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Study & Application of Bipolar Junction Transistor

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Abstract:

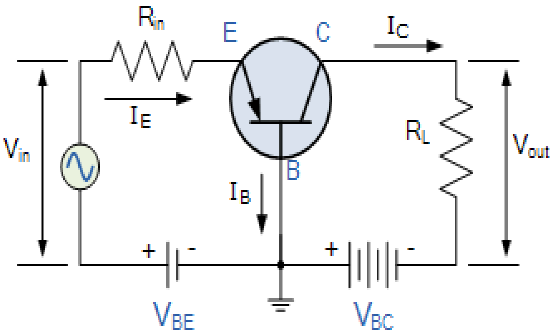
The first germanium alloy bipolar junction transistor (BJT) was invented by Bardeen, Brattain, and Shockley in 1948. The bipolar junction transistor is considered to be one of the most important electronic components used in integrated circuits (ICs) for computers, communications and power systems, and in many other digital and analog electronic circuit applications. In this paper explain application of BJT in various fields

Keywords : Bipolar junction transistor (BJT) ,Transfer resistor npn-junction transistor pnp junction transistor ,Emitter of a BJT Base of a BJT ,Collector of a BJT Emitter-base junction (EBJ) ,Collector-base junction (CBJ

Introduction

In the diode paper we saw that simple diodes are made up from two pieces of semiconductor material to form a simple pn-junction and we also learnt about their properties and characteristics.

If we now join together two individual signal diodes back-to-back, this will give us two PN-junctions connected together in series that share a common **P** or **N** terminal. The fusion of these two diodes produces a three layer, two junction, three terminal device forming the basis of a **Bipolar Junction Transistor**, or **BJT** for short.



Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage. The transistor's ability to change between these two states enables it to have two basic functions: "switching" (digital electronics) or "amplification" (analogue electronics). Then bipolar transistors have the ability to operate within three different regions:

- Active Region – the transistor operates as an amplifier and Ic = β.Ib
- Saturation – the transistor is "Fully-ON" operating as a switch and Ic = I(saturation)
- Cut-off – the transistor is "Fully-OFF" operating as a switch and Ic = 0

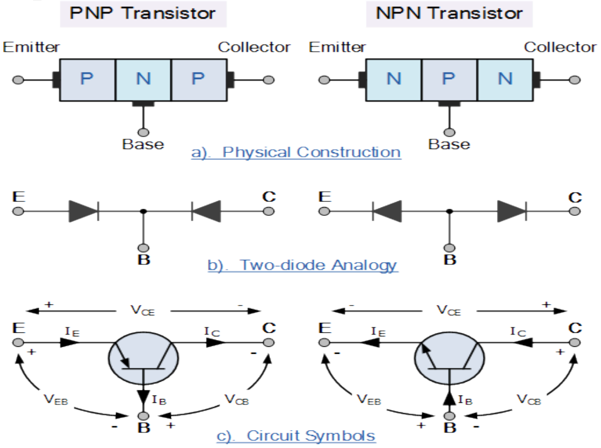
A Typical Bipolar Transistor

The word Transistor is a combination of the two words Transfer Varistor which describes their mode of operation way back in their early days of electronics development. There are two basic types of bipolar transistor construction, PNP and NPN, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

The **Bipolar Transistor** 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 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 transistor types PNP and NPN, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type

Bipolar Transistor Construction



The construction and circuit symbols for both the PNP and NPN bipolar transistor are given above 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.

Bipolar Transistor Configurations

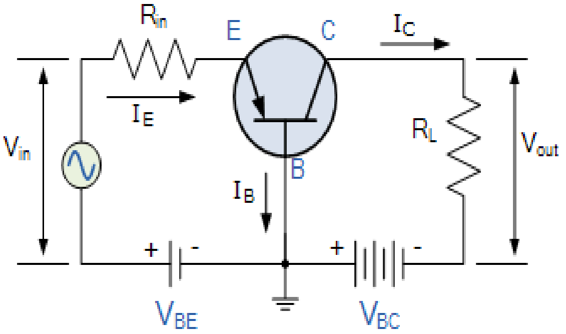
As the **Bipolar Transistor** is a three terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Each method of connection responding differently to its input signal within a circuit as the static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

- Common Base Configuration – has Voltage Gain but no Current Gain.
- Common Emitter Configuration – has both Current and Voltage Gain.
- Common Collector Configuration – has Current Gain but no Voltage Gain.

The Common Base (CB) Configuration

As its name suggests, in the **Common Base** or grounded base configuration, the Base connection is common to both the input signal AND the output signal. The input signal is applied between the transistors base and the emitter terminals, while the corresponding output signal is taken from between the base and the collector terminals as shown. The base terminal is grounded or can be connected to some fixed reference voltage point.The input current flowing into the emitter is quite large as its the sum of both the base current and collector current respectively therefore, the collector current output is less than the emitter current input resulting in a current gain for this type of circuit of "1" (unity) or less, in other words the common base configuration "attenuates" the input signal.

The Common Base Transistor Circuit



This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages Vin and Vout are "in-phase". This type of transistor arrangement is not very common due to its unusually high voltage gain characteristics. Its input characteristics represent that of a forward biased diode while the output characteristics represent that of an illuminated photo-diode. Also this type of bipolar transistor configuration has a high ratio of output to input resistance or more importantly "load" resistance (RL) to "input" resistance (Rin) giving it a value of "Resistance Gain". Then the voltage gain (Av) for a common base configuration is therefore given as:

Common Base Voltage Gain

$$A_V = \frac{Vout}{Vin} = \frac{I_C \times R_L}{I_E \times R_{IN}}$$

Where: Ic/Ie is the current gain, alpha (α) and RL/Rin is the resistance gain.

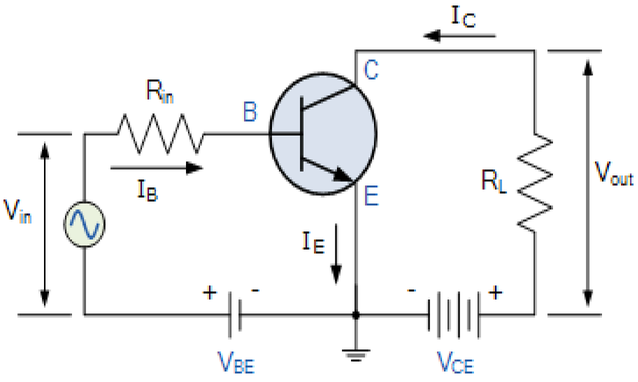
The common base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or radio frequency (Rf) amplifiers due to its very good high frequency response.

The Common Emitter (CE) Configuration

In the **Common Emitter** or grounded emitter configuration, the input signal is applied between the base and the emitter, 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.

The common emitter amplifier configuration produces the highest current and power gain of all the three bipolar transistor configurations. This is mainly because the input impedance is LOW as it is connected to a forward biased PN-junction, while the output impedance is HIGH as it is taken from a reverse biased PN-junction.

The Common Emitter Amplifier Circuit



In this type of configuration, the current flowing out of the transistor must be equal to the currents flowing into the transistor as the emitter current is given as Ie = Ic + Ib.

As the load resistance (RL) is connected in series with the collector, the current gain of the common emitter transistor configuration is quite large as it is the ratio of Ic/Ib. A transistors current gain is given the Greek symbol of Beta, (β).As the emitter current for a common emitter configuration is defined as Ie = Ic + Ib, the ratio of Ic/Ie is called Alpha, given the Greek symbol of α.

Note: that the value of Alpha will always be less than unity.Since the electrical relationship between these three currents, Ib, Ic and Ie is determined by the physical construction of the transistor itself, any small change in the base current (Ib), will result in a much larger change in the collector current (Ic).Then, small changes in current flowing in the base will thus control the current in the emitter-collector circuit. Typically, Beta has a value between 20 and 200 for most general purpose transistors. So if a transistor has a Beta value of say 100, then one electron will flow from the base terminal for every 100 electrons flowing between the emitter-collector terminal.By combining the expressions for both Alpha, α and Beta, β the mathematical relationship between these parameters and therefore the current gain of the transistor can be given as:

$$\text{Alpha}, (\alpha) = \frac{I_C}{I_E} \quad \text{and} \quad \text{Beta}, (\beta) = \frac{I_C}{I_B}$$

$$\therefore I_C = \alpha . I_E = \beta . I_B$$

$$\text{as:} \ \alpha = \frac{\beta}{\beta + 1} \qquad \beta = \frac{\alpha}{1 - \alpha}$$

$$I_E = I_C + I_B$$

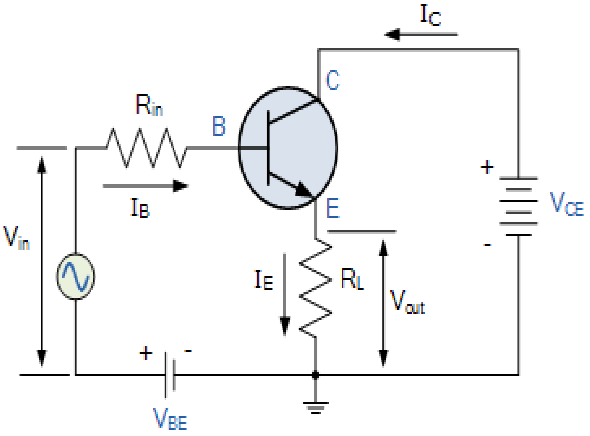
Where: “Ic” is the current flowing into the collector terminal, “Ib” is the current flowing into the base terminal and “Ie” is the current flowing out of the emitter terminal.Then to summarise a little. This type of bipolar transistor configuration has a greater input impedance, current and power gain than that of the common base configuration but its voltage gain is much lower. The common emitter configuration is an inverting amplifier circuit. This means that the resulting output signal is 180° “out-of-phase “with the input voltage signal.

The Common Collector (CC) Configuration

In the **Common Collector** or grounded collector configuration, the collector is now common through the supply. The input signal is connected directly to the base, while the output is taken from the emitter load as shown. This type of configuration is commonly known as a **Voltage Follower** or **Emitter Follower** circuit.

The common collector, or emitter follower configuration is very useful for impedance matching applications because of the very high input impedance, in the region of hundreds of thousands of Ohms while having a relatively low output impedance.

The Common Collector Transistor Circuit



The common emitter configuration has a current gain approximately equal to the βvalue of the transistor itself. In the common collector configuration the load resistance is situated in series with the emitter so its current is equal to that of the emitter current.

As the emitter current is the combination of the collector AND the base current combined, the load resistance in this type of transistor configuration also has both the collector current and the input current of the base flowing through it. Then the current gain of the circuit is given as:

The Common Collector Current Gain

$$I_E = I_C + I_B$$

$$A_i = \frac{I_E}{I_B} = \frac{I_C + I_B}{I_B}$$

$$A_i = \frac{I_C}{I_B} + 1$$

$$A_i = \beta + 1$$

This type of bipolar transistor configuration is a non-inverting circuit in that the signal voltages of Vin and Vout are "in-phase". It has a voltage gain that is always less than "1" (unity). The load resistance of the common collector transistor receives both the base and collector currents giving a large current gain (as with the common emitter configuration) therefore, providing good current amplification with very little voltage gain.

We can now summarise the various relationships between the transistors individual DC currents flowing through each leg and its DC current gains given above in the following table.

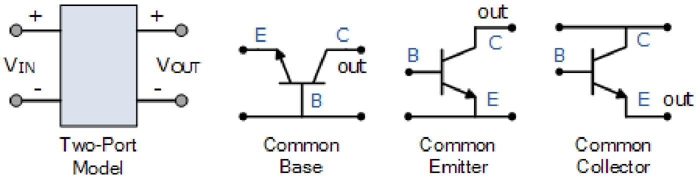
Relationship between DC Currents and Gains

$I_E = I_B + I_C$ $I_C = I_E - I_B$ $I_B = I_E - I_C$	$\alpha = \frac{I_C}{I_E} = \frac{\beta}{1+\beta}$ $\beta = \frac{I_C}{I_B} = \frac{\alpha}{1-\alpha}$
$I_B = \frac{I_C}{\beta} = \frac{I_E}{1+\beta} = I_E(1-\alpha)$	
$I_C = \beta . I_B =$	$(I_E = \frac{I_C}{\alpha} = I_B ($

Bipolar Transistor Summary

Then to summarise, the behaviour of the bipolar transistor in each one of the above circuit configurations is very different and produces different circuit characteristics with regards to input impedance, output impedance and gain whether this is voltage gain, current gain or power gain and this is summarised in the table below.

Bipolar Transistor Configurations



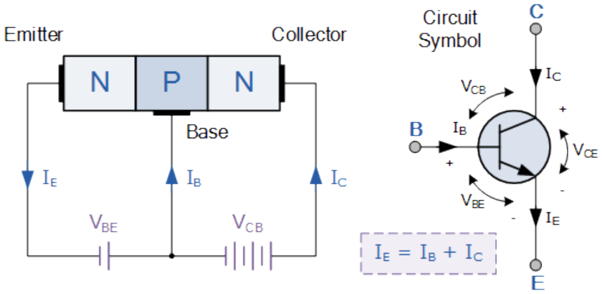
with the generalised characteristics of the different transistor configurations given in the following table:

Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Angle	0º	180º	0º
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

NPN Transistor

In the previous tutorial we saw that the standard **Bipolar Transistor** or BJT, comes in two basic forms. An **NPN** (**N**egative-

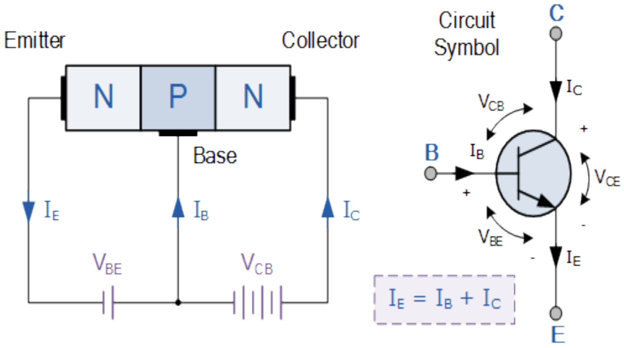
Positive-**N**egative) type and a **PNP** (**P**ositive-**N**egative-**P**ositive) type



The most commonly used transistor configuration is the **NPN Transistor**. We also learnt that the junctions of the bipolar transistor can be biased in one of three different ways – **Common Base**, **Common Emitter** and **Common Collector**.

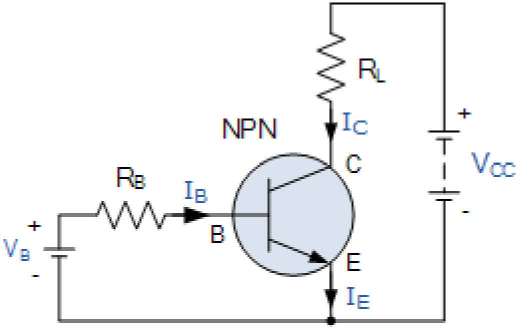
In this tutorial about bipolar transistors we will look more closely at the "Common Emitter" configuration using the **Bipolar NPN Transistor** with an example of the construction of a NPN transistor along with the transistors current flow characteristics is given below.

A Bipolar NPN Transistor Configuration



(Note: Arrow defines the emitter and conventional current flow, "out" for a Bipolar NPN Transistor.)

The construction and terminal voltages for a bipolar NPN transistor are shown above. The voltage between the Base and Emitter (V_{BE}), is positive at the Base and negative at the Emitter because for an NPN transistor, the Base terminal is always positive with respect to the Emitter. Also the Collector supply voltage is positive with respect to the Emitter (V_{CE}). So for a bipolar NPN transistor to conduct the Collector is always more positive with respect to both the Base and the Emitter.



NPN Transistor Connection

Then the voltage sources are connected to an NPN transistor as shown. The Collector is connected to the supply voltage V_{CC} via the load resistor, RLwhich also acts to limit the maximum current flowing through the device. The Base supply voltage V_B is connected to the Base resistor R_B, which again is used to limit the maximum Base current.

So in a NPN Transistor it is the movement of negative current carriers (electrons) through the Base region that constitutes transistor action, since these mobile electrons provide the link between the Collector and Emitter circuits. This link between the input and output circuits is the main feature of transistor action because the transistors amplifying properties come from the consequent control which the Base exerts upon the Collector to Emitter current.

Then we can see that the transistor is a current operated device (Beta model) and that a large current (Ic) flows freely through the device between the collector and the emitter terminals when the transistor is switched "fully-ON". However, this only happens when a small biasing current (Ib) is flowing into the base terminal of the transistor at the same time thus allowing the Base to act as a sort of current control input.

The transistor current in a bipolar NPN transistor is the ratio of these two currents (Ic/Ib), called the *DC Current Gain* of the device and is given the symbol of hfe or nowadays Beta, (β). The value of β can be large up to 200 for standard transistors, and it is this large ratio between Ic and Ib that makes the bipolar NPN transistor a useful amplifying device when used in its active region as Ib provides the input and Ic provides the output. Note that Beta has no units as it is a ratio.

Also, the current gain of the transistor from the Collector terminal to the Emitter terminal, Ic/Ie, is called Alpha, (α), and is a function of the transistor itself (electrons diffusing across the junction). As the emitter current Ie is the sum of a very small base current plus a very large collector current, the value of alpha α, is very close to unity, and for a typical low-power signal transistor this value ranges from about 0.950 to 0.999

α and β Relationship in a NPN Transistor

$$\text{DC Current Gain} = \frac{\text{Output Current}}{\text{Input Current}} = \frac{I_C}{I_B}$$

$$I_E = I_B + I_C \;\ldots..\;(\text{KCL}) \quad \text{and} \quad \frac{I_C}{I_E} = \alpha$$

$$\text{Thus: } I_B = I_E - I_C$$

$$I_B = I_E - \alpha I_E$$

$$I_B = I_E\left(1-\alpha\right)$$

$$\therefore\ \beta = \frac{I_C}{I_B} = \frac{I_C}{I_E\left(1-\alpha\right)} = \frac{\alpha}{1-\alpha}$$

By combining the two parameters α and β we can produce two mathematical expressions that gives the relationship between the different currents flowing in the transistor.

$$\alpha = \frac{\beta}{\beta+1} \quad \text{or} \quad \alpha = \beta\left(1-\alpha\right)$$

$$\beta = \frac{\alpha}{1-\alpha} \quad \text{or} \quad \beta = \alpha\left(1+\beta\right)$$

$$\text{If} \quad \alpha = 0.99 \qquad \beta = \frac{0.99}{0.01} = 99$$

The values of Beta vary from about 20 for high current power transistors to well over 1000 for high frequency low power type bipolar transistors. The value of Beta for most standard NPN transistors can be found in the manufactures data sheets but generally range between 50 – 200.

The equation above for Beta can also be re-arranged to make Ic as the subject, and with a zero base current (Ib = 0) the resultant collector current Ic will also be zero, (β x 0). Also when the base current is high the corresponding collector current will also be high resulting in the base current controlling the collector current. One of the most important properties of the **Bipolar Junction Transistor** is that a small base current can control a much larger collector current. Consider the following example.

<u>NPN Transistor Example No1</u>

A bipolar NPN transistor has a DC current gain, (Beta) value of 200. Calculate the base current Ib required to switch a resistive load of 4mA.

$$I_B = \frac{I_C}{\beta} = \frac{4\times10^{-3}}{200} = 20\mu A$$

Therefore, β = 200, Ic = 4mA and Ib = 20µA. One other point to remember about **Bipolar NPN Transistors**. The collector voltage, (Vc) must be greater and positive with respect to the emitter voltage, (Ve) to allow current to flow through the transistor between the collector-emitter junctions. Also, there is a voltage drop between the Base and the Emitter terminal of about 0.7v (one diode volt drop) for silicon devices as the input characteristics of an NPN Transistor are of a forward biased diode.

Then the base voltage, (Vbe) of a NPN transistor must be greater than this 0.7V otherwise the transistor will not conduct with the base current given as.

$$I_B = \frac{V_B - V_{BE}}{R_B}$$

Where: Ib is the base current, Vb is the base bias voltage, Vbe is the base-emitter volt drop (0.7v) and Rb is the base input resistor. Increasing Ib, Vbe slowly increases to 0.7V but Ic rises exponentially.

NPN Transistor Example No2

An NPN Transistor has a DC base bias voltage, Vb of 10v and an input base resistor, Rb of 100kΩ. What will be the value of the base current into the transistor.

$$I_B = \frac{V_B - V_{BE}}{R_B} = \frac{10 - 0.7}{100k\Omega} = 93\mu A$$

Therefore, Ib = 93µA.

The Common Emitter Configuration.

As well as being used as a semiconductor switch to turn load currents "ON" or "OFF" by controlling the Base signal to the transistor in either its saturation or cut-off regions, **Bipolar NPN Transistors** can also be used in its active region to produce a circuit which will amplify any small AC signal applied to its Base terminal with the Emitter grounded.

If a suitable DC "biasing" voltage is firstly applied to the transistors Base terminal thus allowing it to always operate within its linear active region, an inverting amplifier circuit called a single stage common emitter amplifier is produced.

One such *Common Emitter Amplifier* configuration of an NPN transistor is calle . A "Class A Amplifier" operation is one where the transistors Base terminal is biased in such a way as to forward bias the Base-emitter junction.

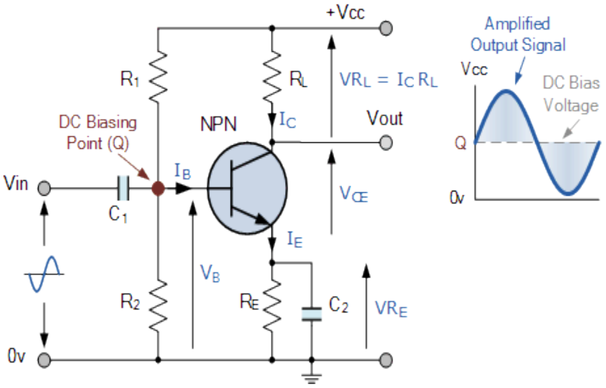
The result is that the transistor is always operating halfway between its cut-off and saturation regions, thereby allowing the transistor amplifier to accurately reproduce the positive and negative halves of any AC input signal superimposed upon this DC biasing voltage.

Without this "Bias Voltage" only one half of the input waveform would be amplified. This common emitter amplifier configuration using an NPN transistor has many applications but is commonly used in audio circuits such as pre-amplifier and power amplifier stages.

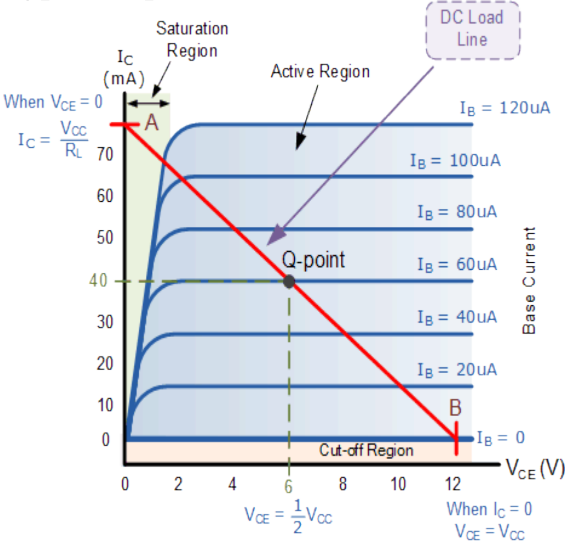
With reference to the common emitter configuration shown below, a family of curves known as the **Output Characteristics Curves**, relates the output collector current, (Ic) to the collector voltage, (Vce) when different values of Base current, (Ib). Output characteristics curves are applied to the transistor for transistors with the same β value.

A DC "Load Line" can also be drawn onto the output characteristics curves to show all the possible operating points when different values of base current are applied. It is necessary to set the initial value of Vce correctly to allow the output voltage to vary both up and down when amplifying AC input signals and this is called setting the operating point or Quiescent Point, **Q-point** for short and this is shown below.

Single Stage Common Emitter Amplifier Circuit



Output Characteristics Curves of a Typical Bipolar Transistor



The most important factor to notice is the effect of Vce upon the collector current Icwhen Vce is greater than about 1.0 volts. We can see that Ic is largely unaffected by changes in Vce above this value and instead it is almost entirely controlled by the base current, Ib. When this happens we can say then that the output circuit represents that of a "Constant Current Source".

It can also be seen from the common emitter circuit above that the emitter current Ie is the sum of the collector current, Ic and the base current, Ib, added together so we can also say that Ie = Ic + Ib for the common emitter (CE) configuration.

By using the output characteristics curves in our example above and also Ohm´s Law, the current flowing through the load resistor, (RL), is equal to the collector current, Icentering the transistor which in turn corresponds to the supply voltage, (Vcc) minus the voltage drop between the collector and the emitter terminals, (Vce) and is given as:

$$\text{Collector Current, } I_C = \frac{V_{CC} - V_{CE}}{R_L}$$

Also, a straight line representing the **Dynamic Load Line** of the transistor can be drawn directly onto the graph of curves above from the point of "Saturation" (A) when Vce = 0to the point of "Cut-off" (B) when Ic = 0 thus giving us the "Operating" or **Q-point** of the transistor. These two points are joined together by a straight line and any position along this straight line represents the "Active Region" of the transistor. The actual position of the load line on the characteristics curves can be calculated as follows:

$$\text{When: } \left(V_{CE} = 0\right) \quad I_C = \frac{V_{CC} - 0}{R_L}, \quad I_C = \frac{V_{CC}}{R_L}$$

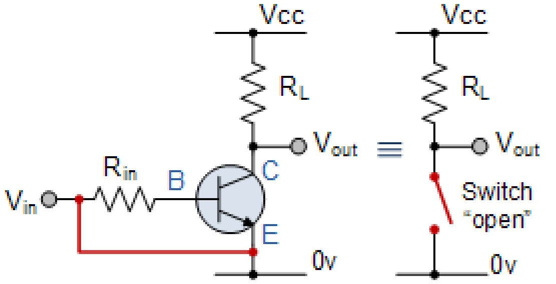
$$\text{When: } \left(I_C = 0\right) \quad 0 = \frac{V_{CC} - V_{CE}}{R_L}, \quad V_{CC} = V_{CE}$$

Then, the collector or output characteristics curves for **Common Emitter NPN Transistors** can be used to predict the Collector current, Ic, when given Vce and the Base current, Ib. A Load Line can also be constructed onto the curves to determine a suitable Operating or **Q-point** which can be set by adjustment of the base current. The slope of this load line is equal to the reciprocal of the load resistance which is given as: $-1/R_L$

Then we can define a **NPN Transistor** as being normally “OFF” but a small input current and a small positive voltage at its Base (B) relative to its Emitter (E) will turn it “ON” allowing a much large Collector-Emitter current to flow. NPN transistors conduct when Vc is much greater than Ve.

Transistor as a Switch

When used as an AC signal amplifier, the transistors Base biasing voltage is applied in such a way that it always operates within its “active” region, that is the linear part of the output characteristics curves are used.

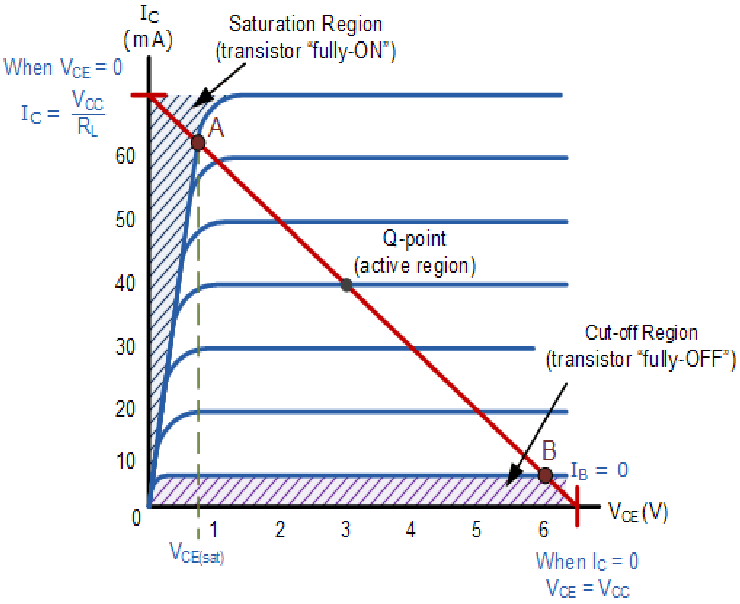


However, both the NPN & PNP type bipolar transistors can be made to operate as “ON/OFF” type solid state switch by biasing the transistors Base terminal differently to that for a signal amplifier.Solid state switches are one of the main applications for the use of transistor to switch a DC output “ON” or “OFF”. Some output devices, such as LED’s only require a few milliamps at logic level DC voltages and can therefore be driven directly by the output of a logic gate. However, high power devices such as motors, solenoids or lamps, often require more power than that supplied by an ordinary logic gate so transistor switches are used.

If the circuit uses the **Bipolar Transistor as a Switch**, then the biasing of the transistor, either NPN or PNP is arranged to operate the transistor at both sides of the “ I-V ” characteristics curves we have seen previously.

The areas of operation for a transistor switch are known as the **Saturation Region** and the **Cut-off Region**. This means then that we can ignore the operating Q-point biasing and voltage divider circuitry required for amplification, and use the transistor as a switch by driving it back and forth between its “fully-OFF” (cut-off) and “fully-ON” (saturation) regions as shown below.

Operating Regions

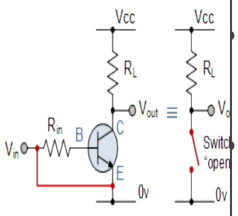


The pink shaded area at the bottom of the curves represents the “Cut-off” region while the blue area to the left represents the “Saturation” region of the transistor. Both these transistor regions are defined as:

1. Cut-off Region

Here the operating conditions of the transistor are zero input base current (I_B), zero output collector current (I_C) and maximum collector voltage (V_{CE}) which results in a large depletion layer and no current flowing through the device. Therefore the transistor is switched “Fully-OFF”.

Cut-off Characteristics

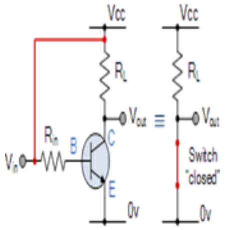
	• The input and Base are grounded (0v) • Base-Emitter voltage $V_{BE} < 0.7$v • Base-Emitter junction is reverse biased • Base-Collector junction is reverse biased • Transistor is "fully-OFF" (Cut-off region) • No Collector current flows ($I_C = 0$) • $V_{OUT} = V_{CE} = V_{CC}$ = "1″ • Transistor operates as an "open switch"

Then we can define the "cut-off region" or "OFF mode" when using a bipolar transistor as a switch as being, both junctions reverse biased, $V_B < 0.7$v and $I_C = 0$. For a PNP transistor, the Emitter potential must be negative with respect to the Base.

2. Saturation Region

Here the transistor will be biased so that the maximum amount of base current is applied, resulting in maximum collector current resulting in the minimum collector emitter voltage drop which results in the depletion layer being as small as possible and maximum current flowing through the transistor. Therefore the transistor is switched "Fully-ON".

Saturation Characteristics

	• • The input and Base are connected to V_{CC} • • Base-Emitter voltage $V_{BE} > 0.7$v • Base-Emitter junction is forward biased • Base-Collector junction is forward biased • Transistor is "fully-ON" (saturation region) • Max Collector current flows ($I_C = Vcc/R_L$) • $V_{CE} = 0$ (ideal saturation) • $V_{OUT} = V_{CE}$ = "0″ • Transistor operates as a "closed switch"

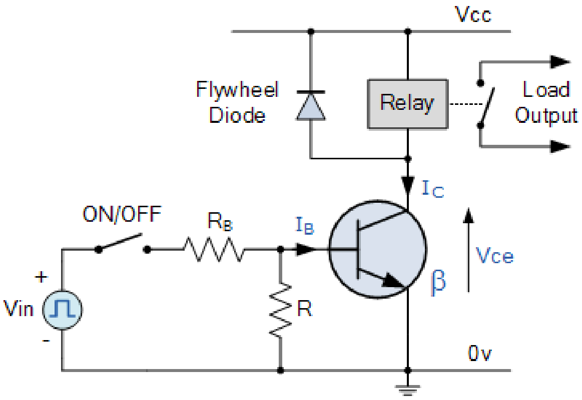
Then we can define the "saturation region" or "ON mode" when using a bipolar transistor as a switch as being, both junctions forward biased, $V_B > 0.7$v and I_C = Maximum. For a PNP transistor, the Emitter potential must be positive with respect to the Base.

Then the transistor operates as a "single-pole single-throw" (SPST) solid state switch. With a zero signal applied to the Base of the transistor it turns "OFF" acting like an open switch and zero collector current flows. With a positive signal applied to the Base of the transistor it turns "ON" acting like a closed switch and maximum circuit current flows through the device.

The simplest way to switch moderate to high amounts of power is to use the transistor with an open-collector output and the transistors Emitter terminal connected directly to ground. When used in this way, the transistors open collector output can thus "sink" an externally supplied voltage to ground thereby controlling any connected load.

An example of an NPN Transistor as a switch being used to operate a relay is given below. With inductive loads such as relays or solenoids a flywheel diode is placed across the load to dissipate the back EMF generated by the inductive load when the transistor switches "OFF" and so protect the transistor from damage. If the load is of a very high current or voltage nature, such as motors, heaters etc, then the load current can be controlled via a suitable relay as shown.

Basic NPN Transistor Switching Circuit



The circuit resembles that of the *Common Emitter* circuit we looked at in the previous tutorials. The difference this time is that to operate the transistor as a switch the transistor needs to be turned either fully "OFF" (cut-off) or fully "ON" (saturated). An ideal transistor switch would have infinite circuit resistance between the Collector and Emitter when turned "fully-OFF" resulting in zero current flowing through it and zero resistance between the Collector and Emitter when turned "fully-ON", resulting in maximum current flow.

In practice when the transistor is turned "OFF", small leakage currents flow through the transistor and when fully "ON" the device has a low resistance value causing a small saturation voltage (V_{CE}) across it. Even though the transistor is not a perfect switch, in both the cut-off and saturation regions the power dissipated by the transistor is at its minimum.

In order for the Base current to flow, the Base input terminal must be made more positive than the Emitter by increasing it above the 0.7 volts needed for a silicon device. By varying this Base-Emitter voltage V_{BE}, the Base current is also altered and which in turn controls the amount of Collector current flowing through the transistor as previously discussed.

When maximum Collector current flows the transistor is said to be **Saturated**. The value of the Base resistor determines how much input voltage is required and corresponding Base current to switch the transistor fully "ON".

Transistor as a Switch Example No1

Using the transistor values from the previous tutorials of: β = 200, Ic = 4mA and Ib = 20uA, find the value of the Base resistor (Rb) required to switch the load fully "ON" when the input terminal voltage exceeds 2.5v.

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{2.5v - 0.7v}{20x10^{-6}} = 90k\Omega$$

The next lowest preferred value is: 82kΩ, this guarantees the transistor switch is always saturated.

Transistor as a Switch Example No2

Again using the same values, find the minimum Base current required to turn the transistor "fully-ON" (saturated) for a load that requires 200mA of current when the input voltage is increased to 5.0V. Also calculate the new value of Rb.

Transistor Base current:

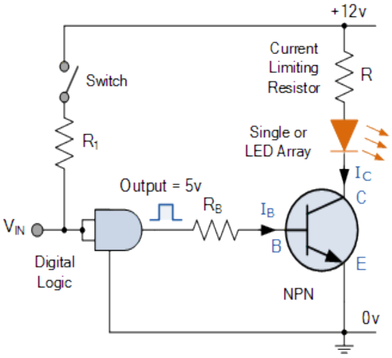
$$I_B = \frac{I_C}{\beta} = \frac{200mA}{200} = 1mA$$

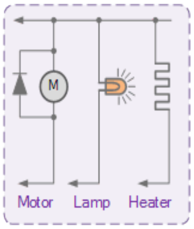
Transistor Base resistance:

$$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{5.0v - 0.7v}{1\times10^{-3}} = 4.3k\Omega$$

Transistor switches are used for a wide variety of applications such as interfacing large current or high voltage devices like motors, relays or lamps to low voltage digital logic IC's or gates like AND gates or OR gates. Here, the output from a digital logic gate is only +5v but the device to be controlled may require a 12 or even 24 volts supply. Or the load such as a DC Motor may need to have its speed controlled using a series of pulses (Pulse Width Modulation). transistor switches will allow us to do this faster and more easily than with conventional mechanical switches.

Digital Logic Transistor Switch





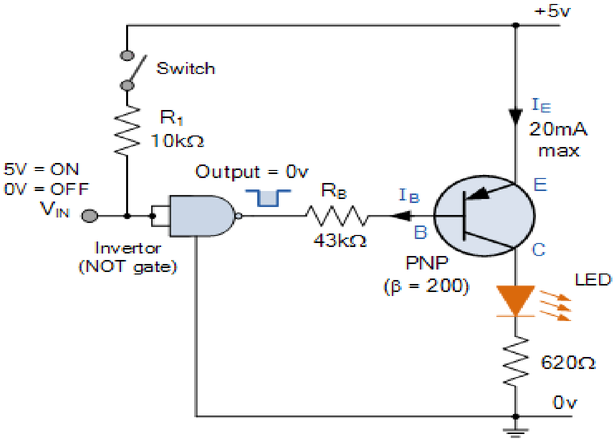
Different Collector Loads

The base resistor, Rb is required to limit the output current from the logic gate.

PNP Transistor Switch

We can also use the PNP Transistors as a switch, the difference this time is that the load is connected to ground (0v) and the PNP transistor switches the power to it. To turn the PNP transistor operating as a switch "ON", the Base terminal is connected to ground or zero volts (LOW) as shown.

PNP Transistor Switching Circuit



The equations for calculating the Base resistance, Collector current and voltages are exactly the same as for the previous NPN transistor switch. The difference this time is that we are switching power with a PNP transistor (sourcing current) instead of switching ground with an NPN transistor (sinking current).

Darlington Transistor Switch

Sometimes the DC current gain of the bipolar transistor is too low to directly switch the load current or voltage, so multiple switching transistors are used. Here, one small input transistor is used to switch "ON" or "OFF" a much larger current handling output transistor. To maximise the signal gain, the two transistors are connected in a "Complementary Gain Compounding Configuration" or what is more commonly called a "**Darlington Configuration**" were the amplification factor is the product of the two individual transistors.

Darlington Transistors simply contain two individual bipolar NPN or PNP type transistors connected together so that the current gain of the first transistor is multiplied with that of the current gain of the second transistor to produce a device which acts like a single transistor with a very high current gain for a much smaller Base current.

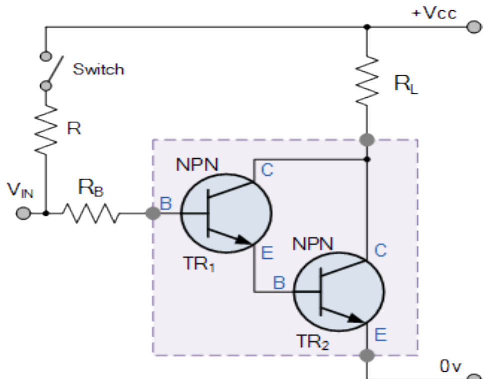
The overall current gain Beta (β) or Hfe value of a Darlington device is the product of the two individual gains of the transistors and is given as:

$$\beta_{TOTAL} = \beta_1 \times \beta_2$$

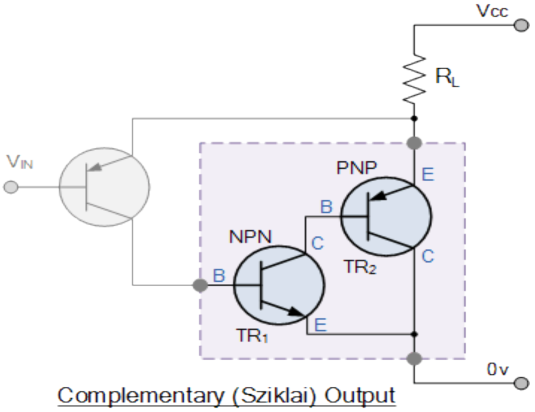
So Darlington Transistors with very high β values and high Collector currents are possible compared to a single transistor switch. For example, if the first input transistor has a current gain of 100 and the second switching transistor has a current gain of 50 then the total current gain will be 100 x 50 = 5000. So for example, if our load current from above is 200mA, then the darlington base current is only 200mA/5000 = 40uA. A huge reduction from the previous 1mA for a single transistor.

An example of the two basic types of Darlington transistor configurations are given below.

Darlington Transistor Configurations



NPN Darlington Output



Complementary (Sziklai) Output

The above NPN Darlington transistor switch configuration shows the Collectors of the two transistors connected together with the Emitter of the first transistor connected to the Base terminal of the second transistor therefore, the Emitter current of the first transistor becomes the Base current of the second transistor switching it “ON”.

The first or “input” transistor receives the input signal to its Base. This transistor amplifies it in the usual way and uses it to drive the second larger “output” transistors. The second transistor amplifies the signal again resulting in a very high current gain. One of the main characteristics of **Darlington Transistors** is their high current gains compared to single bipolar transistors.

As well as its high increased current and voltage switching capabilities, another advantage of a "Darlington Transistor Switch" is in its high switching speeds making them ideal for use in inverter circuits, lighting circuits and DC motor or stepper motor control applications.

One difference to consider when using Darlington transistors over the conventional single bipolar types when using the transistor as a switch is that the Base-Emitter input voltage (V_{BE}) needs to be higher at approx 1.4v for silicon devices, due to the series connection of the two PN junctions.

Transistor as a Switch Summary

Then to summarise when using a **Transistor as a Switch** the following conditions apply:

- Transistor switches can be used to switch and control lamps, relays or even motors.
- When using the bipolar transistor as a switch they must be either "fully-OFF" or "fully-ON".
- Transistors that are fully "ON" are said to be in their **Saturation** region.
- Transistors that are fully "OFF" are said to be in their **Cut-off** region.
- When using the transistor as a switch, a small Base current controls a much larger Collector load current.
- When using transistors to switch inductive loads such as relays and solenoids, a "Flywheel Diode" is used.
- When large currents or voltages need to be controlled, **Darlington Transistors** can be used.

Applications of Transistors

Applications of Transistors

The transistor as an amplifier

1. A transistor can be used to amplify current. This is because a small change in base current causes a large change in collector current.
2. Example is a microphone.
3. Sound waves that are fed into the microphone cause the diaphragm in the microphone to vibrate.
4. The electrical output of the microphone changes according to the sound waves.
5. As a result, the base current is varying because of the small alternating voltage produced by the microphone.
6. A small change in the base current causes a large change in the collector current.
7. The varying collector current flows into the loudspeaker. There, it is changed into the sound waves corresponding to the original sound waves.
8. The frequencies of both waves are equivalent but the amplitude of the sound wave from the loudspeaker is higher than the sound waves fed into the microphone.

Component:	Function
Microphone:	To change sound signal to electrical signal
Capacitor:	To block a steady current from flowing into the transistor and microphone.
Potential divider:	To apply a proportion of the total voltage across the emitter-base junction so that the junction is forward-biased.
Transistor:	To amplify the input wave form.
Loudspeaker:	To change the electrical signal to sound wave.

The transistor as switch

1. In a transistor, no current can flow in the collector circuit unless a current flows in the base circuit. This property allows a transistor to be used as switch.
2. The transistor can be turned on or off by changing the base.
3. There are a few types of switching circuits operated by transistors.

(a) Light-Operated Switch

1. The circuit is designed to light the bulb in a bright environment and to turn it off in the

dark.

2. One of the components in the potential divider is a light-dependent resistor (LDR). When it is placed in DARKNESS, its resistance is large. The transistor is switched OFF.

3. When LDR is lighted by bright light, its resistance falls to small value resulting in more supply voltage and raising the base current. The transistor is switched on, collector current flows and bulb lights up.

(b) Heat-operated switch

1. One important component in the circuit of a heat-operated switch is the thermistor.

2. Thermistor is type of resistor that responds to the surrounding temperature. Its resistance increases when the temperature is low and vice versa.

3. When heat is applied to the thermistor, its resistance drops and a greater share of supply voltage is dropped across R. The base current increases followed by a greater increase in the collector current. The bulb will glow and the siren will sound.

4. This particular circuit is suitable as a fire alarm system.

Integrated Circuits (C)

1. An integrated circuit (IC) consists of transistors, resistors, diodes and capacitors combined together in one wafer-thin chip of silicon.

2. This is one wafer-thin chip is called a microchip.

3. The microchip is only a few millimeters square with a thickness of 0.5 mm.

Advantages of an IC:

a. Consumes a small amount of electrical energy.

b. Very little heat is generated.

c. Occupies a small space which reduces the size of circuits.

d. Can be built at low cost.

Conclusion

The use and characteristics of the Bipolar Junction Transistor as an amplifier was explored in this experiment using the DC operating point (Q-Point) for transistor circuit which function as a single stage transistor amplifier and the distinct disadvantages of the DC Operating point (Q-Point) for a transistor amplifier. We also verify the correspondence of a small-signal gain of a single stage to the predicted gain from an analysis of the small-signal equivalent circuit. There were some percent error exist between our measured value and the predicted value. These errors occurred due to the inaccuracy of the equipment we were used in order to build the signal circuit. There were three fundamental configurations layer covered that are known as the Bipolar Junction Transistor. We call the layer as the emitter, the base and the collector. Each layer has unique beneficial characteristics as well as limitations. It is very crucial that the canonic cells are well understood, as they will give a circuit designer the ability to evaluate complex circuit topologies virtually by inspection.

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