LESSON 7 TRANSISTORS

By the end of the lesson the learner should be able to:

(i) Explain the construction of BJT
(ii) Describe the different configurations of BJT
(iii) Describe output characteristics curve of BJT
(iv) Describe the application of BJT transistors

Definition: The word Transistor is an acronym, and is a combination of the words Transfer Varistor used to describe their mode of operation way back in their early days.

There are TWO main types of transistors:

1) Bipolar Transistor BTJ
2) Field Effect Transistor FET

(A) Transistor - Bipolar Junction Transistors BJT

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. This type of transistor is generally known as a Bipolar Transistor, because its basic construction consists of two PN-junctions with each terminal or connection being given a name to identify it and these are known as the Emitter, Base and Collector respectively.

Bipolar Transistors are "CURRENT" Amplifying or current regulating devices that control the amount of current flowing through them in proportion to the amount of biasing current applied to their base terminal. The principle of operation of the two transistor types NPN and PNP, is exactly the same the only difference being in the biasing (base current) and the polarity of the power supply for each type.

Bipolar Transistor Construction

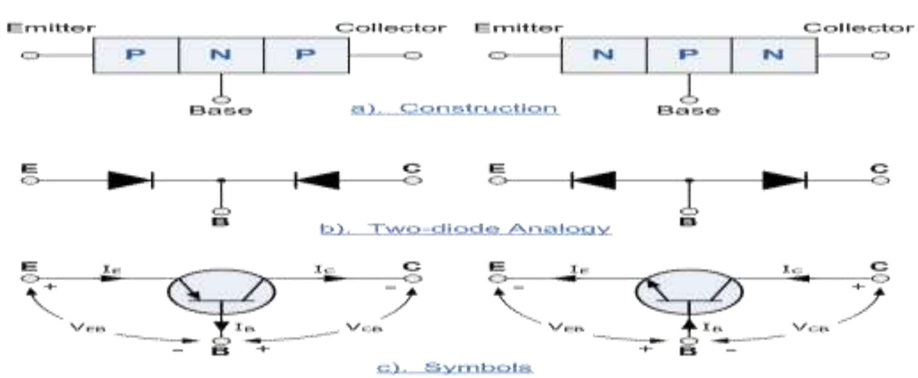

Fig 7.1 BJT Construction (a), Analogy (b) and Symbol (c)

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

There are basically three possible ways to connect a Bipolar Transistor within an electronic circuit with each method of connection responding differently to its input signal as the static characteristics of the transistor vary with each circuit arrangement.

1. Common Base Configuration - has Voltage Gain but no Current Gain.

2. Common Emitter Configuration - has both Current and Voltage Gain.

3. Common Collector Configuration - has Current Gain but no Voltage Gain.

The Common Base Configuration.

In the Common Base or Grounded Base configuration, the BASE connection is common to both the input signal AND the output signal with the input signal being applied between the base and the emitter terminals. The corresponding output signal is taken from between the base and the collector terminals as shown with the base terminal grounded or connected to a 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 less than "1", or in other words it "Attenuates" the signal.

The Common Base Amplifier Circuit

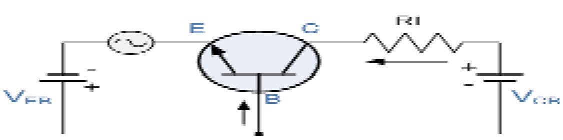

Fig 7.2 Common Base Amplifier Circuit

This type of amplifier configuration is a non-inverting voltage amplifier circuit, in that the signal voltages V_{in} and V_{out} are In-Phase. This type of arrangement is not very common due to its unusually high voltage gain characteristics. Its Output characteristics represent that of a forward biased diode while the Input characteristics represent that of an illuminated photo-diode. Also this type of configuration has a high ratio of Output to Input resistance or more importantly "Load" resistance (RL) to "Input" resistance (R_{in}) giving it a value of "Resistance Gain". Then the Voltage Gain for a common base can therefore be given as:

Common Base Voltage Gain

$$A_V = \frac{I_c \times R_L}{I_e \times R_{IN}} = \alpha \times \frac{R_L}{R_{IN}}$$

The Common Base circuit is generally only used in single stage amplifier circuits such as microphone pre-amplifier or RF radio amplifiers due to its very good high frequency response.

The Common Emitter 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. This type of configuration is the most commonly used circuit for transistor based amplifiers and which represents the "normal" method of 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 junction, while the output impedance is HIGH as it is taken from a reverse-biased junction.

The Common Emitter Amplifier Circuit

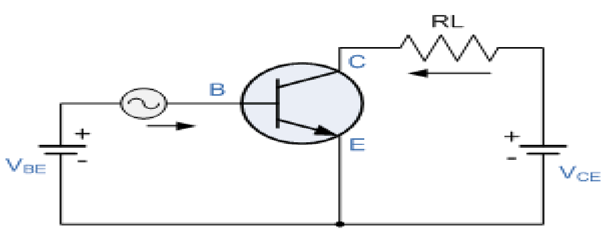

Fig 7.3 Common Emitter Amplifier Circuit

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. Also, as the load resistance (RL) is connected in series with the collector, the Current gain of the Common Emitter Transistor Amplifier is quite large as it is the ratio of Ic/Ib and is given the symbol of Beta, (β). Since the relationship between these three currents is determined by the transistor itself, any small change in the base current will result in a large change in the collector current. Then, small changes in base current will thus control the current in the Emitter/Collector circuit.

By combining the expressions for both Alpha, α and Beta, β the mathematical relationship between these parameters and therefore the current gain of the amplifier can be given as:

$$I_E = I_C + I_B$$

$$\alpha = \frac{I_C}{I_E} \quad \text{and} \quad \beta = \frac{I_C}{I_B}$$

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

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.

In summary, 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 is an inverting amplifier circuit resulting in the output signal being 180o out of phase with the input voltage signal.

The Common Collector Configuration.

In the Common Collector or Grounded Collector configuration, the collector is now common and the input signal is connected 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 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, and it has relatively low output impedance.

The Common Collector Amplifier Circuit

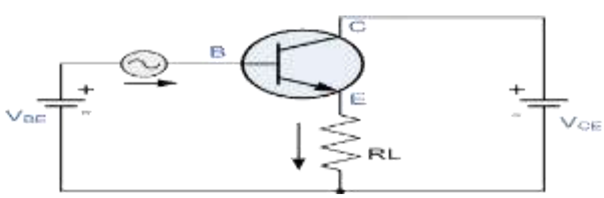

Fig 7.4 Common Collector Amplifier Circuit

The Common Emitter configuration has a current gain equal to the β value 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 base currents combined, the load resistance in this type of amplifier 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:

$$I_E = I_C + I_B$$

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

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

$$\therefore A_i = \beta + 1$$

This type of bipolar transistor configuration is a non-inverting amplifier circuit in that the signal voltages of V_{in} and V_{out} are "In-Phase". It has a voltage gain that is always less than "1" (unity). The load resistance of the common collector amplifier configuration 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.

Bipolar Transistor Summary.

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 and this is summarised in the table below.

Transistor Characteristics

The static characteristics for Bipolar Transistor amplifiers can be divided into the following main groups.

Input Characteristics:-	Common Base -	IE ÷ VEB
	Common Emitter -	IB ÷ VBE
Output Characteristics:-	Common Base -	IC ÷ VC
	Common Emitter -	IC ÷ VC
Transfer Characteristics:-	Common Base -	IE ÷ IC
	Common Emitter -	IB ÷ IC

With the 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	0^o	180^o	0^o
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

An NPN Transistor Configuration

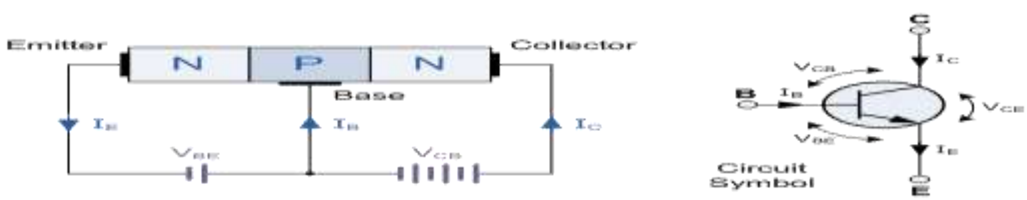

Fig 7.5 NPN Transistor Configuration

Note: Conventional current flow.

We know that the transistor is a "CURRENT" operated device and that a large current (Ic) flows freely through the device between the collector and the emitter terminals. However, this only happens when a small biasing current (Ib) is flowing into the base terminal of the transistor thus allowing the base to act as a sort of current control input. The ratio of these two currents (Ic/Ib) is called the DC Current Gain of the device and is given the symbol of hfe or nowadays Beta, (β). Beta has no units as it is a ratio. Also, the current gain from the emitter to the collector terminal, Ic/Ie, is called Alpha, (α), and is a function of the transistor itself. As the emitter current Ie is the product of a very small base current to a very large collector current the value of this parameter 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 Relationships

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

$$\beta = \frac{I_C}{I_B} \qquad \alpha = \frac{I_C}{I_E}$$

$$I_E = I_C + I_B$$

$$V_{CE} = V_{CB} + V_{BE}$$

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.

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

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 equation for Beta can also be re-arranged to make Ic as the subject, and with 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.

Example No1.

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

$$I_B = \frac{I_C}{\beta} = \frac{4 \times 10^{-3}}{200} = 20\text{uA}$$

Therefore, β = 200, Ic = 4mA and Ib = 20µA.

One other point to remember about NPN Transistors.

The collector voltage, (Vc) must be greater than the emitter voltage, (Ve) to allow current to flow through the device between the collector-emitter junction. Also, there is a voltage drop between the base and the emitter terminal of about 0.7v for silicon devices as the input characteristics of an NPN Transistor are of a forward biased diode. Then the base voltage, (Vbe) of an NPN Transistor must be greater than this 0.7 V 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.

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 switch to turn load currents "ON" or "OFF" by controlling the Base signal to the transistor, NPN Transistors can also be used to produce a circuit which will also amplify any small AC signal applied to its Base terminal. 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 Common Emitter Amplifier is produced.

One such Common Emitter Amplifier configuration is called a Class A Amplifier. A Class A Amplifier operation is one where the transistors Base terminal is biased in such a way that the transistor is always operating halfway between its cut-off and saturation points, thereby allowing the transistor amplifier to accurately reproduce the positive and negative halves of the AC input signal superimposed upon the DC Biasing voltage. Without this "Bias Voltage" only the positive half of the input waveform would be amplified. This type of amplifier 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 commonly as the Output Characteristics Curves, relates the output collector current, (Ic) to the collector voltage, (Vce) when different values of base current, (Ib) 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.

The Common Emitter Amplifier Circuit

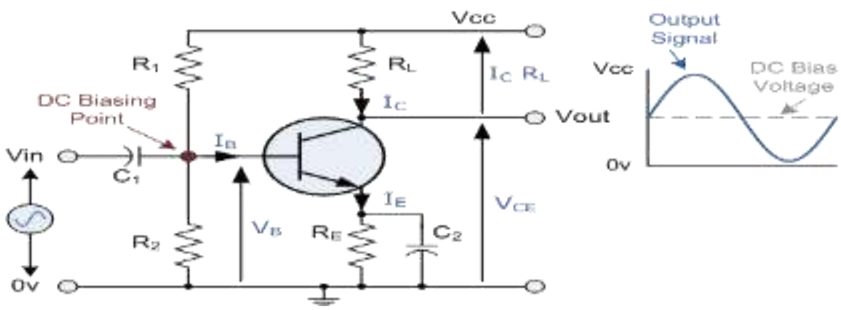

Fig 7.6 Single Stage Common Emitter Amplifier Circuit

Output Characteristics Curves for a Typical Bipolar Transistor

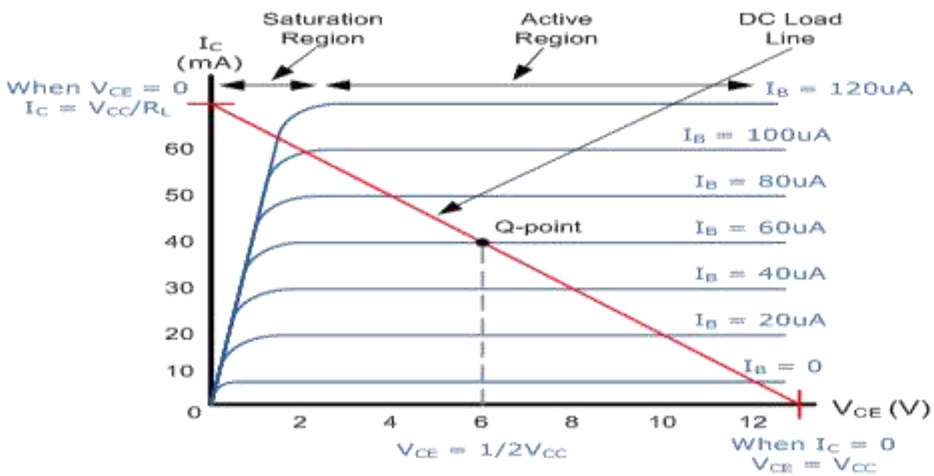

Fig 7.7 Output Characteristic of Single Stage Common Emitter BJT Amplifier

The most important factor to notice is the effect of Vce upon the collector current Ic when Vce is greater than about 1.0 volts. You 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 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, Ic entering 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 Load Line can be drawn directly onto the graph of curves above from the point of "Saturation" when Vce = 0 to the point of "Cut-off" when Ic = 0 giving us the "Operating" or Q-point of the transistor. These two points are calculated as:

$$\text{When } V_{CE} = 0, \quad I_C = \frac{V_{CC} - 0}{R_L}, \quad I_C = \frac{V_{CC}}{R_L}$$

$$\text{When } I_C = 0, \quad 0 = \frac{V_{CC} - V_{CE}}{R_L}, \quad V_{CC} = V_{CE}$$

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 PNP Transistor

The PNP Transistor is the exact opposite to the NPN Transistor device. Basically, in this type of transistor construction the two diodes are reversed with respect to the NPN type, with the arrow, which also defines the Emitter terminal this time pointing inwards in the transistor symbol. Also, all the polarities are reversed which means that PNP Transistors "sink" current as opposed to the NPN transistor which "sources" current. PNP Transistors use a small output base current and a negative base voltage to control a much larger emitter-collector current. The construction of a PNP transistor consists of two P-type semiconductor materials either side of the N-type material as shown below.

A PNP Transistor Configuration

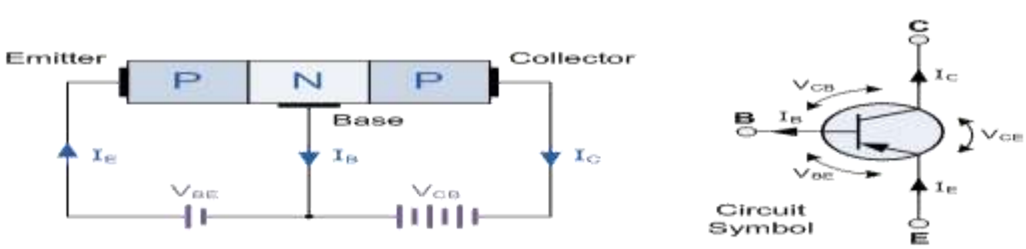

Fig 7.8 PNP Transistor Configuration

Note: Conventional current flow.

The PNP Transistor has very similar characteristics to their NPN bipolar cousins, except that the polarities (or biasing) of the current and voltage directions are reversed for any one of the possible three configurations looked at in the first tutorial, Common Base, Common Emitter and Common Collector. Generally, PNP Transistors require a negative (-ve) voltage at their Collector terminal with the flow of current through the emitter-collector terminals being Holes as opposed to Electrons for the NPN types. Because the movement of holes across the depletion layer tends to be slower than for electrons, PNP transistors are generally slower than their equivalent NPN counterparts when operating.

To cause the Base current to flow in a PNP transistor the Base needs to be more negative than the Emitter (current must leave the base) by approx 0.7 volts for a silicon device or 0.3 volts for a germanium device with the formulas used to calculate the Base resistor, Base current or Collector current are the same as those used for an equivalent NPN transistor and is given as.

$$I_E = I_C + I_B$$

$$I_C = \beta I_B \qquad I_B = \frac{I_C}{\beta}$$

Generally, the PNP transistor can replace NPN transistors in electronic circuits, the only difference is the polarities of the voltages, and the directions of the current flow. PNP Transistors can also be used as switching devices and an example of a PNP transistor switch is shown below.

A PNP Transistor Circuit

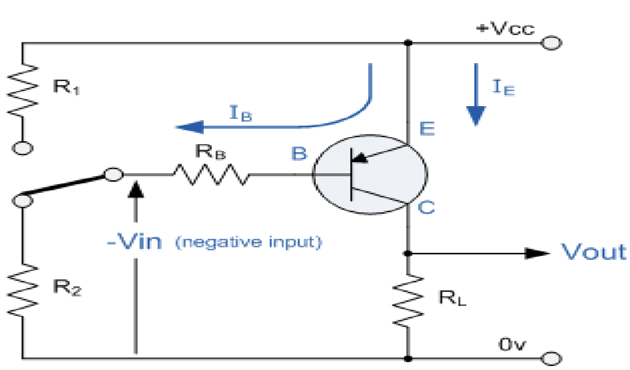

Fig 7.9 PNP Transistor Circuit

The Output Characteristics Curves for a PNP transistor look very similar to those for an equivalent NPN transistor except that they are rotated by 180º to take account of the reverse polarity voltages and currents, (the currents flowing out of the Base and Collector in a PNP transistor are negative).

Transistor Matching

You may think what is the point of having a PNP Transistor, when there are plenty of NPN Transistors available?. Well, having two different types of transistors PNP & NPN, can be an advantage when designing amplifier circuits such as Class B Amplifiers that use "Complementary" or "Matched Pair" transistors or for reversible H-Bridge motor control circuits. A pair of corresponding NPN and PNP transistors with near identical characteristics to each other are called Complementary Transistors for example, a TIP3055 (NPN), TIP2955 (PNP) are good examples of complementary or matched pair silicon power transistors. They have a DC current gain, Beta, (Ic / Ib) matched to within 10% and high Collector current of about 15A making them suitable for general motor control or robotic applications.

Identifying the PNP Transistor

Transistors are basically made up of two Diodes connected together back-to-back. We can use this analogy to determine whether a transistor is of the type PNP or NPN by testing its Resistance between the three different leads, Emitter, Base and Collector. By testing each pair of transistor leads in both directions will result in six tests in total with the expected resistance values in Ohm's given below.

- Emitter-Base Terminals - The Emitter to Base should act like a normal diode and conduct one way only.
- Collector-Base Terminals - The Collector-Base junction should act like a normal diode and conduct one way only.
- Emitter-Collector Terminals - The Emitter-Collector should not conduct in either direction.

Transistor Resistance Values for the PNP transistor and NPN transistor types

Between Transistor Terminals		PNP	NPN
Collector	Emitter	RHIGH	RHIGH
Collector	Base	RLOW	RHIGH
Emitter	Collector	RHIGH	RHIGH
Emitter	Base	RLOW	RHIGH
Base	Collector	RHIGH	RLOW
Base	Emitter	RHIGH	RLOW

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 below.

Transistor Curves

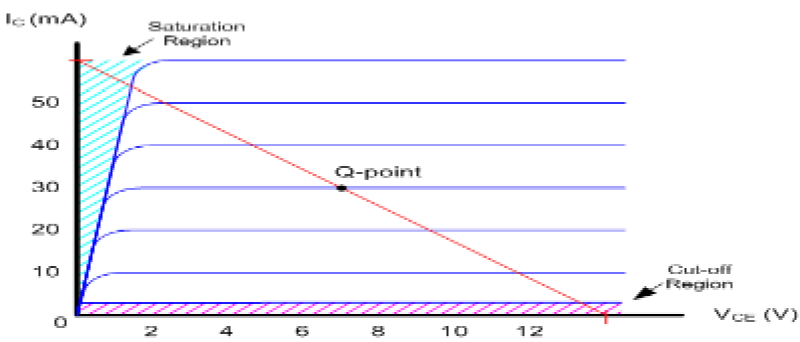

Fig 7.10 Transistor as a Switch

The pink shaded area at the bottom represents the "Cut-off" region. Here the operating conditions of the transistor are zero input base current (Ib), zero output collector current (Ic) and maximum collector voltage (Vce) which results in a large depletion layer and no current flows through the device. The transistor is switched "Fully-OFF". The lighter blue area to the left represents the "Saturation" region. Here the transistor will be biased so that the maximum amount of base current is applied, resulting in maximum collector current flow and minimum collector emitter voltage which results in the depletion layer being as small as possible and maximum current flows through the device. The transistor is switched "Fully-ON". Then we can summarize this as:

1. Cut-off Region - Both junctions are Reverse-biased, Base current is zero or very small resulting in zero Collector current flowing, and the device is switched fully "OFF".

2. Saturation Region - Both junctions are Forward-biased, Base current is high enough to give a Collector-Emitter voltage of 0v resulting in maximum Collector current flowing, the device is switched fully "ON".

Darlington Transistors

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 generally called a "Darlington Configuration" where 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. 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. An example of the two basic types of Darlington transistor are given below.

Darlington Transistor Configurations

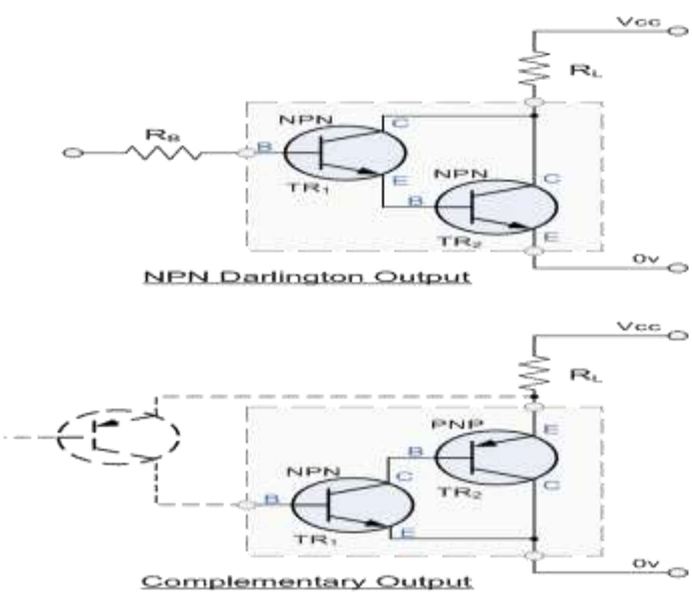

Fig 7.11 NPN Darlington Output and NPN/PNP Transistors Amplifier

The above NPN Darlington transistor configuration shows the Collectors of the two transistors connected together with the Emitter of the first transistor connected to the Base of the second transistor therefore, the Emitter current of the first transistor becomes the Base current of the second transistor.

The first or "input" transistor receives an input signal, amplifies it and uses it to drive the second or "output" transistors which amplifies it again resulting in a very high current gain. As well as its high increased current and voltage switching capabilities, another advantage of a Darlington transistor is in its high switching speeds making them ideal for use in Inverter circuits and DC motor or stepper motor control applications.

One difference to consider when using Darlington transistors over the conventional single bipolar transistor type is that the Base-Emitter input voltage Vbe needs to be higher at approximately 1.4v for silicon devices, due to the series connection of the two PN junctions.

In summary, when using a Transistor as a Switch.

- Transistor switches can be used to switch and control lamps, relays or even motors.
- When using bipolar transistors as switches they must be 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.
- In a transistor switch a small Base current controls a much larger Collector current.
- When using transistors to switch inductive relay loads a "Flywheel Diode" is required.
- When large currents or voltages need to be controlled, Darlington Transistors are used

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