

Bipolar Junction Transistors

Module 3.1

Bipolar Junction Transistors

What you'll learn in Module 3

[Section 3.1 Bipolar Junction Transistors \(BJTs\).](#)

- BJT circuit symbols.
- BJT output transistors.
- Complementary pairs.
- Small signal BJTs.
- Common transistor packages.

[Section 3.2 Making Transistors.](#)

- Germanium Alloy Diffused Transistors.
- Silicon Planar Transistors.

[Section 3.3 How a BJT Works.](#)

- Doping.
- Current Flow.

[Section 3.4 BJT Animation.](#)

- Base bias
- Collector current
- Junction potential

[Section 3.5 Current Gain.](#)

- Bipolar Transistor Characteristics
- Transfer.
- Input.
- Output.
- Mutual.

[Section 3.6 Transistor Connections.](#)

- Common Emitter.
- Common Collector.
- Common Base.

[Section 3.7 Bipolar Transistor Quiz.](#)

- Check your understanding of Bipolar Transistors.

What are BJTs?

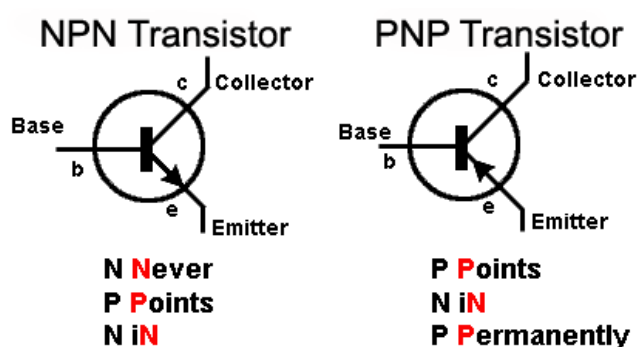


Fig. 3.1.1 Bipolar Junction Transistors

Bi-polar transistors are amongst the most widely used devices for amplification of all types of electrical signals in discrete circuits, i.e. circuits made from individual components rather than integrated circuits (I/Cs). BJTs are also used in circuits together with I/Cs, since it is often more practical to use discrete output transistors where a higher power output is needed than the I/C can provide. For example an integrated circuit may carry out all of the processing of the signals in a system, but then pass the processed signal to a single discrete transistor or a pair of matched transistors for power amplification to drive a loudspeaker or other output device. It is also often more convenient to use a discrete transistor for an individual circuit within a larger system, for which I/Cs are not readily available.

Transistors come in many shapes and types. A selection of typical bipolar junction transistors (BJTs) is shown in Fig 3.1.2

- **1. BUH515**
High Voltage (1500V) high power (50W) NPN fast switching transistor in an ISOWATT218 package, originally designed for use in analogue TV timebases but also used in switched mode power supplies.
- **2. 2N3055**
NPN Silicon Power transistor (115W) designed for switching and amplifier applications. Can be used as one half of a complementary push-pull output pair with the PNP MJ2955 transistor.
- **3. 2N2219**
NPN silicon transistor in a metal cased TO-39 package, designed for use as a high speed switch or for amplification at frequencies from DC (0Hz) up to UHF at about 500MHz.
- **4. 2N6487**
General purpose NPN output transistor with a power rating up to 75W in a TO-220 package.
- **5. BD135/BD136**
Complementary (NPN/PNP) pair of low-medium power audio output transistors in a SOT-32 package.
- **6, 7 and 8. 2N222**
Small signal general purpose amplifier and switching transistors like the 2N2222 and 2N3904 are commonly available in a variety of package types such as the TO-18 metal cased package (6), and the cheaper plastic TO-92 version (7) for through-hole mounting on printed circuit boards, as well as in surface mount SOT-23 versions (8).

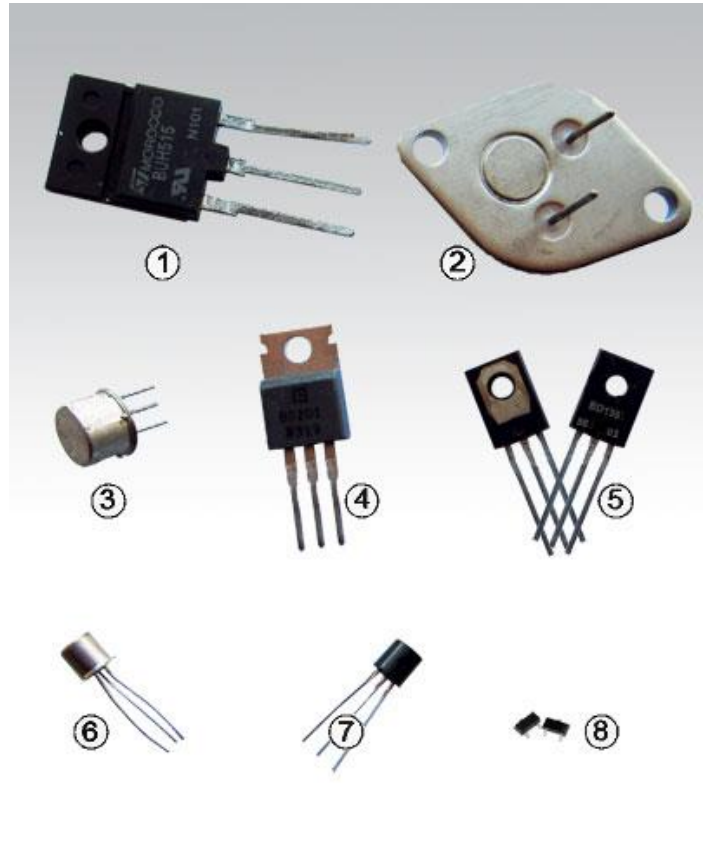


Fig. 3.1.2 Typical Bipolar Junction Transistors

Many transistor package types are also available with alternative connection layouts. The TO-92 package for example has variants TO-94, TO-96, TO-97 and TO-98 all with similar physical appearance, but each with a different pin configuration. Where different package variants are available, these are usually identified on the data sheet for each particular transistor type. Typical variations, such as those for the TO-92 to 98 series of packages used for transistors such as the 2N2222 are illustrated in Fig. 3.1.3.

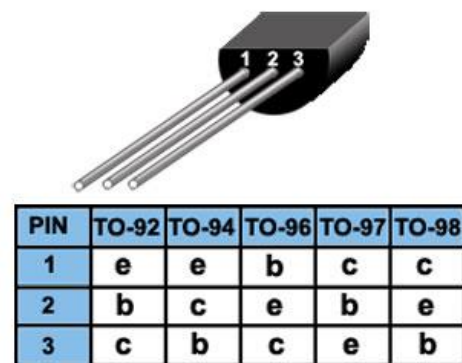


Fig. 3.1.3 TO-92 package variations

Module 3.2
How Transistors Are Made

What you'll learn in Module 3.2

After studying this section, you should be able to:

- Recognise alloy diffused & silicon planar transistors.
- Recognise the advantages of silicon planar technology.
- Describe the basic steps in planar transistor manufacture.

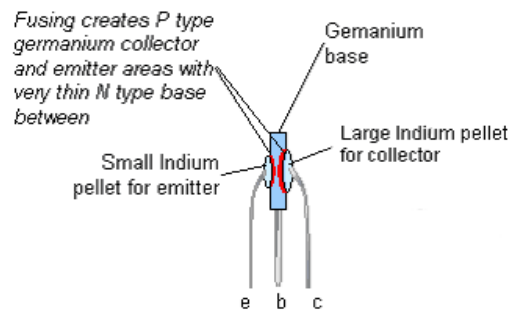


Fig 3.2.1 Germanium Alloy Diffused Transistor

Alloy Diffused Transistors



Early bipolar junction transistors used a variety of methods to produce a current amplifier. Typically a thin wafer of Germanium was used for the base of the transistor. The emitter and collector were made by diffusing two pellets of Indium (a trivalent material, having three electrons in their valence shell) into either side of a wafer of N type base, as shown in Fig 3.2.1.

The fusion process causes the indium to diffuse into the germanium. As the two metals fuse together indium atoms (with 3 valence electrons) mix with the pure germanium atoms (with 4 valence electrons) creating P type material where the Indium atoms will appear to be short of one electron, and so will bond with only three instead of four neighbouring atoms. This creates a "hole" charge carrier at each Indium atom. Fusing is stopped just before the two P type regions meet. The result is an extremely thin layer of N type semiconductor (the BASE) sandwiched between two thicker P type layers, which form the other two terminals, the emitter and the collector. Notice that the P type region used for the collector is larger than the emitter region. This is because most of the heat generated within the transistor is generated at the base/collector junction. This junction therefore needs to be larger to dissipate this extra heat.

Alloy diffused transistors suffer from several drawbacks:

1. They have a poor frequency response due mainly to their large junction capacitances.
2. Their collector current increases as their temperature increases, making them susceptible to destruction due to thermal runaway.
3. They have relatively high leakage currents across the junctions.
4. They cannot withstand high voltages.

Silicon Planar Transistors

The disadvantages of diffused alloy transistors was overcome in the 1950s by developing transistors that use silicon as the semiconductor material and the planar (layered) type of construction, illustrated in Figures 3.2.2 to 3.2.3 These transistors are built up as a series of very thin layers (or planes) of semiconductor material built up rather like a multi layer sandwich). Construction is more complex than the alloy diffusion technique, requiring

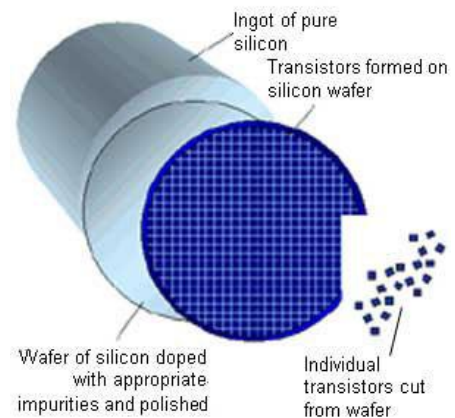


Fig 3.2.2 Multi Layer Construction of a Silicon Planar Transistor.

many separate steps, depositing oxide layers on the silicon wafer and using photo lithographic techniques to etch away unwanted silicon areas. These steps are repeated with variations to build up the required patterns and layers to form either individual transistors or complete interconnected integrated circuits.

Although the many individual manufacturing steps are complex, from forming an ingot of very pure silicon, slicing it into wafers and forming the required components on the wafer, thousands of transistors can be made at the same time on a single wafer of silicon, this method of construction then becomes much cheaper and more reliable than the ‘one transistor at a time’ alloy diffusion method.

Once the transistors have been formed on the wafer, each one is tested automatically and any faulty transistors are marked with a spot of dye. The wafer is then cut up into the individual transistors and those marked as faulty are discarded.

The planar process is even more efficient when used to manufacture integrated circuits where numbers of interconnected transistors are fabricated on a single chip of silicon at the same time. The integrated circuits produced by this method may contain just a few interconnected transistors (Small Scale Integration or SSI), hundreds of transistors (Medium Scale Integration or MSI), thousands of transistors (Large Scale Integration or LSI), or devices such as microprocessors with millions of interconnected transistors (Very Large Scale Integration or VLSI). Figs. 3.2.2 to 3.2.4 illustrate the basic steps in the manufacturing process, assuming a wafer populated with single transistors.

1. Layer 1 - Heavily doped N type Silicon.
2. Lightly doped N type silicon is deposited on top of layer 1 making a two layer collector. (see "[How BJTs Work](#)").
3. Part of the collector layer is etched away to form a depression for the P type base layer.
4. P type base layer is added.
5. Part of the base layer is etched away leaving a very thin base layer.
6. A heavily doped N type emitter layer is added.
7. Finally metal connectors are added allowing leads to be fixed after testing, and separating from the wafer.

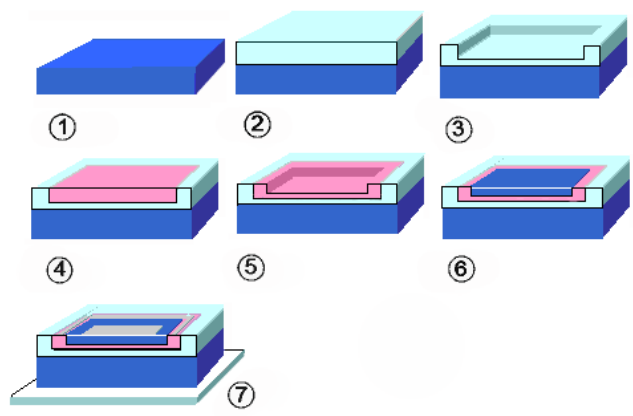


Fig 3.2.3 The Planar Construction Process.

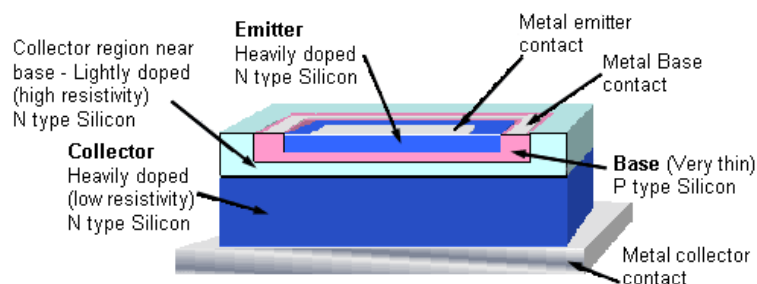


Fig 3.2.4 Completed Silicon Planar Transistor.

Module 3.3

How a BJT (Bipolar Junction Transistor) Works

What you'll learn in Module 3.3

After studying this section, you should be able to:

- Describe the basic operation of a silicon planar transistor.
- Understand the operation of the base/emitter and base/collector junctions.
- Describe the effects of doping in the transistor materials.

Fig 3.3.2 How a Transistor Amplifies Current

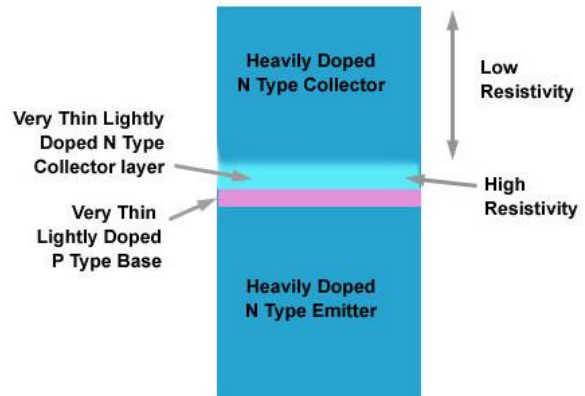


Fig 3.3.1 How a Transistor is Doped

It's all in the doping

The way a transistor works can be described with reference to Fig. 3.3.1, which shows the basic doping of a junction transistor and Fig. 3.3.2 showing how the BJT works.

The operation of the transistor is very dependent on the degree of doping of the various parts of the semiconductor crystal. The N type emitter is very heavily doped to provide many free electrons as majority charge carriers. The lightly doped P type base region is extremely thin, and the N type collector is very heavily doped to give it a low resistivity apart from a layer of less heavily doped material near to the base region. This change in the resistivity of the collector, ensures that a large potential is present within the collector material close to the base. The importance of this will become apparent from the following description.

During normal operation, a potential is applied across the base/emitter junction so that the base is approximately 0.6V more positive than the emitter, this makes the base/emitter junction forward biased.

A much higher potential is applied across the base/collector junction with a relatively high positive voltage applied to the collector, so that the base/collector junction is heavily reverse biased. This makes the depletion layer between base and collector quite wide once power is applied. As mentioned above, the collector is made up of mainly heavily doped, low resistivity material with a thin layer of lightly doped, high resistivity material next to the base/collector junction. This means that most of the voltage between collector and base is developed across this thin high resistivity layer, creating a high voltage gradient near the collector base junction.

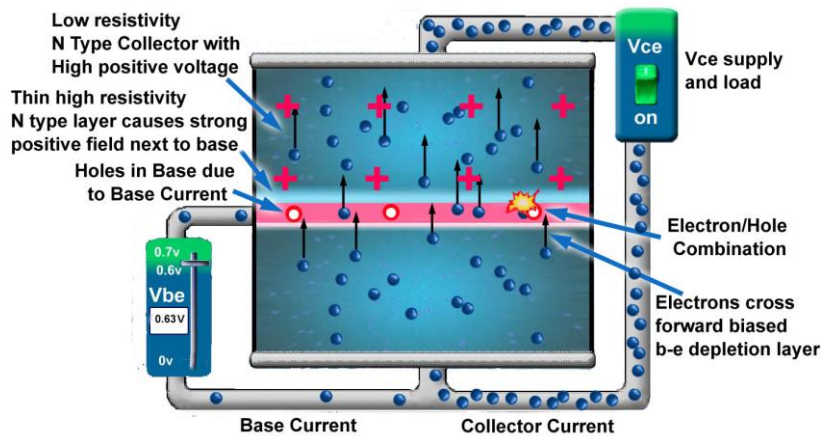


Fig 3.3.2 How a Transistor Amplifies Current

When the base emitter junction is forward biased, a small current will flow into the base. Therefore holes are injected into the P type material. These holes attract electrons across the forward biased base/emitter junction to combine with the holes. However, because the emitter region is very heavily doped, many more electrons cross into the P type base region than are able to combine with the available holes. This means there is a large concentration of electrons in the base region and most of these electrons are swept straight through the very thin base, and into the base/collector depletion layer. Once here, they come under the influence of the strong electric field across the base/collector junction. This field is so strong due to the large potential gradient in the collector material mentioned earlier, that the electrons are swept across the depletion layer and into the collector material, and so towards the collector terminal.

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Varying the current flowing into the base, affects the number of electrons attracted from the emitter. In this way very small changes in base current cause very large changes in the current flowing from emitter to collector, so current amplification is taking place.

Module 3.4

BJT Video

What you'll learn in Module 3.4

After studying this section, you should be able to:

- Describe the basic operation of a silicon planar transistor.
- Understand the effect of varying the base/emitter and base/collector potentials.
- Describe the action of charge carriers in the transistor.

Our video illustrating how a BJT is made and how it operates is available at:

The video thumbnail features a blue header with the text "Learnabout Electronics semiconductors". Below this, the title "Bipolar Junction Transistors" is written in a large, black, cursive font, followed by "Fabrication & Operation" in a smaller, black, cursive font. The central part of the thumbnail shows a collection of various BJT components, including a metal transistor package, a TO-18 package, a TO-18 package with a hole, two TO-18 packages, a TO-18 package with a hole, and two TO-18 packages. Below the components are three smaller images: the first shows a cross-section of a transistor with a grid overlay and labels "Faulty" and "Good"; the second shows a 3D model of a transistor; the third is a detailed cross-section diagram of a transistor with labels for "Free Electrons", "Holes", "Electron-Hole Combination", "Vce", "Vbe", "c-b depletion layer", and "c", "b", "e" terminals.

A full screen version can be downloaded from the website.

http://www.learnabout-electronics.org/Semiconductors/bjt_04.php

Module 3.5
Current Gain

What you'll learn in Module 3.5

After studying this section, you should be able to:

Understand the use of common transistor characteristic graphs.

- Transfer Characteristics.
- Input & Output Characteristics.
- Mutual Characteristics.

In describing the operation of junction transistors.



A BJT is a current operated transistor, which means that the current flowing between emitter and collector of a transistor is much greater than that flowing between base and emitter. So a small base current is controlling the much larger collector/emitter current. The ratio of the two currents, I_{CE} / I_{BE} is constant, provided that the collector emitter voltage V_{CE} is constant. Therefore, if the base current rises, so does collector current.

The BJT Transfer Characteristic

This ratio is the CURRENT GAIN of the transistor and is given the symbol h_{fe} . A fairly low gain transistor might have a current gain of 20 to 50, while a high gain type may have a gain of 300 to 800 or more. The spread of values of h_{fe} for any given transistor is quite large, even in transistors of the same type and batch. The graph of I_{CE} / I_{BE} shown in Fig. 3.5.1 is called the TRANSFER CHARACTERISTIC and the slope of the graph shows the h_{fe} for that transistor

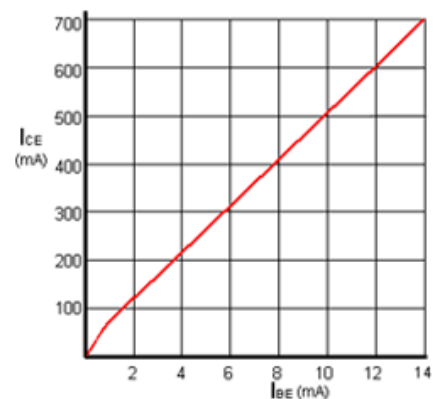


Fig. 3.5.1 Transfer Characteristic

Characteristic curves (graphs) can be drawn to show other parameters of a transistor, and are used both to detail the performance of a particular device and as an aid to the design of amplifiers. The examples shown here are typical of BJTs, when used as voltage amplifiers.

The BJT Input Characteristic

The INPUT CHARACTERISTIC (Fig.3.5.2), a graph of base emitter current I_{BE} against base emitter voltage V_{BE} (I_{BE}/V_{BE}) shows the input CONDUCTANCE of the transistor. As conductance I/V is the reciprocal of RESISTANCE (V/I) this curve can be used to determine the input resistance of the transistor. The steepness of this particular curve when the V_{BE} is above 1 volt shows that the input conductance is very high, and there is a large increase in current (in practice, usually enough to destroy the transistor!) for a very small increase in V_{BE} . Therefore the input RESISTANCE must be low. Around 0.6 to 0.7 volts the graph , showing that the input resistance of a transistor varies, according to the amount of base current flowing, and below about 0.5 volts base current ceases.

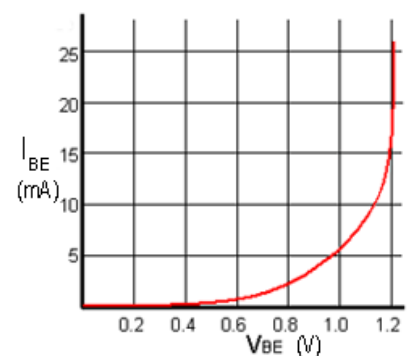


Fig. 3.5.2 Input Characteristic

The BJT Output Characteristic

Fig. 3.5.3 shows the OUTPUT CHARACTERISTIC whose slope gives the value of output conductance (and by implication output resistance). The near horizontal parts of the graph lines show that a change in collector emitter voltage V_{CE} has almost no effect on collector current in this region, just the effect to be expected if the transistor output had a large value resistor in series with it. Therefore the graph shows that the output resistance of the transistor is high.

These characteristic graphs show that, for a silicon transistor with an input applied between base and emitter, and output taken between collector and emitter (a method of connection called common emitter mode) one would expect;

- Low input resistance (from the input characteristic).
- Fairly high gain (from the transfer characteristic).
- High output resistance (from the output characteristic).

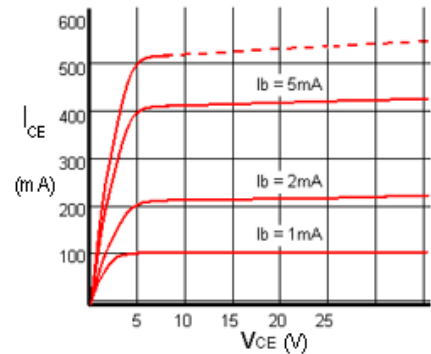


Fig. 3.5.3 Output Characteristic

The BJT Mutual Characteristic

Fig. 3.5.4, the MUTUAL CHARACTERISTIC shows a graph of MUTUAL CONDUCTANCE I_C/V_{BE} and illustrates the change in collector current which takes place for a given change in base emitter voltage, (i.e. input signal voltage). This graph is for a typical silicon power transistor. Notice the large collector currents possible, and the nearly linear relationship between the input voltage and output current.

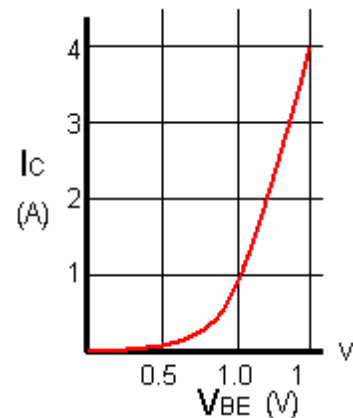


Fig. 3.5.4 Mutual Characteristic

The characteristics described on this page are those relating to a typical power transistor connected in the 'common emitter' mode. This is one of three possible modes of connection for a transistor described in BJT Module 3.6. - Transistor Connections.

Note: In many transistors the currents will be much smaller than shown in these examples. For small signal amplifiers, base currents will be a few micro-amps rather than milliamps.

Module 3.6

Transistor Connections

What you'll learn in Module 3.6

After studying this section, you should be able to:

Recognise basic transistor amplifier connection modes.

- Common emitter.
- Common collector.
- Common base.

Describe the basic parameters of each amplifier mode.

- Voltage gain.
- Current gain.
- Input & output impedances.

How a transistor is connected to make an amplifier.

Because an amplifier must have two input and two output terminals, a transistor used as an amplifier must have one of its three terminals common to both input and output as shown in

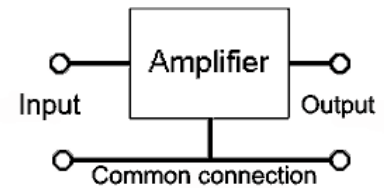


Fig. 3.6.1 Amplifier Connections

Fig 3.6.1. The choice of which terminal is used as the common connection has a marked effect on the performance of the amplifier.

A transistor connected in the three modes illustrated in Figs. 3.6.2 to 3.6.4 would show quite different characteristic curves for each mode. These differences can be exploited by the circuit designer to give an amplifier with characteristics that

are most suited a particular purpose. Note that the diagrams are shown here reduced to their most basic form and are not intended to be practical circuits.

In a transistor amplifier circuit, such as those shown in Figs. 3.6.2 to 3.6.4, the +V supply line and the 0V line can be considered as the same point, as far as any AC signal is concerned. This is because, although there is obviously a voltage (the supply voltage) between these two points, the DC supply is always de-coupled by a large capacitor (e.g. the reservoir capacitor in the power supply) so there can be no AC voltage difference between +V and 0V rails.

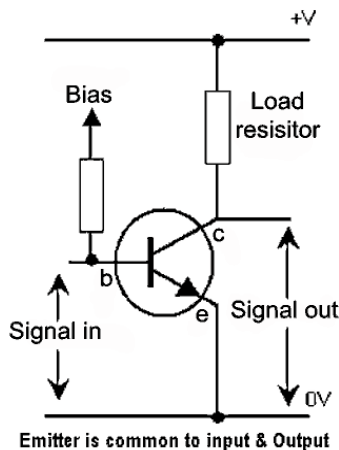


Fig. 3.6.2 Common Emitter Mode

Common Emitter Mode

The most common function of a transistor is to be used in COMMON EMITTER mode. In this method of connection small changes in base/emitter current cause large changes in collector/emitter current. Therefore the circuit is that of a CURRENT amplifier. To give VOLTAGE amplification, a load resistor (or an [impedance](#) such as a tuned circuit) must be connected in the collector circuit, so that a change in collector current causes a change in the voltage developed across the load resistor. The value of the load resistor will affect the VOLTAGE GAIN of the amplifier. This is because the larger the load resistor, the larger the change in voltage that will be caused by a given change in collector current. Notice that because of this method of connection the output waveform will be in anti-phase to the input

waveform. This is because an increase in base/emitter voltage will cause an increase in base current. This will in turn cause an increase in collector current, but as collector current increases, the voltage drop across the load resistor increases and as the voltage on the top end of the load resistor (the supply voltage) will not change, the voltage on the bottom end must decrease. Therefore an increase in base/emitter voltage causes a decrease in collector/emitter voltage.

Common Emitter Parameters

Voltage Gain: High (about 100).

Current Gain: High (about 50 to 800).

Input Impedance: Medium (about 3kΩ to 5kΩ).

Output Impedance: Medium (Approximately the load resistor value).

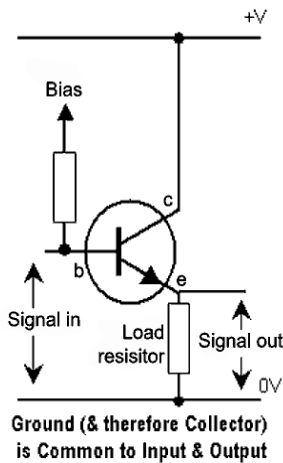


Fig. 3.6.3 Common Collector Mode

Common Collector Mode

Fig. 3.6.3 illustrates the COMMON COLLECTOR mode; also called the emitter follower mode as in this circuit the output waveform at the emitter is not inverted and so ‘follows’ the input waveform at the base. This method of connection is often used as a BUFFER AMPLIFIER for such jobs as matching [impedances](#) between two other circuits. This is because this mode gives the amplifier a high input impedance and a low output impedance. The voltage gain in this mode is slightly less than unity ($\times 1$), but high current gain (called h_{fc} in common collector mode) is available. Another use for this mode of connection is a CURRENT AMPLIFIER, often used for output circuits that have to drive high current AC devices such as loudspeakers or DC devices such as motors etc.

Common Collector Parameters

Voltage Gain: Slightly less than unity (1).

Current Gain: High (about 50 to 800)

Input Impedance: High (Several $k\Omega$)

Output Impedance: Low (A few ohms)

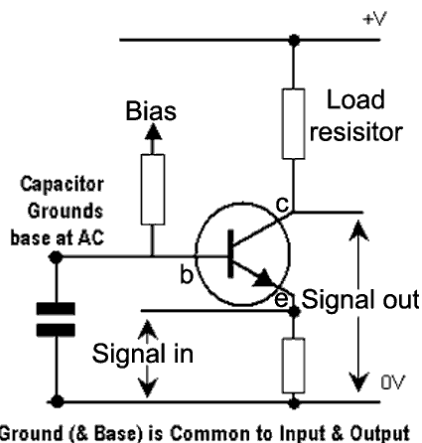


Fig. 3.6.4 Common Base Mode

Common Base Mode

COMMON BASE MODE is usually used for VHF and UHF amplifiers where, although the voltage gain is not high, there is little chance of the output signal being fed back into the input circuit (which can be a problem at these frequencies). Because the base of the transistor is connected to ground in this mode, it forms an effective grounded (earthed) screen between output and input. As the collector current in this mode will be the emitter current minus the base current, the current gain (h_{fb} in common base mode) is less than unity (<1).

Common Base Parameters

Voltage Gain: Medium (about 10 to 50).

Current Gain: Less than unity (<1)

Input Impedance: Low (about 50Ω)

Output Impedance: High (about $1M\Omega$)

Module 3.7

Bipolar Junction Transistor Quiz

Try this quiz based on bipolar transistors. All the information you need is on <http://www.learnabout-electronics.org>

You can answer the questions here, but to check your answers go to Semiconductors Module 3.7 on the website. Hopefully your answers will all be correct, but don't be disappointed if you get some answers wrong. Follow the hints on the website results page to find the right answer, and learn more about transistors as you go.

1.

In a BJT, why is a thin layer of high resistivity semiconductor included between the base and collector regions?

- a) To create a high voltage gradient between the base and collector regions.
- b) To help prevent collector/base breakdown.
- c) To ensure the voltage difference between base and collector is kept as low as possible.
- d) To prevent holes contaminating the N type collector region.

2.

The forward junction potential for a silicon junction is:

- a) 0.015 Volts
- b) 0.15 Volts
- c) 0.06 Volts
- d) 0.6 Volts

3.

Refer to Fig. 3.7.1. What do the graphs shown illustrate?

- a) The transfer characteristics of a BJT in common emitter mode.
- b) The output characteristics of a BJT in common emitter mode.
- c) The transfer characteristics of a BJT in common collector mode.
- d) The mutual characteristics of a BJT in common emitter mode.

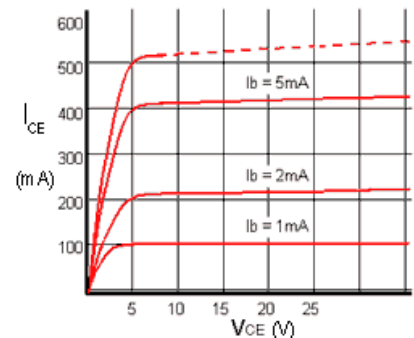


Fig. 3.7.1

4.

For a NPN silicon bipolar transistor, which of the following statements is true?

- a) A thin area of the collector near to the base is heavily doped.
- b) A thin area of the emitter near to the base is heavily doped.
- c) The resistivity of the collector decreases near to the base.
- d) A thin area of the collector near to the base is lightly doped.

5.

The formula for the small signal current gain of a bipolar transistor is given by:

- a) I_{CE} / I_{BE}
- b) I_{ce} / I_{be}
- c) I_{ce} / V_{be}
- d) I_{CE} / V_{BE}

6.

When testing the resistance of a junction in a silicon bipolar transistor, the expected junction resistance, when forward biased will be approximately:

- a) 1k Ohms
- b) 5k Ohms
- c) Infinite
- d) Zero Ohms

7.

The voltage gain of a bipolar transistor used in Common Collector (emitter follower) mode will be:

- a) About 50 to 100
- b) About 50 to 800
- c) 1 (Unity)
- d) Several thousand

8.

The number of valence electrons in a silicon atom is:

- a) Three
- b) Five
- c) Eight
- d) Four

9.

To increase the number of free electrons in silicon for use in transistors, manufacturers add small amounts of:

- a) Germanium
- b) Aluminium
- c) Boron
- d) Arsenic

10.

When identifying the connections on a large power transistor, a useful tip to remember is:

- a) The base is always the middle pin.
- b) The collector is usually identified by a metal tab or paint spot.
- c) The collector is usually connected to the metal case.
- d) The resistance measured between emitter and the metal case will be zero ohms.