Lesson 8A

Semiconductors

A semiconductor is a device somewhere between a conductor and an insulator. So, depending on its use, a semiconductor can behave as either a conductor or an insulator.

The base material of semiconductors is usually silicon (Si) or germanium (Ge). Neither of these is a great conductor; so, the manufacturer dopes (injects an impurity) into the material. Doping with aluminium creates a base material lacking an electron and these are called holes. The resulting material is called P-type.

Doping the base material with phosphorus creates a base material with an extra electron. The resulting material is called N-type.

When N-type and P-type base materials are joined, the N-type has electrons looking to fill the P-type holes. A small number of electrons will flow to fill the holes at the junction. This small junction area is called the *depletion layer*, also known as the depletion zone and depletion region.

Semiconductor devices have a standard numbering system, depending on who makes them and where. Many manufacturers stick with the Joint Electron Device Engineering Council (JEDEC) standard semiconductor numbering system. In this system, the leading number of the semiconductor type indicates the number of junctions in the device.

- 1N4001 is a semiconductor with one junction (a diode).
- 2N3904 is a semiconductor with two junctions (a transistor).

Bipolar Transistors

The two basic types of transistors in use today are the Bipolar Junction Transistor (BJT) and the Field Effect Transistor (FET). Field Effect Transistor (FET) uses different terms for the legs and will be addressed as a separate topic. This article will focus on the BJT.

In the previous article on diodes, I addressed the issue of conventional current flow and electron current flow. I will continue using electron flow for this article. Refer to Figure 1 for a refresh.

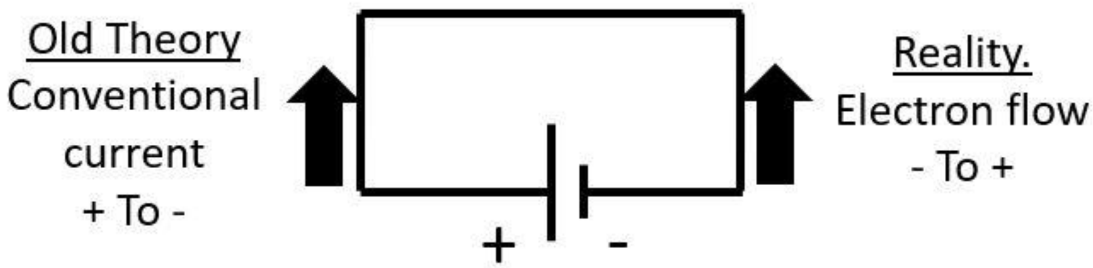


Figure 1: Diagram of old current theory and reality.

Sandwich Transistor

The bipolar point-contact transistor was invented in December 1947 at the Bell Telephone Laboratories by John Bardeen, Walter Brattain and William Shockley. The junction version known as the Bipolar Junction Transistor (BJT), was invented by Shockley in 1948. A press release in 1951 announced the discovery of this new "sandwich" transistor.

The origin of the name transistor seems different depending on the source. The common theme is that it is an abbreviated combination of the words transconductance (or transfer) and Varistor. Researcher John Pierce suggested the name transistor, and this has remained the name of choice.

The transistor revolutionised the electronics field. The size of devices shrunk, and the power consumption levels dropped. No longer did the devices need mains power to run as they could be easily powered by a battery. The development of battery-operated domestic transistor radios expanded the consumer base.

Since their development, the design of transistors has reduced in size many fold. Now hundreds of components, including transistors, are etched into integrated circuits (ICs).

Modern Transistor

A transistor can be used as a fast switch, or as an amplifying device. The main concept is that a small current in one leg of the transistor can control a greater current in another leg.

Looking at Figure 2, a BJT, as a black box, has three legs: Collector, Base, Emitter. A small input on the base can produce a greater output on the collector[i]. This signal is inverted as the base voltage rises, the current through the transistor increases, dropping the voltage at the collector.

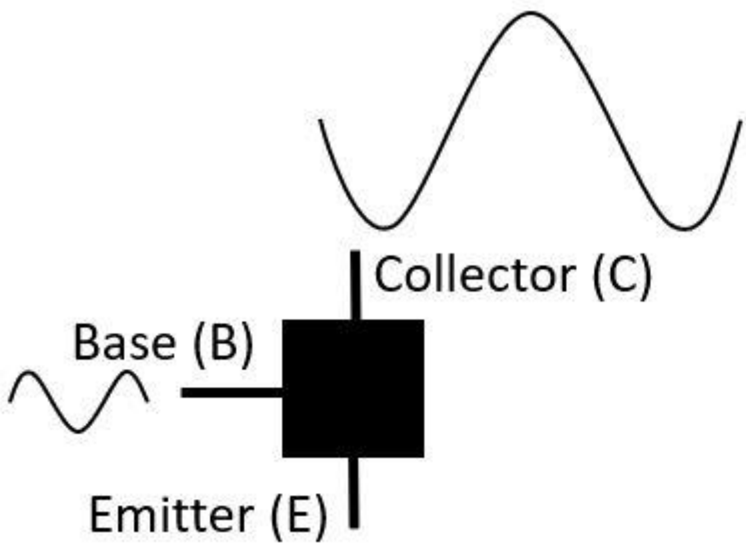


Figure 2: BJT as a black box.

The measure of the amplification or gain of a transistor is called Beta (β) or hfe. There are many applications for transistors and the gain will vary depending on the application.

Some transistors have metal cases and these need to be attached to heat sinks to remove excess heat from the transistor during operation.

Base material

The base material of transistors is usually Silicon (Si) or Germanium (Ge). Neither of these are great conductors so the manufacturer will dope (inject an impurity) into the material. Doping with aluminium creates a base material lacking an electron and these are called holes. The resulting material in called a P type.

Doping the base material with phosphorus creates a base material with an extra electron. The resulting material in called a N type.

When a N type and P type base material are joined, the P type has the holes, and the N type has the electrons looking to fill the holes. A small number of electrons will flow to fill the holes at the junction. This small junction area is called the depletion layer.

As the name BJT implies, there are two junctions in the transistor where the materials join. Using the two material types, the BJTs can be configured as:

- NPN
- PNP

NPN

The NPN transistor needs a voltage on the base approximately 0.7 V greater than the emitter to cause the electrons to flow. This voltage is needed to pull the electrons across the depletion layer. In doing so, electrons will also flow from the emitter to the collector. Refer to Figure 3.

NPN transistor applications

- NPN transistors are mainly used in switching applications.
- Used in amplification circuits.
- Used in the Darlington pair circuits to amplify weak signals.
- NPN transistors are used in applications where there is a need to sink (take in) a current (i.e. current flows into the collector).
- Used in some classic amplifier circuits, such as ‘push-pull’ amplifier circuits.
- Temperature sensors.
- Very High Frequency applications.

A common small signal NPN transistor is the 2N3904. Search and read the data sheet.

A common power NPN transistor is the 2N3055. Search and read the data sheet for a comparison.

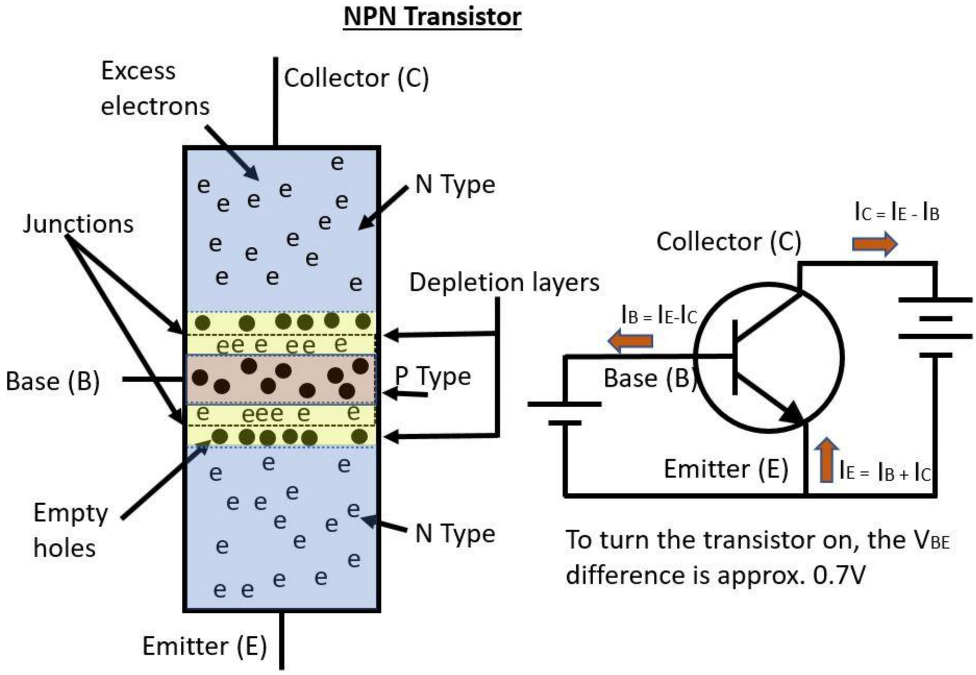


Figure 3: NPN Transistor.

PNP

The PNP transistor needs a voltage on the base approximately 0.7 V less than the emitter to cause the electrons to flow. This voltage is needed to pull the electrons across the depletion layer. In doing so, electrons will also flow from the collector to the emitter. Refer to Figure 3.

PNP transistor applications

- Used to source (send out) a current (i.e. current flows out of the collector).
- Used as switches.
- Amplifying circuits.
- PNP transistors are used when we need to turn off something by button push (e.g. emergency shutdown).
- Used in Darlington pair circuits.
- Used in matched pair circuits to produce continuous power.
- Used in heavy motors to control current flow.
- Used in robotic applications.

A common small signal PNP transistor is the 2N3906. Search and read the data sheet.

A common power NPN transistor is the 2N3054. Search and read the data sheet for a comparison.

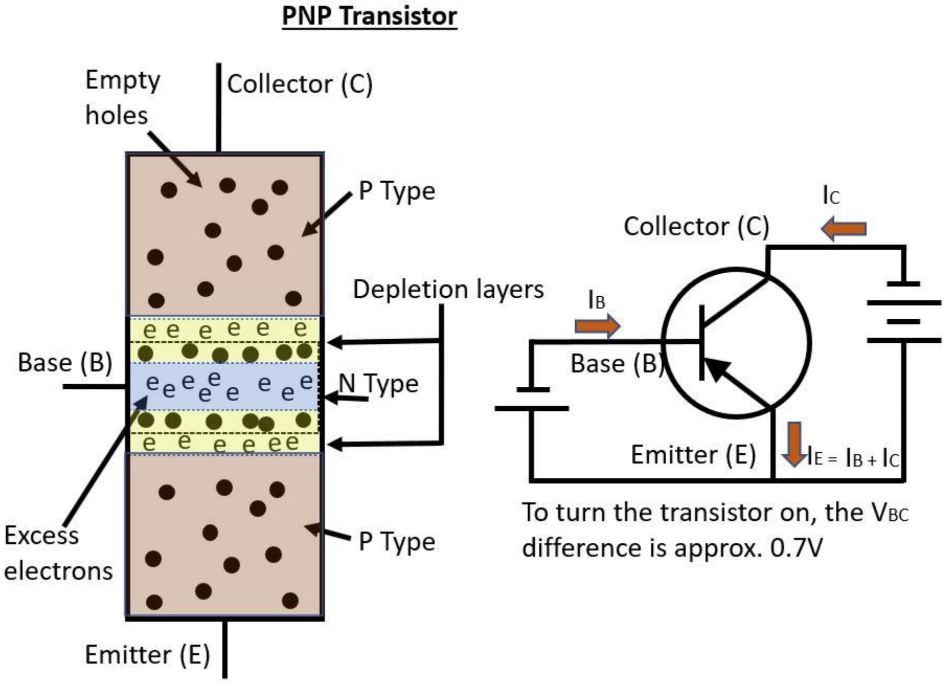


Figure 4: PNP Transistor.

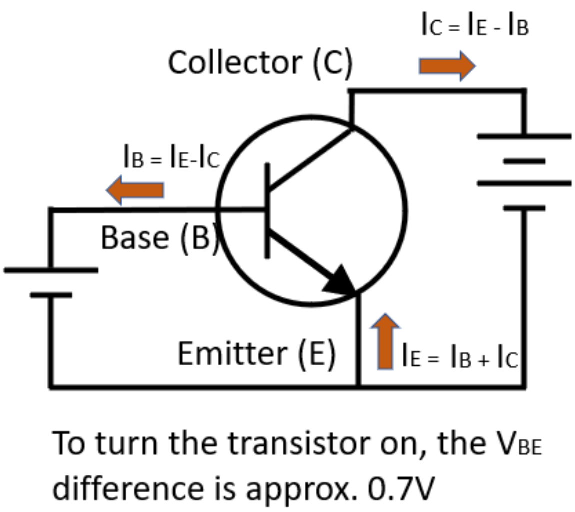
Tip. Looking at the symbol for the BJTs, I use the arrowhead to remind me which is which.

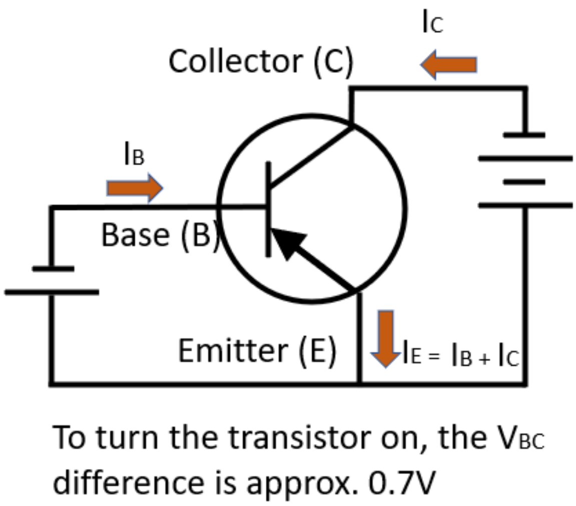
If it points inward, it is a PNP and points outward it is an NPN. Also, electron flow goes opposite to the arrow in the transistor.

Current Flow

An important fact on transistors is that Kirchhoff's Current Law applies to transistors as well.

$0 = I_B$ (Current in the base) + I_C (Current in the collector) + I_E (Current in the emitter)





Analyse the current paths through the transistors.

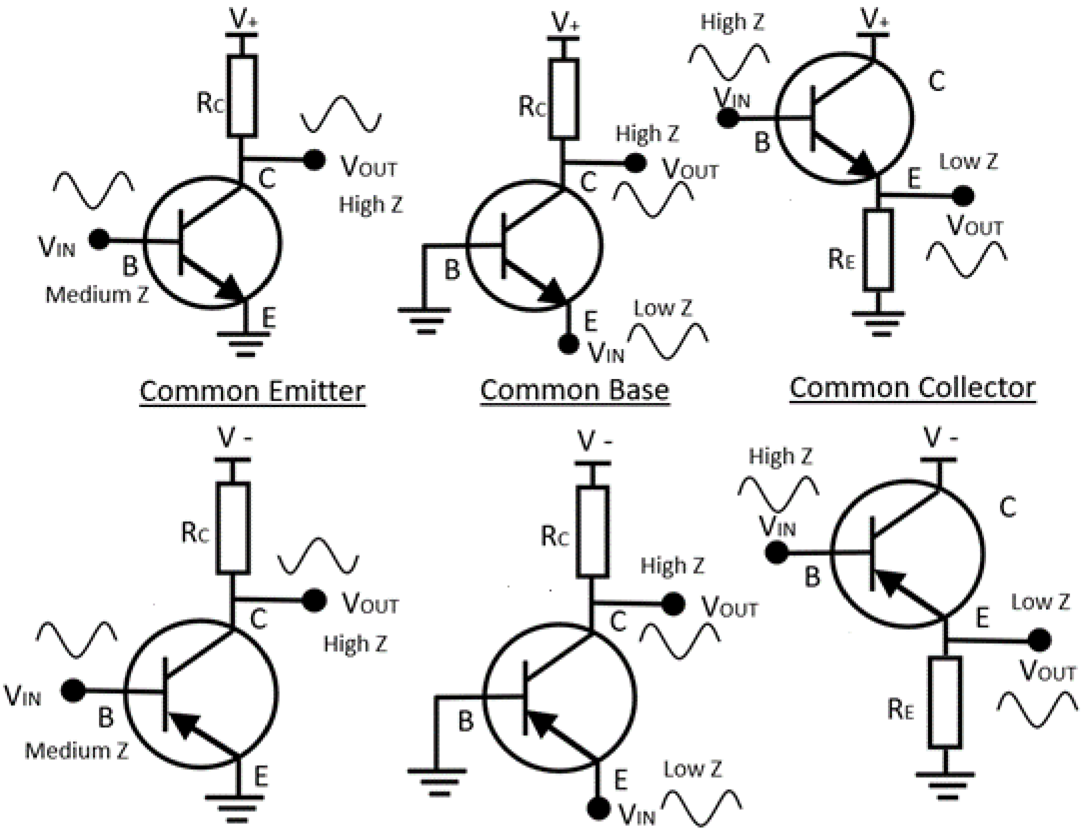
Configurations

There are three basic single-stage BJT amplifier configurations as shown in Figure 5.

Common-emitter - A common-emitter typically used as a voltage amplifier and offers high current gain (typically two hundred), medium input resistance, and a high output resistance. The output of a common emitter amplifier is 180 degrees out of phase to the input signal.

Common-base - A common-base (also known as grounded-base) is typically used as a current buffer or voltage amplifier.

Common-collector - A common collector amplifier (also known as an emitter follower) is typically used as a voltage buffer.



Configuration	Input Impedance	Output impedance	Gain	Orientation
Common Emitter	Medium	High	High	Inverting
Common Base	Low	High	Unity	Non - inverting
Common Collector	High	Low	High	Non - inverting

Gain

hfe: This is the current gain for a transistor expressed as an h parameter (hybrid parameter). The letter f indicates that it is a forward transfer characteristic, and the letter e indicates it is for a common emitter configuration. The small letter h indicates it is a small signal gain. hfe and small signal Beta are the same. This figure is widely used in transistor data sheets and hence within the circuit design calculations.

hFE : The hFE parameter differs from hfe in that it is the h parameter for the DC or large signal steady state forward current gain. This figure will be used when setting up bias conditions or for use within power supply circuit designs, or other circuits where the DC gain is important.

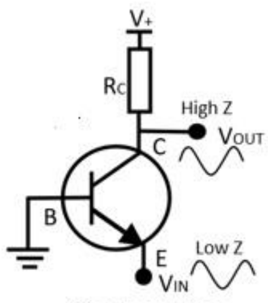
The different abbreviation used for the transistor gain, hFE, hfe & Beta are all widely used, although the parameters Hfe, hfe tend to be more widely used in datasheets.

Alpha

The ratio of the transistor's collector current (Ic) and the transistor's emitter current (I_E) is called Alpha (α). In the common base transistor configuration, input through emitter and output through the collector, current gain is defined as the ratio of collector current to emitter current. The value of Alpha will always be less than unity. (The triangle Δ is called Delta and represents change. So, the change in I_C over the change in I_E.*)*

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

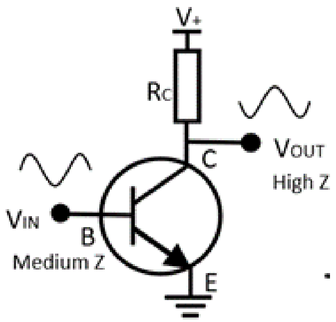
Example: Collector current is 10 mA and emitter current is 12 mA. α or current gain equals 0.83.



Common Base

Beta

The common-emitter current gain (β) is the ratio of the transistor's collector current (IC) to the transistor's base current.



Common Emitter

The gain of the most used transistor configuration, common emitter, is measured by the comparison of the Base current (I_B) to the Collector current (I_C) and is signified by the Greek letter Beta (β). The symbol β is used for NPN transistors while the symbol β' is used for PNP transistors.

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

Example: Base current of 1 mA and a collector current of 100 mA gives a β of 100.

Common Terms

Below is a shortened list of common terms when referring to transistors. Understanding these will aid in reading the transistor data sheets.

V_{EB}	Voltage between the Emitter and Base
V_{CB}	Voltage between the Collector and Base
V_{CE}	Voltage between the Collector and Emitter
$V_{BE\ (sat)}$	The voltage between the Base and Emitter, when sufficient Ibe current is being applied, to fully saturate the BJT.
V_B	Voltage between the Base and ground.
V_C	Voltage between the Collector and ground.
V_E	Voltage between the Emitter and ground.
Beta (β) or hfe	Beta (hfe) is a transistor's DC current gain. $\beta = I_C / I_B$
hFE	hFE is a transistor's AC current gain which is less and decreases with increasing frequency.
I_B	Current in the Base
I_C	Current in the Collector
I_E	Current in the Emitter

Read the data sheets for the following two transistors.

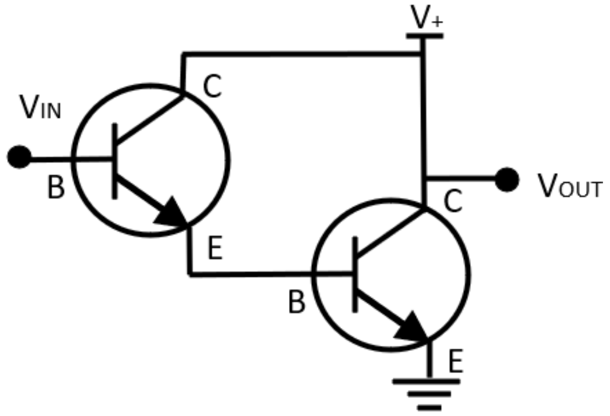
- 2N3904 a small signal NPN transistor. SMALL SIGNAL NPN TRANSISTOR (sparkfun.com)
- 2N3906 a small signal PNP transistor. SMALL SIGNAL PNP TRANSISTOR (sparkfun.com)

Darlington Pair

A Darlington transistor (also known as a Darlington pair) combines two BJTs in a way that it creates a very high current gain. Compounding amplification is where the current is amplified by the first transistor and then amplified again by the second transistor.

The transistor is a single unit as it has only one emitter, collector, and base. The Darlington transistor was invented by Sidney Darlington in 1953.

This transistor is also known as a “Super Beta Transistor” due to its high amplification properties.

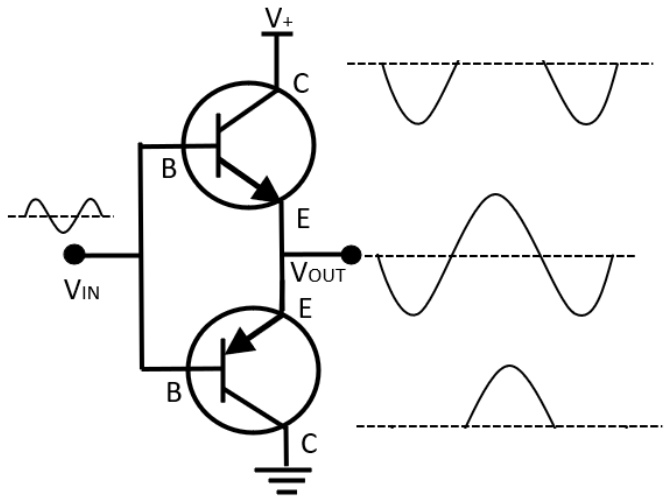


Darlington Pair

Push Pull Amplifier

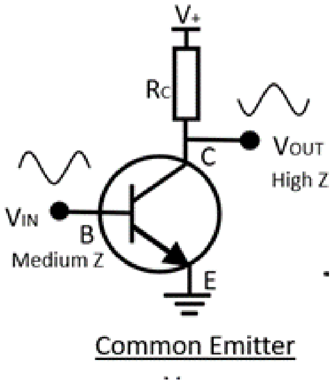
A Push-Pull Amplifier is a power amplifier using a PNP and a NPN transistor to supply high power to the load. One transistor, a NPN, pushes the output on positive half cycle and other, a PNP pulls on negative half cycle. The advantage of Push-Pull amplifier is that there is no power dissipated in the output transistor when a signal is not present. Disadvantage is the potential dead zone before the transistors turn on.

Push Pull Amplifier

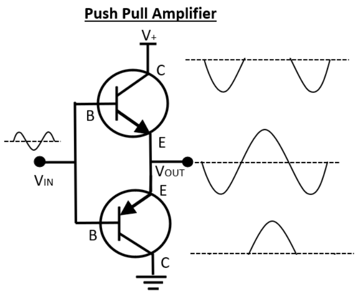


Amplifier Classes

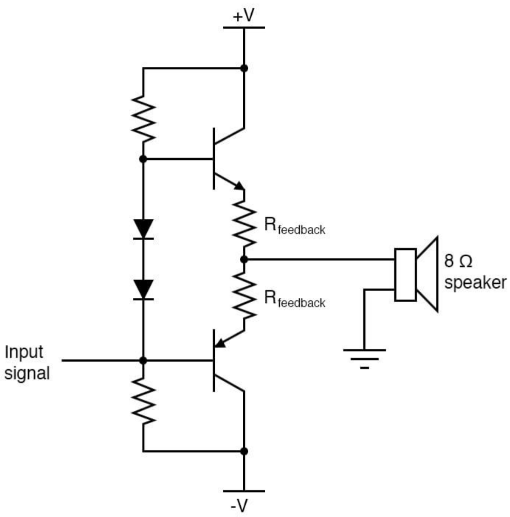
Class A - Class A amps are simple devices using one transistor and transmit over the full 360 degrees of the signal. Class A efficiency is only 30%.



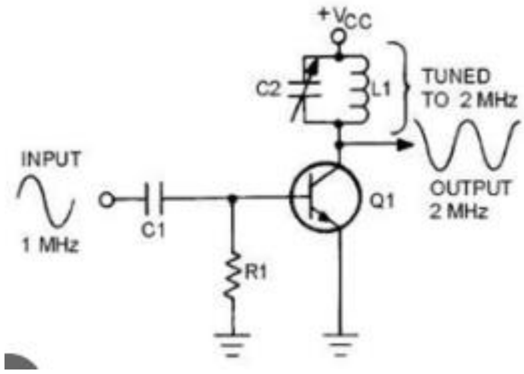
Class B – Class B uses two transistors, each operating in only 180 degrees of the signal. This provides a greater amplification and clearer signal. The downside is that each transistor requires 0.7 V to turn on and this can cause distortion. This area is termed the 'Dead Zone'.



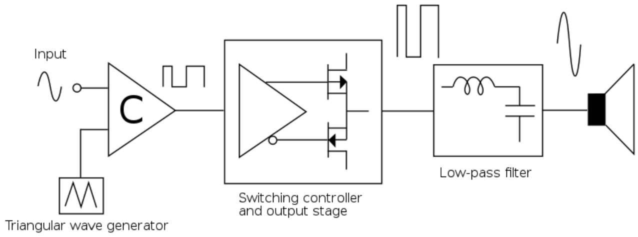
Class AB – Diodes are fitted to the circuit to bias the transistors across the dead zone and minimise distortion.



Class C – Class C power amplifier is where the transistor conducts for less than one half of the input cycle. The reduced conduction angle improves efficiency but causes distortion. Theoretical maximum efficiency of a Class C amplifier is around 90%. A class-C amplifier can only generate a signal at a single frequency, but that frequency can vary within the bandwidth of the output filter. The amplitude that is determined by its voltage supply.



Class D - A class-D amplifier or switching amplifier is an electronic amplifier in which the amplifying devices (transistors, usually MOSFETs) operate as electronic switches, and not as linear gain devices as in other amplifiers.



In later years, additional amplifier classes have been developed. Further information about these and the above classes can be sourced from reputable sources.

Study amplifier drawings on the internet and see if you can recognise any of the amplifier configurations.

Good video explaining amplifier types. **HERE**

Diodes

Although a simple semiconductor device, diodes are found in a massive range of applications. In your journey through radio and electronics, you'll mostly encounter 'everyday' diodes widely used in two application areas – signal circuits on one hand, and power circuits on the other. Beyond that, specialised diodes have been developed for particular applications. Diodes – simple explanations without complex mathematics.

When electricity was discovered, the initial belief was that current flowed from the positive terminal to the negative terminal. This description of electricity flow is called 'Conventional Current'. In 1897, a British physicist, J J Thomson (1856 – 1940) discovered that current flow is actually electrons moving from the negative to the positive. This is what really happens and is termed 'Electron Flow'. Both terms are in use today in various engineering spheres.

In describing semiconductors, I will use 'Electron Flow'.

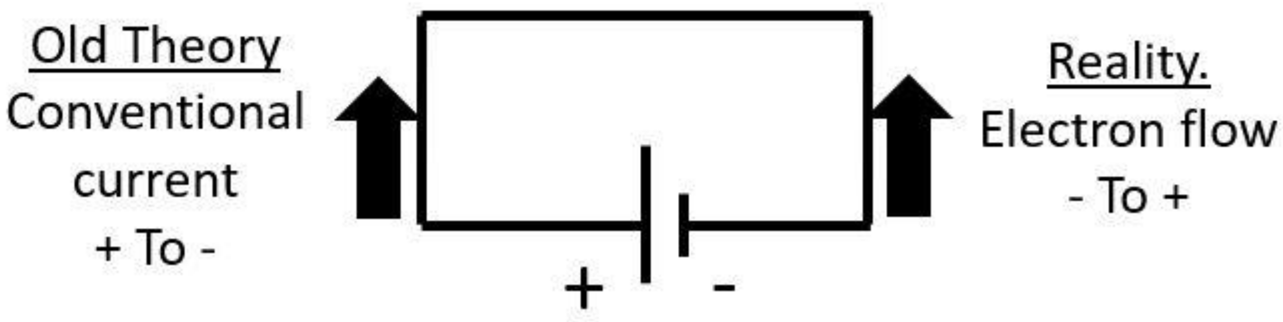
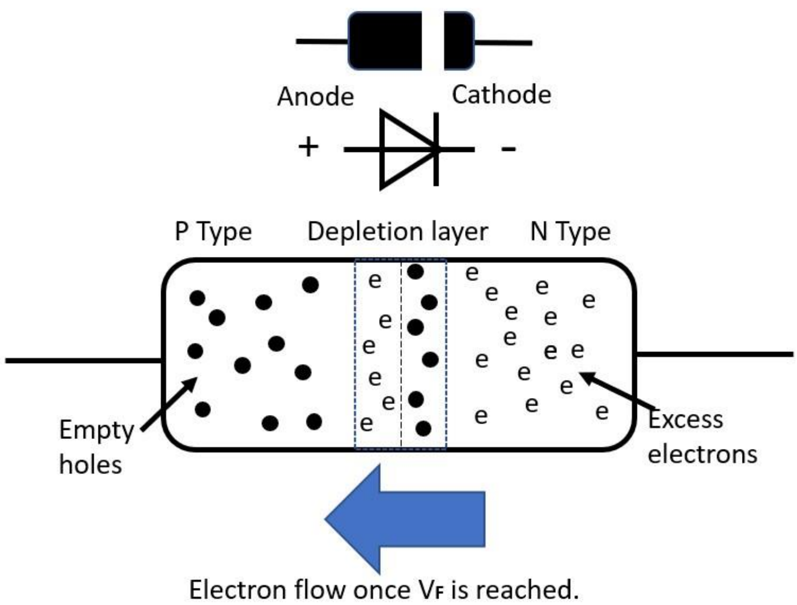


Figure 1. Diagram of old theory and reality

Looking at the two layers, the electrons want to move from the N-type, with excess electrons, to the P-type, with the holes. This is the natural path and called *forward bias*. The electrons will not go the other way unless a high voltage is applied, which is called *reverse bias*.



The forward voltage in the circuit across the N- and P-types must exceed a defined level – called Forward Voltage (V_F), which is around 0.7 V for silicon devices, but varies with devices. This is the voltage level required to cause electrons to flow through the depletion layer.

A diode has a forward conduction point depending on the type. A Silicon diode has a forward bias of approx. 0.7 V and a Germanium diode forward bias of 0.2 V.

Diodes are polarised, anode (positive lead) and cathode (negative lead). Most diodes allow current to flow only when positive voltage is applied to the anode.

There are speciality diodes that are operated in the reverse bias region.

Diode specifications and applications are set out in manufacturers' data sheets, which are generally available on the internet. To learn about a particular diode type, a good suggestion is to download and read the data sheet.

A widely used diode is the 1N4001 rectifier diode. It would be one of the most commonly used for many electronic projects. This diode is made by many manufacturers so there may be slight specification variations between manufacturers of the 1N4001.

Looking at the diode, it has these basic characteristics:

- Cylindrical and black;
- Axial leads extend from each end;
- Its type number is screen-printed on the black surface;
- A white band denotes the cathode end of the diode;

Other diodes types can look different.

Characteristics data

I_F (AV) – 1.0 A The average forward current this diode can operate at is 1 A.

V_{RRM} – 50 V The maximum repetitive voltage applied in the reverse direction. So, this diode is not good at rectifying voltages over 50 VAC. Other diodes can work at higher voltages, e.g, the 1N4007 can handle 1000 VAC.

I_{FSM} – 30 A This is the maximum non-repeated forward surge current it can withstand over 8.3 milliseconds (sine wave). So, 1 A average forward current to 30 A surge is a tolerant device.

I_{FSM} – 45 A These two look the same, but this is only for a 1 ms square wave.

V_F = 1.1 V This diode requires 1.1 V applied before the electrons will move through the depletion layer and start conducting.

I_R = 5 uA This is the reverse leakage current when the V_{RRM} is reached. This is temperature dependent, increasing with temperature rise.

T_J max = 150^{O} C Maximum operating temperature.

Plotting these numbers shows a diagram of the diode's current flow. See **Figure 3**.

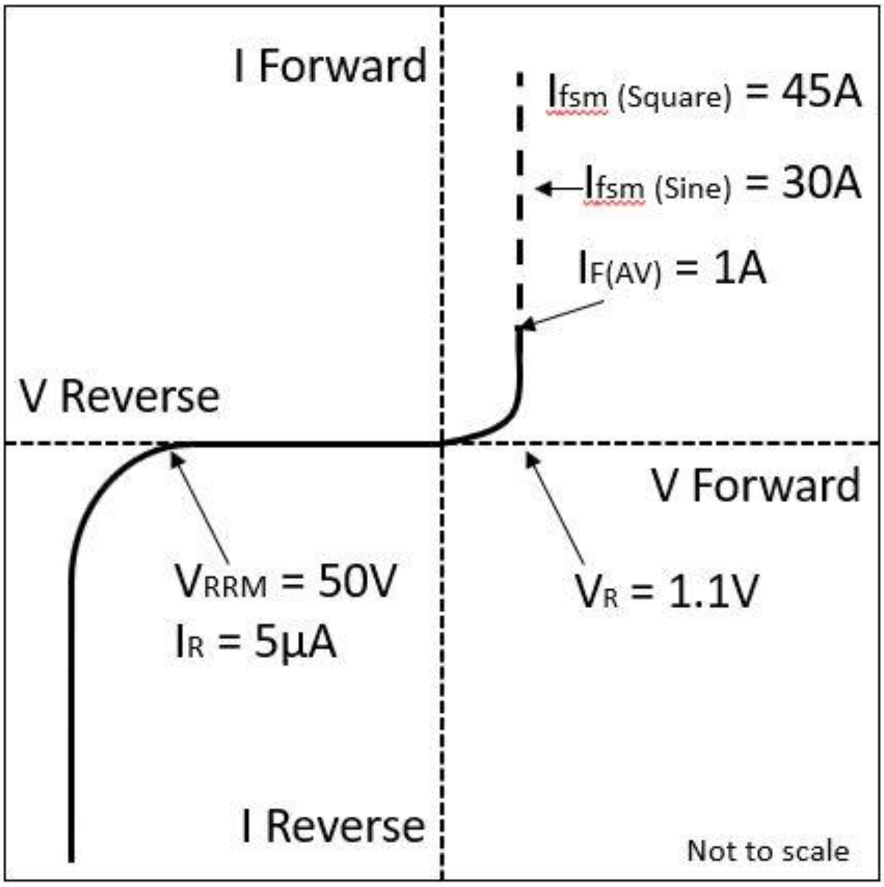


Figure3: IN4001 voltage vs current (V-I) plot.

This is just a short look at the 1N4001's datasheet.

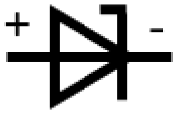
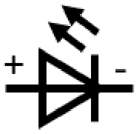
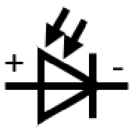
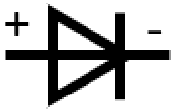
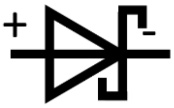
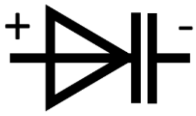
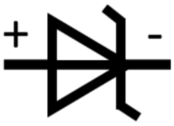
Explore a datasheet such as the KBP005G bridge rectifier for yourself. This device has four diodes in the package connected as a bridge rectifier; the numbers are worth reading.

There are many variances on the diode. Some diodes, like Zener diodes operate in the reverse bias mode.

Diode types and symbols

There are many diode types available. The table here is a short list of diode types with symbols drawn in accordance with the International Standard, IEC 60617. The Australian Standard, AS/NZS 1102, was withdrawn from publication in 2017.

The anode end is annotated with a **+** symbol and the cathode end is annotated with a **-** symbol.

Table of diode types and their applications		
Avalanche diodes		A diode that works in the reverse bias region as a 'relief valve' in a circuit. Example is if DC power is connected the wrong way the current will flow through the diode and not damage the circuit.
Light-emitting diodes (LED)		Special diodes that emit light when activated.
Photodiodes		Light sensing diode.
Power diode, signal diode		Power diodes are used to rectify AC in power supplies, while signal diodes have much lower ratings for use in signal circuits.
Schottky diodes		Low V_F and fast switching times. Used in high-speed circuitry and RF devices such as mixers, and detectors. Also found in switched-mode power supplies.
Varicap or varactor		Diode acting as a voltage-controlled capacitor.
Zener diodes		More correctly termed reverse breakdown diodes. This effect, called Zener breakdown, occurs at a defined voltage, enabling the diode to be used as a voltage reference.

An old tech once said to me that semiconductors operate by smoke and mirrors. But, once the smoke gets out, they are stuffed. Over my years, I have succeeded in letting smoke out of many semiconductors. Bear this thought in mind when passing on your knowledge to a budding tech.

Go to Lesson 8A questions.

Have fun and stay safe.

