

EXPERIMENT

10

A STUDY OF TRANSISTOR CHARACTERISTICS

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10.1 INTRODUCTION

The transistor derives its name from its action as resistor that transfers charges: **Transfer resistor**

In the preceding experiment, you learnt to plot the I - V characteristics of a p - n junction and a Zener diode. A diode permits current to pass through it in only one direction. That is why its applications are limited mostly to rectification and detection. A more useful semiconductor device is a bipolar junction transistor (BJT). Transistors find many and varied uses in our daily life ranging from gas lighter and toys to amplifiers, radio sets and televisions. In fact, their use is consistently increasing. In the form of switching device, these can be used to regulate vehicular traffic on the roads. They form key elements in computers, space vehicles, power systems, satellites and communication. In a sense, transistors have brought about a revolution, which has helped upgrade technology and improve efficiency. It is therefore important for you to know how a transistor works.

The practical use of a semiconductor device in electronic circuits depends on the current and voltage (I - V) relationship, as it gives vital information to a circuit designer as well as a technician. Therefore, the first thing of interest is: How does a transistor respond to voltage applied to it? Is the response linear? In your school physics, you have learnt that for a resistor, the characteristic curve (I - V plot) is a straight line passing through the origin. This is manifestation of Ohm's law. For a p - n junction and Zener diode, the characteristic curves are non-linear. In this experiment, you will obtain characteristic curves for a transistor in the common-emitter mode and calculate current gain, input resistance and output admittance.

Objectives

After performing this experiment, you should be able to:

- study variation of base current with potential difference between the base and the emitter (input characteristics) in common-emitter (CE) configuration;
- study variation of collector current with potential difference between the collector and the emitter (output characteristics) in CE -configuration;
- examine the relationship between collector current and base current (transfer characteristics) in CE -configuration; and
- calculate current gain, input resistance and output admittance.

10.2 WHAT IS A TRANSISTOR?

A transistor is a three-terminal device consisting of alternate regions of p - and n -type semiconductors, as shown in Fig. 10.1. The three segments of the transistor are called emitter (E), base (B) and collector (C). Note that (i) the emitter is sandwiched between the emitter and the collector, (ii) the emitter and collector are of the same type (p or n), and (iii) the base and emitter (or collector) are of different materials.

You may recall that a diode is a unidirectional device. That is, it controls the direction of current flow. However, by itself, it cannot control the amount of current passing through it. But in a transistor, the base terminal controls the current flowing between the emitter and the collector. This control action gives the transistor an added advantage over the diode.

Depending on the type of doping, the transistors are classified as $n-p-n$ or $p-n-p$. In general, the level of doping decreases from emitter to collector to base.

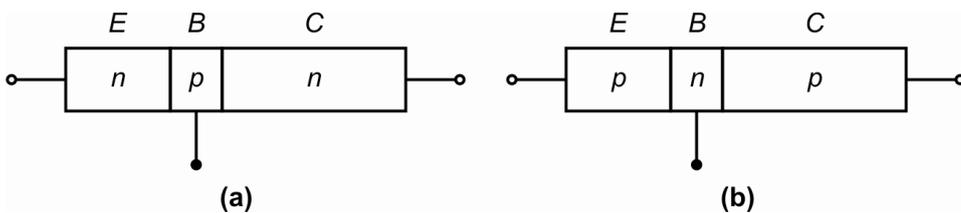


Fig.10.1: a) $n-p-n$ transistor and (b) $p-n-p$ transistor

The names of the terminals of a transistor give clear indication of their functions. In case of a $n-p-n$ transistor, the majority carriers (electrons) from the **emitter** enter the base region. Since **base** is a very lightly doped thin layer, it allows most of these electrons (originating in the emitter) to pass into the **collector**. (The doping level of collector is in-between that of the emitter and the base.) The collector is the largest of the three regions, and it dissipates more heat compared to the other two regions.

The symbolic representations of $n-p-n$ and $p-n-p$ transistors are given in Fig.10.2. The arrow indicates the direction of current flow when emitter-base junction is forward biased.

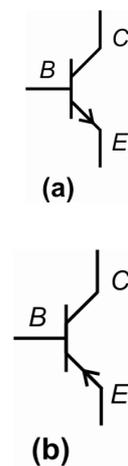


Fig.10.2: Symbols for a) $n-p-n$ and b) $p-n-p$ transistors

10.3 WORKING PRINCIPLE OF A TRANSISTOR

You are familiar with p -type and n -type semiconductors as also the $p-n$ junction. We now discuss the working principle of a transistor and consider an $n-p-n$ transistor because it is more commonly used.

When no voltage is applied across the transistor, diffusion of free electrons across the emitter-base and collector-base junctions produces two depletion layers, as shown in Fig. 10.3. For each depletion layer, the barrier potential is about 0.7 V at 25°C for a silicon transistor and 0.3V for a germanium transistor. Do you know that silicon transistors are more widely used than germanium transistors because of higher voltage rating, greater current ratings, and low temperature sensitivity? For our discussion, we will refer to silicon transistors, unless indicated otherwise.

Since the three regions of the transistor have different doping levels, the depletion layers have different widths. If a region is heavily doped, the concentration of ions near the junction will be more resulting in thin depletion

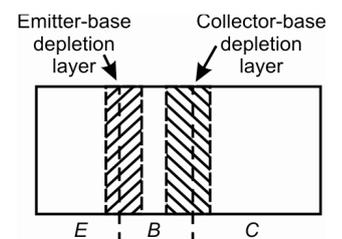


Fig.10.3: Depletion layers in a transistor when no voltage is applied

layer and vice versa. In a transistor, since the base is lightly doped as compared to emitter and collector, the depletion layers extend well into the base, whereas penetration in emitter/ collector regions is somewhat less (Fig. 10.3). Moreover, the emitter-base depletion layer is narrower compared to collector-base depletion layer.

To make a transistor function properly, it is necessary to apply suitable voltages to its terminals. This is called **biasing** of the transistor. A typical biasing scheme of an *n-p-n* transistor is shown in Fig. 10.4a. Note that **the emitter-base junction is forward biased while the collector-base junction is reverse biased**. We therefore expect a large emitter current and low collector current. But in practice, we observe that the collector current is almost as large as the emitter current. Do you know the reason? Let us discover the answer. When forward bias is applied to the emitter, free electrons in the emitter have to overcome the barrier potential to enter the base region (see Fig. 10.4b). If V_{BE} is greater than the barrier potential (0.6 V to 0.7 V for silicon transistor), these electrons enter the base region, as shown in Fig. 10.4c. Once inside the base, these electrons can flow either through the thin base into the external base lead, or across the collector junction into the collector region. Since the base region is very thin and it receives a large number of electrons for $V_{BE} > 0.7V$, most of these electrons diffuse into the collector depletion layer. The free electrons in this layer are pushed (by the depletion layer field) into the collector region (Fig. 10.4d) and flow into the external collector lead.

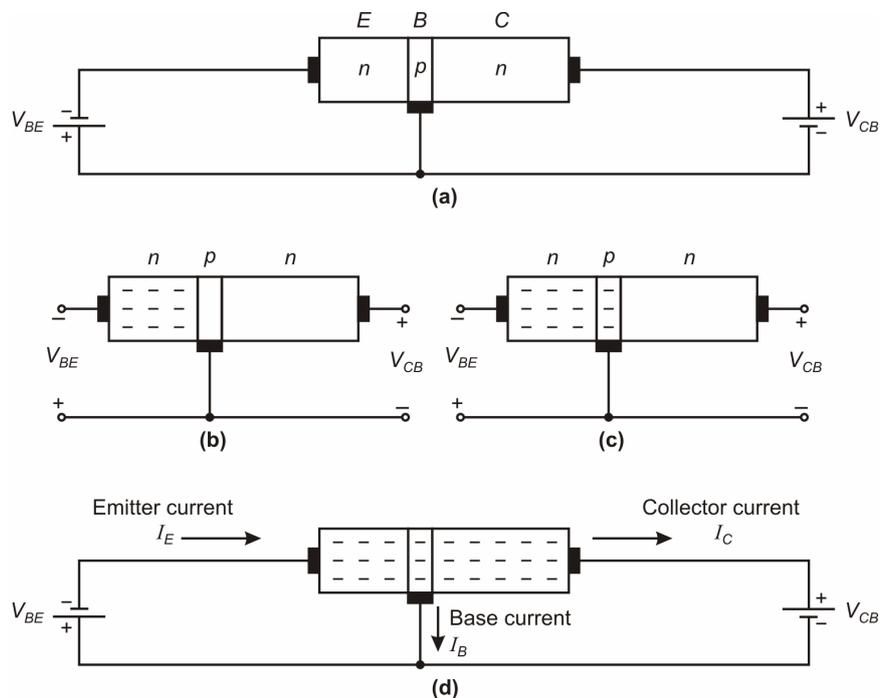


Fig.10.4: An *n-p-n* transistor when a) emitter is forward-biased and collector is reverse-biased; b) emitter has many free electrons; c) free electrons injected into base; and d) free electrons pass through base to collector

So, we can say that a steady stream of electrons leaves the negative source terminal and enters the emitter region. The forward bias forces these electrons to enter the base region. Almost all these electrons diffuse into the

collector depletion layer, through the base. The depletion layer field then pushes a steady stream of electrons into the collector region. In most transistors, more than 95 percent emitter-injected electrons flow to the collector; less than 5 percent flow out in the external base lead.

From this you should not conclude that you can connect two discrete diodes back to back to get a transistor. This is because in such a circuit, each diode has two doped regions, and the overall circuit would have four doped regions and the base region is not the same as in a transistor. **The key to transistor action therefore is the lightly doped thin base between the heavily doped emitter and the intermediately doped collector.** Free electrons passing through the base stay in base for a short time and reach the collector.

The *dc alpha* of a transistor indicates how close collector current (I_C) and emitter current (I_E) are. It is defined as

$$\alpha_{dc} = \frac{I_C}{I_E}. \quad (10.1)$$

The dc alpha is also referred to as large signal current gain. You should note that the value of α_{dc} is nearly equal to but always less than one.

Similarly, you can relate the collector current to the base current. It is referred to as *dc beta* of a transistor:

$$\beta_{dc} = \frac{I_C}{I_B}. \quad (10.2)$$

Beta signifies the current gain of the transistor in common-emitter configuration. Value of β_{dc} is considerably larger than one.

Since emitter current is sum of collector current and the base current, we can write

$$I_E = I_C + I_B$$

or

$$\frac{I_E}{I_C} = 1 + \frac{I_B}{I_C}. \quad (10.3)$$

In terms of α_{dc} and β_{dc} , we can rewrite it as

$$\frac{1}{\alpha_{dc}} = 1 + \frac{1}{\beta_{dc}}$$

or

$$\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}. \quad (10.4)$$

We hope you have understood the working principle of a transistor. Let us now discuss the different ways in which a transistor is configured in a circuit.

10.4 TRANSISTOR CONFIGURATIONS

A transistor is a two-port device. It can take an input and deliver an output. For both input and output, two terminals are needed. This can be done in a transistor by making one of the three terminals common. The configurations of a transistor in which one of the terminals is common to both input and output are shown in Fig. 10.5:

- i) when emitter is common to both input and output circuits, we obtain common emitter (*CE*) configuration (Fig. 10.5a);
- ii) when base is common to both input and output circuits, we obtain common base (*CB*) configuration (Fig. 10.5b); and
- iii) when collector is common to both input and output circuits, we have common collector (*CC*) configuration (Fig. 10.5c).

In each of these configurations, the transistor characteristics are unique. The *CE* configuration is used most widely because it provides voltage, current and power gains. In the *CB* configuration, the transistor can be used as a constant current source while the *CC* configuration is frequently used for impedance matching.

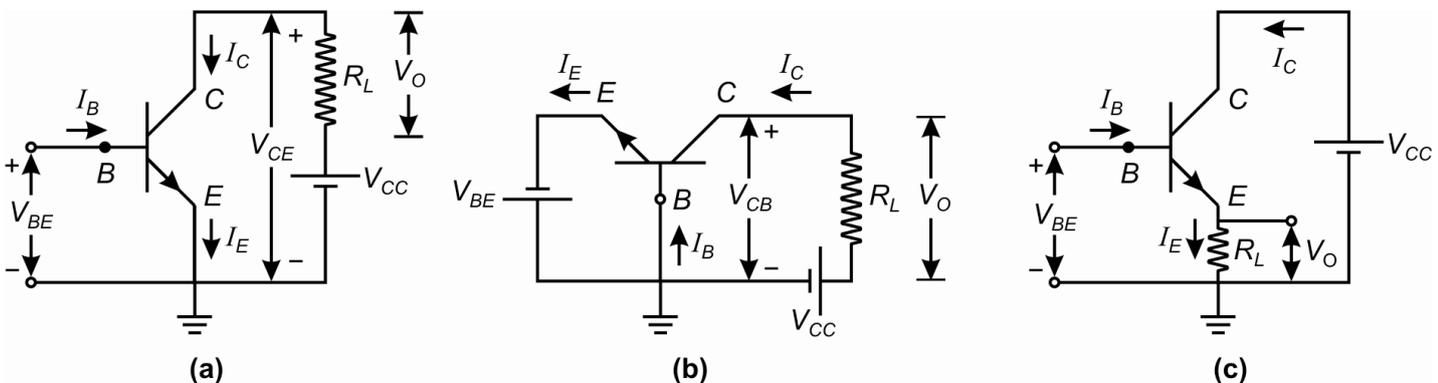


Fig.10.5: Transistor configuration (a) *CE*; (b) *CB*; and (c) *CC*

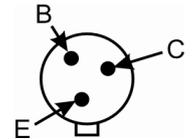
For each configuration, we can plot three different characteristics: a) **input characteristics**; b) **output characteristics**; and c) **transfer characteristics**, depending on the nature of quantities involved.

Table 10.1 gives various quantities related to each of these characteristics in all the three configurations and the transistor constants of interest.

Before you start the experiment, it is essential for you to know to differentiate the base, emitter and collector leads of the given transistor. You will now learn to identify the three terminals of a transistor.

Table 10.1: Physical quantities of interest in different characteristics of a transistor

Configuration	Input characteristic	Output characteristic	Transfer characteristic	Important transistor constant
CE	V_{BE} and I_B with V_{CE} as parameter	V_{CE} and I_C with I_B as parameter	I_B and I_C	Current gain, β
CB	V_{BE} and I_E with V_{CB} as parameter	V_{CB} and I_C with I_E as parameter	I_E and I_C	Large signal current gain, α
CC	V_{CB} and I_B with V_{CE} as parameter	V_{CE} and I_E with I_B as parameter	I_B and I_E	



10.6: Identifying transistor leads: transistor bottom view

10.5 IDENTIFICATION OF TERMINALS OF A TRANSISTOR

A transistor is usually enclosed in a metal cap. It radiates to the surroundings whatever heat is generated due to flow of electrons. A small notch is provided on this cap and the *terminal close to the notch is emitter*. To identify other two terminals, turn the transistor up-side-down. By referring to Fig. 10.6, you can easily identify the base and the collector. (Some other packages of transistors are shown in Appendix A.)

In a digital multimeter, usually a slot is provided to measure β -value of the transistor. By inserting the transistor in this slot, its β -value is displayed on the panel of the digital multimeter. Usually β ranges from 50 to 150 and depending on the application, a transistor of proper β value can be chosen. The commonly used transistors like BC107 and BC108 are *n-p-n* transistors with β value around 100.

You may now like to answer an SAQ.

SAQ 1 : Identifying a transistor

Spend
3 min.

How can we distinguish a *n-p-n* transistor from a *p-n-p* transistor using a multimeter?

In this experiment you will work with a transistor in the CE configuration. The apparatus required for this purpose is listed below:

Apparatus

Two low range (0-3V and 0-15V) variable dc power supplies, a multimeter, a multi-range microammeter (up to 100 μ A), two multi-range milliammeters (100mA), two multi-range voltmeters, a BC107 *n-p-n* transistor (or any other *n-p-n* transistor) with a socket, two 2.5 k Ω /2W potentiometers, one (500-1000) Ω variable resistor and leads for connection.

Like semiconductor diodes, transistors are also designated with two letters followed by a serial number. The first letter gives an indication of the material: A is used for germanium and B is used for silicon. The second letter indicates the main application: C is used for audio frequency transistors, D for power transistors, and F for radio frequency applications. The serial number consists of digits. The serial number is an identifying number assigned by the manufacturer and can be used to identify a transistor of particular rating, as mentioned in the data sheets. For example, AC125 represents germanium transistor for AF application and BC107 represents silicon transistor for AF application.

10.6 TRANSISTOR CHARACTERISTICS IN CE-CONFIGURATION

First of all, identify the emitter, base and collector of the given transistor following the steps given above. Next check that it is working properly by using a multimeter; that is check that emitter-base and collector-base junctions are in order. Now, follow the procedure given below to obtain the input and output characteristics.

10.6.1 Input Characteristics

1. Make the connections as shown in Fig. 10.7. V_{BB} is a variable dc supply of 0-3V and V_{CC} is a variable dc supply of 0-15V. R_1 and R_2 are 2.5 k Ω /2W potentiometers, and R is a variable resistor.

In case a transistor kit is given to you, ensure that the basic circuit given in Fig. 10.7 is in operation. (If you are given a $p-n-p$ transistor, you will have to reverse the polarities of batteries and various meters.) By means of potentiometers R_1 and R_2 , you can adjust the voltage in the base and collector circuits, respectively.

2. Keep collector to emitter voltage (V_{CE}) at zero volt.
3. Change V_{BE} from 0 in steps of 0.1V and observe corresponding base current I_B in μ A. Record your readings in Observation Table 10.2. We expect that so long as $V_{BE} < 0.5$ V, there will be no measurable base current, i.e., $I_B = 0$.

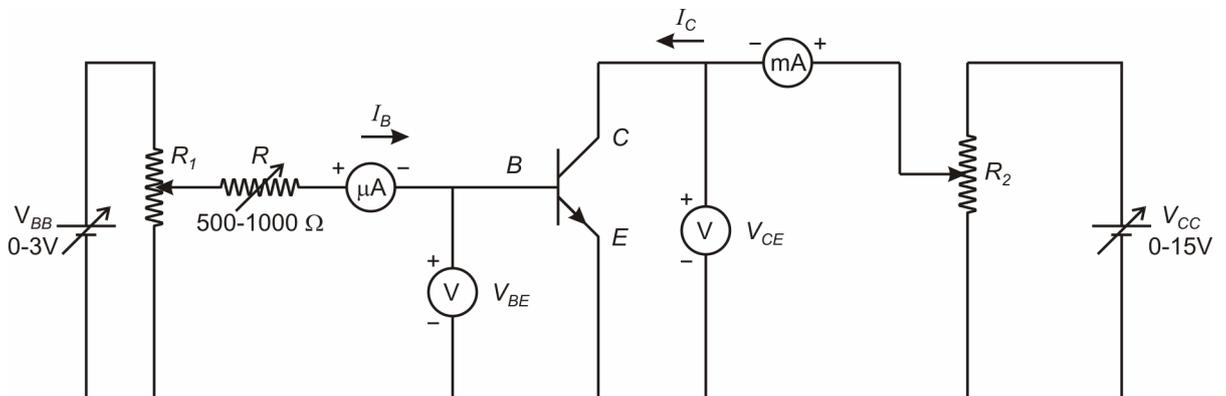


Fig.10.7: Circuit diagram for determining characteristics of a $n-p-n$ transistor in CE-configuration

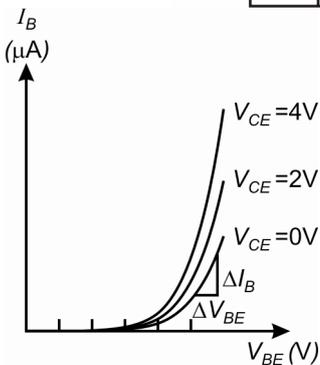


Fig.10.8: Typical input characteristics of a transistor in CE-mode

4. When V_{BE} is about 0.5V or 0.6V, there may be a small base current of about 2 μ A. With a slight increase in voltage (say, by 0.1V), the base current I_B may begin to rise steeply, say upto 20 μ A or more. The voltage should not be increased further. In case of BC107 or BC108 transistor, the base current should not exceed 60 μ A. In case you are using some other transistor, you should obtain the maximum base current rating from your Counsellor. Otherwise, the transistor can get damaged.
5. Repeat steps 3 and 4 for a few values of V_{CE} (say) = 2V, 4V, 6V etc. by varying R_2 . Note that in no case, V_{CE} should exceed 12V.

Observation Table 10.2: Input characteristics of a transistor in CE-mode

V_{BE} (V)	I_B (μA)			
	$V_{CE} = 0$	$V_{CE} = 2\text{V}$	$V_{CE} = 4\text{V}$	$V_{CE} = 6\text{V}$
0.1				
0.2				
0.3				
0.4				
0.5				
0.6				

Now plot a graph by taking I_B along the y -axis and V_{BE} along the x -axis for each value of V_{CE} and draw best fit curves, as shown in Fig. 10.8. These are referred to as *input characteristics*. Select a suitable point in the linear portion of the curve and calculate the slope at that point by drawing a tangent. This will give you the value of input resistance, defined as $h_{ie} = \frac{\Delta V_{BE}}{\Delta I_B}$, where ΔV_{BE}

and ΔI_B denote small changes in base to emitter voltage and base current, respectively.

Result: The input resistance h_{ie} for the given transistor is Ω .

10.6.2 Output Characteristics

For obtaining output characteristics also, you should use the circuit shown in Fig.10.7 and follow the steps given below:

1. Fix the base current I_B at $20\mu\text{A}$ by adjusting R_1 and R .
2. Vary the collector to emitter voltage V_{CE} by varying R_2 from 0 to 10V in steps of 0.5V.
3. Note the collector current I_C in each case and record it in Observation Table 10.3.
4. Repeat steps 2 and 3 for $I_B = 40\mu\text{A}$, $60\mu\text{A}$, and $80\mu\text{A}$. Make sure that you do not exceed the maximum base current rating of the transistor.
5. Plot V_{CE} versus I_C for different values of I_B . Draw smooth curves for each I_B . These are the output characteristics. Typical *output characteristics* of a transistor are shown in Fig. 10.9.

You can calculate output admittance (h_{oe}) using the relation $h_{oe} = \frac{\Delta I_C}{\Delta V_{CE}}$.

Observation Table 10.3: Output characteristics of a transistor

S.No.	V_{CE} (V)	Collector current I_C (mA)			
		$I_B = 20\mu\text{A}$	$I_B = 40\mu\text{A}$	$I_B = 60\mu\text{A}$	$I_B = 80\mu\text{A}$
1.	0.0				
2.	0.5				
3.	1.0				
.	.				

Result: The output admittance for the given transistor is = Ω^{-1} .

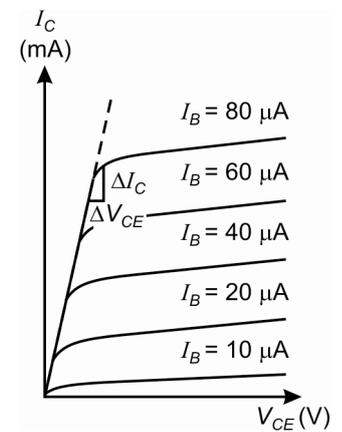


Fig.10.9: Typical output characteristics of a transistor

10.6.3 Transfer Characteristics

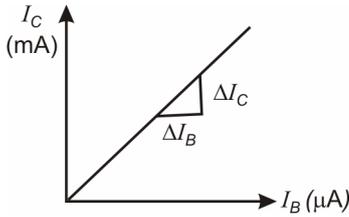


Fig.10.10: Typical transfer characteristic of a transistor in CE-mode

To obtain transfer characteristics, follow the steps given below:

1. Set V_{CE} at 5.0 V.
2. Set the base current I_B at $10\mu\text{A}$ by adjusting R_1 and R . Measure the collector current I_C and record it in Observation Table 10.4.
3. Change the base current to $15\mu\text{A}$. Do you observe any change in V_{CE} ? If yes, then you should adjust R_2 to restore V_{CE} at 5.0V. Again note the collector current.
4. Repeat your observations by increasing I_B in step of $5\mu\text{A}$ till the maximum of $50\mu\text{A}$, keeping V_{CE} constant at 5.0V. You may have to adjust R_2 every time. Record the collector current in Observation Table 10.4.
5. Next fix V_{CE} at 6.0V and repeat steps 2-4.
6. If time permits, you may repeat the above procedure by keeping V_{CE} at 4.0V.
7. Now plot I_B along x -axis and I_C along y -axis for different values of V_{CE} .

Observation Table 10.4: Transfer characteristics of a transistor

S. No.	$I_B (\mu\text{A})$	Collector current I_C (mA)	
		$V_{CE} = 5.0\text{V}$	$V_{CE} = 6.0\text{V}$
1.	10		
2.	15		
3.	20		
.	.		
.	.		
.	.		
9	50		

Draw a smooth best-fit curve through the observed points. We expect you to get a straight line graph. Calculate current gain β using the relation

$$\beta = h_{fe} = \frac{\Delta I_C}{\Delta I_B} .$$

Result: The current gain for the given transistor is =.....

APPENDIX A: MEASUREMENT OF RESISTANCE AND SOME COMMON TRANSISTOR PACKAGES

1. Measurement of Resistance by an Analog Multimeter

Insert the black and red cords in multimeter sockets marked 'common' and 'ΩA' respectively. Place multimeter selector in the position marked for measurement of resistance. You will note that the scale provides typically four options: (× 1), (× 10), (× 100) and (× 1000). Now keep the test ends of the cord apart. In this position, the resistance placed across it is infinite. The pointer must indicate ∞ in the topmost scale (i.e. the ohm-scale). If it does not indicate so, bring the pointer to the ∞ mark by turning the infinity adjustment knob. (If your multimeter does not have the infinity adjustor, the infinity-error, when present, cannot be corrected.) Now make the zero-adjustment, which is very vital. For this, make the test ends of the cord to touch. The pointer should indicate zero for the selector in each scale. If it does not do so, bring the pointer to zero-mark by turning the zero-adjustment knob. The multimeter is now ready for the measurement of resistance.

Now place the selector in the position (× 1). Connect the test ends of the cords across the terminals of the resistance to be measured. Note the reading of the position of the pointer corresponding to the ohm-scale. If the pointer stops at 50, the resistance is 50Ω. If the pointer overshoots the scale, change the selector to (× 10) and repeat the above procedure. If even now the pointer overshoots the scale, you should place the selector at (× 100) or (× 1000) marks. In these cases, you will have to multiply the observed reading by 10 or 100 or 1000, depending on the position of the selector.

2. Some Common Transistor Packages

Fig.10.A.1 shows typical configurations of *E*, *B* and *C* in the transistor in side and bottom views. This would help you to identify different kinds of transistors.

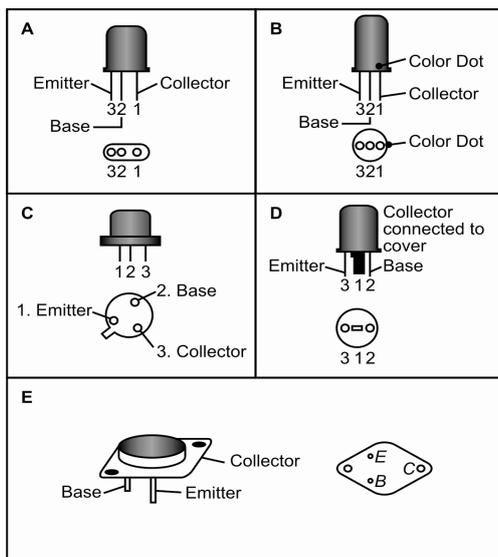


Fig.10. A.1: Identifying some common transistor packages

3. Identifying the type of transistor

The emitter-base and collector-base are two separate $p-n$ junctions. So you can determine their types by measuring the resistance between the ends of these diodes using a multimeter. For this, the multimeter has to be kept in the resistance measurement mode. In this mode, a battery placed inside the multimeter is operative. The 'common' terminal is the positive end of the battery, whereas the (Ω VA) terminal is its negative end. Now let us indicate the two ends of the diode by '1' and '2'. Measure the resistance between these ends by connecting 1 with the black cord and 2 with the red cord. Repeat the measurement by interchanging 1 and 2. The measured resistance will not be same. The arrangement for which the resistance is smaller will be the case of connecting the diode in forward bias. Corresponding to that configuration, the end connected to the black cord will be the p -side. By measuring the resistance between terminals 1-2, 2-3 and 1-3, you can identify the terminal, which is common to both the diodes. This is the base of the transistor. If it is of p -type, then the transistor is $n-p-n$. However, if it is of n -type, the transistor is $p-n-p$ type.