Sheikh Hasina University, Netrokona

Department of Computer Science and Engineering

CSE-2205: Introduction to Mechatronics

Lec-10: Light Sensors

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Contents

Light sensors, also known as photodetectors or optical sensors, are devices that detect or measure the presence, intensity, or characteristics of light.

Photodiode

A photodiode is a p-n junction or pin semiconductor device that consumes light energy to generate electric current. It is also sometimes referred as photo-detector, photo-sensor, or light detector.

Photodiodes are specially designed to operate in reverse bias condition. Reverse bias means that the p-side of the photodiode is connected to the negative terminal of the battery and n-side is connected to the positive terminal of the battery.

Photodiode is very sensitive to light so when light or photons falls on the photodiode it easily converts light into electric current. Solar cell is also known as large area photodiode because it converts solar energy or light energy into electric energy. However, solar cell works only at bright light.

Types of photodiodes

The working operation of all types of photodiodes is same. Different types of photodiodes are developed based on specific application. For example, PIN photodiodes are developed to increase the response speed. PIN photodiodes are used where high response speed is needed.

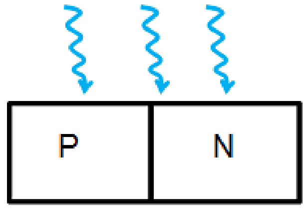
The different types of photodiodes are

- PN junction photodiode
- PIN photodiode
- Avalanche photodiode

Among all the three photodiodes, PN junction and PIN photodiodes are most widely used.

PN junction photodiode

PN junction photodiodes are the first form of photodiodes. They are the most widely used photodiodes before the development of PIN photodiodes. PN junction photodiode is also simply referred as photodiode. Nowadays, PN junction photodiodes are not widely used.

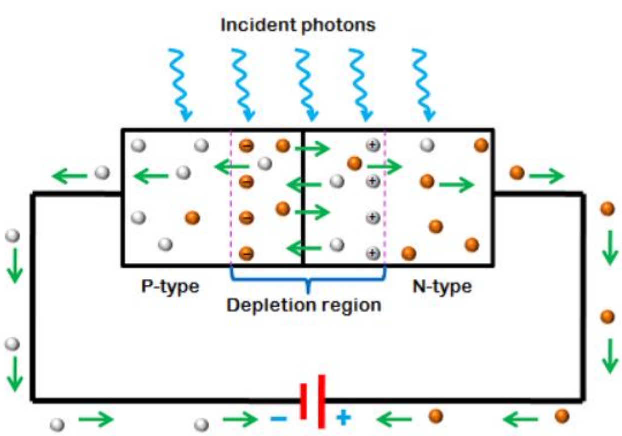


When external light energy is supplied to the p-n junction photodiode, the valence electrons in the depletion region gains energy.

If the light energy applied to the photodiode is greater the band-gap of semiconductor material, the valence electrons gain enough energy and break bonding with the parent atom. The valence electron which breaks bonding with the parent atom will become free electron. Free electrons move freely from one place to another place by carrying the electric current.

When the valence electron leave the valence shell an empty space is created in the valence shell at which valence electron left. This empty space in the valence shell is called a hole. Thus, both free electrons and holes are generated as pairs. The mechanism of generating electron-hole pair by using light energy is known as the inner photoelectric effect.

The minority carriers in the depletion region experience force due to the depletion region electric field and the external electric field. For example, free electrons in the depletion region experience repulsive and attractive force from the negative and positive ions present at the edge of depletion region at p-side and n-side. As a result, free electrons move towards the n region. When the free electrons reaches n region, they are attracted towards the positive terminals of the battery. In the similar way, holes move in opposite direction.



The strong depletion region electric field and the external electric field increase the drift velocity of the free electrons. Because of this high drift velocity, the minority carriers (free electrons and holes) generated in the depletion region will cross the p-n junction before they recombine with atoms. As a result, the minority carrier current increases.

When no light is applied to the reverse bias photodiode, it carries a small reverse current due to external voltage. This small electric current under the absence of light is called dark current. It is denoted by I_{λ}.

In a photodiode, reverse current is independent of reverse bias voltage. Reverse current is mostly depending on the light intensity.

In photodiodes, most of the electric current is carried by the charge carriers generated in the depletion region because the charge carriers in depletion region has high drift velocity and low recombination rate whereas the charge carriers in n-side or p-side has low drift velocity and high recombination rate. The electric current generated in the photodiode due to the application of light is called photocurrent.

The total current through the photodiode is the sum of the dark current and the photocurrent. The dark current must be reduced to increase the sensitivity of the device.

The electric current flowing through a photodiode is directly proportional to the incident number of photons.

PIN photodiode

PIN photodiodes are developed from the PN junction photodiodes. The operation of PIN photodiode is similar to the PN junction photodiode except that the PIN photodiode is manufactured differently to improve its performance.

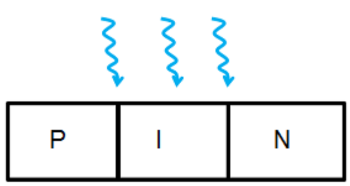
The PIN photodiode is developed to increase the minority carrier current and response speed.

PIN photodiodes generate more electric current than the PN junction photodiodes with the same amount of light energy.

Layers of PIN photodiode

A PN junction photodiode is made of two layers namely p-type and n-type semiconductor whereas PIN photodiode is made of three layers namely p-type, n-type and intrinsic semiconductor.

In PIN photodiode, an addition layer called intrinsic semiconductor is placed between the p-type and n-type semiconductor to increase the minority carrier current.



<u>P-type semiconductor</u>

If trivalent impurities are added to the intrinsic semiconductor, a p-type semiconductor is formed.

In p-type semiconductors, the number of free electrons in the conduction band is lesser than the number of holes in the valence band. Therefore, holes are the majority charge carriers and free electrons are the minority charge carriers. In p-type semiconductors, holes carry most of the electric current.

N-type semiconductor

If pentavalent impurities are added to the intrinsic semiconductor, an n-type semiconductor is formed.

In n-type semiconductors, the number of free electrons in the conduction band is greater than the number of holes in the valence band. Therefore, free electrons are the majority charge carriers and holes are the minority charge carriers. In n-type semiconductors, free electrons carry most of the electric current.

Intrinsic semiconductor

Intrinsic semiconductors are the pure form of semiconductors. In intrinsic semiconductor, the number of free electrons in the conduction band is equal to the number of holes in the valence band. Therefore, intrinsic semiconductor has no charge carriers to conduct electric current.

However, at room temperature a small number of charge carriers are generated. These small number of charge carriers will carry electric current.

PIN photodiode operation

A PIN photodiode is made of p region and n region separated by a highly resistive intrinsic layer. The intrinsic layer is placed between the p region and n region to increase the width of depletion region.

The p-type and n-type semiconductors are heavily doped. Therefore, the p region and n region of the PIN photodiode has large number of charge carriers to carry electric current. However, these charge carriers will not carry electric current under reverse bias condition.

On the other hand, intrinsic semiconductor is an undoped semiconductor material. Therefore, the intrinsic region does not have charge carriers to conduct electric current.

Under reverse bias condition, the majority charge carriers in n region and p region moves away from the junction. As a result, the width of depletion region becomes very wide. Therefore, majority carriers will not carry electric current under reverse bias condition.

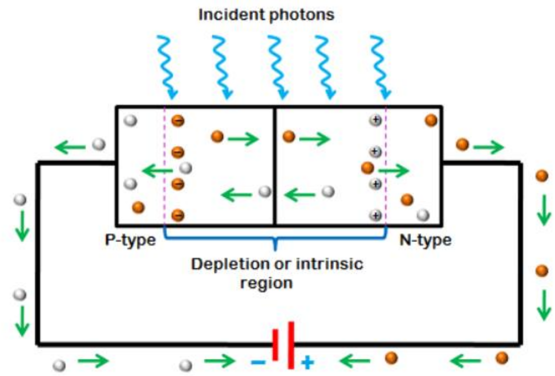
However, the minority carriers will carry electric current because they experience repulsive force from the external electric field.

In PIN photodiode, the charge carriers generated in the depletion region carry most of the electric current. The charge carriers generated in the p region or n region carry only a small electric current.

When light or photon energy is applied to the PIN diode, most part of the energy is observed by the intrinsic or depletion region because of the wide depletion width. As a result, a large number of electron-hole pairs are generated.

Free electrons generated in the intrinsic region move towards n-side whereas holes generated in the intrinsic region move towards p-side. The free electrons and holes moved from one region to another region carry electric current.

When free electrons and holes reach n region and p region, they are attracted to towards the positive and negative terminals of the battery.



The population of minority carriers in PIN photodiode is very large compared to the PN junction photodiode. Therefore, PIN photodiode carry large minority carrier current than PN junction photodiode.

When forward bias voltage is applied to the PIN photodiode, it behaves like a resistor.

We know that capacitance is directly proportional to the size of electrodes and inversely proportional to the distance between electrodes. In PIN photodiode, the p region and n region acts as electrodes and intrinsic region acts as dielectric.

The separation distance between p region and n region in PIN photodiode is very large because of the wide depletion width. Therefore, PIN photodiode has low capacitance compared to the PN junction photodiode.

In PIN photodiode, most of the electric current is carried by the charge carriers generated in the depletion region. The charge carriers generated in p region or n region carry only a small electric current. Therefore, increasing the width of depletion region increases the minority carrier electric current.

Advantages of PIN photodiode

1. Wide bandwidth
2. High quantum efficiency
3. High response speed

Avalanche photodiode

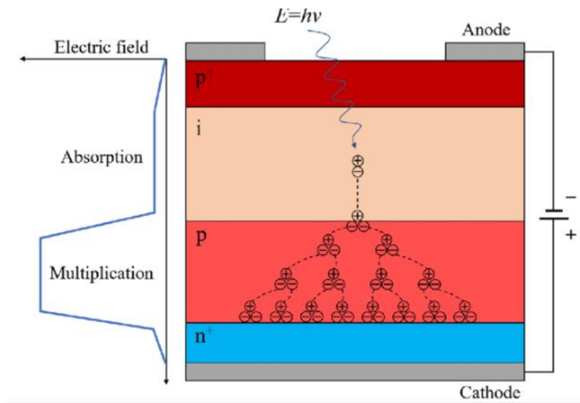
The operation of avalanche photodiode is similar to the PN junction and PIN photodiode except that a high reverse bias voltage is applied in case of avalanche photodiode to achieve avalanche multiplication.

Applying high reverse bias voltage to the avalanche photodiode will not directly increase the generation of charge carriers. However, it provides energy to the electron-hole pairs generated by the incident light.

When light energy is applied to the avalanche photodiode, electron-hole pairs are generated in the depletion. The generated electron-hole pairs experience a force due to the depletion region electric field and external electric field.

In avalanche photodiode, a very high reverse bias voltage supplies large amount of energy to the minority carriers (electron-hole pairs). The minority carriers which gains large amount of energy are accelerated to greater velocities.

When the free electrons moving at high speed collides with the atom, they knock off more free electrons. The newly generated free electrons are again accelerated and collide with other atoms. Because of this continuous collision with atoms, a large number of minority carriers are generated. Thus, avalanche photodiodes generate more number of charge carriers than PN and PIN photodiodes.



Avalanche photodiodes are used in the applications where high gain is an important factor.

<u>Advantages of avalanche photodiode</u>

1. High sensitivity
2. Larger gain

<u>Disadvantages of avalanche photodiode</u>

Generates high level of noise than a PN photodiode

Photodiode operation modes

A photodiode can be operated in one of the two modes: photovoltaic mode or photoconductive mode.

Operation mode selection of the photodiode is depends upon the speed requirements of the application and the amount of dark current that is tolerable.

<u>Photovoltaic mode</u>

In the photovoltaic mode, the photodiode is unbiased. In other words, no external voltage is applied to the photodiode under photovoltaic mode.

In photovoltaic mode, dark current is very low. Photodiodes operated in photovoltaic mode have low response speed.

The photodiodes operated in photovoltaic mode are generally used for low speed applications or for detecting low light levels.

<u>Photoconductive mode</u>

In photoconductive mode, an external reverse bias voltage is applied to the photodiode.

Applying a reverse bias voltage increases the width of depletion region and reduces the junction capacitance which results in increased response speed. The reverse bias also increases the dark current.

Photodiodes operated in photoconductive mode has high noise current. This is due to the reverse saturation current flowing through the photodiode.

Dark current

Dark current is the leakage current that flows in the photodiode in the absence of light. The dark current in the photodiode increases when temperature increases. The material used to construct the photodiode also affects the dark current.

The different materials used to construct photodiodes are Silicon (Si), Germanium, (Ge), Gallium Phosphide (GaP), Indium Gallium Arsenide (InGaAs), Indium Arsenide Antimonide (InAsSb), Extended Range Indium Gallium Arsenide (InGaAs), Mercury Cadmium Telluride (MCT, HgCdTe).

Germanium, Indium Arsenide Antimonide, Indium Gallium Arsenide and Mercury Cadmium Telluride generates large dark current because they are very sensitive to temperature.

The response speed of Silicon, Gallium Phosphide, Indium Gallium Arsenide and Extended Range Indium Gallium Arsenide is very high.

Performance parameters of a photodiode

Responsivity

Responsivity is the ratio of generated photocurrent to the incident light power.

Quantum efficiency

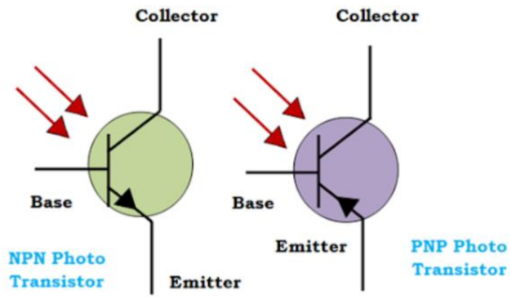
Quantum efficiency is defined as the ratio of the number of electron-hole pairs (photoelectrons) generated to the incident photons.

Response time or transit time

The response time of a photodiode is defined as the time it takes for light generated charge carriers to cross p-n junction.

Phototransistor

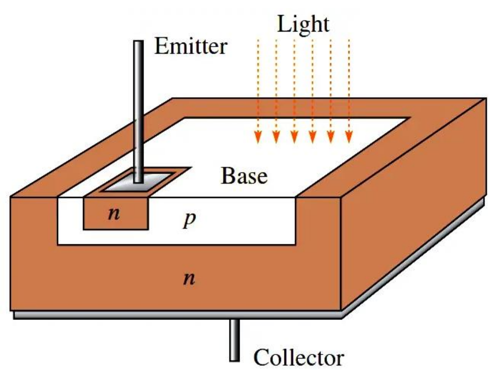
Photo Transistor is a three terminal semiconductor device which converts the incident light into photocurrent. Light is incident on the base terminal and it is converted into current which flows through emitter and collector. It is the combination of photo diode and transistor an amplifier. The current produced by the photo diode is low, so it is sent through the transistor and amplified.



The symbol of Photo Transistor is similar to the transistor. The arrows show the light incident on the base terminal.

Construction of Photo Transistor

A phototransistor can be either a two-lead or a three-lead device. In the three-lead configuration, the base lead is brought out so that the device can be used as a conventional BJT with or without the additional light-sensitivity feature. In the two-lead configuration, the base is not electrically available, and the device can be used only with light as the input. In many applications, the phototransistor is used in the two-lead version.

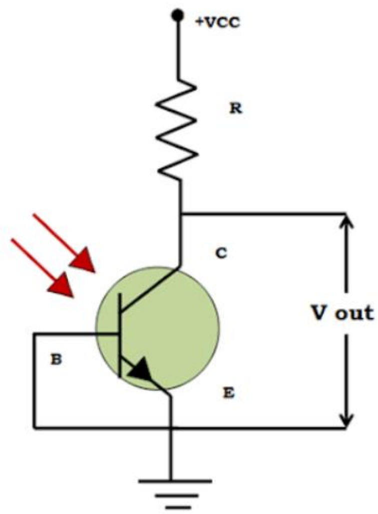


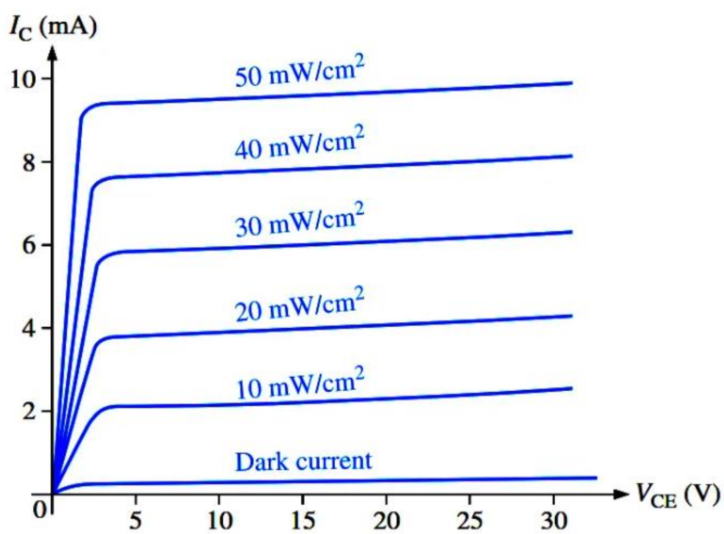
When compared to normal transistor, in photo transistor the base and collector area is large. The base area is increased to increase the amount of current generated. Because more the light falls more the current is generated. Earlier it was made up of single semiconductor material like silicon or germanium. Recently photo transistors are made up of Gallium and Arsenic to obtain higher efficiency. Finally, photo transistor is placed inside a metallic case and a lens is kept at the top of the case to absorb the incident radiation.

Working of Photo Transistor

From the above circuit we can know that base is not connected to any external bias and only light is incident on the base terminal. Collector terminal is connected to the positive side of external supply and output is taken from the emitter terminal.

When no light is incident on the base terminal only some leakage current flows and it is called as dark current. When light is incident on the lens at the base collector junction, base current is generated which is proportional to the intensity of the incident light.





Phototransistors are not sensitive to all light but only to light within a certain range of wavelengths. They are most sensitive to particular wavelengths in the red and infrared part of the spectrum.

Advantages:

- Efficiency is high
- Faster response

- Less noise interference
- Low cost
- Small in size

Disadvantages:

- Poor performance at high frequency
- Slower than photodiode

Applications:

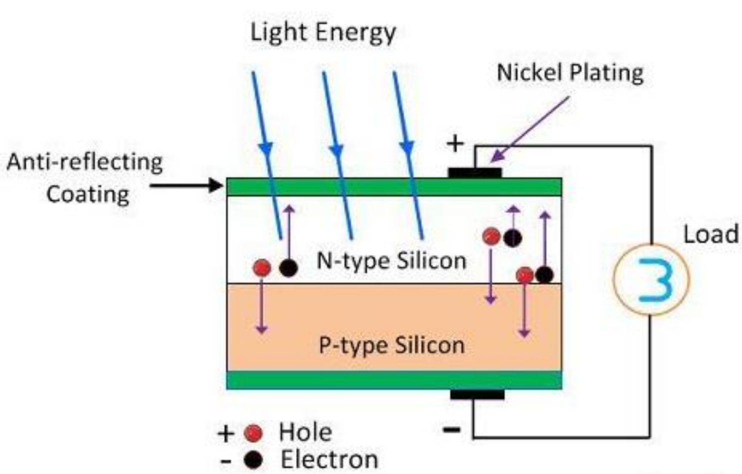
- Used in Counting systems
- Used in Optical tape reader
- Used to detect Object
- Used in printers

Photovoltaic Cells (Solar Cells)

Photovoltaic cells, commonly known as solar cells, convert light energy into electrical energy. When photons strike the semiconductor material of a solar cell, they create an electric current. Solar cells are used in solar panels to generate electricity from sunlight.

1. **Built-In Electric Field:** Solar cells are constructed with a p-n junction, which is the interface between two semiconductor materials with different electrical properties. Specifically, the p-type region is doped with materials that introduce positive charge carriers (holes), and the n-type region is doped with materials that introduce negative charge carriers (electrons).

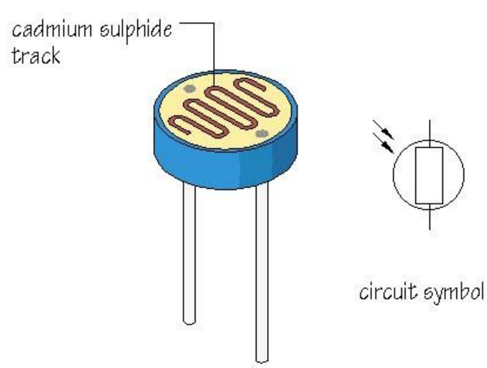
2. **Electron-Hole Pairs:** When sunlight (photons) strikes the semiconductor material of the solar cell, it excites electrons in the valence band, allowing them to move into the conduction band. This process creates electron-hole pairs. Electrons in the conduction band are free to move, while holes in the valence band are positively charged.



3. **Electrostatic Attraction and Repulsion:** Due to the presence of the p-n junction, an electric field is established within the solar cell. This electric field exerts electrostatic forces on the charge carriers, causing them to move in specific directions.
   - Electrons, which are negatively charged, are pushed toward the n-type region, where there is a surplus of positively charged holes. This movement is driven by the electrostatic attraction between electrons and holes.
   - Holes, which are positively charged, are pushed toward the p-type region, where there is an abundance of negatively charged electrons. This movement is also driven by electrostatic attraction.
4. **Separation of Charge Carriers:** As electrons move toward the n-type region and holes move toward the p-type region, they become spatially separated within the solar cell. This spatial separation prevents electrons and holes from recombining with each other, a process that would negate the generation of electrical current.
5. **Electric Voltage Generation:** The spatial separation of charge carriers across the p-n junction creates an electric voltage, or a potential difference, between the front and back surfaces of the solar cell. This voltage serves as the driving force for the flow of electrical current.
6. **Collection of Current:** Metal contacts are attached to the front and back surfaces of the solar cell to collect the separated charge carriers. When an external electrical circuit is connected to these contacts, the electrons and holes flow through the circuit, producing an electrical current.

Light-dependent Resistors (LDRs)

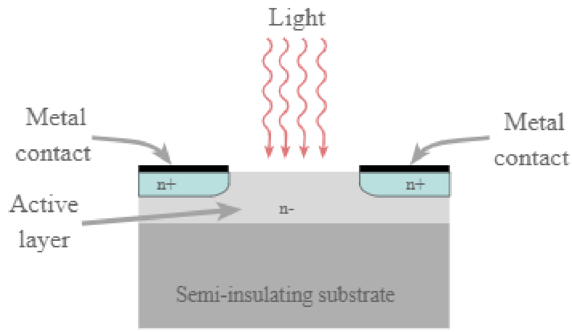
LDRs are passive components whose electrical resistance changes with varying light levels. When exposed to light, the resistance of an LDR decreases, and when in the dark, its resistance increases. LDRs are used in applications like streetlights, camera exposure control, and simple light-sensing circuits.



Photoresistor / LDR structure

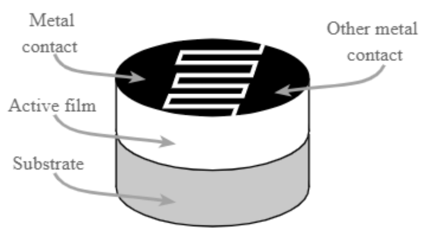
Structurally the photoresistor is a light sensitive resistor that has a horizontal body that is exposed to light.

The basic format for a photoresistor is that shown below:



The active semiconductor region is normally deposited onto a semi-insulating substrate and the active region is normally lightly doped.

In many discrete photoresistor devices, an interdigital pattern is used to increase the area of the photoresistor that is exposed to light. The pattern is cut in the metallisation on the surface of the active area and this lets the light through. The two metallise areas act as the two contacts for the resistor. This area has to be made relatively large because the resistance of the contact to the active area needs to be minimised.

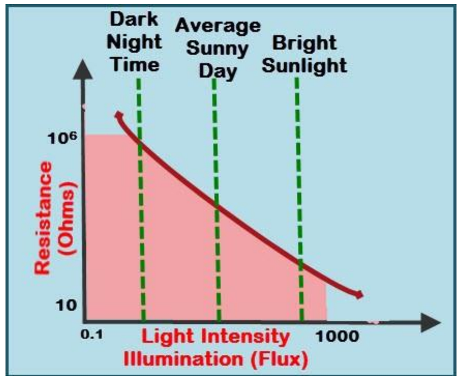


How an LDR works

It is relatively easy to understand the basics of how an LDR works without delving into complicated explanations. It is first necessary to understand that an electrical current consists of the movement of electrons within a material.

Good conductors have a large number of free electrons that can drift in a given direction under the action of a potential difference. Insulators with a high resistance have very few free electrons, and therefore it is hard to make the them move and hence a current to flow.

An LDR or photoresistor is made any semiconductor material with a high resistance. It has a high resistance because there are very few electrons that are free and able to move - the vast majority of the electrons are locked into the crystal lattice and unable to move. Therefore, in this state there is a high LDR resistance.



As light falls on the semiconductor, the light photons are absorbed by the semiconductor lattice and some of their energy is transferred to the electrons.

The amount of energy transferred to the electrons gives some of them sufficient energy to break free from the crystal lattice so that they can then conduct electricity. This results in a lowering of the resistance of the semiconductor and hence the overall LDR resistance.

The process is progressive, and as more light shines on the LDR semiconductor, so more electrons are released to conduct electricity and the resistance falls further.

Circuit Diagram of a Light Dependent Resistor

The circuit diagram of a LDR is shown below. When the light intensity is low, then the resistance of the LDR is high. This stops the current flow to the base terminal of the transistor. So, the LED does not light. However, when the light intensity onto the LDR is high, then the resistance of the LDR is low. So current flows onto the base of the first transistor and then the second transistor. Consequently, the LED lights. Here, a preset resistor is used to turn up or down to increase or decrease the resistance.