TTE Training Ltd.

Phase 1

Electrical Course Notes

E-CN-004

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SEMICONDUCTORS

Semiconductor materials

Before considering semiconductor materials it is necessary to establish what they are. Semiconductors are substances with a solid chemical element or compound that can conduct electricity under some conditions but not in others, making them ideal for the control of electrical current. Its conductance varies depending on the current or voltage applied.

Semiconductors sit between **conductors and insulators**, being neither good conductors, nor good insulators. Semiconductor materials also contain 4 electrons in their outer electron shell (valence shell).

Most group 14 elements in the periodic table can be semiconductors. The arrangement of atoms in the semiconductor is very important, semiconductors must have a cubic crystal structure to function properly, pure silicon or germanium is never used to manufacture working semiconductor components as its resistance cannot be controlled very well, it is only effected by changes in temperature.

Materials

Elemental semiconductors include antimony, arsenic, boron, carbon, germanium, silicon, sulphur, and tellurium. Silicon is the best known of these, forming the basis of most integrated circuits (IC's).

Doping to produce P and N type Semiconductors

Two different types of semiconductor can be made by adding tiny amounts of impurities to the semiconductor material in a process known as doping. One type of semiconductor is the P type which is made by adding a small amount of boron.

Boron (B) is a group 13 element, that has 3 electrons in its outer shell, so when its added to the crystal structure it leaves a gap known as a 'hole', because of this it is known as an accepter impurity because the **hole** can accept an electron.

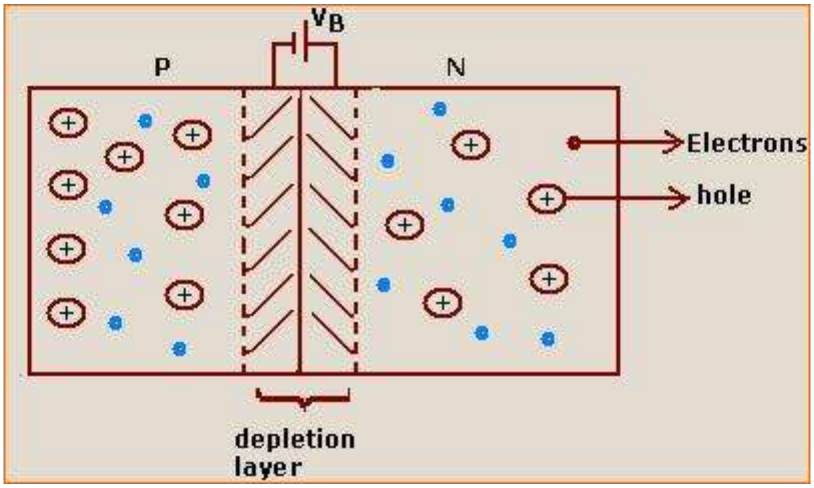
The other type is the N type semiconductor which is doped with phosphorous (P) which is a group 15 element that has 5 electrons in its outer shell, when added to the crystal structure it leaves a **free electron**, known as a donor impurity.

A hole is an empty space in the crystal lattice that can accept an electron to fill the gap. Holes cannot move as such, however they may appear to do so as electrons in the semiconductor move around. P type semiconductors have many holes and few electrons, thus holes are the majority charge carrier with electrons being the minority.

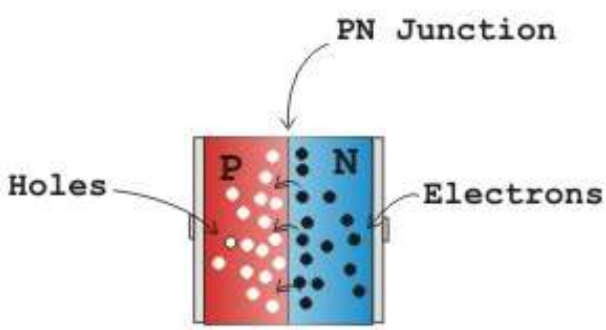
The reverse of the above is true with N type semiconductors, electrons are the majority charge carrier with holes as the minority.

Diode

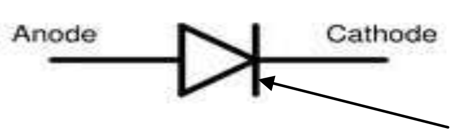
This semiconductor device is produced by placing the P type and N type semiconductor together. (Refer to diagram below). This results in the some of the electrons from the N material jump over to fill some of the holes in the P material. This results in a small region forming where the materials touch known as the depletion region.



This depletion region has a direct effect upon which direction current can flow through the diode. The diode PN junction diagram shown below indicates a barrier that has in fact been created by its depletion region at the junction between the two materials



PN junction



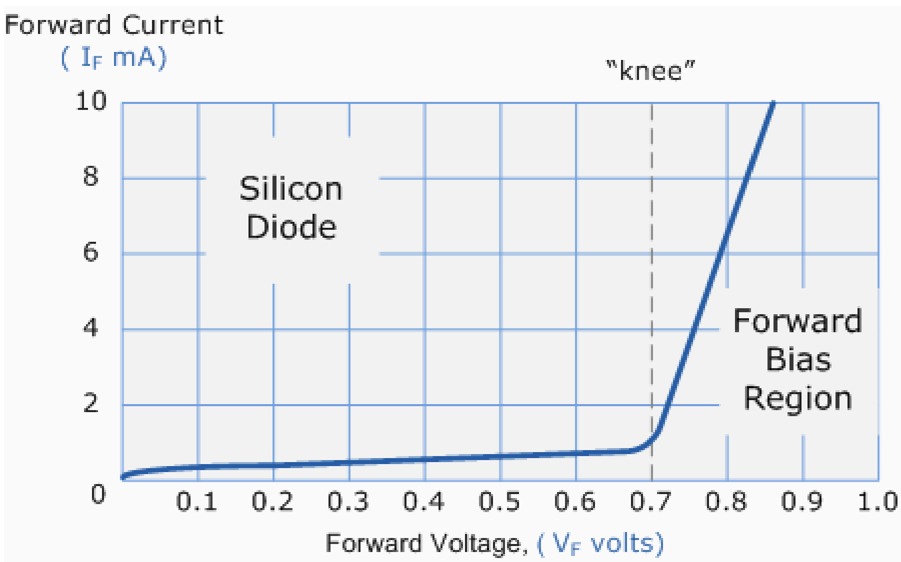
Indicates the barrier formed at PN junction

Diode symbol

Forward biased junction diode

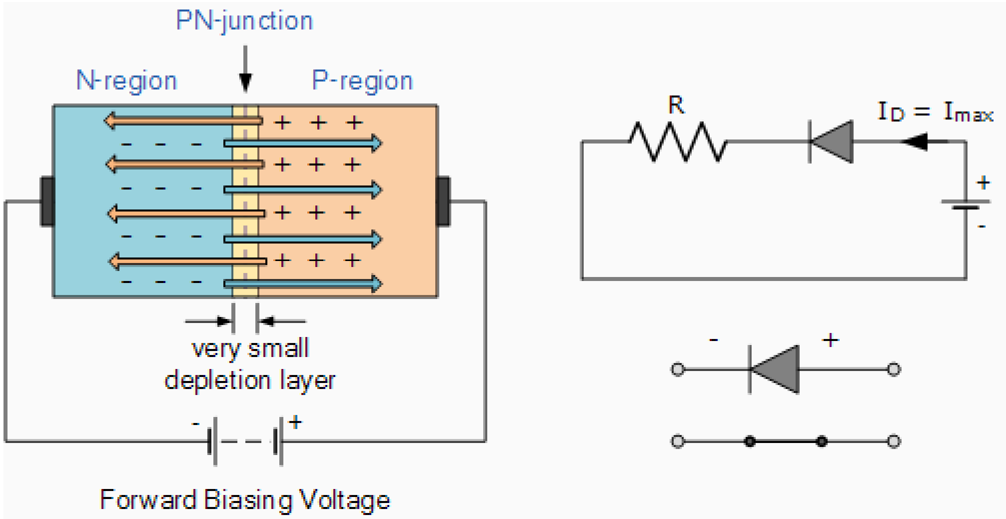
When a diode is connected in a Forward Bias condition, a negative voltage is applied to the N-type material and a positive voltage is applied to the P-type material. If this external voltage becomes greater than the value of the potential barrier, approx. 0.6 volts for silicon and 0.3 volts for germanium, the potential barriers opposition will be overcome and current will start to flow. This results in a characteristics curve of zero current flowing up to this voltage point, called the "knee" on the static curves and then a high current flows through the diode with little increase in the external voltage as shown below.

Forward characteristic curve for a junction diode



The application of a forward biasing voltage on the junction diode results in the depletion layer becoming very thin and narrow, which represents a low resistance path through the junction thereby allowing high currents to flow. The point at which this sudden increase in current takes place is represented on the static I-V characteristics curve above as the "knee" point.

Forward biased junction diode showing a reduction in the depletion layer

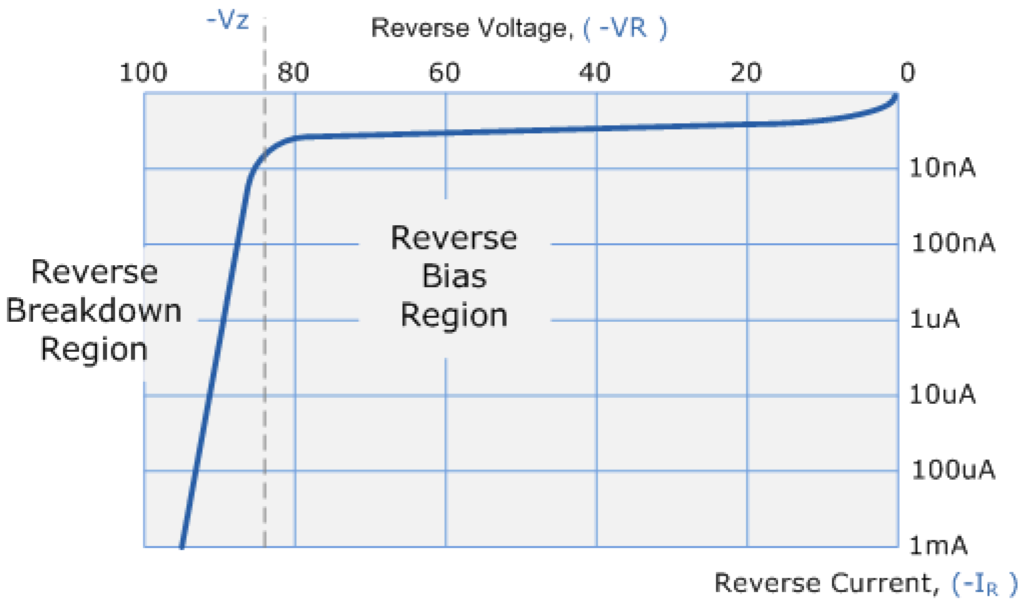


This condition represents the low resistance path through the PN junction allowing very large currents to flow through the diode with only a small increase in bias voltage. The actual potential difference across the junction or diode is kept constant by the action of the depletion layer at approximately 0.3v for germanium and approximately 0.6v for silicon junction diodes. Since the diode can conduct "infinite" current above this knee point as it effectively becomes a short circuit, therefore resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat than it was designed for resulting in a very quick failure of the device.

Reverse biased junction diode

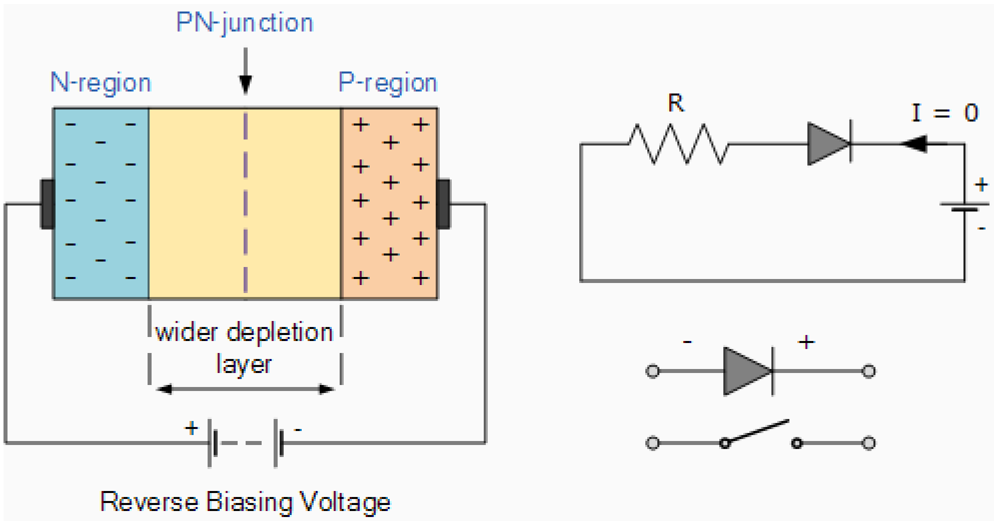
When a diode is connected in a **Reverse Bias** condition, a positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material. The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode. The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

Reverse characteristics curve for a junction diode



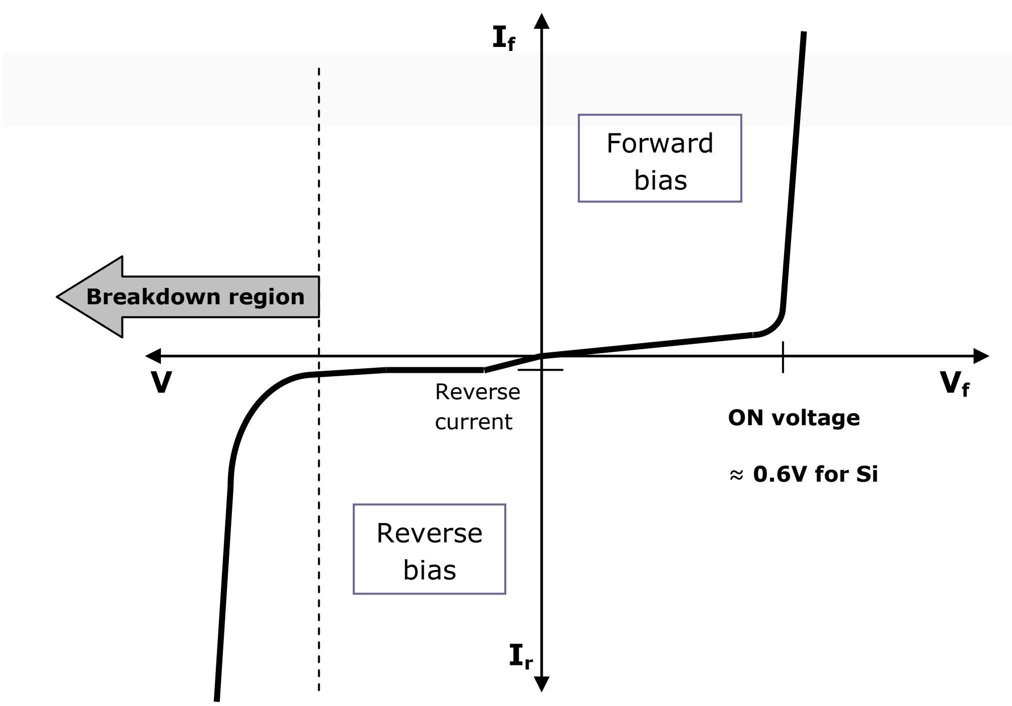
The application of a reverse biasing voltage on the junction diode results in the depletion layer becoming wider, which represents a high resistance path through the junction thereby blocking pre-determined currents. The point at which larger current increases cause a failure to take place will depend on the tolerances of the manufacturer and is represented on the static I-V characteristics curve above as the "breakdown" region.

Reverse biased junction diode showing an increase in the depletion layer



This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. If the reverse bias voltage Vr applied to the diode is increased to a sufficiently high enough value, it will cause the PN junction to overheat and fail due to the avalanche effect around the junction. This may cause the diode to become short circuited and will result in the flow of maximum circuit current, which in turn if it continues to flow could eventually cause an open circuit.

Forward and reverse characteristics curves for a junction diode



Types of Diodes

Light Emitting Diode (LED): Light is produced when current flows between the electrodes. In most of the diodes, the light (infrared) cannot be seen as they are at frequencies that do not permit visibility. When the diode is switched on or forward biased, the electrons recombine with the holes and release energy in the form of light (electroluminescence). The colour of light depends on the energy gap of the semiconductor.

Avalanche Diode: This type of diode operates in the reverse bias, and uses the avalanche effect for its operation. Generally, the avalanche diode is used for photo-detection, because high levels of sensitivity can be obtained by the avalanche process.

Laser Diode: This type of diode is different from the LED type, as it produces visible light. These diodes are used in DVD and CD drives, and laser printers.

Schottky Diodes: These diodes feature lower forward voltage drop as compared to the ordinary silicon PN junction diodes. These diodes are used in RF applications, rectifier applications and clamping diodes.

Zener diode: This type of diode provides a stable reference voltage, thus is a very useful type. The diode runs in reverse bias, and breaks down on the arrival of a certain voltage. A stable voltage is produced, if the current through the resistor is limited. In power supplies, these diodes are widely used to provide a reference voltage.

Photodiode: Photodiodes are used to detect light. Generally, these diodes operate in reverse bias mode, when small amounts of current flow, resulting in light being detected with ease. Photodiodes can also be used to generate electricity and hence used in solar cells and in photometry.

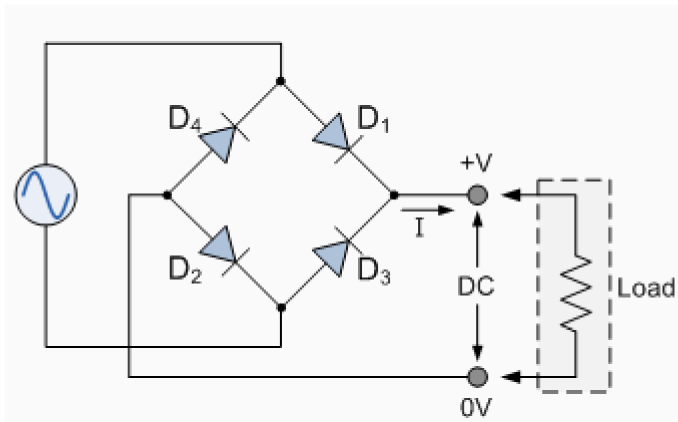
Varicap Diode or Varactor Diode: This diode acts as a capacitor and capacitor plates are formed by the extent of conduction regions and the depletion region as the insulating dielectric. By altering the bias on the diode, the width of the depletion region changes, thereby varying the capacitance.

Rectifier Diode: These diodes are used to rectify alternating power inputs in power supplies. They can rectify current levels that range from an amp upwards. Generally these diodes are PN junction diodes.

Besides the above mentioned types of diodes, the other diodes are PIN diode, point contact diode, signal diode, step recovery diode, tunnel diode, and gold doped diodes.

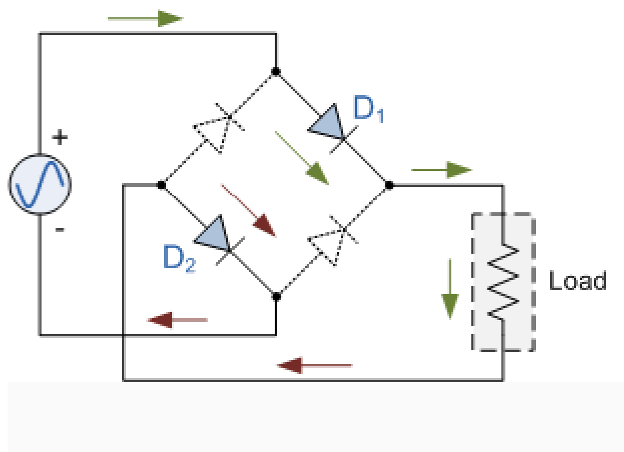
The Full Wave bridge rectifier

Full Wave Bridge Rectifier This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop "bridge" configuration to produce the desired output. The main advantage of this bridge circuit is that it does not require a special centre tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown below.



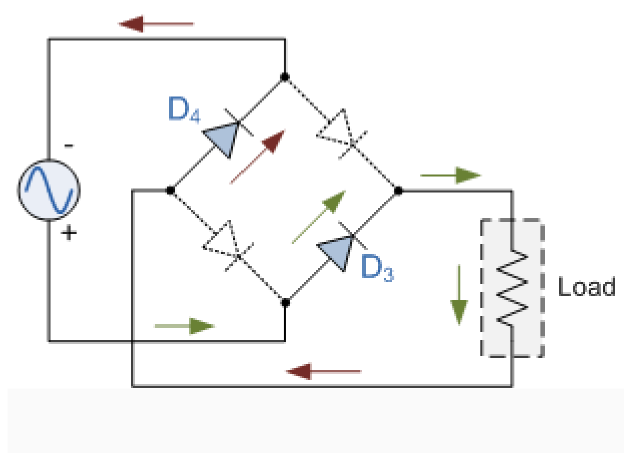
The four diodes labelled D_1 to D_4 are arranged in "series pairs" with only two diodes conducting current during each half cycle. During the positive half cycle of the supply, diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through the load as shown below.

The Positive Half-cycle



During the negative half cycle of the supply, diodes D3 and D4 conduct in series, but diodes D1 and D2 switch "OFF" as they are now reverse biased. The current flowing through the load is the same direction as before.

The Negative Half-cycle



As the current flowing through the load is unidirectional, so the voltage developed across the load is also unidirectional the same as for the previous two diode full-wave rectifier, therefore the average DC voltage across the load is $0.637V_{max}$. However in reality, during each half cycle the current flows through two diodes instead of just one so the amplitude of the output voltage is two voltage drops (2 x 0.7 = 1.4V) less than the input V_{MAX} amplitude. The ripple frequency is now twice the supply frequency (e.g. 100Hz for a 50Hz supply)

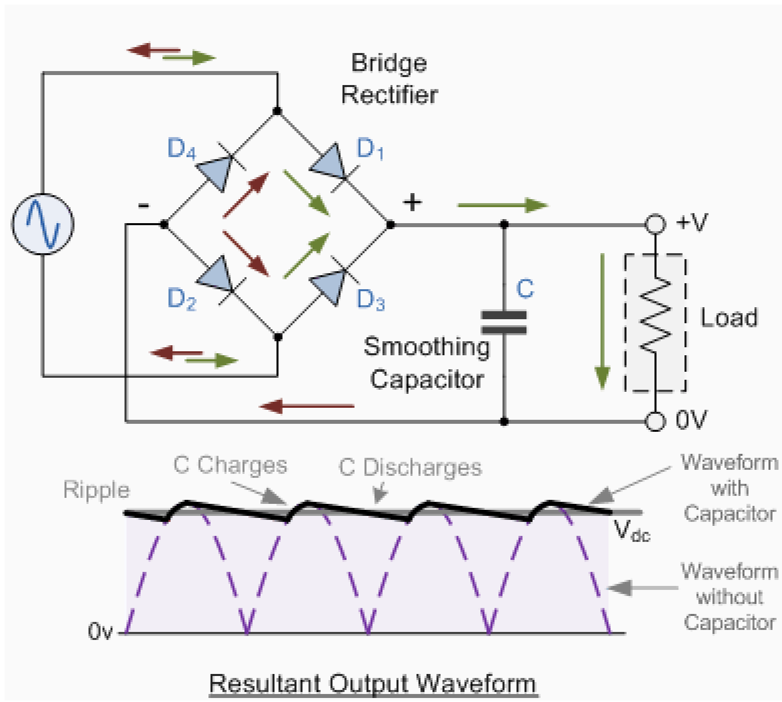
Typical Bridge Rectifier

The image directly above shows a typical single phase bridge rectifier with one corner cut off. This cut-off corner indicates that the terminal nearest to the corner is the positive or +ve output terminal or lead with the opposite (diagonal) lead being the negative or -ve output lead. The other two connecting leads are for the input alternating voltage from a transformer secondary winding.

The Smoothing Capacitor

We saw in the previous section that the single phase half-wave rectifier produces an output wave every half cycle and that it was not practical to use this type of circuit to produce a steady DC supply. The full-wave bridge rectifier however, gives us a greater mean DC value (0.637 Vmax) with less superimposed ripple while the output waveform is twice that of the frequency of the input supply frequency. We can therefore increase its average DC output level even higher by connecting a suitable smoothing capacitor across the output of the bridge circuit as shown below.

Full-wave rectifier with smoothing capacitor



The smoothing capacitor converts the full-wave rippled output of the rectifier into a smooth DC output voltage. Generally for DC power supply circuits the smoothing capacitor is an Aluminium Electrolytic type that has a capacitance value of 100uF or more with repeated DC voltage pulses from the rectifier charging up the capacitor to peak voltage. However, their are two important parameters to consider when choosing a suitable smoothing capacitor and these are its *Working Voltage*, which must be higher than the no-load output value of the rectifier and its *Capacitance Value*, which determines the amount of ripple that will appear superimposed on top of the DC voltage. Too low a value and the capacitor has little effect but if the smoothing capacitor is large enough (parallel capacitors can be used) and the load current is not too large, the output voltage will be almost as smooth as pure DC. As a general rule of thumb, we are looking to have a ripple voltage of less than 100mV peak to peak.

Bipolar Transistor

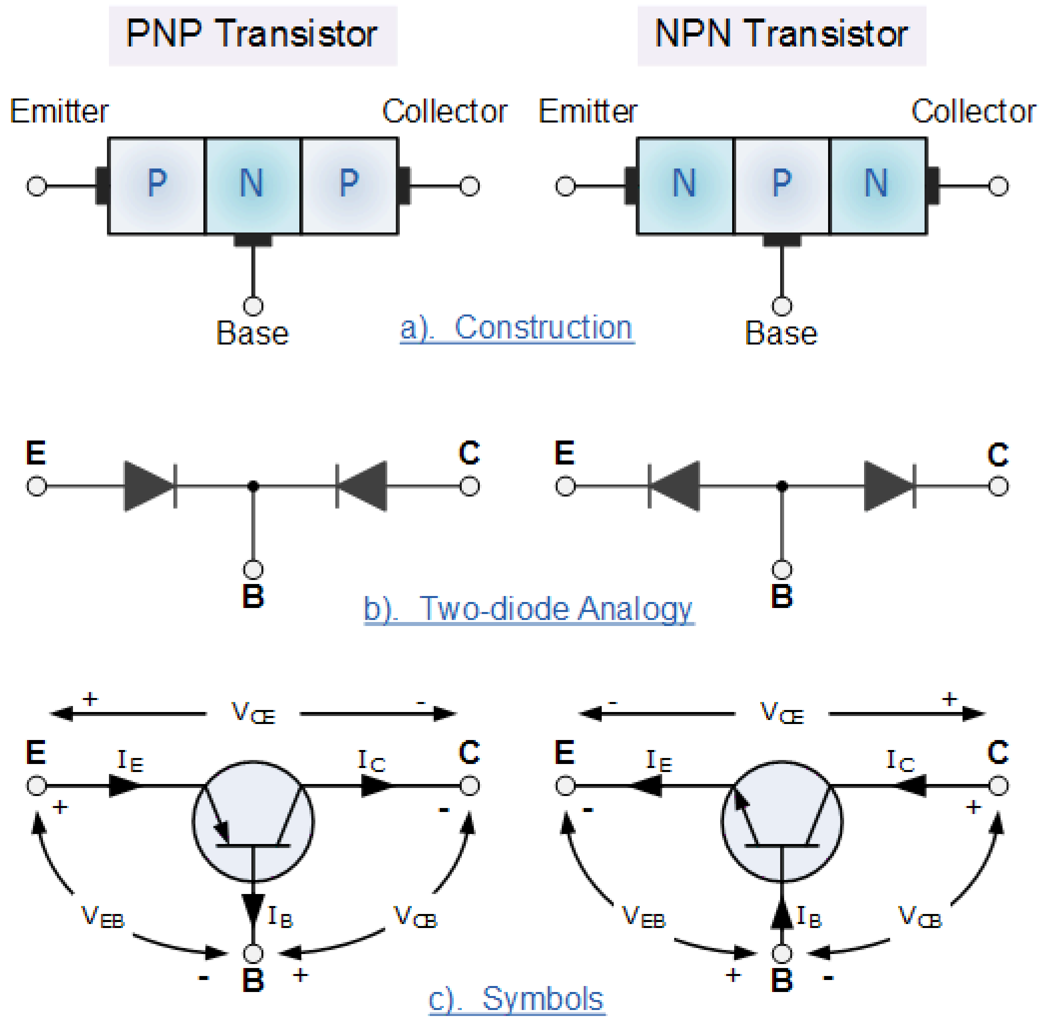
Typical Bipolar Transistor

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 of development. There are two basic types of bipolar transistor construction, PNP and NPN, which basically describes the physical arrangement of the P-type and N-type semiconductor materials from which they are made.

The **Bipolar Transistor** basic construction consists of two PN-junctions producing three connecting terminals with each terminal being given a name to identify it from the other two. These three terminals are known and labelled as the Emitter (E), the Base (B) and the Collector (C) respectively.

Bipolar Transistors are current regulating devices that control the amount of current flowing through them in proportion to the amount of biasing voltage applied to their base terminal acting like a current-controlled switch. The principle of operation of the two transistor types PNP and NPN, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

Bipolar Transistor Construction



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

Bipolar transistor configurations

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

Circuit arrangement

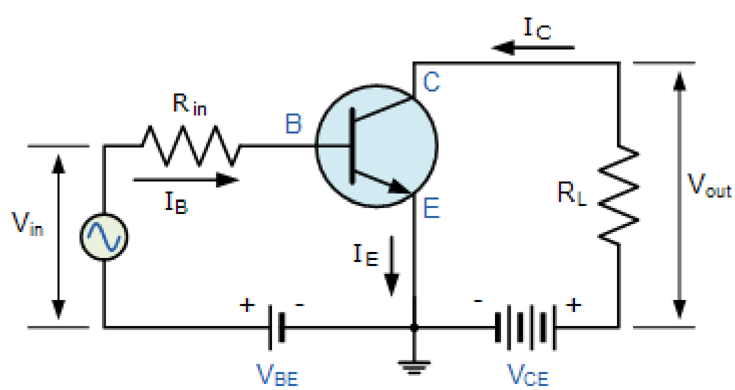
1. Common Base Configuration

2. Common Emitter Configuration

3. Common Collector Configuration

We will look at one of the above configurations only

The Common Emitter as an Amplifier Circuit



This transistor has the ability to amplify the AC input signal voltage (V_{in}) in such away as to produce an output voltage across the load resistor (R_L) that is much larger in magnitude than that of the input signal voltage. The magnitude of this magnified output voltage depends upon the value of the signal voltage (V_{in}), as well as the value of the collector current (I_C) that flows through it that's controlled by the values of the base current (I_B) and emitter current (I_E). Any variation in either or both of these values will result in changes in $V_{out.}$

Transistor as a Switch

Because a transistor's collector current is proportionally limited by its base current, it can be used as a sort of current-controlled switch. A relatively small flow of electrons sent through the base of the transistor has the ability to exert control over a much larger flow of electrons through the collector.

Suppose we had a lamp that we wanted to turn on and off with a switch. Such a circuit would be extremely simple as in Figure 1 (a).

For the sake of illustration, let's insert a transistor in place of the switch to show how it can control the flow of electrons through the lamp. Remember that the controlled current through a transistor must go between collector and emitter. Since it is the current through the lamp that we want to control, we must position the collector and emitter of our transistor where the two contacts of the switch were. We must also make sure that the lamp's current will move against the direction of the emitter arrow symbol to ensure that the transistor's junction bias will be correct as in Figure 1(b).

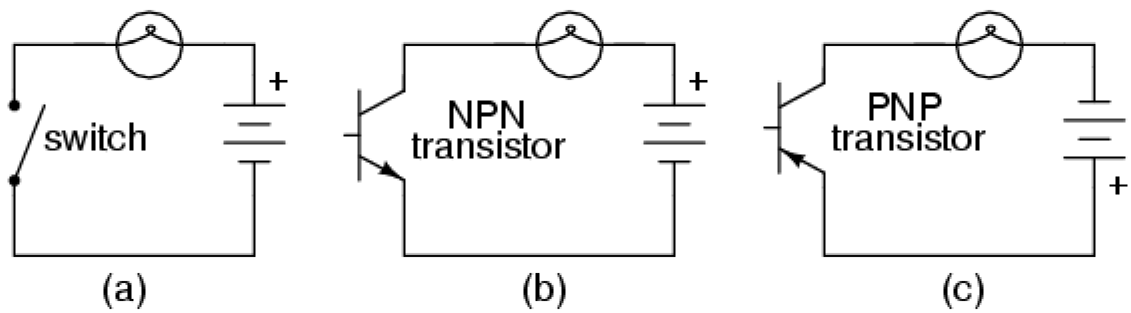


Fig 1(a) mechanical switch, (b) NPN transistor switch, (c) PNP transistor switch.

A PNP transistor could also have been chosen for the job. Its application is shown in Figure 1(c).

The choice between NPN and PNP is really arbitrary. All that matters is that the proper current directions are maintained for the sake of correct junction biasing (electron flow going against the transistor symbol's arrow).

Going back to the NPN transistor in our example circuit, we are faced with the need to add something more so that we can have base current. Without a connection to the base wire of the transistor, base current will be zero, and the transistor cannot turn on, resulting in a lamp that is always off. Remember that for an NPN transistor, base current must consist of electrons flowing from emitter to base (against the emitter arrow symbol, just like the lamp current). Perhaps the simplest thing to do would be to connect a switch between the base and collector wires of the transistor as in Figure 2(a).

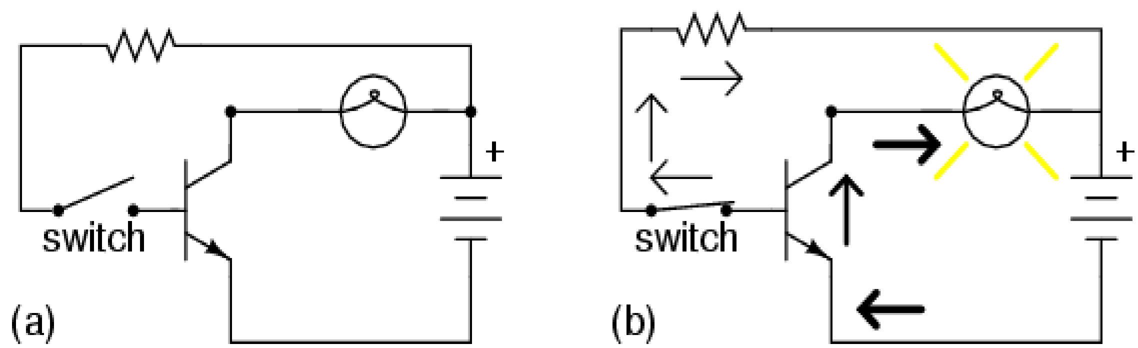


Fig 2 *Transistor: (a) cutoff, lamp off; (b) saturated, lamp on.*

If the switch is open as in (Figure 2(a), the base wire of the transistor will be left “floating” (not connected to anything) and there will be no current through it. In this state, the transistor is said to be cutoff. If the switch is closed as in (Figure 2(b), however, electrons will be able to flow from the emitter through to the base of the transistor, through the switch and up to the left side of the lamp, back to the positive side of the battery. This base current will enable a much larger flow of electrons from the emitter through to the collector, thus lighting up the lamp. In this state of maximum circuit current, the transistor is said to be saturated.

Of course, it may seem pointless to use a transistor in this capacity to control the lamp. After all, we're still using a switch in the circuit, aren't we? If we're still using a switch to control the lamp -- if only indirectly -- then what's the point of having a transistor to control the current? Why not just go back to our original circuit and use the switch directly to control the lamp current?

Two points can be made here, actually. First is the fact that when used in this manner, the switch contacts need only handle what little base current is necessary to turn the transistor on; the transistor itself handles most of the lamp's current. This may be an important advantage if the switch has a low current rating: a small switch may be used to control a relatively high-current load. More important, the current-controlling behavior of the transistor enables us to use something completely different to turn the lamp on or off.

Consider Figure 3, where a pair of solar cells provides 1 V to overcome the 0.6 VBE of the transistor to cause base current flow, which in turn controls the lamp.

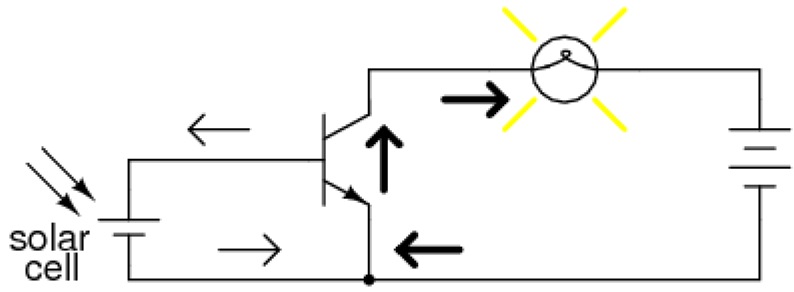


Fig 3 *Solar cell serves as light sensor.*

Or, we could use a thermocouple (or many connected in series) to provide the necessary base current to turn the transistor on in Figure 4.

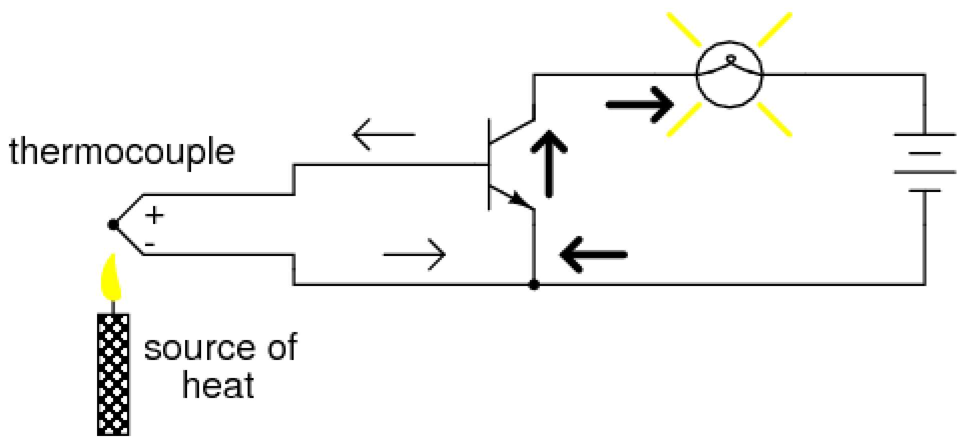


Fig 43 *Thermocouple serves as heat sensor.*

Fig 4 single thermocouple provides 10s of mV. Many in series could produce in excess of the 0.6V transistor (VBE) to cause base current flow and consequent collector current to the lamp.

Even a microphone (Figure 5) with enough voltage and current (from an amplifier) output could turn the transistor on, provided its output is rectified from AC to DC so that the emitter-base PN junction within the transistor will always be forward-biased:

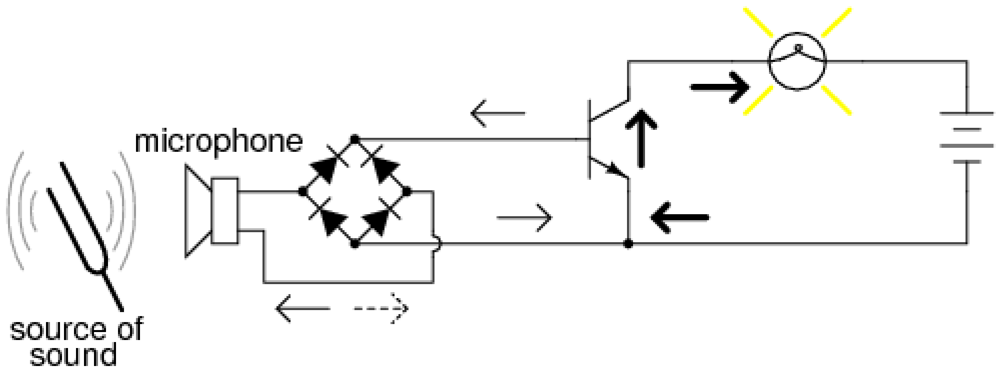


Fig 5*Amplified microphone signal is rectified to DC bias the base of the transistor providing a larger collector current.*

It should be quite apparent by now that: any sufficient source of DC current may be used to turn the transistor on, and that source of current only need be a fraction of the current needed to energize the lamp. Here we see the transistor functioning not only as a switch, but as a true amplifier: using a relatively low-power signal to control a relatively large amount of power. Please note that the actual power for lighting up the lamp comes from the battery to the right of the schematic. It is not as though the small signal current from the solar cell, thermocouple, or microphone is being magically transformed into a greater amount of power. Rather, those small power sources are simply controlling the battery's power to light up the lamp.

Recapping:

- Transistors may be used as switching elements to control DC power to a load. The switched (controlled) current goes between emitter and collector; the controlling current goes between emitter and base.
- When a transistor has zero current through it, it is said to be in a state of cut-off (fully none conducting).
- When a transistor has maximum current through it, it is said to be in a state of saturation (fully conducting).

Light Emitting Diode

A light-emitting diode (LED) is a semiconductor device that emits visible light when an electric current passes through it. The light is not particularly bright, but in most LEDs it is monochromatic, occurring at a single wavelength. The output from an LED can range from red (at a wavelength of approximately 700 nanometers) to blue-violet (about 400 nanometers). Some LEDs emit infrared (IR) energy (830 nanometers or longer); such a device is known as an *infrared-emitting diode* (IRED).

An LED or IRED consists of two elements of *P-type semiconductor*s and *N-type semiconductor*s. These two elements are placed in direct contact, forming a *P-N junction*. In this respect, the LED or IRED resembles most other diode types, but there are important differences. The LED or IRED has a transparent package, allowing visible or IR energy to pass through. Also, the LED or IRED has a large PN-junction area whose shape is tailored to the application.

Benefits of LEDs and IREDs, compared with incandescent and fluorescent illuminating devices, include:

- **Low power requirement**: Most types can be operated with battery power supplies.
- **High efficiency:** Most of the power supplied to an LED or IRED is converted into radiation in the desired form, with minimal heat production.
- **Long life:** When properly installed, an LED or IRED can function for decades.

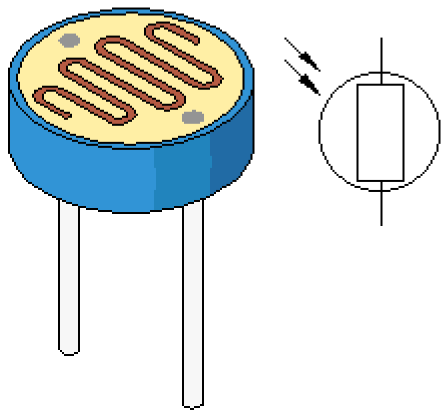
Typical applications include:

- **Indicator lights:** These can be two-state (i.e., on/off), bar-graph, or alphabetic-numeric readouts.
- **LCD panel backlighting:** Specialized white LEDs are used in flat-panel computer displays.
- **Fiber optic data transmission:** Ease of modulation allows wide communications bandwidth with minimal noise, resulting in high speed and accuracy.
- **Remote control:** Most home-entertainment "remotes" use IREDs to transmit data to the main unit

Light Dependant Resistor

Light-dependent resistor alternatively called an **LDR**, **photo resistor**, **photoconductor**, or **photocell**, is a variable resistor whose value decreases with increasing incident light intensity. An LDR is made of a high-resistance semiconductor. If light falling on the device is of high enough frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electron (and its hole partner) conduct electricity, thereby lowering resistance.

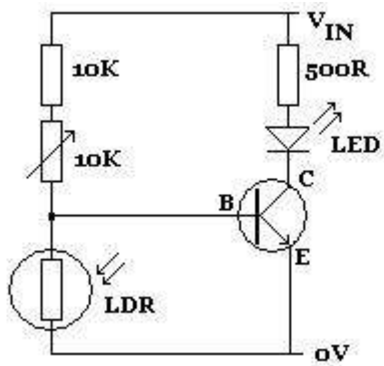
Two of its earliest applications were as part of smoke and fire detection systems and camera light meters. Because cadmium sulphide cells are inexpensive and widely available, LDRs are still used in electronic devices that need light detection capability, such as security alarms, street lamps, and clock radios.



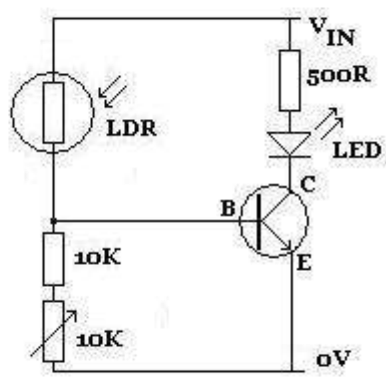
Light dependant resistor and symbol

Light Dependent Resistor Circuits

There are two basic circuits using **light dependent resistors** - the first is activated by darkness, the second is activated by light. The two circuits are very similar and just require an **LDR**, some standard resistors, a variable resistor (potentiometer), and any small signal transistor



In the circuit diagram above the **<u>LED</u> lights up** whenever the LDR is in **darkness**. The 10K variable resistor is used to fine-tune the level of darkness required before the LED lights up. The 10K standard resistor can be changed as required to achieve the desired effect, although any replacement must be at least **1K** to protect the transistor from being damaged by excessive current.



By swapping the LDR over with the 10K and the 10K (variable resistor) (as shown above), the circuit will be activated instead by light. Whenever sufficient light falls on the LDR (manually fine-tuned using the 10K variable resistor), the LED will light up.