Lesson 09

Title of the Experiment: Introduction to transistor and design of a simple transistor switch
(Activity number of the GCE Advanced Level practical Guide - 22)

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Introduction

The discovery of the first transistor in 1948 by a team of physicists at the Bell Telephone Laboratories sparked an interest in solid-state research that spread rapidly. The transistor, which began as a simple laboratory oddity, was rapidly developed into a semiconductor device of major importance. The transistor demonstrated for the first time in history that amplification in solids was possible. Before the transistor, amplification was achieved only with vacuum electron tubes. Transistors now perform numerous electronic tasks with new and improved transistor designs being continually put on the market. Transistors have infiltrated virtually every area of science and industry, from the family car to satellites. Even the military depends heavily on transistors. In many cases, transistors are more desirable than vacuum tubes because they are small, rugged, require no filament power, and operate at low voltages with comparatively high efficiency. The development of a family of transistors has even made possible the miniaturization of electronic circuits.

The ever increasing uses for transistors have created an urgent need for sound and basic information regarding their operation. From your study of the PN-junction diode in Lesson 08, you now have the basic knowledge to grasp the principles of transistor operation. In this experiment you will first become acquainted with the basic types of transistors, their construction, and their theory of operation. You will also find out just how and why transistors amplify and switching. Once this basic information is understood, transistor terminology, capabilities, limitations, and identification will be discussed.

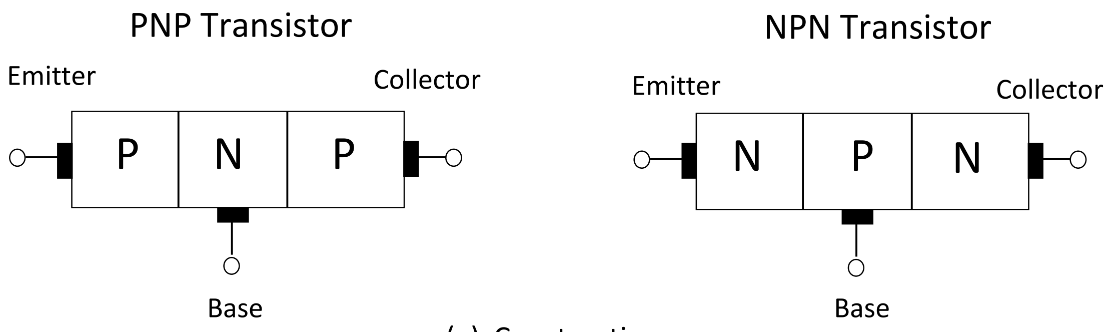
Bipolar Junction Transistor Basics

The word Transistor is an acronym, and is a combination of the words ***Trans***fer and Var***istor*** used to describe their mode of operation way back in their early days of development. There are two basic types of bipolar transistor construction, NPN and PNP, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

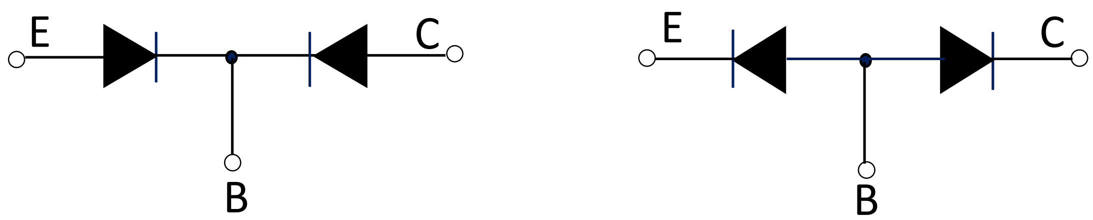
The **Bipolar Junction Transistor (BJT)** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively.

Bipolar Transistor Construction

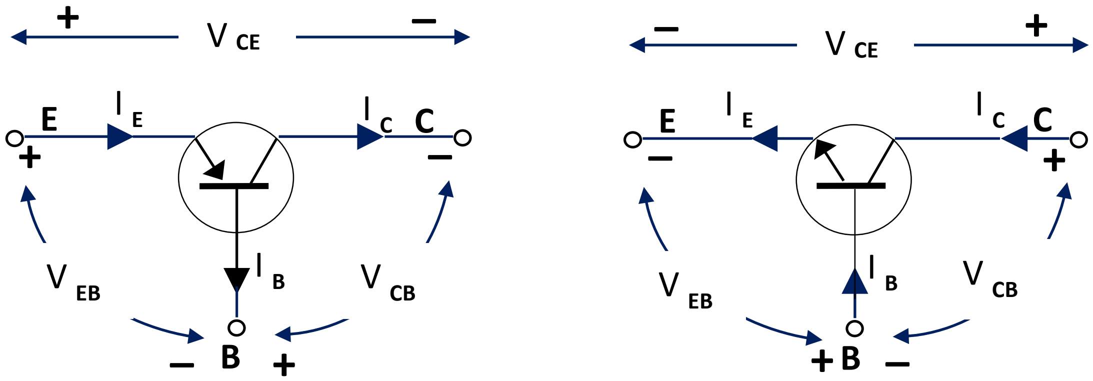
The construction and circuit symbols for both the NPN and PNP bipolar transistors are given below in figure 1 with the arrow in the circuit symbol always showing the direction of "conventional current flow" between the base terminal and its emitter terminal. The direction of the arrow always points from the positive P-type region to the negative N-type region for both transistor types, exactly the same as for the standard diode symbol.



(a) Construction



(b) Two-diode Analogy



(c) Symbols

Figure 1: The construction and circuit symbols for both NPN and PNP bipolar transistor

The emitter is heavily doped so that it can inject a large number of charge carriers (electrons or holes) into the base. The base is lightly doped and very thin; it passes most of the emitter injected charge carriers to the collector. The collector is moderately doped.

Bipolar Transistors are current regulating devices that control the amount of current flowing through them in proportion to the amount of biasing voltage applied to their base terminal acting like a current-controlled switch. The principle of operation of the two transistors types NPN and PNP, is exactly the same, the only difference being in their biasing and the polarity of the power supply for each type.

Working of NPN Transistors

To activate the transistor the emitter base junction has to be forward biased, and the collector base junction has to be reverse biased as shown in Figure 2.

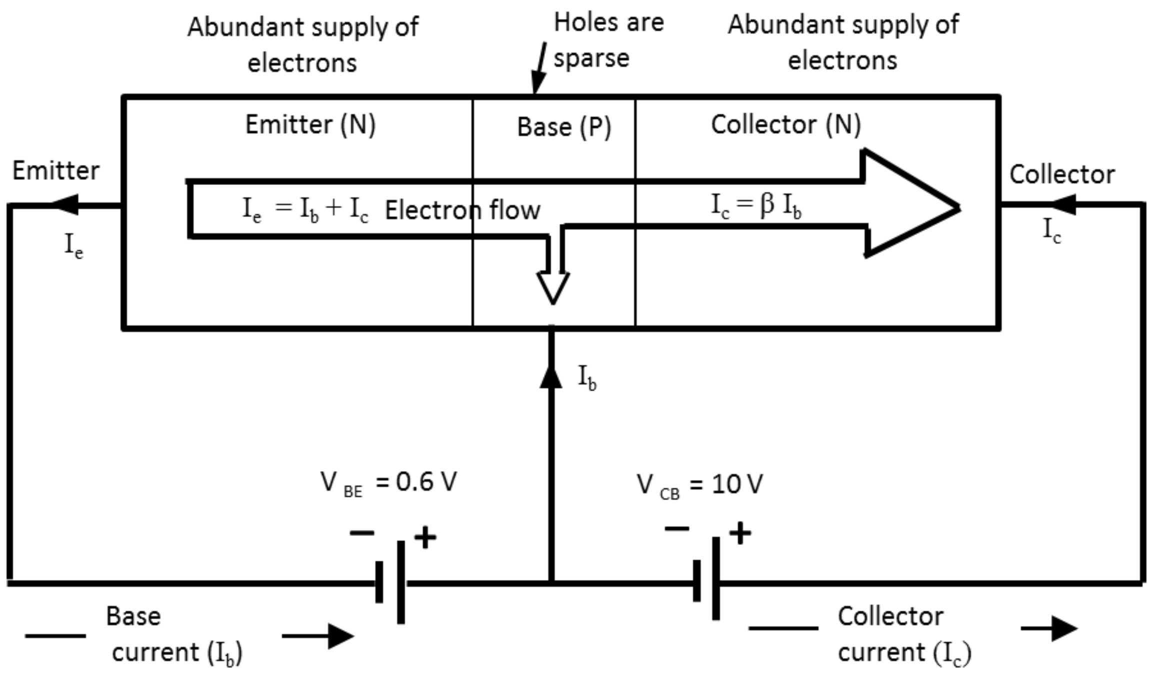


Figure 2: Basic Connection of NPN Transistor

The forward bias causes the electrons in the N-type emitter to flow toward the base. This constitutes the emitter current (I_E).

We know that by convention, direction of the current is against the direction of the flow of electrons. Therefore the current in the circuit (Figure 2) is shown against the direction of carries.

As these electrons flow through the P-type base, they tend to combine with holes. As the base is very lightly doped and very thin, only a few electrons (around 2%) combine with holes to constitute base current I_B. The remainder (about 98%) cross over into the collector region to constitute collector current I_C.

We can see that almost all the entire emitter current flows in the collector circuit.

It is clear that emitter current is the sum of collector current and base current, That is;

$$I_E = I_B + I_C$$

Transistor Configurations

As the **Transistor** is a three terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Each method of connection responds differently to its input signal within a circuit as the static characteristics of the transistor vary with each circuit arrangement.

1. Common Base Configuration

2. Common Emitter Configuration.

3. Common Collector Configuration

In a common emitter arrangement the current gain is very high and ranges from 20 to 1000 by depending on the transistor. Also the common emitter circuit has the high voltage and power gain. ***As such for signal amplification, Common Emitter (CE) arrangement is widely used.*** Therefore we will focus our attention only on the common emitter configuration**.**

The Common Emitter (CE) Configuration

In the Common Emitter or grounded emitter configuration, the input signal is applied between the base, while the output is taken from between the collector and the emitter as shown. This type of configuration is the most commonly used circuit for transistor based amplifiers and which represents the "normal" method of bipolar transistor connection.

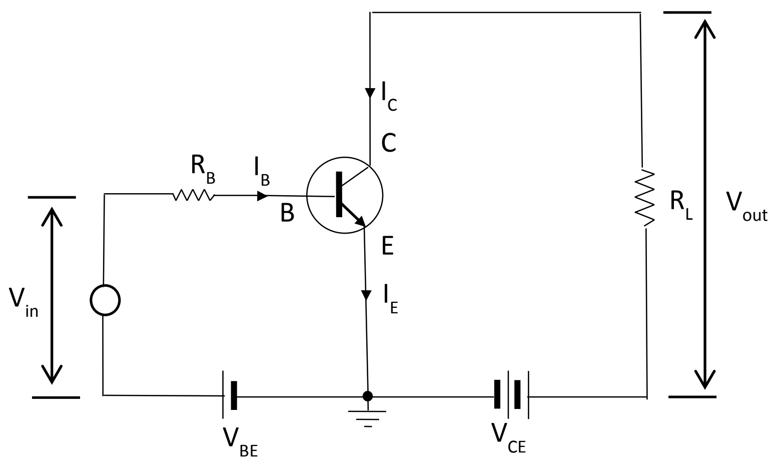


Figure 3: NPN transistor common emitter configuration

Input Characteristics

In common emitter configuration, it is the curve plotted between the input current (I_B) verses input voltage (V_{BE}) for various constant values of output voltage (V_{CE}). The approximated plot for input characteristic is shown in figure 4. This characteristic reveals that for a fixed value of output voltage V_{CE}, as the base to emitter voltage increases, the emitter current increases in a manner that closely resembles the diode characteristics.

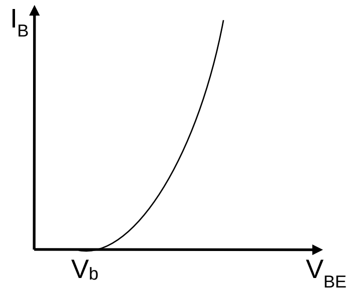


Figure 4: Input characteristic of an NPN transistor in common emitter configuration

Output Characteristic

This is the curve plotted between the output current I_C verses output voltage V_{CE} for various constant values of input current I_B. The output characteristic has three basic region of interest as indicated in figure 5 the active region, cutoff region and saturation region. In active region the collector base junction is reverse biased while the base emitter junction if forward biased. This region is normally employed for linear (undistorted) amplifier. In cutoff region the collector base junction and base emitter junction of the transistor both are reverse biased. In this region transistor acts as an 'Off' switch. In saturation region the collector base junction and base emitter junction of the transistor both are forward biased. In this region transistor acts as an on switch.

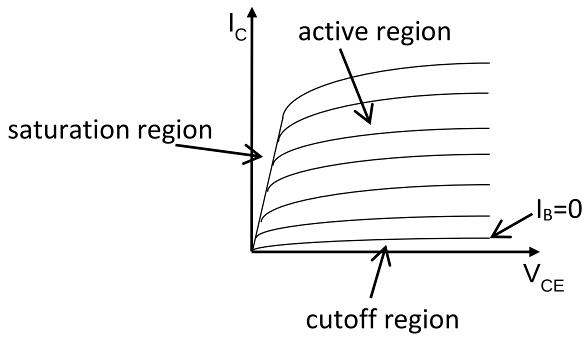


Figure 5: Output characteristic of an NPN transistor in common emitter configuration

- Active Region - the transistor operates as an amplifier and $I_C = \beta.I_B$
- Saturation - the transistor is "fully-ON" operating as a switch and I_C = I (saturation)
- Cut-off - the transistor is "fully-OFF" operating as a switch and $I_C = 0$

Transfer Characteristics (*I_C vs I_B*)

When an NPN transistor is in CE configuration the curve that indicates the variation of I_c against the variation of I_B when V_{CE} held constant at a given value is known as the transfer characteristic of the transistor.

Using the common emitter circuit we can increase the base current I_B from zero upward and plot the changes in I_c. Then we will obtain a graph as given in Figure 6.

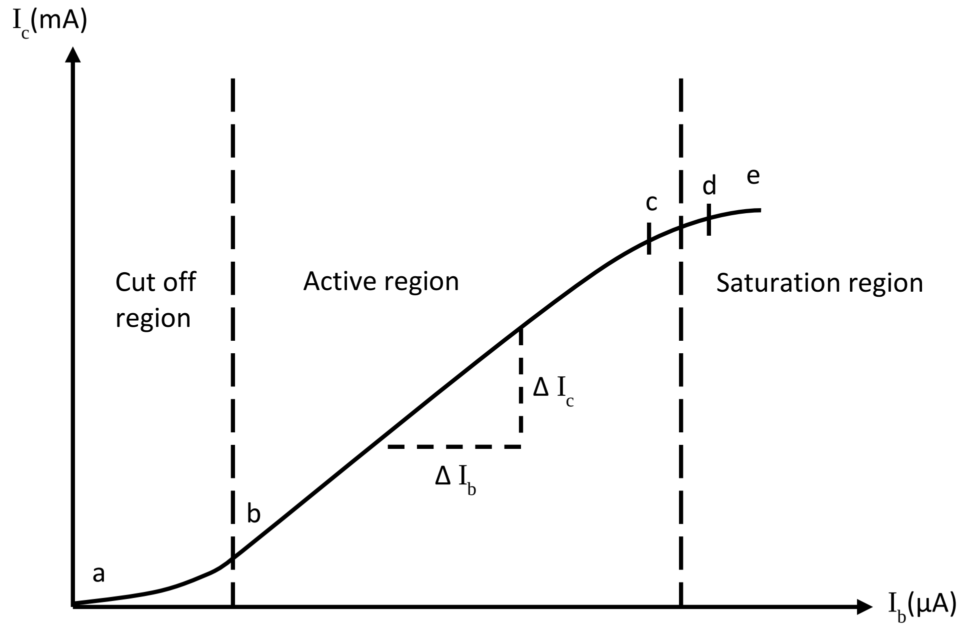


Figure 6: Transfer characteristic of an NPN transistor in common emitter configuration

When we observe the $I_C - I_B$curve in Figure 6, we can identify three clear divisions. Let us consider the three sections 'ab", 'bc' and 'de' in the curve.

AB section: I_C - I_B curve is not linear

I_B is zero or near zero

I_c is very small or I_c =0

As such this region is known as the *cut- off* region

V_{BE} is less than 0.7 V and V_{BC} is reverse biased

BC Section: I_C- I_B curve is almost linear.

At this section BE Junction is forward biased and BC junction is reverse biased. That means I_C is directly proportional to I_B

We also can derive the current gain β.

Where $\beta = \frac{\Delta I_C}{\Delta I_B}$

i.e. $I_C = \beta I_B$

This linear section is known as the active region.

DE Section : I_C is constant

I_B is high and I_C is high

At this stage V_{BE} is forward biased

$\beta = \frac{\Delta I_C}{\Delta I_{\underline{B}}}$

but $\Delta I_c \approx 0$

If we increase the value of V_{CC}, I_C would reach a higher, constant value.

This section is known as the saturation region.

A transistor can be operated in any one of these states. By operating a transistor in the active region, it can be used as an amplifier. Depending on the transistor, β value can range from 20 to 1000.

Transistor Packages

There are many transistor case designs. Some conform to JEDEC standards and are defined by Transistor Outline (TO) designations. Several case designs are illustrated below. In general, the larger the unit, greater the current or power rating of the device.

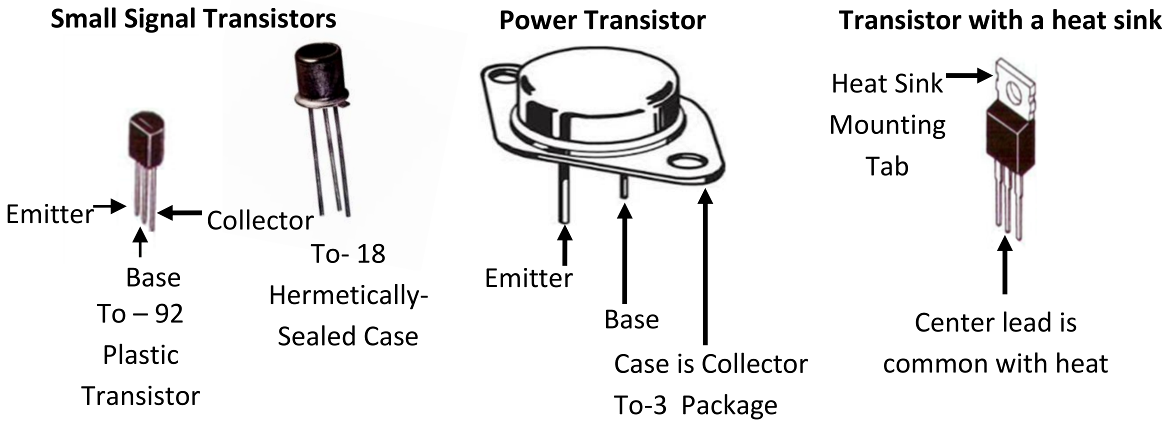


Figure 7: Transistor packages

Identifying Transistor Terminal by its pin configuration

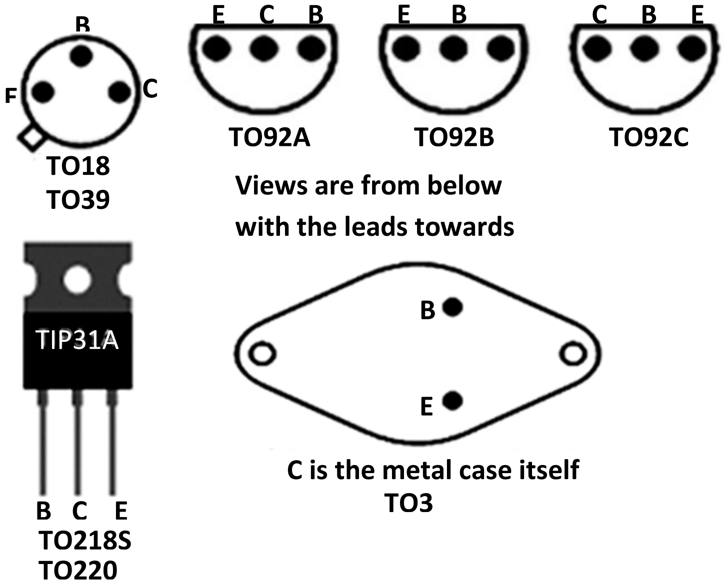


Figure 8: Transistor terminals by its pin configuration

A transistor has three leads which must be connected in the correct way round. Please take care of it, because a wrongly connected transistor may be damaged instantly when you switch on.

If you are lucky the orientation of the transistors will be clear from the PCB or strip board layout diagram, if not, however, you will need to refer to a supplier's catalogue to identify the leads. Figure 8 shows the drawings of the leads for some of the most common case styles. Please note that transistor lead diagrams show the view from below with the leads towards you.

Theory:

The Transistor as a Switch

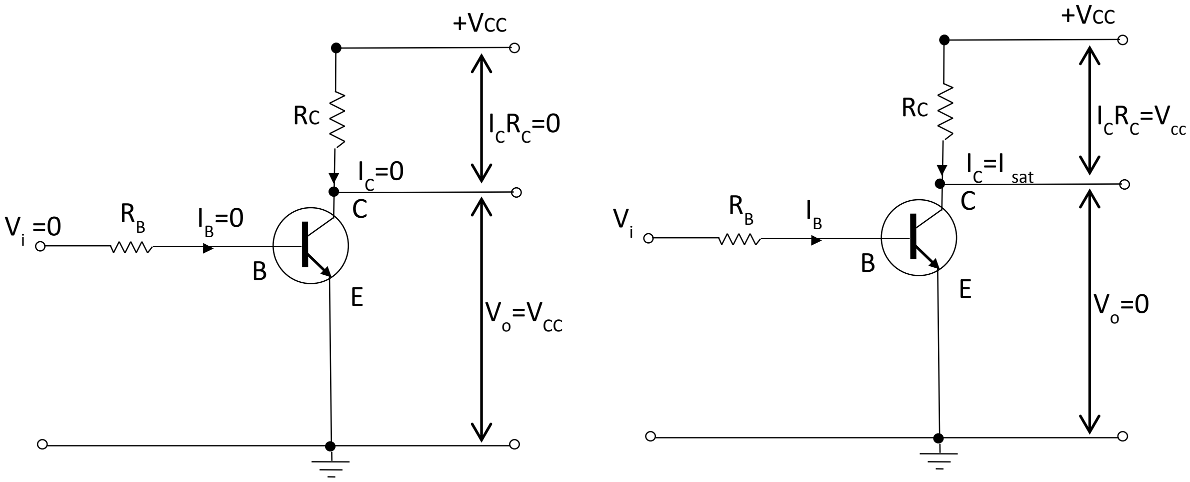
When used as an AC signal amplifier, the transistors Base biasing voltage is applied so that it operates within its "**Active**" region and the linear part of the output characteristics curves are used. However, both the NPN & PNP type bipolar transistors can be made to operate as an "ON/OFF" type solid state switch for controlling high power devices such as motors, solenoids or lamps. If the circuit uses the **Transistor as a Switch**, then the biasing is arranged to operate in the output characteristics curves seen previously in the areas known as the "**Saturation**" and "**Cut-off**" regions as shown in figures 5 and 6.

Let us go back to figure 6 which presents the $I_C - I_B$ curve. In this curve we identified three regions namely, cut off, active, and saturation regions.

When a transistor operates only at cut off and saturation regions, it functions as a switch.

Figure 9 shows a circuit with a transistor that can function as a switch.

This circuit is a common emitter (CE) NPN transistor circuit. The supply voltage V_{CC} can be around 6 V.



(a) cutoff stage (switch off) (b) saturation stage (switch on)

Figure 9: Transistors as a Switch

The resistance R_C represents a load, that operates with current I_C, controlled by the switch circuit. Base resistor R_B is to control the current I_B, in order to prevent damage to B-E junction, due to excessive current. Depending on the input voltage V_i and the load resistance R_c, the value of R_B should be selected, so that when V_i is applied the transistor invariably reaches the saturation stage.

Figure 9 (a) and (b) depicts the cut off and saturated stages respectively, In both these case output voltage is;

$$V_0 = V_C = V_{CC} - I_C.R_C$$

When $V_i = 0$, $I_B = 0$ and as a result the transistor is in the cut off state. Then as $I_c = 0$ the voltage across $R_C = I_C R_c = 0$.

As such the output voltage $V_0 = V_{CE} = V_{CC}$

That means the output voltage is equal to the supply voltage. This state where no current flows across R_c is known as the “off” state of the transistor switch.

When the magnitude of the input voltage V_i is sufficiently large, the B-E junction will be forward biased and the transistor will reach the saturated stage.

$$\text{Then } I_c = I_{c(sat)}$$

At this instance the voltage between C-E is as small as 0.1-0.2 V. Therefore we can consider $V_0 = 0$ approximately. This is the “on” state of the transistor switch.

Now the current $I_{c(sat)}$ flows through R_c. The value of the current depends on the value of V_{CC} and R_c.

$$V_{CE} = 0 = V_{CC} - R_C I_{C(sat)}$$

$$I_{c(SAT)} = \frac{V_{cc}}{R_c}$$

Before starting on the design of the transistor circuit, it is necessary to define the requirements. Without knowing what is required of the circuit, it is not possible to design the circuit. There are no aims for it. There can be a number of parameters required in the requirements for the transistor circuit design: you can find those parameters using a data sheet.

Transistor specifications

Transistors are available in a large variety of shapes and sizes, each with its own unique characteristics. The characteristics for each of these transistors are usually presented on specification sheets or they may be included in transistor manuals. Although many properties of a transistor could be specified on these sheets, manufacturers list only some of them. The specifications listed vary with different manufacturers, the type of transistor, and the application of the transistor. The specifications usually cover the following items.

1. A general description of the transistor that includes the following information:
    a. The kind of transistor. This covers the material used, such as germanium or silicon; the type of transistor (NPN or PNP); and the construction of the transistor (whether alloy-junction, grown, or diffused junction, etc.).
    b. Some of the common applications for the transistor, such as audio amplifier, oscillator, rf amplifier, etc.
    c. General sales features, such as size and packaging mechanical data.
2. The "Absolute Maximum Ratings" of the transistor are the direct voltage and current values that if exceeded in operation may result in transistor failure. Maximum ratings usually include collector-to-base voltage, emitter-to-base voltage, collector current, emitter current, and collector power dissipation.
3. The typical operating values of the transistor.

   These values are presented only as a guide. The values vary widely, are dependent upon operating voltages, and also upon which element is common in the circuit. The values listed may include collector-emitter voltage, collector current, input resistance, load resistance, current-transfer ratio (another name for alpha or beta), and collector cutoff current, which is leakage current from collector to base when no emitter current is applied. Transistor characteristic curves may also be included in this section. A transistor characteristic curve is a graph plotting the relationship between currents and voltages in a circuit.

More than one curve on a graph is called a "family of curves."

4. Additional information for engineering-design purposes.

The collector, emitter and base terminals on transistors are usually not labeled. Additionally, putting a transistor into a circuit in the wrong orientation can cause the circuit to not function or permanently damage the transistor. For these reasons, it is important that you be able to identify the terminals of a transistor. To do this, however, you may use transistor data sheet. In this experiment you have to use C828 transistor data sheet.

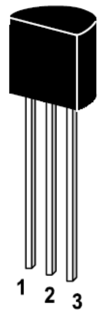
C 828 transistor data sheet

ST 2SC828 / 828A

NPN Silicon Epitaxial Planar Transistor
for switching and AF amplifier applications.

These transistors are subdivided into three groups Q, R and S according to their DC current gain.

On special request, these transistors can be manufactured in different pin configurations.



1. Emitter 2. Collector 3. Base

TO-92 Plastic Package
Weight approx. 0.19g

Absolute Maximum Ratings (T_a = 25°C)

	Symbol	Value		Unit
		ST 2SC828	ST 2SC828A	
Collector Base Voltage	V_{CBO}	30	45	V
Collector Emitter Voltage	V_{CEO}	25	45	V
Emitter Base Voltage	V_{EBO}	7		V
Peak Collector Current	I_{CM}	100		mA
Collector Current	I_C	50		mA
Power Dissipation	P_{tot}	400		mW
Junction Temperature	T_j	150		°C
Storage Temperature Range	T_S	-55 to +150		°C

ST 2SC828 / 828A

Characteristics at T_{amb}=25 °C

	Symbol	Min.	Typ.	Max.	Unit
DC Current Gain at I_C=2mA, V_{CE}=5V Current Gain Group Q	h_{FE}	130	-	280	-
R	h_{FE}	180	-	360	-
S	h_{FE}	260	-	520	-
Collector Base Breakdown Voltage at I_C=10μA ST 2SC828	$V_{(BR)CBO}$	30	-	-	V
ST 2SC828A	$V_{(BR)CBO}$	45	-	-	V
Collector Emitter Breakdown Voltage at I_C=2mA ST 2SC828	$V_{(BR)CEO}$	25	-	-	V
ST 2SC828A	$V_{(BR)CEO}$	45	-	-	V
Emitter Base Breakdown Voltage at I_E=10μA	$V_{(BR)EBO}$	7	-	-	V
Collector Saturation Voltage at I_C=50mA, I_B=5mA	$V_{CE(sat)}$	-	0.14	-	V
Base Emitter Voltage at I_C=10mA, V_{CE}=5V	V_{BE}	-	-	0.8	V
Gain Bandwidth Product at I_C=-2mA, V_{CE}=10V	f_T	-	220	-	MHz
Noise Figure at V_{CE}=5V,I_E=0.2mA, R_G=2kΩ,f=1kHz	NF	-	6	-	dB

Learning outcomes:
At the end of this experiment, you will be able to interpret manufacturer's data sheets and learn how to design transistors as switches for controlling dc devices.

Materials/Equipment:
C 828 transistor; Power supply (0-6 V); Resistors (10 kΩ, 220 Ω); LED; Multimeters; Bread board; Connecting wires.

Methodology/Procedure:

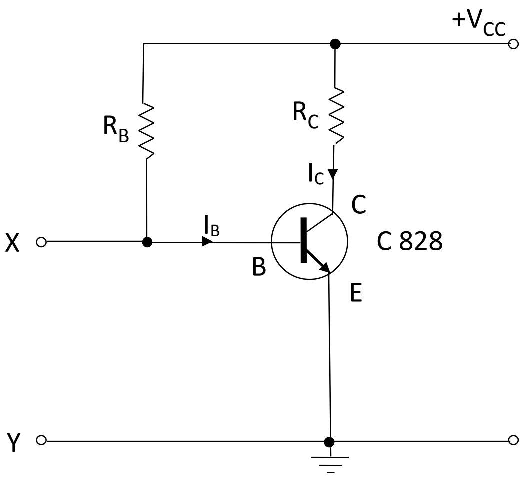


Figure 10: ANPN common emitter biasing circuit

According to figure 10 you may write

$$Vcc = I_C R_C + V_{CE}$$

From C 828 data sheet you may find
Collector saturation current

I_C =............................

Collector saturation voltage

$V_{CE\ (sat)}$ =............................

Then you may find R_C.

From data sheet you may find

β (h_{fe}) =

As we know; $\beta = \frac{I_C}{I_B}$

Then I_B =..........................

$$I_B R_B + V_{BE} = V_{CC}$$

From data sheet you may find V_{BE} =...................

Then you may find R_B=...........................

Now you can Replace R_C by series connected LED and 220 Ω resistor and connect the circuit as shown in the Figure11.

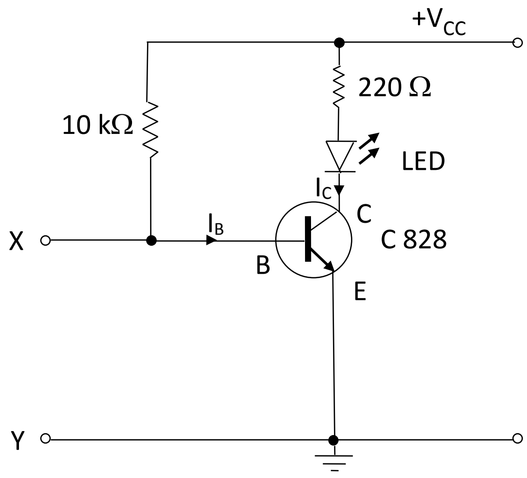


Figure 11: A simple Transistor switch

Measure and tabulate base-emitter V_{BE}, collector-emitter V_{CE} voltages and base current I_B, collector current I_C when the XY open and when it is connected with wire.

Readings/Observations:

status	I_B (µA)	V_{BE} (V)	I_C (mA)	V_{CE} (V)	LED
XY Open					
XY connect with wire					

Discussions:

Conclusions:

References:

Floyd, T. L. (2013). Electronic Devices (Conventional Current Version), 9th Edition, Prentice-Hall International.

Hambley, A. R., (2002). Electrical Engineering: Principles and Applications 3rd Edition, Prentice Hall

Horowitz, P. and Hill, W. (1997). The Art of Electronics, 2nd Edition, Cambridge University Press.