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Electronics 2 Checkbook

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Preface

This book presents in a convenient form all the relevant facts and formulae required by the syllabus of the TEC level 2 course in electronics. It provides a comprehensive introduction to the subject assuming very little prior electrical, electronic or mathematical knowledge. It will also be of particular value to the established technician needing a quick refresher course, in basic electronics.

Each chapter contains the relevant theory and definitions in summarised form, together with the necessary formulae. Worked examples showing the best way in which examination questions should be answered by the student, take up a major part of the book. Conventional and multi-choice problems for self-working are also included.

Special thanks are due to the General Editors, John Bird and Tony May, for their valuable comments and suggestions. Thanks are also due to Mrs Joan Bodimeade who patiently typed a legible manuscript from a pile of almost illegible notes.

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Contents

1 Elementary theory of semiconductors

A. MAIN POINTS CONCERNED WITH ELEMENTARY THEORY OF SEMICONDUCTORS

1 (i) All matter exists in a solid, liquid or gaseous state. The smallest particle of any substance that retains the characteristics of that substance is called a **molecule**. Each molecule is built up from a number of chemical elements, the smallest particles of each element being known as **atoms**.

Atoms are believed to be made up of a positively charged core or nucleus about which one or more negatively charged particles called **electrons** rotate in planetary orbits. The charge on an electron is very small, about -1.6×10^{-19} coulomb and its mass is estimated to be 9.1×10^{-31} kg.

Normally an atom is electrically neutral, the effect of the negative charges carried by the rotating electrons being exactly balanced by the positive charge carried by the nucleus. The nucleus is itself made up of two other types of particle, **protons** and **neutrons**, though not necessarily equal in number. Only the proton carries a postive charge, the neutrons being without charge. Hence, since the entire atom is neutral, the charge on a proton is equal to the charge on an electron but is of opposite sign. The proton is about 1840 times as massive as an electron, however, so the nucleus constitutes almost the entire mass of the atom.

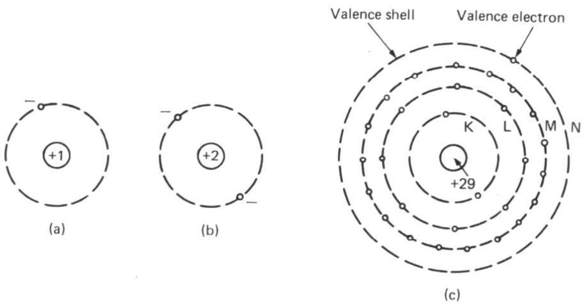


Fig 1(a) Hydrogen atom–a single proton in the nucleus with a single orbital electron
(b) Helium atom—two protons and two neutrons in the nucleus with two orbital electrons
(c) Copper atom—29 protons and 35 neutrons in the nucleus with 29 orbital electrons

(ii) The number of planetary electrons and the structure of the nucleus in an atom varies with the element. The lightest element, hydrogen, has only one proton as nucleus around which revolves a single electron. Next in the order is helium whose nucleus consists of two neutrons and two protons and about this revolves two electrons. Much further along the scale, an atom of copper consists of 29 protons and 35 neutrons in the nucleus, with 29 orbital electrons. These atoms are shown in *Fig 1*.

(iii) The revolving electrons are held in their respective orbital rings or **shells** by the attractive force of the nucleus. Most atoms have a number of shells and these are distinguished by assigning to them letters of the alphabet, starting at K for the innermost shell and proceeding through L, M and N to the outermost. The electrons making up the outermost shell are called **valence** electrons and these are least tightly bound to the nucleus. It is the valence electrons that play the active part in electrical conduction.

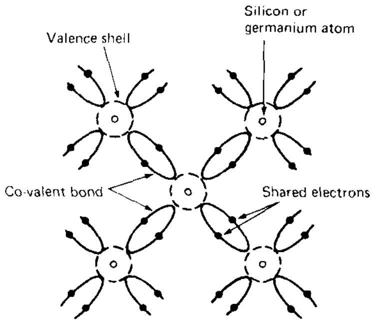
2 Solid materials are either **conductors** or **insulators** in their electrical properties. The behaviour of the valence electrons decides to which of these classes a particular material belongs. In insulating materials, i.e., mica, rubber and most plastics – the valence electrons are sufficiently tightly bound to the nucleus to remain in their orbits even when a large voltage is impressed across a piece of the material. Hence none of them become available to act as current carriers.

In a good conducting material – i.e., copper and aluminium – the valence electrons are only weakly bound to their atoms and many of them break free to drift within the atomic structure of the material. When a voltage is impressed across the material, these free electrons act as current carriers. Copper atoms have one valence electron as shown in *Fig 1* and this electron may become available as a charge carrier.

3 However, the distinction between insulators and conductors is not precisely defined and there are certain substances which are neither good insulators nor good conductors.

Into this category come the **semiconductors** which form the basis of all solid-state electronics. Semiconductors, notably germanium and silicon are crystalline materials in which the atoms are held together in a stable form by what is known as co-valent bonding.

Both germanium and silicon atoms have four valence electrons (they are **tetravalent** atoms). The structure of these elements is brought about by a sharing arrangement in which each atom has in effect, not four but eight valence electrons, its own four valence electrons being shared with those of an adjoining atom. A representation of this covalent bonding is shown in *Fig 2*, each band being a shared valence electron.



Each valence shell has the equivalent of eight electrons in the crystal lattice-four of them come from each atom itself and four others come from adjacent atoms

Fig 2

In this condition the atoms are in a very stable state and form throughout the material a geometrical arrangement which is known as a crystal lattice. Consequently, there are no free electrons available to act as charge carriers and the resulting crystal is an effective insulator. This situation is only true if two conditions are satisfied. Firstly, the crystal structure must be perfect in that all the covalent bonds are satisfied and, secondly, the temperature must be very low.

At room temperature, thermal vibration of the atoms breaks some of the covalent bonds and this, together with structural faults and impurities within the crystal provides free electrons which wander about among the atoms. The effect is accelerated as the temperature increases. Thus **thermally generated** electrons increase in numbers and turn the crystal from a very good insulator into a conductor, even if a relatively poor one.

4 Unlike those in copper (for example), electrons are not the only charge carriers produced in germanium or silicon. Where an electron breaks free, a vacancy or **hole** is left in the crystal structure. Since this hole has been formed by the removal of a negatively charged electron, the hole must behave as a positive charge.

If the material is connected to a voltage source, then the applied field attracts the free electrons towards the positive pole, whilst further free electrons flow in from the positive pole and travel through the semiconductor by moving from hole to hole.

This process can be looked on as electrons moving from negative to positive within the semiconductor (as well as in the external circuit wires) and holes moving from positive to negative within the semiconductor only. Both of these movements contribute to conduction and thus a current is maintained around the circuit (see *Fig 3*).

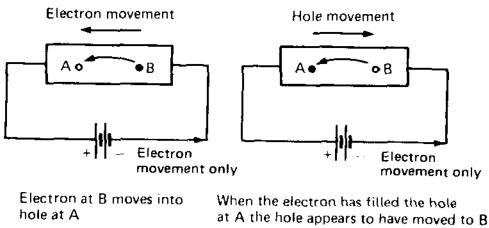


Fig 3

As the temperature is raised, more electron and hole pairs become available and the conductivity increases. The weak conductivity which results from such thermal effects is known as **intrinsic** conductivity.

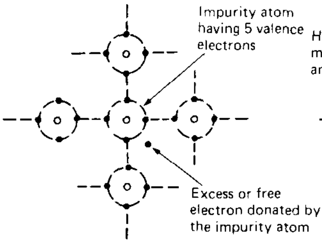
5 Because of its dependence upon temperature, intrinsic conductivity is of no practical importance. The manufacture of useable semiconductor material involves changes in the conduction characteristics so that either electrons *or* holes become the dominant charge carriers. This is done by the addition of an impurity into the semiconductor material.

Certain other elements have atoms which are able to fit into the crystal lattice of germanium or silicon without seriously upsetting the regular geometric construction. If the valency of these added atoms is different from those in the semiconductor material itself, then conductivity is enormously increased.

Fig 4 shows what happens when the atoms of the impurity have five valence electrons. Four of the five valence electrons from each added atom go to satisfy the valence bonds with neighbouring semiconductor atoms, but the fifth is 'left over' to move about the crystal and act as a charge carrier.

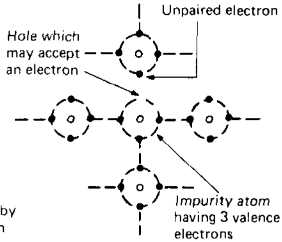
An impurity of this type is called a **donor** since it donates electrons as negative charge carriers. The doped material is now referred to as *n*–type semiconductor and electrons are the majority carriers.

Fig 5 shows the effect of adding impurity atoms which have three valence electrons. As before, each semiconductor atom has four valence electrons but the impurity atom has now only three. Only three valence bonds with neighbouring atoms can therefore be satisfied by the added atoms, so that a hole appears in what would have been the fourth bond.



Structure of *n*-type semiconductor

Fig 4



Structure of *p*-type semiconductor

Fig 5

Such an impurity gives the semiconductor an abundance of holes. We now have *p*–type material and the positive holes are the majority carriers. This time the impurity atoms are called **acceptors** because they can accept electrons from the surrounding crystal structure.

6 The doping of semiconductor material to produce majority carriers and so increase the conductivity does not mean that the thermally generated hole-electron pairs is no longer occurring. In *n*–type material, for example, as well as the many free electrons contributed by the donor impurity, there are a relatively small number of holes present because of such thermal breaking of the co-valent bonds. Similarly, in *p*–type material, thermally generated electrons are present.

Such unwanted carriers are known as minority carriers. Under an impressed voltage minority carriers move in the opposite direction to majority carriers but their numbers depend upon the temperature and *not* upon the added impurity atoms.

When a semiconductor has been doped with a suitable impurity, it is referred to as **extrinsic** *p*– or *n*–type, and the conduction which takes place is extrinsic conduction.

B. WORKED PROBLEMS ON ELEMENTARY THEORY OF SEMICONDUCTORS

Problem 1 Compare the change in conductivity between a semiconductor material and a metal like copper as the temperature is raised.

As the temperature of a semiconductor is raised, more covalent bonds are broken, more hole-electron pairs become available, and the conductivity increases. In a conductor, such as copper where there is an abundance of free electrons available even at a low temperatures, the conductivity depends upon the ability of these electrons to move through the material without colliding with the metal atoms.

As the temperature increases, the amplitude of vibration of the atoms due to the thermal energy increases so that they impede the movement of the charge carriers and the conductivity falls. Hence in semiconductor material resistance *falls* as temperature rises and in a metal conductor resistance *rises* as temperature rises. We say that semiconductors have a negative temperature coefficient.

Problem 2 Name the elements having three and five valence electrons respectively that may be used to dope semiconductor material.

Atoms that have three valence electrons are known as trivalent atoms. Trivalent impurity may be added by the introduction of the element boron, aluminium or indium. Atoms that have five valence electrons are pentavalent atoms. Examples of such impurity atoms are antimony, arsenic or phosphorus.

Problem 3 An atom of aluminium has a nucleus made up of 13 protons and 14 neutrons. It has three electron shells of which the innner contains 2 electrons. How many electrons are there in the middle shell?

Aluminium is trivalent so it has three electrons in the valence shell. As the atom is electrically neutral, there must be 13 electrons in the three shells, hence there must be $13 - 5 = 8$ electrons in the middle shell.

Problem 4 Sketch and briefly describe the make up of germanium and silicon atoms.

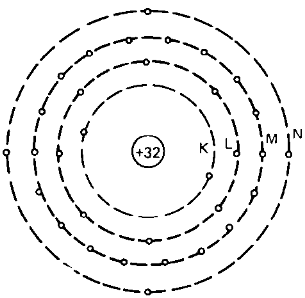


Fig 6(a) Germanium atom—a nucleus of 32 protons and 42 neutrons with 4 shells containing respectively 2, 8, 18 and 4 electrons

Germanium and silicon are the most extensively used semiconductors in the manufacture of transistors. Germanium is a greyish-white metallic element, made by reduction in a hydrogen or helium atmosphere of germanium dioxide. The dioxide is obtained as a component of the chimney soot from gasworks. The germanium atom is shown in *Fig 6(a)*; it has a nucleus of 32 protons and 42 neutrons with 4 orbital shells containing respectively 2, 8, 18 and 4 electrons.

Silicon is a non-metallic element, being second only to oxygen in its abundance in the earth's crust. It never occurs in nature in the free state, but in complex silicon compounds. Because of this it is more difficult to refine to a high degree of purity than is germanium and all the early solid-state devices were germanium based. The silicon atom is shown in *Fig 6(b)*. It has a nucleus of 14 protons and 14 neutrons with three orbital shells containing respectively 2, 8 and 4 electrons.

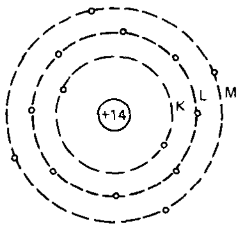


Fig 6(b) Silicon atom—a nucleus of 14 protons and 14 neutrons with 3 shells containing respectively 2, 8 and 4 electrons

Problem 5 **If impurity semiconductors have an excess of electrons or holes as charge carriers, why are these charges not lost when the semiconductor is connected to earth?**

Although, for example, there are free electrons in *n*–type semiconductor due to the addition of impurity atoms having five valence electrons, the crystal as a whole is electrically neutral as each impurity atom introduced is itself electrically neutral. This is true of any conductor; a length of copper wire, for example, although having an abundance of free electrons available as current carriers is not in any way negatively charged.

C. FURTHER PROBLEMS ON ELEMENTARY THEORY OF SEMICONDUCTORS

(a) SHORT ANSWER PROBLEMS (answers on page 107)

1 Atoms are made up from electrons, protons and with one exception, neutrons. Name the exception.

2 The K, L and M shells of a sodium atom contains 2, 8 and 1 electrons respectively. How many protons are there in the nucleus?

3 The phosphorus atom has three shells and its nucleus contains 15 protons. The K and L shells contain 2 and 8 electrons respectively. Would phosphorus impurity produce a p-type or an n-type semiconductor?

4 Fill in the blank spaces in the following table:

	Protons	K	L	M	N	shells
Aluminium	13	2		3	0	
Argon		2	8	8	0	
Copper	29	2	8		1	
Magnesium	12	2	8			

5 Complete the following statements:

(a) The atomic nucleus is made up of . . . . and . . . .

(b) In an intrinsic semiconductor there will always be . . . . number of holes and electrons.

(c) Intrinsic semiconduction is that conduction which takes place in a crystal of pure silicon or germanium when all current carriers are provided by . . . . produced when . . . . energy breaks the covalent bonds.

(d) The impurity atoms added to silicon to produce holes are known as . . . . atoms.

(e) *n*- and *p*-type impurity semiconductors are known as . . . . semi-conductors.

(f) Reducing the temperature causes the resistivity of semiconductors to . . . . and that of conductors to . . . .

6 Are the following true or false?

(a) At 0°C pure silicon is a perfect insulator.

(b) The conductivity of intrinsic germanium increases with temperature.

(c) In extrinsic semiconductors, the majority carriers are determined by the number of impurity atoms present.

(d) The majority carriers in extrinsic material cannot change with change in temperature.

(e) Atoms of phosphorus are known as acceptor impurities.

(f) In *p*-type material the majority carriers are holes.

(g) If the temperature of an intrinsic semiconductor is increased, the number of hole-electron pairs increases.

(h) *n*-type material is made by the addition of pentavalent material to an instrinsic semiconductor.

(j) The charge on a hole is the same as the charge on an electron but of opposite sign.

7 Name three good conductors and three good insulators of electricity.

8 Name two semiconductor materials and compare their properties in relations to (a) a good conductor, (b) a good insulator.

9 Name a suitable doping element for obtaining (a) *n*-type semiconductor material; (b) *p*-type semiconductor material.

10 Name two trivalent materials used in the formation of *p*-type material.

(b) CONVENTIONAL PROBLEMS

1 Explain what is mean by (a) intrinsic; (b) extrinsic action in a semiconductor

2 The current in a copper conductor is 2 A. How many electrons pass a given point in 1 minute? (Charge of electron = 1.6×10^{-19} C)

3 In *Fig 7* the rectangle represents a piece of intrinsic semiconductor. Using arrows, show clearly the flow of charge carriers within the semiconductor and in the external circuit.

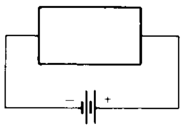


Fig 7

4 Explain the meaning of the following terms:
(a) electron shells; (b) co-valent bonds; (c) impurity atom;
(d) minority carriers; (d) intrinsic semiconductor; (f) extrinsic semiconductor;
(g) donor atoms; (h) acceptor atoms.

2 The *p-n* junction diode

A MAIN POINTS CONCERNED WITH THE *p–n* JUNCTION DIODE

1 (i) If a crystal of *n*-type semiconductor and a crystal of *p*-type semiconductor are joined, the combination is known as a *p-n* junction. Such a junction forms the basis of all diode and transistor action.

It is not possible to get the desired result simply by clamping two pieces of semiconductor crystal together because there is a discontinuity in the crystal structure at the line of contact. The crystal structure must be complete throughout the junction and *Fig 1* shows two possible ways (out of several) of achieving this result. Either the *n*- and *p*-regions are grown into pure semiconductor crystal by mixing the donor and acceptor impurities respectively into the crystal during its formation, diagram (a), so producing a single crystal which has *n*-type characteristics at one end and *p*-type characteristics at the other; or a junction is made by placing a small pellet of, say, acceptor impurity such as indium, on one face of a thin wafer of *n*-type material and then heating the assembly to alloy the impurity pellet into the body of the wafer. This the **alloy-junction** or diffused alloy form of construction, and diagram (b) illustrate the basic process.

(ii) Another form of construction is possible using a fine, pointed tungsten wire, known as the 'catswhisker', pressed into contact with a small wafer of *n*-type material. *Fig 2* shows one typical form of assembly; this is the **point-contact**

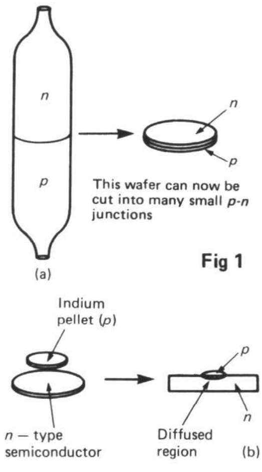
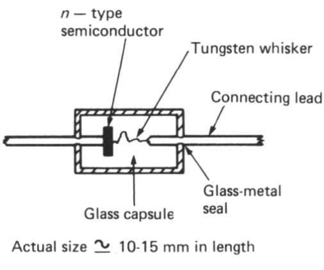


Fig 1



Actual size ≃ 10-15 mm in length

Fig 2

junction. After assembly, a high current pulse is passed momentarily across the junction of whisker and wafer. This current surge creates heat and drives a number of electrons away from the atoms in the region of the point contact, leaving holes and so converting a small volume of the wafer immediately under and around the point into *p*-type material. A *p-n* junction is so produced surrounding the metal point.

2 To understand the operation of a *p-n* junction as a practical semiconductor device, we must look at the way the free charge carriers, electrons and holes, behave in the two types of semiconductor when the junction is formed.

In *Fig 3*, the *p*-region has holes (open circles) and the *n*-region has electrons (filled circles) available as majority carriers. Notice that a few electrons are shown

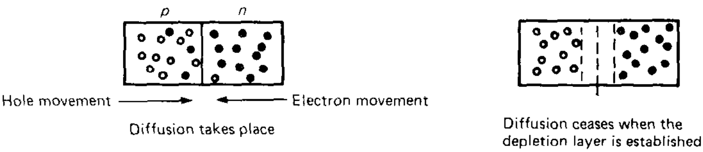


Fig 3

in the *p*-region and a few holes in the *n*-region, but in each case these minority carriers are far outnumbered by the majority carriers.

Holes, having a positive charge, move from the *p*-region on the left of the junction into the *n*-region on the right. At the same time, electrons having a negative charge, move from the *n*-region on the right of the junction into the *p*-region on the left. This initial movement of charges, which takes place as soon as the junction is formed, is known as **diffusion**.

The electrons and holes that have diffused across the junction in this way are soon lost in recombination. Hence a very thin region is established on each side of the junction line in which no free carriers are present. This region is called the **depletion layer** and it separates the charges on the two sides of the junction.

As soon as this separation is established, an electric field is developed across the junction and further diffusion is stopped. Since the *p*-side has gained electrons and the *n*-side has gained holes, the *p*-side will become negative with respect to the *n*-side and the field acts in such a direction that it tends to prevent more negative charges leaving the *n*-region and more positive charges from leaving the *p*-region.

The situation is then equivalent to a source of potential acting across the junction

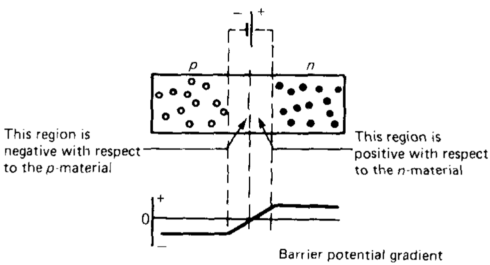


Fig 4

and represented by a hypothetical battery E connected as shown in *Fig 4*. Make a careful note of the polarity of this **barrier potential** as it is called. The graph drawn underneath the diagram is a simple representation of the variation in potential acting across the junction.

The minority carriers have now to be considered. Thermally produced hole-electron pairs will occur in the regions near the junction. The holes produced in the *n*-region and the electrons produced in the *p*-region will be minority carriers and will tend to be *assisted* across the junction by the same barrier potential which is opposing the movement of majority carriers. The movement of these minority carriers is equivalent to a coventional current flowing from *n* to *p*, that is, in the opposing direction to the recombination movement.

Fig 5(a) right

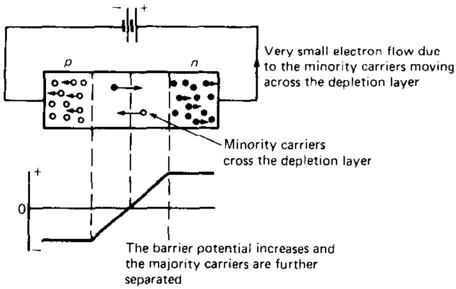
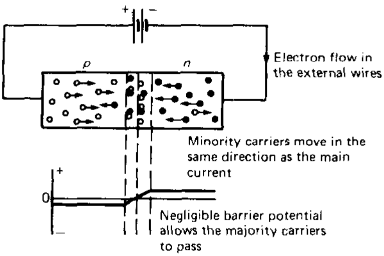


Fig 5(b) below



The actual barrier potential depends upon the densities of the carriers and the semiconductor material. It is about 0.2 – 0.3 V for germanium and 0.6 – 0.7 V for silicon.

3 Suppose now that a battery is connected externally to the *p-n* junction, acting in the direction shown in *Fig 5(a)*. Here the *p*-region is made negative and the *n*-region is made positive. Holes are attracted by the negative field and electrons by the positive field; in other words, the polarity of the external battery is such as to *assist* the junction barrier potential. Holes and electrons are both pulled away from the junction in the direction of the arrows.

This further separation of the majority carriers makes the junction resistance very high and the current flow around the external circuit is very low. It is not zero, however, as we might at first suspect, because the minority carriers on each side of the junction are attracted across the depletion layer by the barrier potential. The resulting flow of current by this movement of the minority carriers is known as