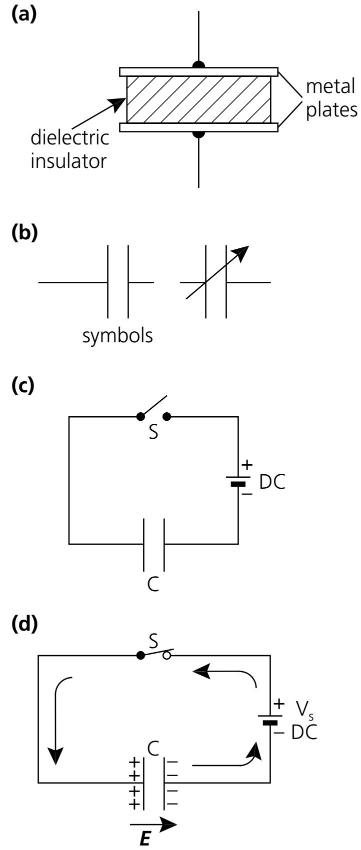



**Photo 23.5**
Capacitors and inductors.

**NOVEL CHALLENGE**

One 'bit' of computer memory consists of a capacitor which stores a half a million excess electrons. In 1970, they required 2 million electrons per 'bit'. In 2025 it is predicted that they will be down to 1 electron per bit. Wouldn't it make more sense to try and get more electrons into each capacitor, not fewer? After 2025, could they try for half an electron? Explain the fallacy of this argument.

*Plastic-film capacitors* These are constructed as shown in Figure 23.8, although most often the metal foil plates and insulating dielectric are rolled into a cylinder. The dielectric for these capacitors is usually mylar or polyester. The popular greencap capacitor uses a metallised polyester film. They have good temperature stability and are used commonly in audio, radio, computer and general electronics. Polystyrene dielectric or styroseal capacitors have a very low leakage rate but they are quite expensive, while mains (240 V AC) rated capacitors use a polycarbonate dielectric that can repair itself. Plastic film capacitors in general are non-polarised, which means they can be connected with either wire to the positive.

*Ceramic capacitors* These are most commonly constructed in the form of a flat circular disc. Silver is vaporised onto both sides of a ceramic material that produces a large capacitance for a small size. This type of capacitor has a very high ability to withstand high voltages without breaking down. Their excellent temperature stability and low inductance make them useful in digital circuits and radio–TV tuning circuits.

*Electrolytic capacitors* An aluminium oxide electrolyte forms the dielectric on the surface of the plates. This type of capacitor is polarised, meaning that it must be connected into circuit the right way round as indicated on the casing, one end to positive and the other to negative. Reverse polarisation allows DC conduction, with possible heating up and explosive breakdown. The electrolytics are usually high capacitance (1 –10 000 μF) but have rather high leakage rates and are thus used in low frequency applications, power supplies and in audio amplifiers. If the electrolyte dielectric is tantalum dioxide, the capacitor is known as a **tag tantalum**. This type has very low leakage and high stability but is expensive.

*Variable capacitors* These are used in conjunction with inductors in radio–TV tuning circuits. Usually they are constructed with two sets of metal vanes that can be rotated against each other on a common shaft. The degree of plate overlap determines the capacitance. The dielectric is often air, or mylar plastic film. A small version of the variable capacitor gang is usually known as a **trimmer**. (See the Photo 23.5 and Chapter 31).

## Combining capacitors

The pigtails or connecting leads attached to capacitor plates are usually arranged to exit either from both ends (axial type) or from the same end (PCB mount type). This allows easy multiple connections in parallel or series to produce variations in capacitance if required. If two capacitors are connected in parallel, the area of the plates is effectively increased. This allows more charge per unit voltage, hence a linear increase in effective capacitance. If two capacitors are connected in series, the effective thickness of the dielectric is increased, resulting in a lower charge storage per unit voltage, that is, an effective capacitance decrease.

- Parallel connection: $C_{tot} = C_1 + C_2$
- Series connection: $\dfrac{1}{C_{tot}} = \dfrac{1}{C_1} + \dfrac{1}{C_2}$

Note that these combination rules for capacitors are opposite in behaviour to resistors. (See Figure 23.9.)

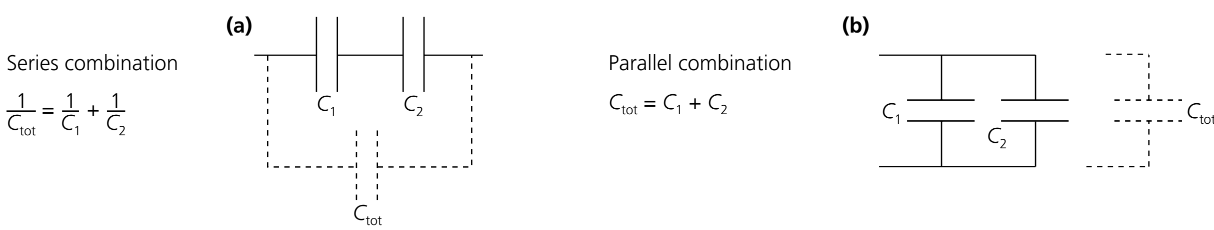



**Figure 23.9** Combining capacitors: series combination **(a)**; parallel combination **(b)**.

## The RC timing constant circuit

If you reconsidered the charging circuit of Figure 23.8**(d)** and added a series resistor, then the time it takes for the capacitor to become fully charged would be increased. The rate at which a capacitor charges (the voltage across it approaches the supply voltage) is determined

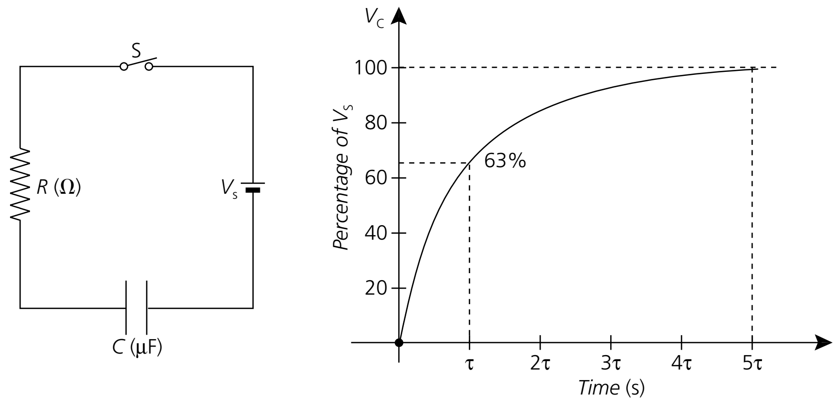



**Figure 23.10**
Charge curve for a capacitor.

by the size of the series resistance in the circuit, as this resistance controls the rate of flow of charge to the plates. The charging curve of a capacitor is shown in Figure 23.10. It is an exponential curve and the length of time it takes for the voltage across the capacitor to reach 63% of the supply voltage, $V_S$, is called one **time constant**. This is given the symbol τ, tau, which is the Greek letter *t*. Notice that the charging exponential curve shows that in theory a capacitor never really fully charges, but mathematical calculations show that after 5 τ the capacitor voltage $V_C$ = 99% of $V_S$. Mathematically, one time constant period, measured in seconds, in this type of **RC circuit** is given by

$$\tau = R \times C$$

Symmetry of shape between the discharge curve and the charge curve allows us to predict that when a capacitor discharges through a resistor, its voltage will drop by 63% of its initial value also in one time constant period ($\tau = RC$).

The timing circuit that is produced by an RC series connection has many uses. To make a **timer** we need a circuit that triggers when a voltage reaches a particular value as determined by a charging capacitor. RC networks can also be used to modify a waveform shape. Usually RC networks are used as **filters**, such as bass and treble or loudness controls in a stereo amplifier. These RC filter circuits alter the frequency response and waveform shapes of the electric signals at their inputs.

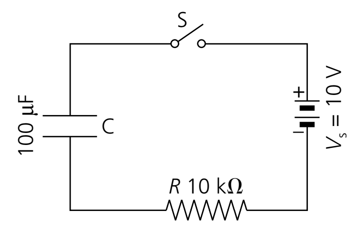
**NOVEL CHALLENGE**

It is sometimes said that the discharge of a capacitor is mathematically similar to the emptying of a bucket of water with a hole in the bottom. *Explain why the two discharge curves are the same.*

## Example

Consider the circuit of Figure 23.11, showing an RC timing circuit with a supply voltage of 10 volts DC. Calculate the time constant, τ, for the circuit and the time it takes for C to become fully charged after switch S is closed.

**Figure 23.11**




## Solution

- If $V_S$ = 10 V, $C$ = 100 μF, $R$ = 10 kΩ,
- then $\tau = RC = 1 \times 10^4 \times 1 \times 10^{-4} = 1.0$ s.

This will represent a voltage $V_C$ = 63% $V_S$ = 6.3 V.
The capacitor will be fully charged, $V_C$ = 10 V, after 5 τ = 5.0 s.

## EI Activity 23.2 CAPACITOR COLOURS

A capacitor purchased from an electronics store has the following markings on it: 473K–1000. This is known as the E.I.A. marking code and allows the capacitance, tolerance and voltage rating to be read.

1. Research the E.I.A. capacitor marking code to determine what these markings represent.
2. Some capacitors, such as TAG tantalums and polycarbonates, have a colour code system. Research the meaning and design of this colour code on these capacitors.

# Inductors and DC

An inductor is another component for storing energy in an electronic circuit. Energy is stored in the form of a magnetic field. **Inductors** are simply coils of fine wire wound on a rigid former and vary in size from very large air-cored devices to handle large currents, to small ferrite (compressed iron dust)-cored devices often called 'choke coils' because they are used to severely reduce certain frequencies in **AC circuits**. (Refer to Photo 23.5.) Two inductors wound on the same laminated core assembly are called transformers and are used to change the magnitudes of AC voltages; see Chapter 26 for more details. Variable inductors can be easily manufactured using a ferrite rod that can be moved in and out of the inductor core (Figure 23.12). In fluorescent lights the inductor is often called the 'ballast'.

**Figure 23.12**
Inductor coils.

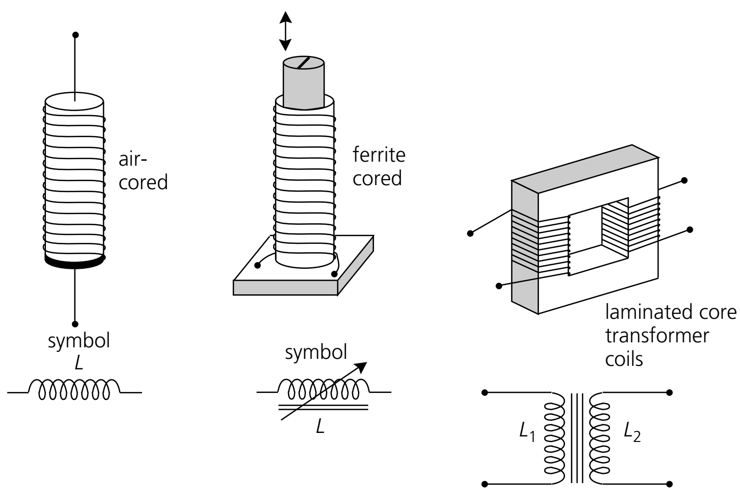
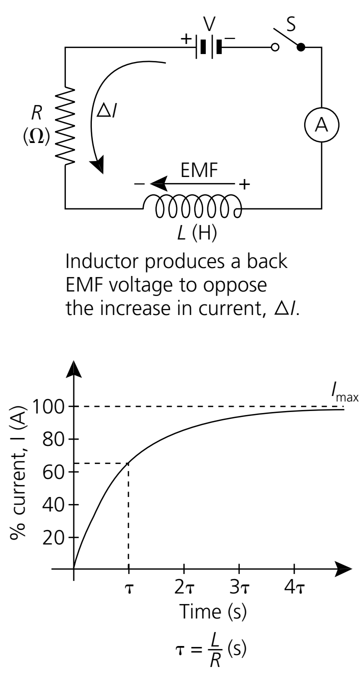



**Figure 23.13**
Inductor time constant.




Several principles are involved in explaining the operation of an inductor. Basically, the inductor follows the theory of an **electromagnet** or **solenoid**, as will be discussed in Chapter 25. It is important here to realise that:

- a constant direct current (DC) flowing through an inductor coil produces a constant magnetic field surrounding the inductor, which is similar in shape to a bar magnet field
- varying DC flowing through the inductor will cause the magnetic field to vary
- the varying magnetic field that cuts the turns of the inductor will induce a voltage or EMF across the inductor. This induced EMF always opposes the flow of a changing electric current through the inductor. Thus, an inductor has greatest influence on continuously varying AC currents and theoretically has no effect at all on DC.

If an inductor is connected into a DC circuit with a resistance, it will take longer for the current flow to reach its maximum value (as determined by Ohm's law) than if the inductor was not present (Figure 23.13). This property of an inductor is called its **self-inductance**, *L*, and is measured in a unit called a **henry** (H). An inductor has a self-inductance of 1 henry if an EMF of 1 volt is induced across its ends for a change of current of 1 amp per second.

$$V = -L \frac{\Delta I}{\Delta t}$$

Typical inductors in electronics have values of microhenrys (μH) or millihenrys (mH).

If the graph of Figure 23.13 is considered, the increase in current through the inductor produces an effective inductive time constant, $\tau$, where $\tau = \frac{L}{R}$. Again, one time constant period is the time it takes for the current through the inductor to reach 63% of its final ohmic value.

All inductors store energy in their associated magnetic fields. When the DC current $I$ reaches a constant value, the energy being stored in the coil will remain constant and is determined by the formula:

$$W = \frac{1}{2} I^2 L \text{ (joules)}$$

where $L$ is the self-inductance in henrys.

Inductors connected in series in a circuit effectively increase the total self-inductance:

$$L_{tot} = L_1 + L_2 + L_3 + \ldots \textit{ in series}$$

Inductors connected in parallel effectively decrease the self-inductance:

$$\frac{1}{L_{tot}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} + \ldots \textit{ in parallel}$$

## Reed switches and relays

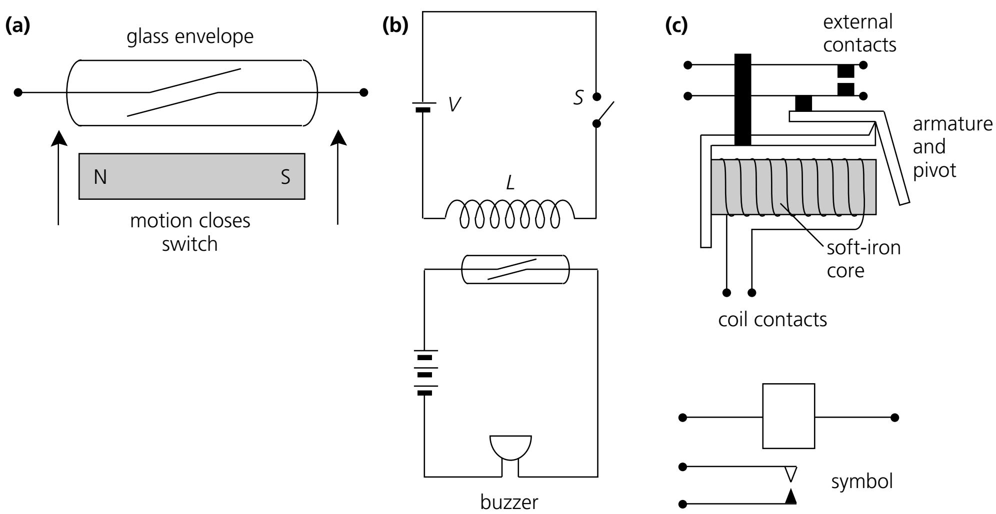
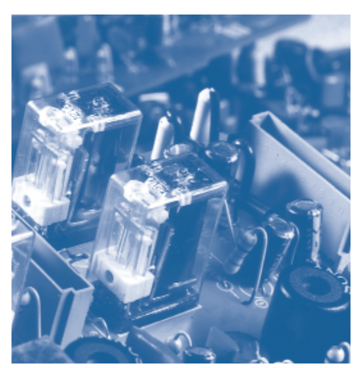



**Figure 23.14**
Reed switches and relays: simple reed switch **(a)**; reed relay **(b)**; electromagnetic relay **(c)**.

A simple **reed switch** consists of two pieces of metal inside a glass housing, which will contact together when an external magnet is brought into close proximity. This closed reed switch can then be used to carry an electric current and turn on a light bulb, for example (Figure 23.14**(a)**).

A **reed relay** replaces the permanent magnet in the reed switch assembly with an inductor coil carrying an electric current. The magnetic field generated by the inductor again closes the reed switch. The reed relay is most useful where one circuit is needed to independently control another. In Figure 23.14**(b)**, a small inductor coil current can control the larger DC current required to operate the buzzer alarm.

**Photo 23.6**
Circuit board relays.



An **electromagnetic relay** takes the concept of a reed relay further. It has an L-shaped armature of soft iron, which is attracted to a much stronger iron-cored inductor coil energised by a small DC voltage (Figure 23.14**(c)** and Photo 23.6). The L-shaped armature is arranged generally to open or close sets of contacts. In this way one relay device may trigger several sets of external circuits from one coil. When the coil current stops, the relay latches out and breaks the external contacts.

Electromagnetic relays, switches and inductors are very common in household devices, such as washing machines and electric circuit-breakers. These applications of electromagnetism will be further discussed in Chapters 25 and 26.

## Questions

5 What is capacitance? If a capacitor is marked 0.01 μF, 240 V, what does this mean?
6 What are the common types of capacitors used in electronics?
7 Determine the time constant for a series RC circuit where $V = 12$ V, $R = 120$ kΩ, $C = 100$ pF.
8 How does an inductor store energy and what determines the amount of energy stored in any particular inductor?
9 An inductor coil has a resistance of 5.0 Ω and an inductance of 120 mH. If a voltage of 12 V is applied, what time will it take for the coil current to reach its maximum value and what will this current maximum be?

# SEMICONDUCTOR DEVICES 23.5

## Conduction and semiconduction

Metals are crystalline materials, with a structure made up of atoms in a regular lattice pattern. The atomic nuclei and inner electrons of the atoms are fixed in position in the lattice, while the outer electrons are virtually free to drift, at normal temperatures under thermal equilibrium, in an electron sea. If an electric field is applied across the metal, these conduction electrons drift with a velocity of about $1 \times 10^{-4}$ m s$^{-1}$ and provide excellent conductivity. Copper, silver and gold are among the best electrical conductors. Electrical insulators such as glass or plastic do not possess an electron sea and, hence, no free conduction electrons. In order to break the bonds between electrons and nuclei, extremely high voltages are necessary. They do not normally conduct electricity.

Semiconductor materials lie between these two conduction extremes and are made from elements of group IV on the periodic table. Some common **semiconductor** crystalline materials are silicon, germanium, gallium arsenide and cadmium sulfide. It is from this class of materials that devices in modern solid state electronics, such as diodes, transistors and integrated circuits, are constructed. Let's look closer at their conduction properties and how to improve them, using pure silicon as the primary example (Figure 23.15).

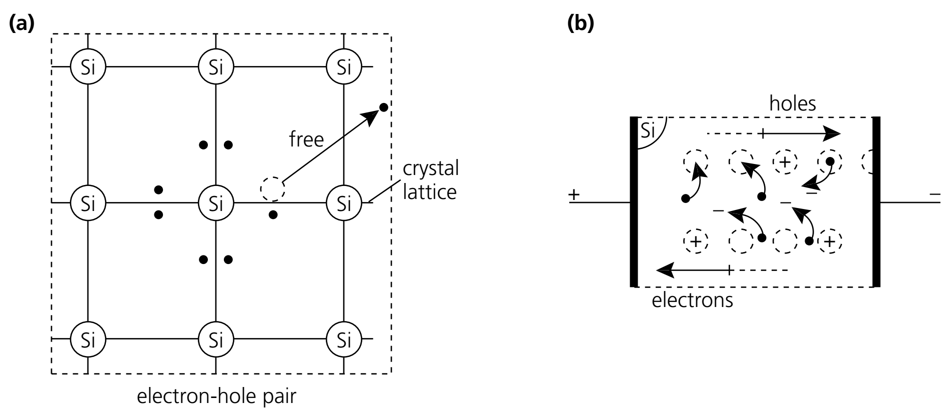



**Figure 23.15** Intrinsic semiconduction in silicon: semiconductor lattice **(a)**; electron charge carriers **(b)**.

Figure 23.15 represents, in 2D, a small region of silicon crystal with the atoms tetrahedrally bonded to each other, with four pairs of electrons sharing covalent bonds. At temperatures above absolute zero (when semiconductors are in fact good insulators) some electrons break away from the nuclei and move into a conduction band where they are able to move easily through the crystal under normal thermal excitation.

In silicon, the thermal energy necessary for a conduction electron to break free is about one electron-volt (1 eV). Notice that this leaves behind a fixed hole in the valence bond of the crystalline lattice into which a free electron may drop. Thus, **electron-hole pairs** are produced randomly at normal ambient temperatures. As the temperature rises, more energy is available and so more electron-hole pairs are produced. Electron-hole pairs are being created and destroyed constantly in the semiconductor lattice as electrons fall back into holes, but an equilibrium is established. It is these electron-hole pairs that are able to conduct electricity through the semiconductor crystal when an external electric field is applied. Notice that semiconductors will therefore increase their conductivity at higher temperatures, which is an effect opposite to that of normal metallic conductors. A disastrous thermal breakdown in semiconductor electronic components can occur if they are allowed to overheat.

Electrical conduction through a semiconductor crystal via negative charge carriers (electrons) and positive charge carriers (holes) is called **intrinsic semiconduction** and is usually not very practical for electric circuits and devices. The basic conduction of semiconductors can be improved by a chemical process calling **doping**, whereby small proportions of impurity atoms are added to the crystal. This is done during a high temperature molten phase so that when the mixture recrystallises, the dopant impurity atoms will take the place of normal silicon atoms in the lattice pattern. Typical doping ratios are of the order of 1 in $10^8$ atoms. Doping can also be produced by neutron bombardment (NTDS). Refer to Chapter 28.

## N-type silicon

The doping addition of pentavalent atoms from group V of the periodic table, such as phosphorus, arsenic or antimony, produces extra electrons available for conduction because these atoms contain five valence electrons, one more than silicon. Since most of the current carriers are electrons, they are referred to as the **majority charge carriers** in this form of **N-type silicon**. Of course, there are still available holes and these are called the **minority charge carriers** in the conduction process through this type of silicon.

## P-type silicon

The doping addition of small amounts of trivalent group III elements, such as aluminium, boron or gallium, produces extra holes available for conduction as these atoms have only three valence electrons, one less than silicon. Within the lattice of **P-type silicon**, majority charge carriers are thus holes, while the minority charge carriers are electrons.

The added versatility and improved electrical conduction of doped semiconductor crystal is much more useful and under certain circumstances approaches the very good conductivity of normal metals. The use of doped semiconductor properties is referred to as **extrinsic semiconduction** (Figure 23.16).

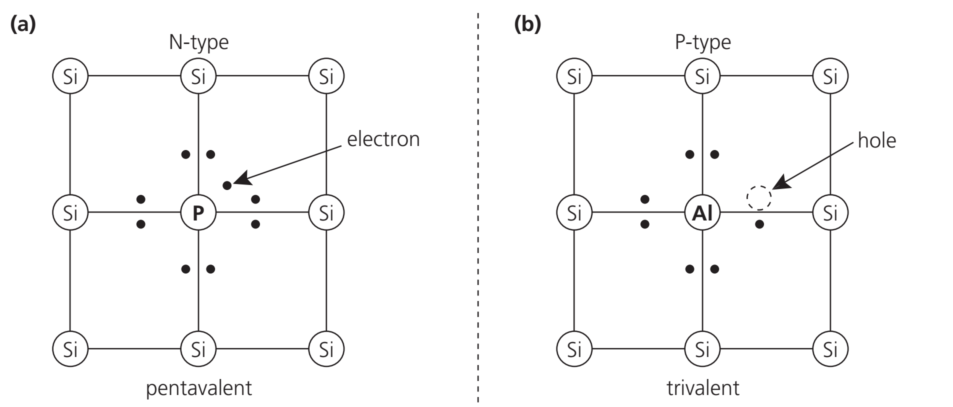



**Figure 23.16**
Impurity doping: N-type silicon **(a)**; P-type silicon **(b)**.

# PN junction and biasing

Semiconductors, via either intrinsic or extrinsic conduction, allow current to flow in either direction through the crystal. When a piece of N-type material is fused with a piece of P-type material in such a way as to provide a continuous crystalline structure, then a device called a

**PN junction diode** is formed. The PN diode has the very useful characteristic of allowing direct current (DC) to flow in only one direction at a time. It becomes a **solid state rectifier** (Figure 23.17). When a PN diode junction is formed, electrons from the N-type side of the junction diffuse across into the P-type side of the junction and combine with holes. This effect produces a small potential difference, which eventually stops any further diffusion of electrons, resulting in a permanent potential barrier at the site of the PN junction. The zone of the crystal across which the potential barrier forms is called a **depletion layer**. At normal ambient temperatures in a silicon-based PN junction diode this depletion layer represents an effective EMF of about 0.6–0.7 V. This value in any particular diode is dependent on the exact doping conditions in the crystal and will decrease with lower temperatures.

**Figure 23.17**
A PN junction diode (silicon).

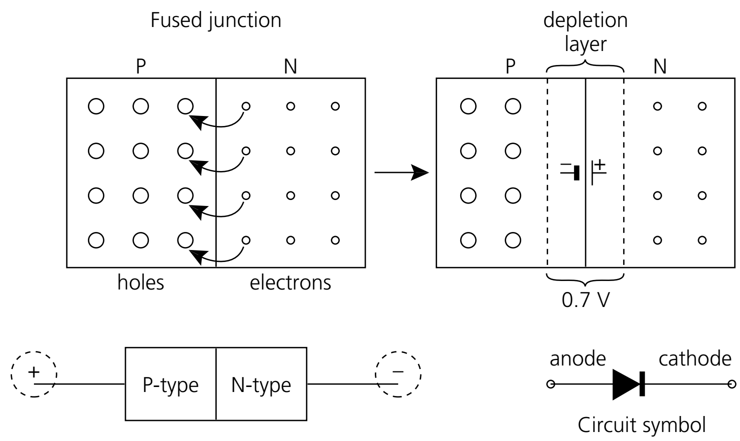
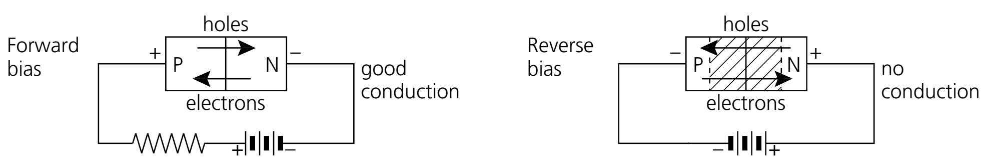



**Figure 23.18**
Bias conditions for a PN diode.




Consider now what occurs when this PN diode is connected in series with a battery whose EMF is greater than 0.7 V (Figure 23.18). The connecting of a fixed voltage to a semiconductor electronic device in order to set its operating conditions is called setting the **bias**. With **forward biasing**, that is, P-type positive and N-type negative, electrons are forced from the N region into the P region, while holes effectively move in the opposite direction. The depletion layer is effectively eliminated and the diode conducts easily, requiring a current-limiting resistor to avoid rapid overheating. With **reverse biasing**, that is, P-type negative and N-type positive, electrons are attracted away from the junction in the N region, and holes effectively move toward the positive end of the crystal. The depletion layer is effectively widened and the potential barrier becomes equal to the bias voltage. Conductivity is stopped through the crystal and no current at all will flow. It should be noted that if a very high external reverse bias voltage is connected to the PN diode, it may very well break down due to the crystalline structure not being large enough to prevent discharge current flow through the diode. This is very damaging to normal diodes and is called **avalanche breakdown**. Because of this, most diodes have a stated peak inverse voltage (PIV), with power diodes between 400 V and 1000 V and small signal diodes between about 70 and 100 V.

In summary, the conduction characteristics for a normal PN diode are represented graphically in Figure 23.19. A diode is a good conductor when forward biased above 0.7 V and a DC block when reverse biased. Notice that the graph of Figure 23.19 definitely shows that a diode is not an ohmic device in its I–V characteristics because it is not a linear relationship.

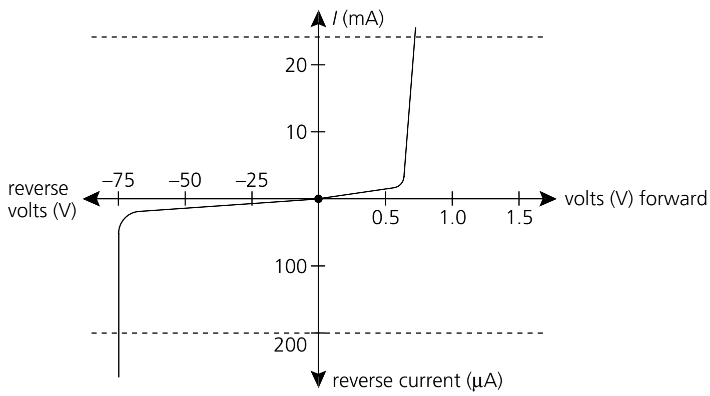



**Figure 23.19**
Current–voltage (I–V) characteristics of a diode.

## Application devices

The PN junction is the basic element in a **silicon solar cell**. Light incident on a PN junction will produce an EMF between the sides of the junction (Figure 23.20). In practice this EMF is about 0.6 V. In an external circuit connected between the two sides of the junction and through a load resistor, R, current flows as long as light is incident on the junction. The current flow depends on the light intensity, as this controls the number of free electron-hole pairs created in the junction. Very pure silicon crystal is needed in solar cell design to minimise possible sites of electron-hole recombination. Low-cost silicon solar cells should make significant contributions to society's future energy production methods.

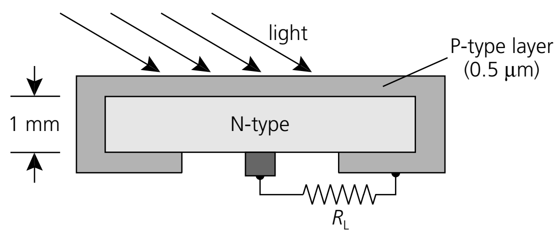
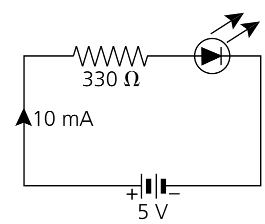



**Figure 23.20**
A silicon solar cell.

Another common usage of diode semiconductor technology is in a **light emitting diode**, or LED. These are unidirectional current-carrying devices based on the light emitting properties of a PN junction. Electrons give up energy as they recombine with holes in the semiconductor crystal lattice, and in certain types of doped semiconductors this energy is released as light of characteristic wavelengths (Figure 23.21). If the semiconductor is gallium arsenide phosphide (GaAsP), then the junction emits red light, but if the material gallium phosphide (GaP) is used then yellow or green light is produced. A blue emitting LED is based on silicon carbide. A typical red LED requires about 10 mA at a forward voltage bias of 2 V and has a very low PIV of only 5 V or so.

**Figure 23.21**
A light emitting diode LED.




A diode can also be used to detect light. The reverse current of a PN junction can be increased if the junction is open to incident light photons. A **photo diode** is constructed so that its junction is illuminated from a lens assembly attached to the top of the diode body. Phototransistors are an improvement on the basic design of a photo diode and will be further discussed in the next chapter.

A very useful diode type is actually designed to work in continuous reverse bias mode and is called the **zener diode** (Figure 23.22). These devices are often used as voltage reference sources in power supply and rectification circuits. If a zener diode is forward biased it

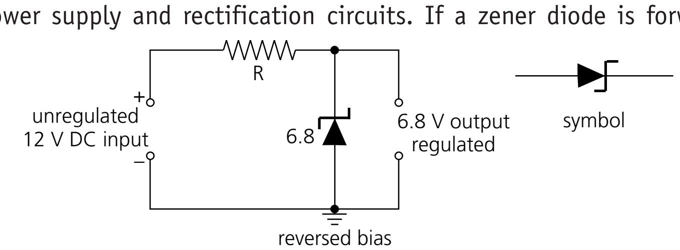



**Figure 23.22**
A zener diode regulator.

conducts as normal, but it will also conduct when it is connected in reverse bias mode. Zener diodes are designed to conduct in reverse bias over a range from about 2 volts up to several hundred volts. When a zener diode conducts in reverse bias, the voltage drop across the device remains almost constant even when there are wide variations in the current flowing through it. It is this property that makes it useful as a voltage regulator. Note that even a zener diode has a maximum reverse current that it can handle, this being dependent on its power rating.

Finally, note that two further transducers are often used in electronic circuits:

- The **thermistor**, which is a resistor whose resistance decreases considerably with temperature increase and thus can be used to indicate temperature changes electrically.
- The **light dependent resistor** (LDR), whose resistance decreases considerably when it is illuminated by light and thus can be used to indicate light level changes electrically. Sometimes this device is called a photocell.

NEI

### Activity 23.3 DIODE RESEARCH

A multitude of semiconductor devices related to the simple PN diode are used in electronics. It should be possible for you to find research material from the library on the following devices and present a short verbal report to your class colleagues on their physical and electronic characteristics:

1. High speed switching or Schottky diodes.
2. Varactors or varicap diodes.
3. Solid state radiation detectors.
4. Laser diodes as used in CD players.
5. Infrared (GaS) diode emitters and detectors.
6. Humidity sensors as used in video cassette recorders.

## AC RECTIFICATION 23.6

Using the properties of components so far discussed in this chapter, it is now possible to construct an operating circuit that efficiently converts AC voltages to DC voltages. This process is called **rectification**. The derivation of this word is from the Latin *rectus*, meaning ‘straight’, which describes exactly what the process does to an AC waveform; it straightens it out. The circuit is one of the commonest blocks in any electronic device, especially if the device needs to be operated from the 240 V AC mains. In most **power supply** units a transformer involving inductor coils steps down the AC voltages from mains 240 $V_{RMS}$ to a much lower value, say, 20 $V_{RMS}$. You may need to refer to Chapter 26 for the underlying physics of these devices. A rectifying circuit is then used to convert the low voltage AC to a DC voltage. Let’s see how this is done.

### Half-wave rectifiers

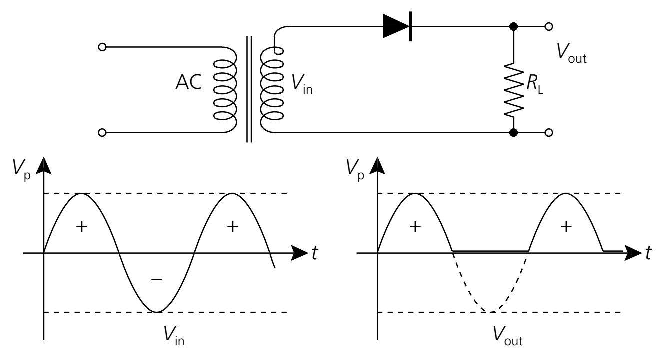



**Figure 23.23**
Half-wave rectifier circuit.

The diode in the circuit (Figure 23.23) will only conduct when the input sine wave is positive and above 0.7 V in amplitude. It will not conduct when the input sine wave is negative because the diode is in reverse bias. Hence, the voltage output waveform of the circuit is referred to as 'half-wave rectified'. If an oscilloscope (CRO) is used to observe this waveform across the load resistor as shown, its amplitude peak will be:

$$V_{out} = V_{in} - 0.7\text{ V}$$

## Full-wave rectifiers

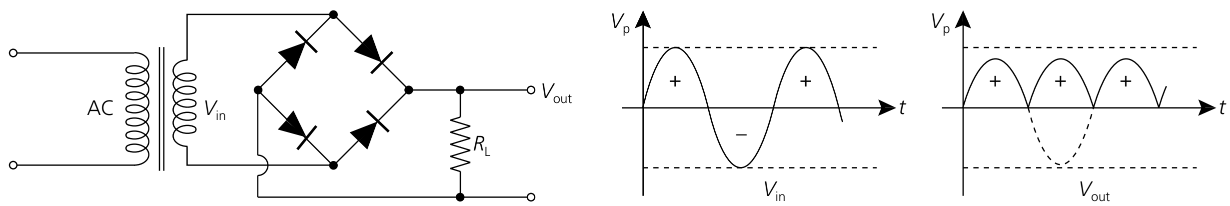



**Figure 23.24**
Full-wave rectifier circuit.

The four diodes in the circuit shown in Figure 23.24 are arranged in a bridge formation and are referred to as a full-wave rectifier. Full-wave rectification allows the output voltage to be pulsed every half-cycle of the input AC waveform, as the diodes combine in pairs to allow conduction through the load resistor during both positive and negative swings of the input sine wave. Often in power supply design, the four diodes are constructed in one package, with two AC terminals and two DC terminals. This package is called a diode bridge or a bridge rectifier. Because two diodes are involved in each forward conduction cycle, the value in peak amplitude of the output of a full-wave rectifier will be:

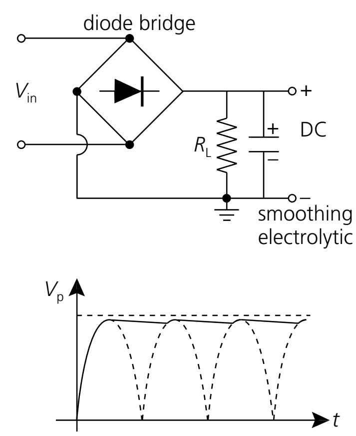
$$V_{out} = V_{in} - 1.4\text{ V}$$

If a DC voltmeter were used at this time to measure the output voltage it would show the average voltage, $V_{av}$, over two half-cycles, where:

$$V_{av} = \frac{2V_{out}}{\pi}$$

## Capacitor smoothing

**Figure 23.25**
Effect of a smoothing capacitor.




The output waveforms of both half-wave and full-wave rectifier circuits still contain what is called **AC ripple** or a variation in amplitude with time, and this requires filtering or smoothing out with a large electrolytic capacitor, as shown in Figure 23.25. Recall that the time constant of a discharging capacitor will prevent it from losing charge quickly. This has the effect of holding the voltage output from the rectifier at a high value from one rectified pulse to another. If an oscilloscope is used to observe the output waveform with a large value (400–1000 μF) capacitor in place, then very little remaining AC ripple will be observed, especially if the current drawn from the load resistor is small. The output of these circuits is now **smoothed DC** because it remains constant over time.

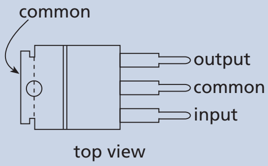
## Voltage regulators

Even though the oscilloscope output waveform of the circuits above looks like smooth DC, we still do not have a fully **regulated DC** power supply. The above circuits are not yet satisfactory for electronic voltage supplies for the following reasons:

- If the load current increases, the voltage available from the transformer will decrease.
- Temperature changes may cause the diodes in the bridge to vary the output voltage.

**VOLTAGE REGULATOR CHIPS**

The three terminal voltage regulator chips in the 78XX and 79XX family make power supply construction simple. These chips only require a filtered DC input voltage. They have internal current-limiting and thermal-shutdown under short-circuiting conditions. A common example is the 7812 positive 12 volt regulator chip in the TO-220 package.




- The mains voltage itself supplying the input transformer may vary, depending on consumer demand and time of day or night.

What is needed is a fully regulated DC supply whose output voltage will remain constant irrespective of these types of changes. The simplest alteration involves the use of a zener diode, which will clamp the output voltage to a particular fixed value, such as 6.8 V. Integrated circuit voltage regulators are a more common device, and will be discussed in Chapter 31.

## Questions

**10** What is the difference between intrinsic and extrinsic semiconduction?

**11** Sketch a circuit that could be used to full-wave rectify an AC voltage of 12 $V_P$. What would be the DC output voltage of the circuit and how would the AC ripple voltage remaining be reduced?

**12** Design a simple application circuit that might use an LDR as part of a voltage divider network controlling a small DC buzzer. The buzzer should go off when ambient light levels fall to a certain point.

## Practice questions

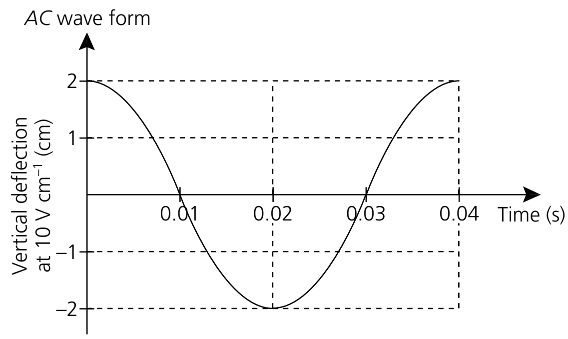
NOTE: Any questions in this set that involve silicon diode conduction will assume 0.7 V as the forward voltage drop.

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

### Review — applying principles and problem solving

***13** Consider Figure 23.26, showing an AC waveform as displayed on an oscilloscope. Determine **(a)** peak voltage $V_P$; **(b)** peak to peak voltage $V_{PP}$; **(c)** average voltage $V_{av}$; **(d)** RMS voltage $V_{RMS}$; **(e)** frequency of the AC wave.

**Figure 23.26**
For question 13.




***14** If the alternating current as a function of time in an AC heating coil is given by the expression $I = 5.6 \sin 120\,\pi t$, what is **(a)** the peak current ($I_P$); **(b)** the RMS current; **(c)** the AC frequency?

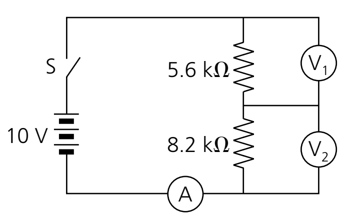
***15** What colour bands would you expect to find on these resistors, assuming a four band system of labelling?

**(a)** 120 Ω ± 5%
**(b)** 330 kΩ ± 5%
**(c)** 5.6 MΩ ± 5%
**(d)** 2.2 kΩ ± 5%
**(e)** 1.5 kΩ ± 10%
**(f)** 470 kΩ ± 10%
**(g)** 1.8 MΩ ± 10%
**(h)** 1.0 kΩ ± 10%

***16** Calculate the largest voltage that is possible across a 5.6 kΩ resistor if it is labelled as a 1 W type. What current is flowing through it at this voltage?

***17** The circuit of Figure 23.27 is set up. Determine the readings on the meters shown in the circuit when switch S is closed.

**Figure 23.27**
For question 17.




***18** Explain the following terms as applied to DC circuits combining resistance, capacitance and inductive components: **(a)** voltage divider; **(b)** self-inductance; **(c)** dielectric; **(d)** millihenry; **(e)** microfarad; **(f)** filter; **(g)** RC time constant; **(h)** electrolytic.

***19** Why should electrolytic capacitors always be connected into the circuit with great care when using DC power supplies?

***20** Determine the time constant for an RC series network where $R = 100\ \text{k}\Omega$ and $C = 470\ \mu\text{F}$. If the applied DC voltage in the network is 9 V, how long will it take for the capacitor to be fully charged and at this point what energy is stored in this component?

***21** Explain, using diagrams where necessary, the following terms applying to semiconductor action in electronics:
**(a)** N-type doping, and majority and minority charge carriers.
**(b)** Barrier potential in a silicon diode.
**(c)** Diode rectification of an AC waveform.
**(d)** Zener diode regulator.

****22** A silicon-based PN junction diode is forward biased and carrying a current of 4.5 A. What power is it dissipating?

****23** An AC wave of $V_{PP} = 15$ V is fed through an unfiltered full-wave rectifier circuit. What would be the peak output voltage and what reading would be indicated by a DC voltmeter at the rectified output if it in fact reads an average value?

***24** What effect would decreasing the output load resistance have on the ripple voltage of a capacitor-filtered full-wave bridge rectifier circuit?

***25** List some of the practical application devices in electronics that make use of PN junction semiconductor technology. Give a typical use for each of your applications.

****26** The circuit of Figure 23.28 is set up and includes a rectifying diode.
**(a)** Sketch the waveforms expected at the points labelled A and B in this circuit as displayed on an oscilloscope with vertical amplification set to 5 V $\text{cm}^{-1}$.
**(b)** Describe how these waveforms would alter if a 470 µF capacitor was connected in parallel with the 1.2 kΩ resistor.

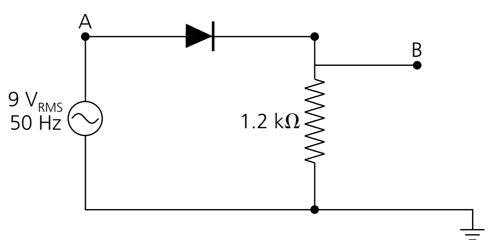



**Figure 23.28**
For question 26.

****27** A student uses the circuit of Figure 23.29 to obtain the data table below. Plot an I–V curve from the data.

| | | | | | | |
|---|---|---|---|---|---|---|
| $I$ (mA) | 0 | 0 | 0.1 | 4 | 16 | 40 |
| V (V) | 0 | 0.2 | 0.4 | 0.6 | 0.7 | 0.8 |

**(a)** What type of semiconductor device is the circuit element X?
**(b)** What is the switch-on voltage for this device?
**(c)** What is the resistance of the device at a voltage of 1.0 V?
**(d)** What current flows if the device is reverse biased by a voltage of 0.8 V?

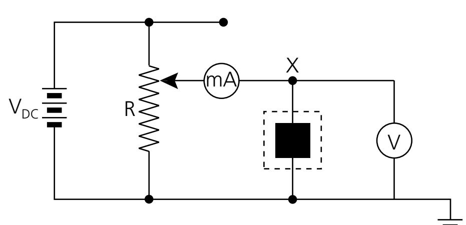



**Figure 23.29**
For question 27.

****28** Draw a circuit to rectify, smooth and regulate the output voltage from a step-down transformer. Incorporate in your circuit diagram a bridge rectifier, a smoothing capacitor, a zener diode and stabilising load resistance connected across the output. Sketch the output voltage waveform expected from your circuit.

## Extension — complex, challenging and novel

**Figure 23.30**
For question 29.

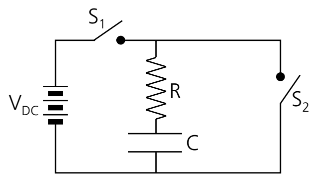
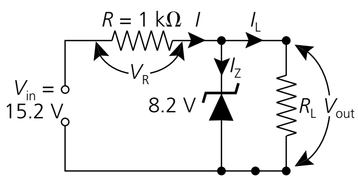



**Figure 23.31**
For question 30.




*****29** Consider the timing circuit of Figure 23.30. Given $R$ = 2.0 kΩ and $C$ = 10 μF,

- **(a)** calculate the time constant of the circuit if switch $S_1$ is closed;
- **(b)** calculate what happens if another similar capacitor is placed in series with C;
- **(c)** if $S_1$ is opened and $S_2$ is closed, describe the current flow in this circuit;
- **(d)** explain why switches $S_1$ and $S_2$ should not be closed at the same time.

*****30** Analyse the zener diode stabiliser circuit of Figure 23.31.

- **(a)** State a relationship between $I$, $I_L$ and $I_Z$.
- **(b)** State a relationship between $V_{in}$, $V_R$ and $V_Z$.
- **(c)** Derive an expression for $R$ in terms of $V_{in}$, $V_Z$, $I_Z$ and $I_L$.
- **(d)** Calculate the maximum power dissipated by the 8.2 V zener diode.
- **(e)** What is the load current, $I_L$, when the zener current $I_Z$ = 3 mA?
- **(f)** What value of $R$ is needed if $I_L$ is to be 10 mA with $I_Z$ = 3 mA?

*****31** Capacitors of 5.0 pF and 20.0 pF respectively are charged so that the respective potential differences between their plates is 200 V and 300 V. They are then connected in parallel maintaining correct charge polarity. Calculate: **(a)** the new charge on each capacitor; **(b)** the common potential difference between plates; **(c)** the energy dissipated during charge rearrangement.

*****32** Light-dependent resistors have a resistance that changes in proportion to the amount of light falling on their windowed surface. The resistance of such a light-dependent resistor was measured over a range of light intensities and the following tabulated data values obtained:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Light intensity in candela (cd) | 100 | 200 | 300 | 350 | 400 | 500 | 600 | 800 |
| Resistance (MΩ) | 540 | 480 | 410 | 380 | 350 | 290 | 230 | 100 |

Graph these data and develop a conversion formula from resistance to light intensity.

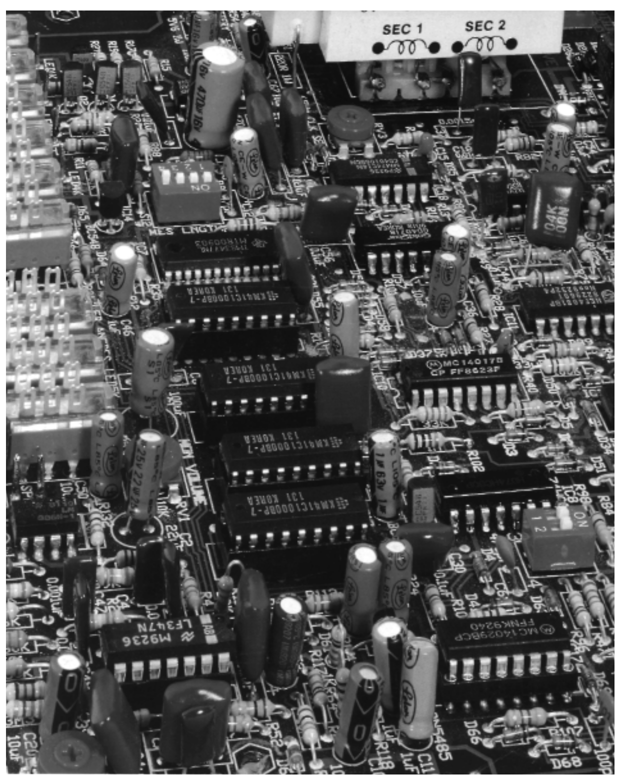



**Photo 23.7**
Complex electronic circuit system involving components discussed in Chapters 23 and 24.