



# Semiconductor material:

Materials are generally categorised as being either electrical conductors or insulators. However, a category of material exists that can behave as either a conductor or an insulator, depending on external conditions. These materials are called **semiconductors**. This property can be very useful in electronics, and semiconductor materials are used in devices such as diodes and transistors.

#### **Atomic Structure**

All materials are made from atoms that consist of a positively charged nucleus with negatively charged electrons orbiting around it. The electrons orbit the nucleus in a number of concentric shells.



In any atom there are the same number of electrons orbiting as protons in the nucleus, so that it is electrically neutral. It is the electrons in the outermost shell and how they interact with the outermost electrons in adjoining atoms that determines the conductivity of the material.

## **Conductors and Insulators**

A good **conductor** has one electron in the outer shell of each atom. This electron is held loosely in place and can easily be pulled free. It is these free electrons that move through a material when a potential difference exists, causing an electrical current.

An **insulator** has many electrons in the outer shell of each atom that form a strong bond with adjacent atoms. These electrons cannot easily be pulled free, so electrical conduction doesn't occur.





#### Semiconductors

**Semiconductor** materials have 4 electrons in the outer shell of each atom. Silicon is an example of a semiconductor material that is frequently used in electronics.

In pure silicon these outer electrons form strong bonds with adjacent silicon atoms, forming a strong crystal lattice structure.

At room temperature, heat energy will cause some of these bonds to break. This releases a very small number of electrons to move through the material, but not enough to allow a noticeable current flow in the material.

Pure silicon is therefore an insulator at room temperature.





## **Adding Impurities**

To increase the conductivity, a material can be added to the silicon to make the silicon impure. The process of adding an impurity is called **doping**. By selecting an appropriate doping material, additional charge carriers can be added to the material. The amount of impurity required to increase the number of charge carriers, and hence increase the conductivity, can be as small as 1 part per million.

#### **N-Type Semiconductor**

If a material with five outer electrons, such as arsenic, is added to silicon, four of the outer arsenic electrons will fit into the crystal lattice, but the fifth **electron** will remain free. This free electron can move very easily in the material.



Doping a material in this way creates free electrons that are negative charge carriers. It is therefore known as an **n-type** semiconductor.

## P-Type Semiconductor

If a material with three outer electrons, such as indium, is added to silicon, the crystal lattice will be an electron short for each impurity atom, creating a **hole** in the crystal lattice. These holes act as spaces into which electrons can move. This will give the appearance that the hole is moving through the material. The hole is said to have a positive charge since it attracts negatively charged electrons. Doping a material in this way creates holes that act like **positive** charge carriers. It is therefore known as a **p-type** semiconductor.





#### **Current Flow in N-Type Semiconductors**

In an n-type semiconductor, free electrons are the charge carriers in the material. With no voltage applied, the free electrons will move around at random within the material. When a voltage is applied across the semiconductor material, the free electrons will be repelled by the negative voltage and attracted to the positive voltage.



This movement of electrons allows a current to flow through the material.



#### **Current Flow in P-Type Semiconductors**

In a p-type semiconductor, holes are the charge carriers in the material. With no voltage applied, the holes will move around at random within the material. With a voltage applied across the material, the positive holes will be attracted to the negative voltage. As a hole moves towards the negative voltage, an electron fills the position the hole was previously occupying.



The movement of the holes therefore results in a movement of electrons and so allows a current to flow through the material.

#### P-N Junction Diode

A simple semiconductor device is the diode. This consists of a region of p-type semiconductor alongside a region of n-type semiconductor. A silicon diode is formed from one complete crystal of silicon with the impurities infused into it to make it part n-type and part p-type. A junction exists at the boundary between the n-type and p-type silicon.





## **Depletion Layer**

When the p-n junction is manufactured some of the free electrons in the n-type material will cross the junction and fill the holes in the p-type material.



Where these electrons fill the holes, a region will be created containing no free electrons. With no free electrons this region becomes an insulator. This region is called the **depletion layer** as it is depleted of free electrons.



## **Barrier Potential**

In the p-type region the increase in the number of electrons will cause a negative charge to build up as there will be more electrons than protons. This negative charge will repel electrons, so preventing more electrons crossing the junction.

Where electrons have moved from the n-type region, the atoms will have an overall positive charge since these atoms will have fewer negative electrons than positive protons. This will cause a positive charge to build up in the n-type region.

The charge that builds up to stop electrons from crossing the junction is called the **barrier potential**.





## Connecting a Voltage to a Diode

Consider a voltage connected across the diode such that the positive voltage is applied to the p-type region and the negative voltage is applied to the n-type region. The positive voltage will repel the holes in the ptype material pushing them towards the junction. The negative voltage will repel the electrons in the n-type material also pushing them towards the junction.



#### **Forward Bias**

If the applied voltage is large enough the depletion layer will totally collapse. Electrons from the negative terminal of the power supply will now be able to enter the diode, cross the junction, and continue round the circuit to the positive terminal. A current will therefore be flowing in the circuit. When voltage is applied to a diode so that a current will flow, the diode is said to be **forward biased**.





## Light Emitting Diode - LED

A special type of diode is the Light Emitting Diode (LED). This diode will emit light when it is forward biased. When reverse biased no current will flow, therefore no light will be emitted. The symbol for an LED is a diode symbol with arrows coming off it to indicate that it emits light.



When electrons jump across the junction between the n-type and p-type material to combine with a hole, their energy level changes. In a silicon diode, this energy is converted to heat, but some materials, such as Gallium Arsenide (GaAs), will convert this energy to heat and also to light. Depending on the material used, LEDs that emit red, green, yellow and blue light can be manufactured.





The I-V characteristic for an LED is similar to a standard diode. It can be seen that LEDs require a higher switch-on voltage than ordinary silicon diodes. From the I-V characteristic curve shown, it can be seen that red LEDs are the most efficient, requiring the lowest switch-on voltage. Typically the forward bias voltage required to switch on an LED is about 2V. This compares with about 0.6V for an ordinary silicon diode.



The semiconductor material for an LED is encapsulated in a plastic case which also helps to colour the emitted light. Like a diode an LED has two connections - anode and cathode. The cathode is identified by a flat edge in the base of the LED and the connection wire for the anode is generally the longer wire, unless someone has cut it!





Each type of bipolar junction transistor has its own circuit symbol showing the base, emitter and collector. The arrow on the symbol always appears on the emitter terminal and points from P to N. For an NPN transistor, the arrow on the emitter will point outwards.



The bipolar junction transistor contains two p-n junctions that behave exactly like a diode. Each junction must be correctly biased to allow electrons to flow between the emitter and collector. For this reason, an NPN transistor cannot be replaced by a PNP transistor.





#### **NPN Transistor Biasing**

For an NPN transistor, to allow the electrons in the emitter to move to the base, the voltage at the base must typically be 0.6V higher than the voltage at the emitter. To allow these electrons to continue on to the collector, the collector voltage must be higher than the base voltage. Although some of the electrons will exit the transistor at the base, the majority of them will continue onto the collector.



When selecting a transistor for an application, there are three main characteristics that must be taken into account. These are generally plotted as graphs.

Input Characteristic

Base current (I<sub>B</sub>) against base-emitter voltage (V<sub>BE</sub>)

**Output Characteristic** 

• Collector current (I<sub>C</sub>) against collector-emitter voltage (V<sub>CE</sub>)

**Transfer Characteristic** 

Collector current (I<sub>c</sub>) against base current (I<sub>B</sub>)





In a practical transistor switch circuit the load is connected between the collector and the positive supply rail. A resistor is connected between the base and the power supply. This is to ensure that the current through the base-emitter junction is kept to a safe level, in order to prevent damage to the transistor.





## Voltage Amplifier

In a voltage amplifier, the output voltage is greater than the input voltage. There may or may not be a gain in current. An input voltage (Vin) sets up a small base current ( $I_b$ ), which in turn causes a much larger collector current ( $I_c$ ) to flow. The relatively large collector current causes a significant voltage (Vc) across the collector resistor. A small change in the input voltage (Vin) will result in a relatively large change in the output voltage (Vout). The emitter is common to both input and output circuits, so this is called a **Common Emitter Amplifier**.



## Junction Field Effect Transistor (JFET)

This is a three-terminal device which is controlled totally by voltage – it does not require any biasing current. The device has a source, gate and drain. Electric charge flows from source to drain through a semiconducting channel. This channel can be 'pinched' by applying a reverse biasing voltage between the gate and source, thereby narrowing the conducting channel between source and drain and lowering the current.







#### **MOSFETs**

The **M**etal **O**xide **S**emiconductor **F**ield **E**ffect **T**ransistor (MOSFET) can be used in many applications where a bipolar junction transistor, (BJT), is used, plus several where a conventional BJT cannot be used. There are two main types of MOSFET: **Depletion** and **Enhancement**.

The main difference between the two types of MOSFET, is that with no voltage on the Gate terminal (equivalent to the base on a BJT), the Depletion type device conducts, and the Enhancement type device does not.

The Enhancement MOSFET device is the most similar, in operation, to a conventional bipolar junction transistor.

The main reasons for using a MOSFET instead of a bipolar junction transistor are its:

- Very high input impedance
- Lack of susceptibility to thermal-runaway (thermal runaway is when the current in the device causes a temperature increase, which in turn causes the current to increase further causing even more heating)
- Low noise characteristics, allowing very small signals to be handled (noise is an unwanted element introduced onto the required signal)

Compared to a BJT amplifier, MOSFET amplifiers have a low gain so their use is limited to low gain applications. Early MOSFETs were susceptible to damage from electrostatic discharge and so had to be handled carefully, although modern MOSFETs have diode protection to prevent damage.



Some applications of MOSFETs are:

Driver - used to interface low current output circuits to relatively high current devices.

**Buffer/Voltage Follower** - Their high input impedance and low noise characteristics make them ideal for applications such as first stages of measurement instruments, radio receivers and amplifiers.

**Voltage Controlled Resistor** - Used as voltage controlled resistors in applications such as Automatic Gain Control, and Voltage Controlled Filters/Attenuators.

**Power Amplifier and Switching Applications** - MOSFETs have very low ON resistances (typically <  $2\Omega$ ), meaning low power dissipation in the device.



The n-channel MOSFET is made on a p-type substrate with an n-type channel diffused into the top surface layer. An insulating layer of silicon dioxide (SiO<sub>2</sub>) is laid on top. Three connections are made to the device, **Source**, **Drain** and **Gate**, which are the MOSFET equivalent of the Emitter, Collector and Base on a bipolar junction transistor.





The channel exists between the source and drain and allows a current to flow even when there is no signal connected to the gate. No current will flow into the gate due to the insulating layer of silicon dioxide.

The characteristic curves for depletion and enhancement MOSFETs are similar except that the curves for the enhancement type are shifted by an amount equal to the threshold voltage. This is because, before it can conduct, the enhancement type MOSFET has to have a gate voltage greater than the threshold voltage.



## Common Source Voltage Amplifier Circuit

This enhancement type MOSFET common source amplifier circuit is similar in configuration and operation to the bipolar junction transistor common-emitter amplifier. It is called a common source amplifier because the source is common to both the input and output circuits. A voltage divider (R1, R3) supplies the necessary bias voltage to the gate, to open up a channel in the MOSFET and provide a quiescent Drain current.



Signals are fed in at the gate with an input capacitor (C1) used to block any DC signal element. The capacitor prevents the low impedance of the signal source interfering with the bias voltage. The varying

