ELECTRONICS FOR ELECTRICIANS AND ENGINEERS

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Preface

The rapidly changing technology of electronics has left many technicians requiring an urgent updating of their skills. The same problems have faced many in other fields of engineering who find now that they require a knowledge of electronics in order to understand new developments in their own subjects. Hardly any part of modern life is now untouched by electronics, and there can be very few people working in any branch of engineering or science who will not find that some understanding of electronics is necessary.

This book has been written in response to the need that now undoubtedly exists. The aim has been to explain principles and devices in clear terms, assuming no high level of prior knowledge. I have assumed only that the reader will have some elementary knowledge of electricity, more from a practical than a theoretical standpoint. For that reason, the early chapters of the book are concerned with a review of modern electrical principles, and may be omitted by anyone who is thoroughly familiar with them. For the reader whose theoretical knowledge may have been dulled by time, these chapters should provide a very useful revision of topics that are essential to the understanding of electronics. In the chapters that deal with electronics, the emphasis has been on principles and devices, but sufficient circuit diagrams have been included to illustrate how the various electronic components are used.

I am most grateful to RS Components Ltd for considerable help and support in this project, particularly with the provision of photographs and datasheets on modern electronic devices.

Ian R. Sinclair

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1
Fundamentals

Asking what electricity *is*, as distinct from how electricity behaves, is not always a help to understanding the behaviour of conventional electrical circuits. When we need to understand how *electronics* devices work, however, some idea of what electricity is becomes essential. In this book, we are concerned not with the kind of precise detail that you might find in a textbook of physics, but with the essentials only. These essentials start with the idea of **atoms**.

We have known for almost two hundred years that all the substances we know on earth and can detect anywhere else in the universe, are built up from about one hundred basic materials that we call **elements** – substances like carbon and silicon, oxygen and hydrogen. Each element is made up from huge quantities of identical units called atoms, one type of atom for each element. This idea, first put forward by the ancient Greeks and in its present form by John Dalton, was the foundation of the study of chemistry in its modern form. It was originally thought that the atoms of a material were indestructible and unchanging, but as evidence accumulated, it became clear by the end of the nineteenth century that this was not so. Atoms seemed in turn to be made up from smaller particles; so much smaller in fact, that each atom was mainly empty space in which tiny particles moved like the planets round the sun in our solar system. This picture of the atom is one that has been very useful, though for some purposes it is inadequate.

If we stay with the 'solar system' idea of the atom, then the place of the sun in this picture is occupied by the **nucleus** of the atom, and the planets by the **electrons**. As far as we are concerned, the central core of the atom, the nucleus, is not of great importance, though it is the part of the atom that is of most interest to a chemist or, of course, a nuclear physicist. The tiny particles, or electrons, that surround this nucleus are responsible for electricity and electronics. We don't know much about what these particles are, except for suspicions that they might be made up out of even smaller particles. We *do* however, know a lot about what they do, and that's the foundation of all electrical science.

The most important feature of electrons is the force that keeps them in place in the atom. This force is called the *electric* or *electrostatic* force; it attracts the electrons to the nucleus and repels them from each other. The strong electric force is balanced by other forces, and this balance of forces ensures that the electrons are held in the atom, but without collapsing completely into the nucleus. It is the balance of forces that ensures that the atom is mainly empty space with a cloud of electrons surrounding the nucleus. Note that the electrons are so small that they can easily pass through the mainly empty space of atoms.

Before we knew about electrons, the effects of the force were known, and were put down to something called **charge**. We still don't know what charge is, but we do know that the electron is the source of it. For historical reasons, we talk of charges having two signs, positive and negative, and the type of charge on the electron is negative. The charge type of the nucleus is positive, and the unit amount of charge is the amount on the electron. We have never found any amount of charge less than this, so there are no fractions of this amount. The idea of charge is useful, because it allows us to form an idea of the way that the nucleus and the electrons are arranged.

In the complete atom, the amount of charge is normally zero. This is because each electron in the atom has a unit negative charge, and the nucleus has a positive charge whose size is equal to the sum of the charges on the electrons. If, for example, an atom consists of a nucleus with 12 electrons, then the nucleus will have 12 units of positive charge, making the atom as a whole neutral. Any substance that has positive charge must have had electrons removed, and a substance that has negative charge must have gained some electrons. This is because the electrons are the only part of the atom that can be comparatively easily removed, temporarily at least.

The balance of forces in the neutral atom ensures that when an electron is removed from or added to the atom, there will be strong forces trying to reverse the situation. These forces are of measurable size when more than a few electrons are involved, and it was from measurements of these forces that we first gained some knowledge of electricity. Even in ancient times, it was known that similar charges repelled each other, and opposite charges attracted. The more precise laws were discovered by Coulomb, forming what we now know as **Coulomb's Law**.

In these days, substances could be classed as **insulators**, which retained charge, and **conductors**, which would lose it. We know rather more about materials now, but the general principles are unchanged. An insulator is a material whose atoms are arranged in such a way as to prevent electrons from moving easily. A spare electron on the surface of an insulator will therefore stay where it lands. A conductor is made from atoms whose arrangement allows electron movement from one atom to another. An electron on the surface of a conductor can easily move to any other part, and if there happens to be any part that has lost an electron, then the movement will ensure that the lost electron will be replaced in a very short time. This essential difference between insulators and conductors is of vital importance both in electricity and in electronics.

Electrostatics and current electricity

When electrical effects were first discovered, it was thought that there were two types of electricity, static and moving. We now know that the differences are due to the way in which electrons were being used. If we shift some electrons to or from an insulator, forces can be measured between this insulator and anything around it. Only small numbers of electrons are involved, so that the total amount of charge is also very small. This is because the forces are so very large that trying to move more than a few electrons is almost impossible – the electrons will return through the air, or even through a vacuum, in what we call a spark. This behaviour is what we now call **electrostatics**. When we allow electrons to move through conductors, by contrast, very large numbers of electrons can be moved because the movement is one of shuffling from atom to atom, with no atom ever losing or gaining an electron for any noticeable time. The forces on the electrons and so on the materials are very small even though such large amounts of charge are being shifted. This behaviour is what we call **electric current**.

The important distinction is that electric current moves in a closed path, called a 'circuit', but electrons on an insulator are held at rest. Very large forces act on these electrons at rest, but not on the moving electrons because in a circuit there is no atom which has a surplus or deficit of electrons for more than a very short time. This does not mean that there are no forces acting on the electrons in a circuit. The forces are very different, however, and are caused by the effect of the movement of the charge rather than by the charge itself. We call these types of forces **magnetism**.

Both the electrostatic forces and the magnetic forces have an effect at a distance, unlike mechanical forces. The electrostatic forces operate on anything that carries an electric charge at rest, with the usual direction – attractive for charges of the same sign and repulsive for opposite signs of charge. The magnetic effects operate on any moving charge and on any material that contains an unbalanced moving charge. This includes both electrical circuits and certain materials such as iron. Just as we can use the amount of electrostatic force to measure the amount of static electrical charge, we can use the amount of magnetic force to measure the amount of moving charge. There is an important difference, however. When we work with electrostatics, the amount of electrons that we can ever displace is very small, and the total force between two charged materials is small. When we work with electrical currents, we are dealing with unbelievably large numbers of electrons, and though the magnetic force for each electron is very small, the huge numbers cause this to add up to a very substantial force. We therefore use this force effect in measuring instruments such as ammeters and voltmeters.

So far, we have thought of the atom in terms of nucleus and electrons, with electrons being shifted to or from the atom. In fact, we can normally only add or remove one electron per atom, because the forces between the electron and the rest of the atom are so strong. When one electron is removed or added, the resulting atom will have an electric charge, and will behave very differently from an ordinary atom. It has become an **ion**, and will try to become neutral again by adding or shedding an electron. We can very seldom strip all the electrons from a nucleus, so that the way that a nucleus behaves is of no great interest as far as electricity and electronics is concerned. The behaviour of ions, by contrast, can be quite important.

Ions can exist in gases and in liquids. When the atoms of a gas become ions, the gas which is normally an insulator can conduct electricity. Similarly when a liquid contains ions, the normally insulating liquid will conduct electricity. The side-effects of the existence of ions are even more interesting and useful. The ions of a gas, moving because of the electrostatic forces on them, will collide with each other and with electrons. When the ions revert to neutral atoms again, the energy that they absorbed in order to become ions is given out again, but in the form of light. Ionised gas tubes are therefore used as neon signs, decorative lights, and in fluorescent lighting. Most of the ionised liquids that we use are solutions in water, and when the ions move in such solutions, there are chemical changes when the ions give up their charges. These allow such effects as electroplating, the isolation of elements that do not occur naturally (like aluminium), and electrolytic polishing.

Conductors and insulators

The old classification of materials into conductors and insulators was rough and ready, but it served for a century or more. Nowadays, we need to be more specific about materials, not least because we know so much more about the movement of electrons. Basically, the difference between a typical insulator and a typical conductor is in how the atoms of the material are packed together. In an insulator, each atom is fairly isolated. An electron lost by or gained by an atom does not cause an electron to move to or from the next atom because distances are too great (by electron standards). In a conductor, by contrast, atoms are packed tightly together, and the nucleus of one atom can even affect the electrons in the next atom. In addition, each atom is of a type that contains a large number of electrons that are some considerable distance from the nucleus and so less strongly bound to the nucleus. This means that the material is dense, strong, and all the other things that we associate with a metal – most common conductors are metals, and all metals are conductors.

The obvious difference between conductors and insulators is that of **resistivity**, the quantity that measures resistance of a material to the flow of electrons. Conductors allow electrons to flow easily through them, and they even allow other movements of charged objects, the objects that we call 'holes'. There are other differences, however. One important difference concerns the effect of raising the temperature of a material. When you raise the temperature of a conductor, the flow of current becomes less easy. More precisely, the resistivity of the material increases (see Figure 1.1). This is because heating the material increases the vibration of all the particles in the material, and that in turn makes it more difficult for electrons to thread their way through the atoms. By contrast, when you heat an insulator you make it easier for electrons to move through it. The vibration of the atoms in the hot material makes it likely that some electrons can break free and move, even if this movement is limited.

There is yet another important difference. Suppose you take two elements, one metal and one non-metal. Elements, in the strict chemical sense, means that each material is made out of its own type of atom, with no other atoms present. Nothing is ever so perfectly pure, but we can prepare many types of elements now in which only one atom in a thousand million (or more) is an impurity atom. Given two pure materials like this at normal temperatures, the metal will be a conductor, and the non-metal will be an insulator. Now the effect of impurity on such materials will not be very dramatic. Adding atoms of a different metal to a metal element will not greatly affect its electrical resistivity unless the addition is on a large scale, certainly 1 per cent or more, and even then the effect is not large. Similarly, adding another non-metal to the non-metal element does not very noticeably affect its resistivity. The elements that are good conductors or good insulators do not have these characteristics greatly changed by the presence of impurities. It is just as well, because we would know rather less about electricity if this had not been the case.

Semiconductors

Semiconductors are not simply materials whose resistivity (or its inverse, conductivity) is somewhere between that of a conductor and that of an insulator. Certainly, one feature of a pure

The *resistance* of a sample of material depends on the dimensions of the sample and on the material from which the sample is made.

Resistivity is a factor that measures the effect of a material on the resistance of any sample. The dimensions of a material are affected by temperature changes, but the effect of temperature on resistivity is very much greater.

As a formula:

$$R = \frac{\rho . s}{A}$$

where ρ is the resistivity (units:ohm-metres), s is the length (units:metres) and A is the area of cross-section (units:metres squared).

Figure 1.1 *Resistance and resistivity. Resistance depends on temperature mainly because resistivity depends on temperature, though the dimensions of a resistor are also slightly affected by temperature*

semiconductor is that it will have a resistivity value that is not so high as that of an insulator, but it certainly does not approach the value that we would expect of a conductor. The two features that make us class a material as a semiconductor are the effect of temperature and the effect of impurity, and both of these effects are closely related.

Suppose, for example, that we have a specimen of pure silicon. Its resistivity is very high, in the same range as most insulators, so that we would normally think of this material as an insulator. When the pure silicon is heated, however, its resistivity drops enormously. Though the drop is not enough to place hot silicon among the ranks of good conductors, the contrast with any other insulators is quite astonishing. Even more remarkable is the effect of impurities. Even traces of some impurities, one part per hundred million or so, will drastically change the resistivity of the material. It is because of this remarkable effect of impurity that we took so long to discover semiconductors – it was only in this century that we discovered methods of purifying elements like silicon to the extent that we could measure the resistivity of the pure material. It is interesting to note, incidentally, that a lot of this research was done during the great depression of the 1930s, and many politicians thought at the time that all this useless research should be scrapped and the money spent on something useful, like the dole.

The main difference between a semiconductor element and any other element is that a semiconductor can have almost any value of resistivity that you like to give it. It is, in other words, a material that can be engineered to have the characteristics that you want of it. The manipulation is done by adding very small quantities of other elements. These cannot be just any elements, however. Semiconductor elements, like metal and many non-metals, form crystals. A crystal is the visible evidence of the arrangement of atoms, and many materials have atoms that will arrange themselves into patterns because of the forces that exist between the atoms. When you add an impurity to a crystalline material, the atoms of the impurity have to take a place in the crystal. If the impurity atoms are very different in size, the result will be to distort the crystals, but it is usually possible to find elements whose atoms are about the same size as the atoms of the semiconductor material. When such atoms are added, it is likely that they will fit neatly into the crystal, taking the place of the normal atoms of the semiconductor. That is one requirement: fitting into the crystal. The other requirement is one of structure. The impurity atoms must not have the same arrangement of electrons as those of the semiconductor.

It's easier to see what is required if we look at some definite example. Pure silicon has atoms in which there are 14 electrons, but of these electrons, four are much less strongly bound – we can think of them as an outer layer. Now there are two elements, boron and phosphorus, that have atoms of fairly similar size, close enough to fit into the crystals of silicon. Of these, boron has only three electrons in its outer layer, and phosphorus has five. Both of these materials greatly affect the resistivity of the pure silicon, because they affect the availability of electrons. The phosphorus atom has one outer electron more than the silicon atom, and this will be set loose when the phosphorus atom is fitted into the crystal. The boron atom has one electron less in its outer layer, and this atom will trap an electron from a silicon atom. Either impurity causes a massive drop in resistivity, so that the material becomes a conductor.

Electrons and holes

Even in the nineteenth century there was a suspicion that electric current through solids was not all caused by electrons. Due in a very large extent to the work of a physicist called Hall, we discovered that there are two ways that electric current can be carried in crystals (note that this applies only to crystals). Crystals are never perfect, and when a crystal of an almost pure material has been deliberately made impure (or *doped*), the crystals contain atoms of a different type. If these atoms possess more or fewer electrons in their outer layer than the normal atoms of the crystal, then the electrical characteristics will also change. One way of changing the characteristics is to release more electrons. The other way is to release more holes. A hole is a part of a crystal that lacks an electron. Because of the structure of the crystal, a hole will move from atom to atom and when it does, it behaves just as if it were a particle with a positive charge. Within the crystal, the hole has a real existence, we can measure its charge and even a figure for mass. The important difference is that the hole is a discontinuity in a crystal, it has no existence outside the crystal. The electron, by contrast, can be separated from the crystal, and can even move in a vacuum (see Chapter 10).

Most metals exist as crystals, and are by no means very pure. As a result, holes exist in the crystals, and contribute to the flow of electric current. In a few metals (one is zinc) more of the current may be conducted by the holes in the crystals than by the electrons. Hole conductivity is even more important in semiconductors because we can control it. As we have described, doping a pure silicon crystal with boron will create holes, and make this silicon conduct mainly by hole movement. Silicon doped in this way is called **p–type**, the p meaning positive. This doesn't mean that the crystal has a positive charge, only that most of the current that flows through it will be carried by the positively charged holes. If, by contrast, we dope the pure silicon with phosphorus, the extra electrons released in this way ensure that most of the current flow is because of moving electrons. Because the electron is negatively charged, we call this doped silicon **n–type**. Once again, this does not mean that the material is negatively charged, only that most of the moving charged particles are electrons. Doped semiconductors, like all other solids, are electrically neutral; for each positive charge there is a negative one. The difference between p–type and n–type is decided by the charges that can move as distinct from the ones that are tightly bound into the atoms. Not only can we make a semiconductor have the amount of resistivity that we want (within limits), but we can decide which type of conductivity it will be. We will come back to the importance of all this in Chapter 11, when we look at the semiconductor diode and how it works.

2
Electrostatics

Electrostatics is about electric charge at rest, which in turn means electrons transferred from one place to another and staying in place. This transfer is not difficult: rub one insulator against another and a large number of electrons will be transferred, making each insulator charged. The presence of the charge will cause the insulators to be attracted to each other, and you can sometimes detect a spark if they are placed close to each other. The spark is the visible sign that the electrons have returned to their places through the air. Most of the effects of what we now call electrostatics had been noted by the middle of the eighteenth century; this was the first form of electricity to be discovered.

Charge and potential

Though the forces between charged insulators are certainly measurable, and we can measure amounts of charge by way of these forces, it is certainly not easy to measure charge in this way. The reason is that the amount of force between two charged objects depends on the distance between the charges, and it is not easy to know exactly where the charges are located. Experimenters like Coulomb used charged objects that were metal spheres supported on insulators, and assumed that the charge was concentrated at the centre of each sphere. This is a reasonable approximation, but since the charge on a metal can move about, it is not ideal. Small inaccuracies like this in the measurement of distance have a large effect on the result when we try to measure charge by the amount of force that it exerts. That's because the distance in the formula is squared (see Figure 2.1), which has the effect of magnifying any errors in distance measurement. It is quite remarkable, in fact, that Coulomb obtained results as precise as he did.

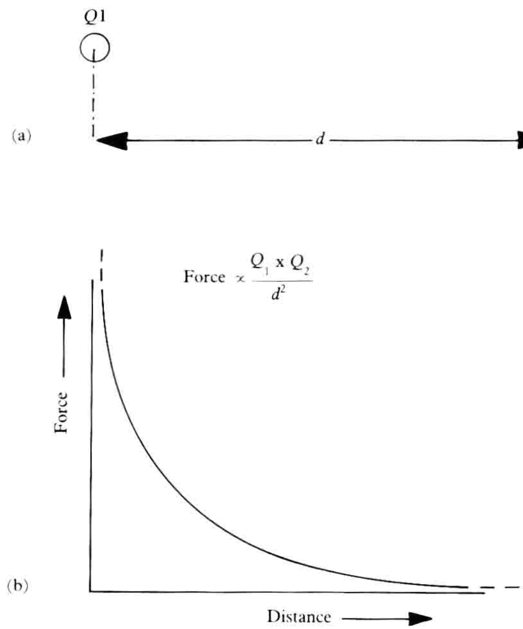

Figure 2.1 *Electrostatic force and distance. (a) The relationship between force, charge (Q) and distance (d) shows that the amount of force between charges depends on the product of the charge amounts divided by the square of the amount of distance. The graph (b) shows how force becomes negligible at larger distances, typically a few centimetres*

There is another effect of electric charge which is much easier to measure. When charge has been moved, some mechanical work is needed to move it. This amount of work divided by the amount of charge gives a quantity called **potential**, and the unit of measurement is called the **volt**. Modern instruments allow us to measure potential much more precisely than we could measure the mechanical force between charges, or the amount of charge, so that potential is a much more useful quantity to work with. In particular, the difference in potential between two points is easily measured, and is known as the PD (potential difference) or more usually, the **voltage**. From this measurable quantity, we can