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# Engineering Training Publication

## Semiconductor Devices 1

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Prepared by:
Training Group.

Authorised by:
Superintending Engineer,
Operations Planning and Programming Branch, HQ.

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**Telecom Australia**

Telecom Australia
ENGINEERING TRAINING
210 Kingsway South Melbourne 3205

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# SEMICONDUCTOR DEVICES 1

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## 1. INTRODUCTION.

1.1 The family of semiconductor or 'solid state' devices includes transistors, diodes, varistors, thyristors, and many others. All are available in a large number of types and ratings, and are widely used in telecommunication equipment. Examples of their applications include use in:

- Amplifying equipment used to raise the power level of communication signals.
- Oscillators, which generate many of the a.c. frequencies used in telecommunications.
- Electronic switching equipment used in automatic mail-handling centres, electronic exchanges, and computers.
- Power-supply equipment in telecommunication stations.
- Test and fault-location instruments used in the servicing of telecommunications equipment.

1.2 This paper describes the basic principles of semiconductor diodes, bipolar transistors, and field-effect transistors. Explanations of other semiconductor devices are given in other papers.

## 2. SEMICONDUCTOR MATERIALS.

2.1 Semiconductor or 'solid state' devices are manufactured from semiconductor elements such as silicon and germanium, or from semiconductor compounds formed from materials such as selenium, cadmium, and sulphur. All semiconductor materials, whether element or compound, have the following electrical characteristics:

(a) Electrical conductivity (and resistivity) between that of metallic conductors and insulators.

(b) A rise in temperature usually decreases the resistivity. (In metallic conductors, a rise in temperature increases the resistivity).

(c) At very low temperatures, (approaching absolute zero, - 273°C) semiconductors become insulators, whilst metals approach zero resistance.

(d) Impurities in semiconductors decrease the resistivity. (In metals, impurities increase resistivity).

Also, semiconductor materials react uniquely to forces such as those from light, electric fields, and magnetic fields. These effects are utilised in semiconductor components such as photo-electric cells, field-effect transistors, and other devices.

2.2 Most of the semiconductor material used in electronic components consists of highly refined silicon or germanium, which has been 'doped' by the addition of minute traces of other elements called 'impurities.' This doping of pure semiconductors has two effects:

- The atomic structure of the semiconductor material undergoes a change.

- This structure change causes a reduction in the resistivity of the material.

Depending on the element used as the impurity, the structure change in the pure semiconductor results in its modification to one of two electrically different types of material. These are known as 'P-type' and 'N-type' semiconductors.

P-TYPE semiconductor materials have an atomic structure which, although electrically neutral, has gaps or 'holes' that will readily accept electrons. This phenomenon is caused by the doping of the pure semiconductor with a carefully controlled amount of an element such as aluminium or indium.

N-TYPE semiconductor materials have an atomic structure which, although electrically neutral, has a number of electrons which are not bound to particular atoms, and can move around freely within the material. This phenomenon is caused by the doping of the pure semiconductor with a carefully controlled amount of an element such as antimony or phosphorus.

2.3 P-N JUNCTIONS. When a junction is made between a piece of P-type material and a piece of N-type material (Fig. 1), a complex electrical action occurs at the junction. This action is based on the free electrons in the N-type and the holes in the structure of the P-type materials, and results in the creation of a 'barrier' region centred on the junction.

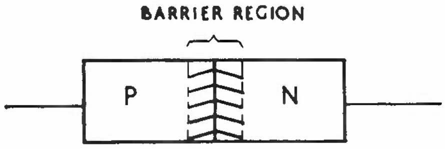
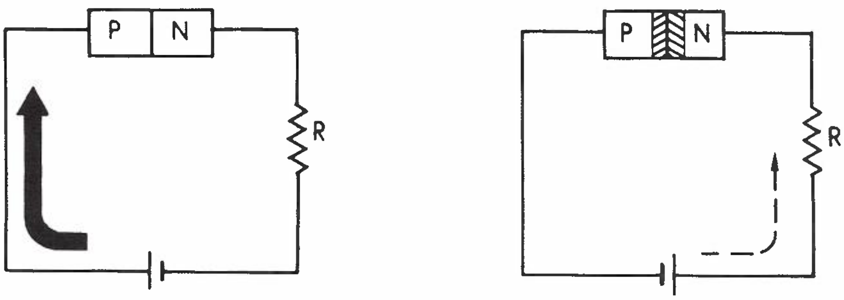



FIG. 1. P-N JUNCTION.

The detailed interaction between free electrons and holes is beyond the scope of this paper, but the effect produced in the barrier region is one of resistance to current flow. The amount of resistance depends on the polarity and value of applied voltage, as follows:

- When the voltage is applied as in Fig. 2a, the effect of the barrier region is reduced. At a certain critical value of voltage, (0.2 volt for germanium, 0.6 volt for silicon) the resistance decreases to a very low value. The resultant current has to be limited by a series resistor to prevent over-heating of the junction.

- When the applied voltage is reversed, as in Fig. 2b, the barrier effect is greatly increased. The junction, under this condition, behaves like a resistor of extremely high value.




(a) (b)

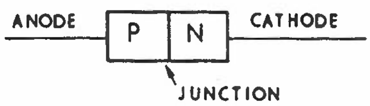
FIG. 2. P-N JUNCTION WITH VOLTAGES APPLIED.

These effects at the junction of P-type and N-type semiconductor materials are the basis of operation for semiconductor devices such as diodes, transistors, thyristors, photo-diodes, and many others.

## 3. SEMICONDUCTOR DIODES.

3.1 The 'one-way' current flow characteristic of the P-N junction is the basis of the semiconductor diode. Generally, a diode is considered to be a device which conducts readily when a voltage is applied in one direction, and blocks current flow when the voltage is applied in the other direction. Because of this property, diodes are commonly used in circuits where it is required that a device or circuit be energised only when current flows along the circuit path in a particular direction. Figs. 3a and 3b show the diode symbol and junction diagram respectively.


(a) Circuit Symbol.

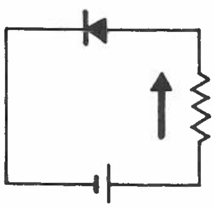



(b) Junction Diagram.

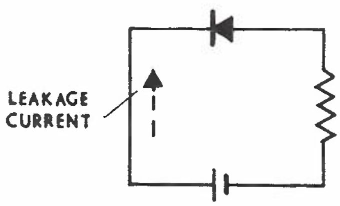
FIG. 3. SEMICONDUCTOR JUNCTION DIODE.

3.2 When a voltage is applied across the leads such that the Anode becomes positive and the Cathode negative (Fig. 4a), the diode conducts quite readily. The diode thus has a low resistance in the forward direction, and is said to be "forward biassed".

Reversal of the applied polarity (as in Fig. 4b) causes the diode resistance to increase to a very high value. The diode is then effectively 'blocking' current flow in the reverse direction, and is said to be 'reverse biassed'. Ideally, a reverse biassed diode will completely block current flow. However, in practice there is always a small current flow called the 'leakage current'. In some diodes its value is usually so small as to be negligible.



(a) Diode Conducting Current.




(b) Diode Blocking Current.

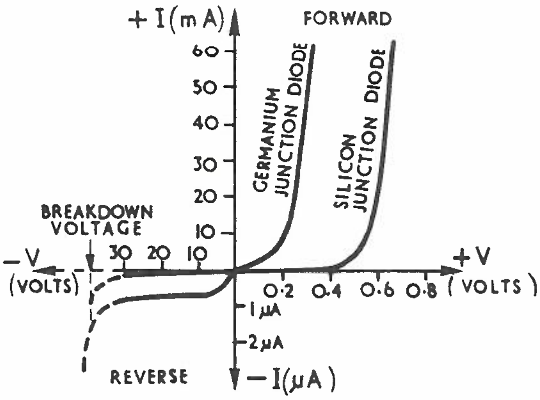
FIG. 4. ELECTRICAL PROPERTIES OF A DIODE.

**3.3 DIODE CHARACTERISTIC GRAPH.** The electrical characteristics of a diode are found by measuring the current-flow values of an appropriate range of forward and reverse voltages. The characteristic graph for the diode is then developed by plotting these figures on to a graph. Fig. 5 shows a typical diode characteristic graph. Note that each axis has different scales for its forward and reverse values; in this example, the current axis is scaled in milliamps for forward currents, and microamps for reverse currents. Also, there are three important points to be observed. They are:

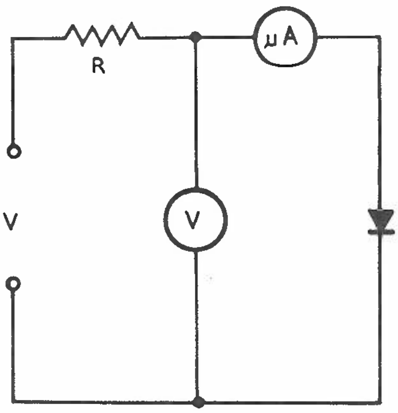
(a) The graph shows that the reverse current increases steeply when the reverse voltage exceeds 40 volts. This indicates the highest voltage that this particular diode can withstand. Higher voltages will cause destruction of the semiconductor junction.

(b) The graph also shows that the silicon diode requires 0.6 volt of forward bias before it is 'turned on', and conducts readily. The figure for germanium devices is 0.2 volt.

(c) The graph indicates that the respective resistances of the diodes are not constant, but change according to current flow. For example, when the current in the silicon diode is 50mA, the P.D. is 0.6 volt, which indicates a resistance of 12 ohms. When I = 5mA, the P.D. = 0.5 volt, which indicates a resistance of 100 ohms. Semiconductor diodes are thus said to have a 'non-linear' resistance characteristic.




(a) Graph.




(b) Test Circuit.

FIG. 5. DIODE CHARACTERISTICS.

**3.4 TYPICAL DIODE APPLICATION.** Fig. 6 shows a simple application for a diode. It is wired in series with a lamp so that the lamp may be used to check the output polarity of D.C. power supplies. When the tester is connected to a polarity as shown in Fig. 6a, the lamp glows to indicate that terminal A is positive with respect to terminal B. If the tester leads are reversed, as in Fig. 6b, the diode prevents the glowing of the lamp.

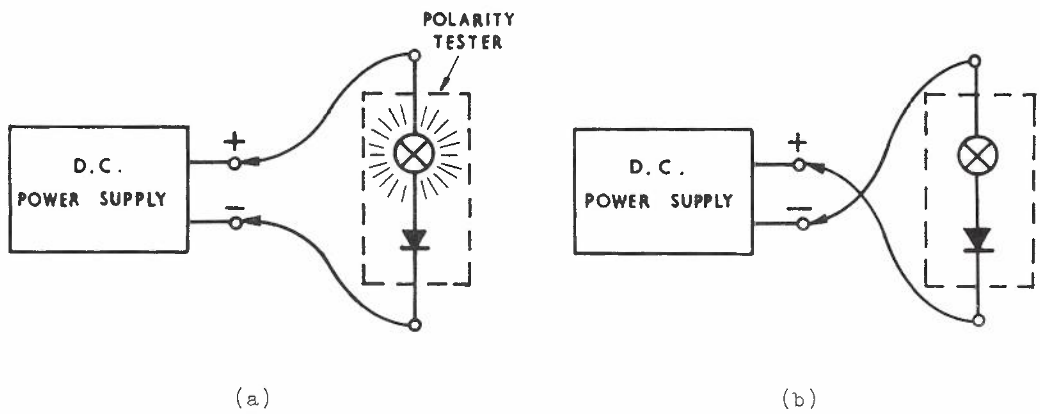



FIG. 6. SIMPLE APPLICATION OF A DIODE.

**3.5 DIODE MARKINGS AND RATINGS.** Most diodes are identified by the manufacturer's code number on the case. This coding does not in itself give the diode characteristics, but refers the user to the maker's reference manual. The polarity of a diode is indicated either by a painted marking (such as a dot or ring) at the cathode end, or by a diode symbol on the case. If there is any uncertainty, the maker's reference manual should be consulted. Fig. 7 shows the various types of markings used on semiconductor diodes. These diodes range from small, 'signal' devices, to 'power' types handling hundreds of watts.

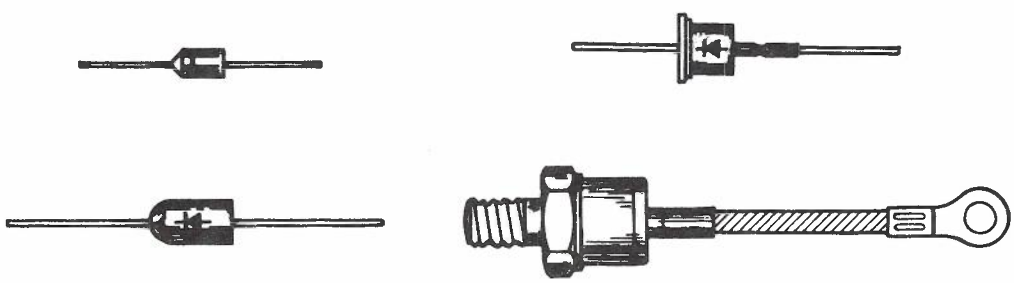


FIG. 7. SEMICONDUCTOR DIODES.

## 4. BIPOLAR TRANSISTORS.

4.1 Transistors are used extensively in applications such as amplification and switching. In these applications, their main function is to use comparatively small amounts of input power to control larger power levels at their outputs. There are two methods used to achieve this control of output power. One of them forms the basis of *bipolar transistors,* which are explained in this section. The other method is the basis for the *field-effect transistors* explained in Section 5.

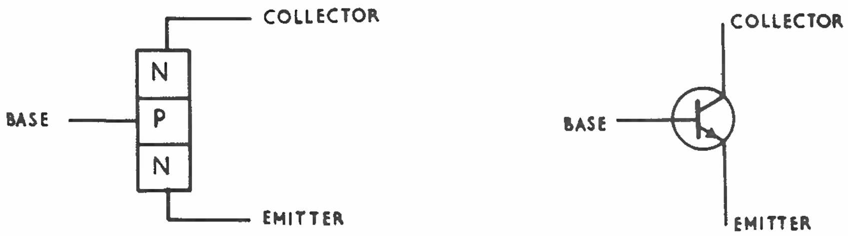
4.2 The bipolar transistor is formed from the same types of P and N semiconductor material as the diode discussed in Section 3. Most bipolar transistors are formed from P-type and N-type silicon, because it can withstand much higher operating temperatures than the germanium commonly used for most early types of transistor. Also, silicon transistors have much lower leakage currents than germanium transistors. (Leakage currents and their effects are explained in para. 4.9). The most common variety of bipolar transistor is the 'junction' transistor, which is formed by the fusion or 'junction' of two pieces of similar semiconductor materials on to a third, dissimilar, piece. This third piece is termed the base, and the relative positioning of the other two pieces on the base is particularly important. The two electrically different types of bipolar transistor which can be formed are called 'NPN' and 'PNP' transistors.

- NPN transistors are formed from two N-type pieces fused on to a P-type base as shown in Fig. 8a.

- PNP transistors are formed from two P-type pieces fused on to a N-type base. These are described in para. 4.8.

In this paper, explanation of bipolar transistor operation is based on the NPN type, as it is the more widely used.

4.3 **NPN TRANSISTORS.** The junction diagram and circuit symbol of an NPN transistor are shown in Fig. 8a and 8b respectively. The junction diagram shows that the NPN transistor consists of a P-N junction from base to emitter, and a P-N junction from base to collector. When tested electrically, each junction has diode characteristics. However, because of the very close proximity of the junctions and their barrier regions, the behaviour of the transistor as a whole does NOT resemble that of two diodes with their anodes connected. The electrical activity occurring in the barrier regions of a transistor is quite complicated, and beyond the scope of this paper.



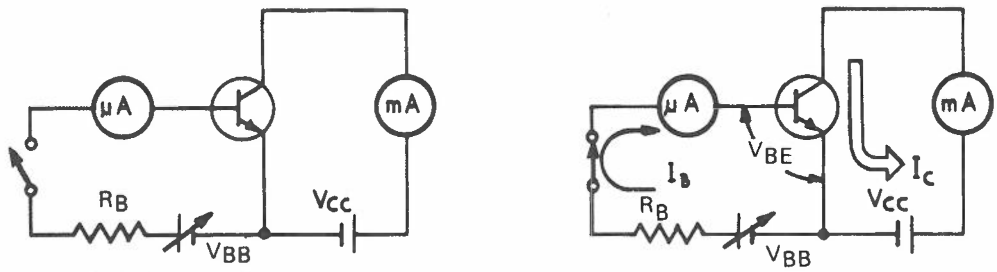

(a) Junction Diagram. (b) Circuit Symbol.

FIG. 8. NPN TRANSISTOR.

POLARITIES FOR NPN TRANSISTORS. In most applications, NPN transistors require that the base and collector electrodes both be positive with respect to the emitter (Fig. 9). Each electrode must have the correct polarity applied if the transistor is to function correctly; incorrect polarities usually cause destruction of one or both junctions.

**4.4 PRINCIPLE OF OPERATION.** Fig. 9 shows a simple test circuit for demonstrating the operation of an NPN transistor. The circuit has meters for measuring the circuit currents, a switch to open and close the base circuit, and a resistor $R_B$ to limit the current through the forward biassed base-emitter junction. The operation of the transistor is demonstrated in the following steps:

- When the switch is closed, (Fig. 9), a 'base current' $I_B$ flows through the base-emitter junction via $R_B$ from battery $V_{BB}$. When the p.d. across the base-emitter junction ($V_{BE}$) exceeds 0.2 volts for a germanium transistor (0.6 volts for silicon transistor) the transistor is 'turned on'. This causes a 'collector current' $I_C$ to flow via the collector-base and base-emitter junctions in series. The value of this collector current is usually much higher than the corresponding base current.
- When the switch is opened, (Fig. 9a) the base current ceases, which in turn stops the collector current (other than for a small amount of leakage current). This shows that collector current flows only when the base-emitter junction is carrying current. This property is used in electronic switching circuits, as described in Section 6.
- When $V_{BB}$ is increased in small steps, $I_B$ increases in an almost direct proportion, and the value of $I_C$ also increases. However, the meter readings (Table 1) indicate that the changes in $I_C$ are much greater than the $I_B$ changes that caused them. This is the property of the bipolar transistor that is used in amplifiers, as described in Section 6.




(a) Switch Open. (b) Switch Closed.

FIG. 9. BIPOLAR TRANSISTOR TEST CIRCUIT.

**4.5 $I_B/I_C$ CHARACTERISTIC.** The ratio of the change in $I_C$ to the change in $I_B$ is usually determined with a circuit such as that shown in Fig. 9. The figures obtained from measurements on a typical low-power transistor in such a test circuit, are shown in Table 1. The current values show, for this particular transistor, that each 10 µA change in base current caused a 500 µA change in collector current. Therefore, for this transistor, the changes in $I_C$ are 50 times larger than the changes in $I_B$.

| $V_{BB}$ | $I_B$ | $I_C$ | $V_{CC}$ |
|---|---|---|---|
| 1.32 v | 10 µA | 0.5 mA | 12 volts |
| 1.77 v | 20 µA | 1.0 mA | |
| 2.22 v | 30 µA | 1.5 mA | |
| 2.68 v | 40 µA | 2.0 mA | |

TABLE 1.

The control of $I_B$ over $I_C$ is achieved by a complex action at the two P-N junctions within the transistor. The amount of control is termed the *current gain* of the transistor, and it is calculated from the formula -

$$\beta = \frac{\Delta I_C}{\Delta I_B} \quad (V_{CE} \text{ constant})$$

*where*

*β represents current gain.*
*Δ means 'small change in'*
*$I_B$ is base current.*
*$I_C$ is collector current.*
*$V_{CE}$ is the collector-emitter voltage.*

This relationship is illustrated graphically in Fig. 10. The $I_B$ axis is calibrated in microamps, and the $I_C$ axis in milliamps, and typical corresponding 'small changes' in $I_B$ and $I_C$ are indicated. It can be checked that the values given will yield a current gain of 50.

This graph is termed the '$I_B/I_C$ characteristic' of the transistor.

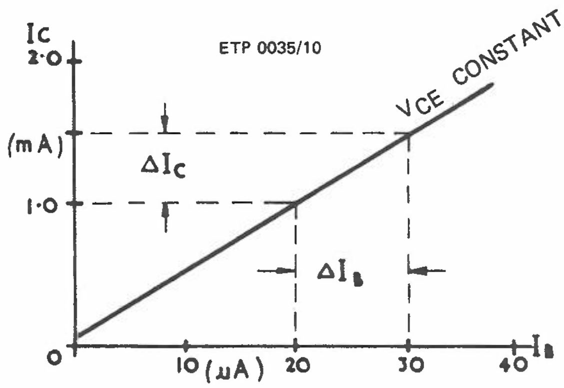



FIG. 10. $I_B/I_C$ CHARACTERISTIC OF A BIPOLAR TRANSISTOR.

**4.6 EMITTER CURRENT ($I_E$) IN A BIPOLAR TRANSISTOR.** Both the collector current and the base current flow via the emitter of a bipolar transistor, as shown in Fig. 9b. The emitter current $I_E$ is therefore the sum of $I_B$ and $I_C$, as expressed in the formula -

$$I_E = I_B + I_C$$

In a typical low power transistor, 98% of the emitter current is from the collector circuit. In high power transistors, the figure is about 90%.

**4.7 EFFECT OF INPUT VOLTAGE ON OUTPUT RESISTANCE.** The figures given in Table 1 show that the battery voltage $V_{BB}$, because of its control of $I_B$, determines the value of $I_C$. In addition to this, it can be shown that the input voltage effectively determines the 'output resistance' between the collector and emitter leads. This is shown by using Ohm's Law to calculate the output resistance for two of the sets of values in Table 1. Example 1 and 2 illustrate the output resistance when $I_b$ is 20μA and 40μA respectively.

Example 1. When $I_B = 20\mu A$, $I_C = 1mA$

Applying Ohm's Law, the output resistance $= \frac{V_{CE}}{I_C}$

$$= \frac{12}{1} \times \frac{1000}{1}$$

$$= 12 \text{ K ohms.}$$

Example 2. When $I_B = 40\ \mu A$, $I_C = 2mA$.

Applying Ohm's Law, the output resistance $= \frac{V_{CE}}{I_C}$

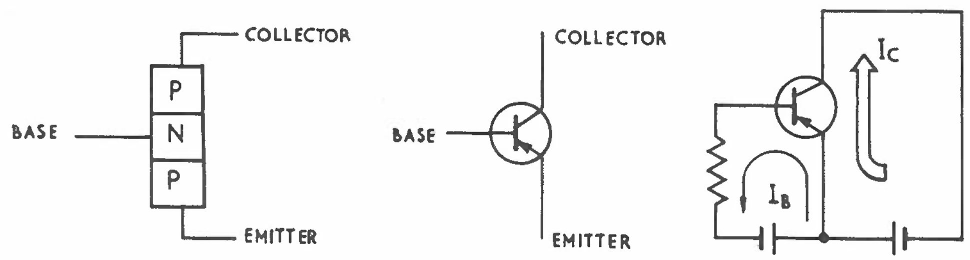
$$= \frac{12}{1} \times \frac{1000}{2}$$

$$= 6\ K\ ohms.$$

These examples demonstrate that an increase in the input voltage $V_{BB}$ causes $I_B$ and $I_C$ to increase proportionally and the output resistance to drop from 12 K ohms to 6 K ohms. The general conclusion, therefore, is that the input voltage to a bipolar transistor determines not only the value of $I_C$, but also the value of the output resistance. This concept will be used in Section 6 as the basis for explanation of the amplifying and switching applications of transistors.

**4.8 PNP TRANSISTORS** have similar principles of operation and characteristics to NPN types, but require different polarities on their electrodes. As in the NPN types, change of the d.c. polarities on the electrodes can cause destruction of the junctions.

The construction principle and circuit symbol are shown in Figs. 11a and 11b respectively. Fig. 11c shows the correct electrode polarities.




(a) Junction Diagram. (b) Circuit Symbol. (c) Electrode Polarities.

FIG. 11. PNP TRANSISTORS.

PNP transistors are used mainly where required by circuit polarities or other restrictions. They are usually formed from silicon, except for early types, which were formed from germanium.

**4.9 LEAKAGE CURRENTS IN TRANSISTORS.** In an ideal transistor, the cessation of base-to-emitter current would cause complete cessation of collector current. In practice, however, collector current does not cease completely; a small residual value of collector-to-emitter current continues to flow via the collector-base and base-emitter junctions in series, as shown in Fig. 12. This current is termed the *leakage current*. It exists because the collector-base junction, which is effectively 'reverse biassed' by the d.c. supply, is not perfect and therefore cannot completely block current flow.

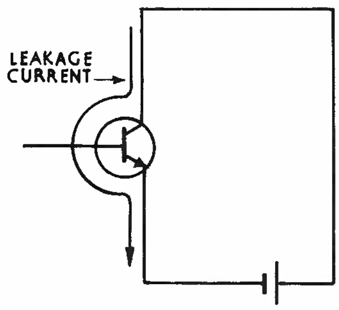


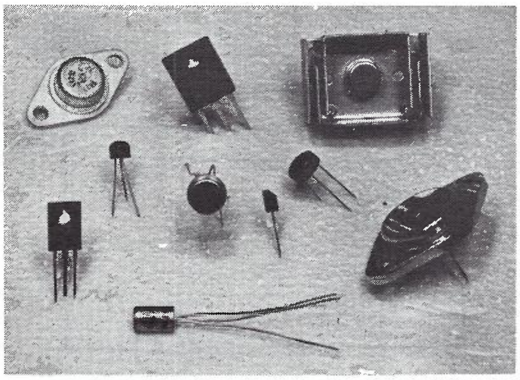

FIG. 12. LEAKAGE CURRENT IN A NPN TRANSISTOR.

The value of leakage current depends on the type of transistor and the temperature at which it is working, for example:

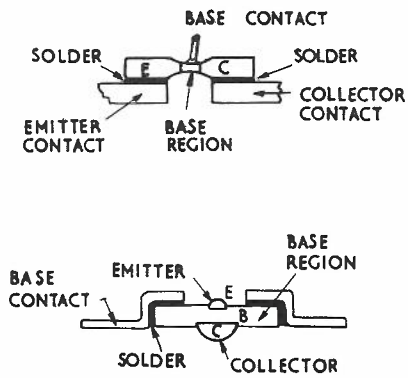
- Germanium transistors have higher leakage currents than silicon types of comparable size.
- High power transistors have higher leakage currents than low-power types.
- All transistors have increased leakage currents with increase in temperature. Excessive values of leakage current can lead to overheating of the junctions.

**4.10 TRANSISTOR CODINGS AND IDENTIFICATION.** Transistors are marked with the manufacturer's name and a code number, which refer the user to the maker's reference manual. The manual lists the characteristics of the transistor, and also identifies the leads. On small, low power transistors, the collector lead is usually identified either by a paint dot or a metal lug on the case. Larger, high power transistors are often marked with 'B' and an 'E' against the base and emitter leads respectively. Where there is any doubt, the maker's reference manual should be consulted.

Fig. 13a shows various bipolar transistors, ranging from low power types handling 300 milliwatts to high-power types capable of handling up to 150 watts. Note the code numbers and lead identification symbols. Fig. 13b shows two common types of transistor construction.



(a) Transistors.




(b) Types of Construction.

FIG. 13. TYPICAL BIPOLAR TRANSISTORS.

## 5. FIELD-EFFECT TRANSISTORS.

5.1 Field-effect transistors (usually termed FETs) are used in many of the switching and amplifying applications that are unsuited to bipolar transistors. For example, one of their electrical characteristics is an extremely high input impedance, which makes them suitable for many high-frequency and measuring instrument applications. Also, the transistor structures in many 'integrated circuits' (IC's) are field effect devices. This is because they are more easily constructed on the IC base than are bipolar devices. There are several different types of FET, but all of them have the same basic principle of operation. The differences between the types are mainly in the materials used and the construction. Typical materials include N-type silicon, P-type silicon, and metal oxides; the materials used in a particular FET determine its characteristics and electrode polarities.

In this section, each of the main types are explained, with the appropriate symbols and characteristic graphs.

5.2 PRINCIPLE OF THE FET. As stated in Section 1, semiconductors are a group of substances which have unique physical and electrical properties. The electrical property utilised in the FET is that of the control of conductivity by the strength of an electric field, a property which was first demonstrated in 1948. It was shown that a strong 'electric field' (i.e. the field between electrostatic charges) acting perpendicular to a thin layer of semiconductor material (Fig. 14a) changes the conductivity of the material to a markedly different value. Variations in the field strength cause variations in the conductivity, and therefore the resistance, of the material. Subsequent development and improvement of this technique have resulted in the present-day family of field-effect transistors.

The application of this principle in the FET is shown in Fig. 14b. In this device, the main current flow is between the collector and emitter, through a region termed the 'channel'. The changes in strength of the electric field between the gate and emitter either increase or decrease the conductivity of the semiconductor material comprising the channel. By this means, the current flow along the channel is controlled by the gate-emitter voltage.

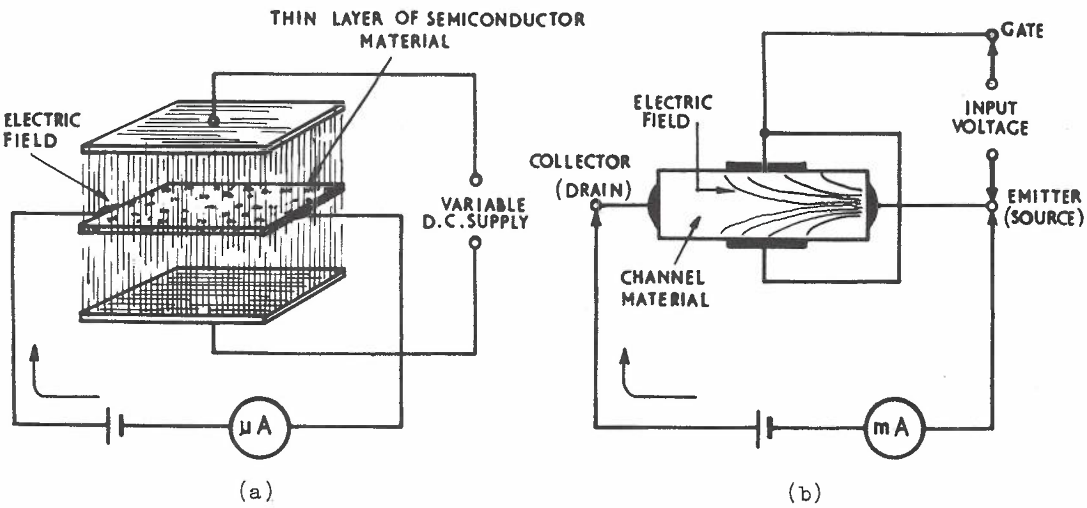
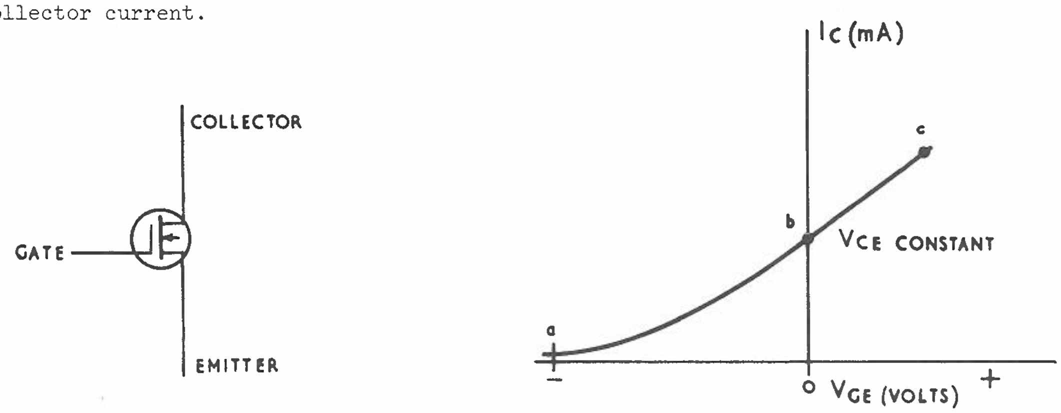



FIG. 14. PRINCIPLE OF THE FIELD-EFFECT TRANSISTOR.

Although there are several types of FET, all of them have this basic principle: *changes in gate-emitter voltage cause changes in collector-emitter current.* The main differences between types are the in-gate structure and the nature of the channel material.

The two main types of FETs are *insulated-gate FETs* and *junction-gate FETs*. The names are derived from the way in which the gate electrode is related to the rest of the transistor, and the resultant electrical characteristics. In this paper, the other two electrodes are termed the 'collector' and 'emitter'. These names correspond with the alternative names of 'drain' and 'source' respectively.

5.3 **INSULATED GATE FETs (IGFETs)** have a gate electrode which is electrically isolated from the rest of the transistor. Many IGFETs consist of a combination of Metal Oxide and Semiconductor materials. This accounts for the alternative IGFET name 'MOSFET'. The symbol of a basic IGFET and its gate voltage versus collector current characteristic are shown in Figs. 15a and 15b respectively. The characteristic shows how the voltage across the gate and emitter controls the collector current.




(a) Symbol.

(b) Gate Voltage Versus Collector Current Characteristics.

FIG. 15. TYPICAL IGFET.

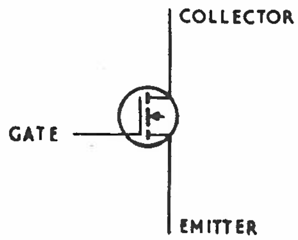
With reference to Fig. 15b, note the following points:

- At point 'a', the value of gate-emitter voltage $V_{GE}$ is sufficiently negative to reduce the channel conductivity to zero. The electric field between the gate and emitter electrodes is said to have 'depleted' the channel region to the 'cut off' point, and thus caused the collector current to cease.
- At point 'b', there is no gate-emitter voltage, and therefore no electric field. The current along the channel depends only on the normal conductance of the channel material.
- From 'b' to 'c', the gate is positive with respective to the emitter, and the collector current increases. The gate voltage is now said to be 'enhancing' the channel region, and increasing its conductivity.

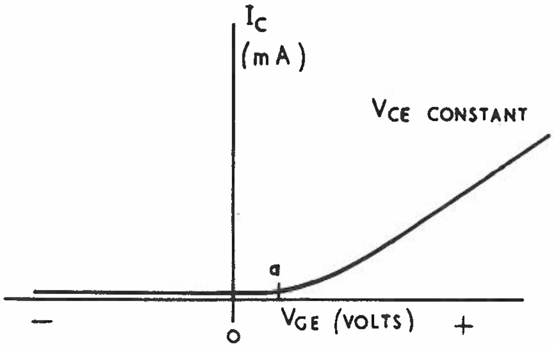
IGFETs which have these characteristics are termed 'depletion-enhancement' types. The thick unbroken line in the symbol represents the channel, and the fact that it conducts without need for bias.

5.4 The IGFET described in para. 5.3, has a channel made from N-type material. This IGFET, and all FETs having N-type channel material, require negative gate polarity for depletion and positive gate polarity for enhancement. In this paper, the FET descriptions are based on N-channel devices. P-channel types differ only in their gate polarities and symbols; the gate polarities are the opposite to those in N-channel types, and the symbols show the arrowhead pointing away from the line instead of towards it.

5.5 The symbol for another basic type of IGFET is shown in Fig. 16. The characteristic graph (Fig. 16b) for this type shows that collector current flows only when the gate voltage is positive with respect to the emitter, and of sufficient amplitude. There is virtually no collector current below point 'a' on the graph.




(a) Symbol.

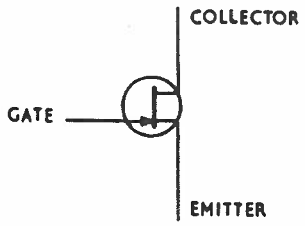



(b) Graph.

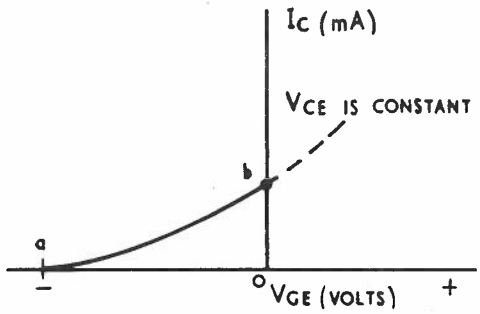
FIG. 16. 'ENHANCEMENT' IGFET.

This type of IGFET is termed the 'enhancement' type, as there must be an enhancing voltage present at the gate before the channel region displays any conductivity. The broken 'channel' line indicates that the channel is 'open' until suitable bias is applied.

5.6 **JUNCTION-GATE FETs (JFETs)** were the earliest type of FET. They differ from IGFETs in that they have a gate electrode which is not insulated from the channel, but has a connection to it in the form of a P-N junction. However, when the correct d.c. polarities are connected to the electrodes, the gate-emitter resistance is that of a reverse-biassed junction, typically hundreds of megohms in value. The symbol and characteristic graph of a typical JFET are shown in Figs. 17a and 17b respectively. The graph shows that as in all FETs, the gate-emitter voltage $V_{GE}$ controls the collector current $I_C$.




(a) Symbol.




(b) Graph.

FIG. 17. JUNCTION-GATE FET.

At point 'a' on the graph, the gate-emitter voltage is sufficiently negative to prevent collector current. Reduction in the value of $V_{GE}$ towards 0 V reduces the depletion effect in the channel, allowing the collector current to increase. At point 'b', $V_{GE}$ is zero, and $I_C$ is at a value determined by the conductivity of the channel and the collector-emitter voltage.

JFETs are not normally operated with enhancement polarities on the gate. They have the disadvantage that enhancement voltages cause the gate-emitter resistance to drop sharply, which is usually an undesirable effect in practical circuits. The JFET in Fig. 15a is an N-channel type, and requires negative potentials for channel depletion. Positive gate polarity would cause channel enhancement, and the resulting undesirable drop in input resistance.

## 5.7 CHARACTERISTICS OF FIELD-EFFECT TRANSISTORS.

A typical test circuit used for deriving the gate voltage versus collector current graph of an IGFET is shown in Fig. 18, with typical values shown in Table 2. Although this IGFET is an N-channel depletion-enhancement type, the figures indicate the characteristic common to all FETs: the control of collector current by gate voltage.

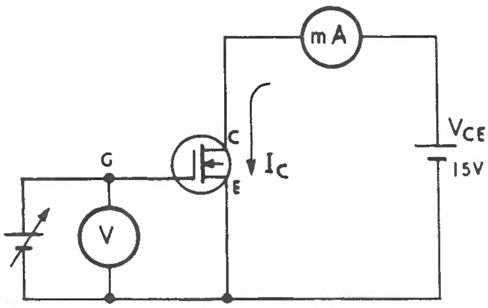



FIG. 18. TEST CIRCUIT FOR AN IGFET.

| $V_{GE}$ (volts) | $I_C$ (mA) | Output Resistance $= \frac{V_{CE}}{I_C}$ (ohms) |
|---|---|---|
| +1.0 | 5 | 3000 |
| +1.5 | 10 | 1500 |
| +2.0 | 15 | 1000 |
| +2.5 | 20 | 750 |

TABLE 2.

The right-hand column of Table 2 gives the values of output resistance corresponding to the successive values of $I_C$. These resistance values, when read with the corresponding input voltages, demonstrate a most important FET concept: that is, changes in input voltage cause changes in output resistance. This concept is used in Section 5 as the basis for the explanation of transistors as amplifiers and switches.

## 5.8 COMPARISON BETWEEN BIPOLAR TRANSISTORS AND FETs.

Although both the bipolar and the field-effect transistor provide the same general property of control over output current by input voltage, there are marked differences in their other electrical properties. For instance, the FET has negligible current flow in its input compared to the bipolar transistor. It therefore has a high input impedance, a worthwhile advantage in many circuits.

Many FETs are far more vulnerable than bipolar transistors to internal damage caused by electrostatic charges on their leads. Electrostatic charges, such as those caused merely by handling the FET, can cause destructive voltages within the device. Because of this, FETs are usually supplied with their leads strapped together, and the straps should not be removed until after the FET has been connected into its circuit. Some of the more recent designs of FET have a built-in protective device in the gate circuit, which reduces the risk of damage. However, unless it is positively known that a FET is of this type, it is essential that it be treated as if it has an unprotected gate circuit.

## 6. TRANSISTOR APPLICATIONS.

6.1 The two main applications for transistors are those of amplification and switching. Bipolar and field-effect transistors are both used extensively in these applications, the type used depending on the electrical characteristics required.

6.2 AMPLIFICATION is the process of increasing the voltage, current, or level of electrical signals. For example, the 'replay' amplifier in a tape recorder raises the level of comparatively weak replay-head signals to the much higher level required to operate the loudspeaker. Other examples are the amplifiers in radio receivers, hearing-aid telephones, and the 'repeater' amplifiers used on long lines. In every case, the task of the amplifier is to raise the signal level to some desirable higher value.

Fig. 19 sets out the basic requirements of an amplifying circuit. The circuit consists of:

- An amplifying device such as a transistor. For explanatory purposes, the transistor is represented as a variable resistance having its value determined by the strength of the input signal.

- A d.c. power supply, which provides the required energy for conversion into the output signal.

- An output device or 'load' which uses the output power to perform a function. A loudspeaker is a typical output device.

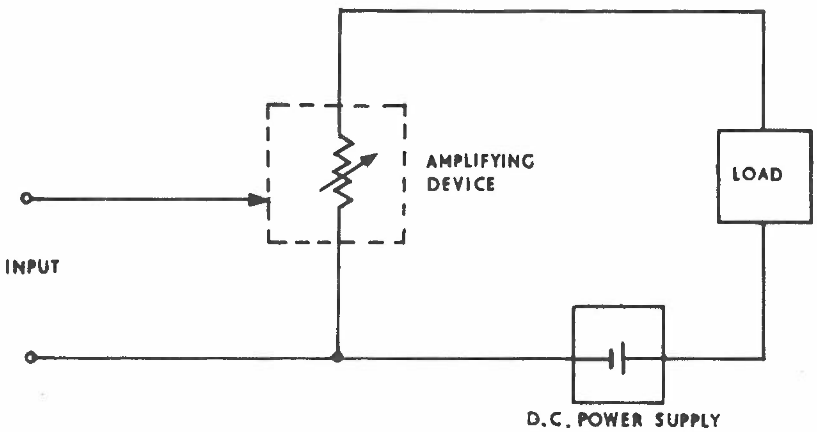



FIG. 19. BASIC REQUIREMENTS FOR AMPLIFICATION.

6.3 The functions of the various parts of Fig. 17 are as follows:

- When an input signal is applied, the collector-emitter (output) resistance of the transistor varies in accordance with the amplitude of the signal.

- The changes in collector-emitter resistance control the current flow from the d.c. supply, and hence the current flow through the load.

- These changes in current flow are sufficient in magnitude to produce a large amount of signal energy in the load. For a typical medium-power transistor, the power in the load would be at least 10 times greater than the input power.

6.4 SWITCHING. Transistors are widely used in 'switching' circuitry for computers, television, automatic control and many other applications. In each application, the function of the transistor is to change the state of a device (or circuit) between the 'on' and 'off' conditions. As a switch, the transistor presents a low resistance when 'closed' and a high resistance when 'open'. Its main advantages over relays are those of low power consumption and very high switching speed.

Fig. 20 shows the connection of a transistor as a switching device for controlling a relay. The circuit consists of:

- The transistor, which for explanatory purposes is shown as a switch.
- A power supply which provides the energy required to operate the load device, in this example a relay.
- The relay, which has two states - the 'operated' state, and the 'released' state.

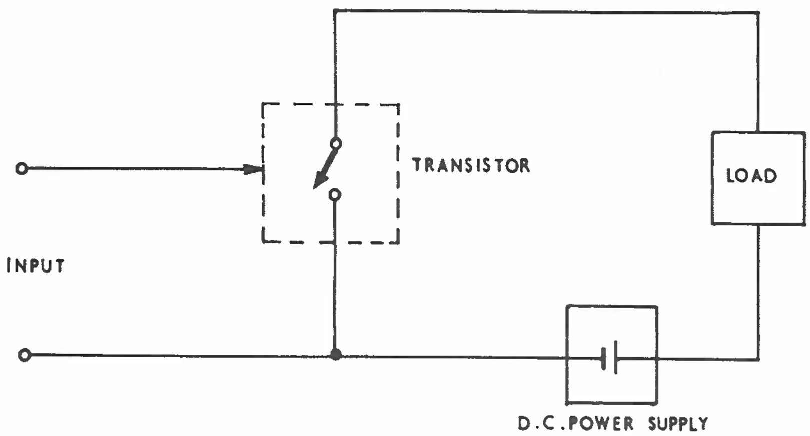



FIG. 20. TRANSISTOR FUNCTIONING AS A SWITCHING DEVICE.

6.5 The functions of the various parts of Fig. 20, are as follows:

- When the input to the transistor is set to the 'on' value, (the actual voltage is determined by circuit design) it causes reduction of the collector-emitter resistance to a low value and thereby 'closes' the circuit.
- The collector current rises to the 'on' value, and the relay operates.
- When the input to the transistor is changed to the 'off' value, the collector-emitter resistance increases to a high value, effectively 'opening' the circuit.
- The 'off' value of current is insufficient to hold the relay operated, so it releases.

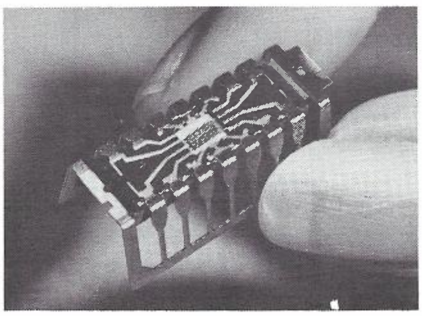
Ideally, a transistor switch would have zero output resistance in the 'closed' condition, and be open-circuit in the 'open' condition. However, these conditions are not achieved in practical circuits; when a transistor switch is 'closed', there is always a small residual voltage drop across the collector and emitter, and in the 'open' condition the collector circuit carries a small (usually negligible) current.

Also, there are many instances of transistor switching circuitry where the 'on' and 'off' states of the transistor correspond to a low and a high value of output resistance, rather than the extremes of short-circuit and open-circuit.

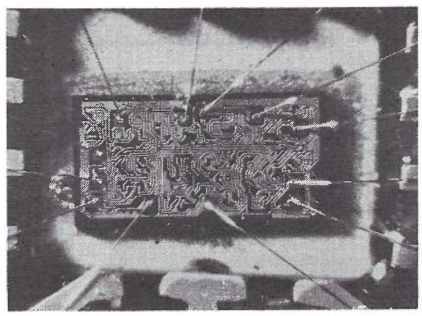
## 7. INTEGRATED CIRCUIT PRINCIPLES.

7.1 The semiconductor devices described in previous sections are all individual components. For example, each of the devices shown in Fig. 13 consists of a package containing a single bipolar transistor, such as is commonly used in circuits in conjunction with individual resistors, capacitors, diodes, etc. When components such as these are mounted and soldered into a circuit as individual items, they are termed 'discrete components'. (Discrete means separate.)

7.2 The alternative to a circuit constructed from discrete components is a circuit in which the components are formed together in a single package. Such a device is termed an 'integrated circuit' or IC, because all of the components are formed or 'integrated' with interconnections on a single tiny chip of silicon or other suitable material. All of the components, such as transistors, capacitors and resistors, are put together in the desired circuit formation by means of a series of photographic and chemical processes. Some idea of the size of an IC chip can be gained from Fig. 21. The chip is the tiny rectangle in the centre of the device, (Fig. 21) which is itself being held between two fingers. Fig. 21b is a 1000 magnification photograph of the chip. In this integrated circuit there are 15 transistors, 32 resistors, and 12 diodes. Typical IC packages are shown in Fig. 21c.



(a) IC package, showing chip



(b) Enlarged photograph of chip

FIG. 21. INTEGRATED CIRCUITS.

7.3 Amplifiers and switching circuits of all kinds are available as ICs. The circuits are usually designed so that they can be used for various functions. The desired function is provided by making the appropriate connections of discrete components and power supplies to the leads of the IC. Typical IC schematic circuits and connections are described in other papers.

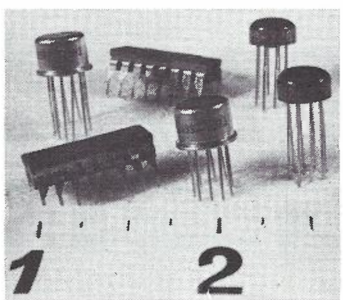



FIG. 22. TYPICAL IC PACKAGES.

## NOTES

## 8. TEST QUESTIONS.

1. *What are the correct names for the electrodes of a diode?*

2. *Draw a circuit containing a battery, lamp, and diode in series, having the diode connected so that the lamp lights.*

3. *A semiconductor diode has a white ring painted around one end. Which electrode is thus indicated?*

4. *Draw and label the circuit symbol for an NPN transistor.*

5. *Draw and label the circuit symbol for a PNP transistor, and show the correct d.c. polarities on the electrodes.*

6. *Figure 7a shows a transistor with collector voltage applied, but no base voltage. Which junction is "reverse biassed" by the collector voltage? Choose from this list:*

   *(a) The collector-emitter junction.*

   *(b) The base-emitter junction.*

   *(c) The collector-base junction.*

   *(d) The emitter-base junction.*

7. *A transistor has a base current of 20mA and an emitter current of 280mA. What is the collector current value?*

8. *Which type of Field-Effect Transistor has the gate electrode insulated from the rest of the structure?*

   *(a) JFET.*

   *(b) Depletion FET.*

   *(c) IGFET.*

   *(d) N-channel FET.*

9. *Write down the meanings of these abbreviations:*

   $V_{GE}$, $I_C$, $I_B$, $V_{CE}$.

10. *The collector current in a bipolar transistor increases from 180mA to 185mA when the base current increases from 730μA to 780μA. What is the value of current gain?*

11. *Draw the symbol for an N-channel depletion-enhancement IGFET. What gate polarity does it require for enhancement?*

12. *In paragraph 3.9, it was stated that a transistor could be overheated by excessive current flow. Name another way in which a transistor could become overheated.*

13. *FETs are susceptible to the destructive effects of electrostatic charges on their leads.*

    *(a) Name one way in which these charges can occur.*

    *(b) Name one way of preventing the undesirable effects of such charges.*

End of Paper.