Lab 4

Light Sources, Their Efficiency, & Light Intensity Measurement

Introduction

In this lab you will investigate different types of lighting systems, the measurement of light intensity, and the efficiency of electric lighting.

- You will learn about diodes and light emitting diodes (LEDs).
- You will learn about light sensors and build a simple light meter.
- You will compare the efficiencies of an incandescent light and a light emitting diode (LED).

Before we can do these experiments, we need to learn about:

- Different types of light sources and how they work.
- How human vision works and what colour ranges we can see.
- How semiconductor light sensors work.

Light Sources

Lighting in the Modern World

Our modern world relies heavily on electric lighting to illuminate the night.

- The needed energy consumption is high, and so efficient light sources are needed.
- What are some of our choices?

Fire as Light: Candles & Lamps

Candles and oil lamps have been used for 1,000's of years.

Candles were made from animal fat or wax (wax smells less, but was more expensive).

Picture from Wikipedia

Oil lamps used a variety of fuels.

- Common animal oils: fish oil, whale oil, ghee (clarified butter, India).
- Common plant oils: olive oil (Mediterranean); caster oil (ancient Egypt); peanut, mustard, carrot, and nettle oils (Africa).
- Petroleum which oozed to the surface has been used for 4000 years in Persia.

Fire as Light: Gas Fuels

Gas lighting has been used for a long time.

- Chinese records from 2300 years ago indicate natural gas fed by bamboo pipes was used in the home for light and heat.
- Around the year 1000, gas street lamps were used in Cordoba Spain by the Arabs.

In the West, the Scottish engineer William Murdoch (1754 - 1839) is credited to be the inventor of gas lighting in the early 1790s. He used coal gas as fuel.

- By the early 1800's, many towns and cities in Britain and other countries were lit by gas. By the the early 20th century, most US and European cities had gaslit streets.

Gas lighting reduced crime at night. It also enabled longer working hours, increasing industrial productivity.

Fire as Light: Distilled Petroleum

In the 9th century, Muhammad ibn Zakariya al-Razi (865 - 925), a Persian alchemist and physician, distilled petroleum into kerosene.

In the West, Abraham Pineo Gesner (1797 - 1864), a Canadian physician and geologist, is credited for inventing kerosene in 1846.

- Kerosene soon replaced whale oil in lamps. It burned cleaner, cost less, and could be stored indefinitely.

Before petroleum, many types of animals were hunted for fuel oil.

Millions of penguins were killed for their oil.

Inexpensive kerosene was the principle factor in the decline of the 19th century whaling industry, and helped save the Galapagos tortoise, which whalers hunted for meat.

Pictures from Wikipedia

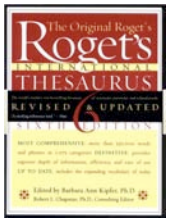
Electric Lighting: Incandescent Lamp

In 1802, the English chemist (and poet) Sir Humphry Davy (1778 - 1829) created the first incandescent light by passing electric current through a thin strip of platinum.

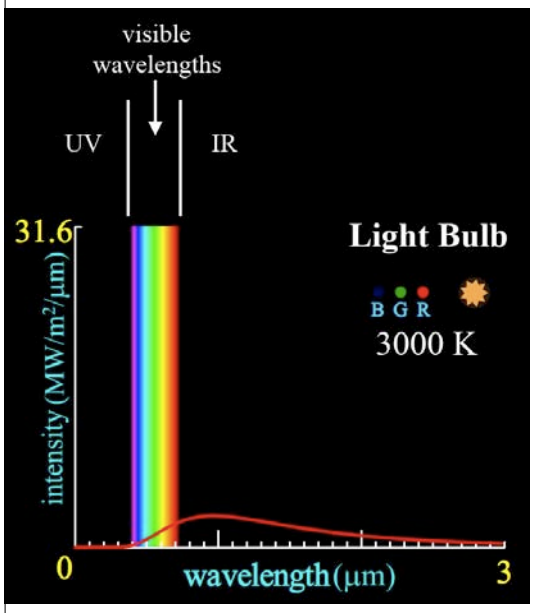
Picture from Wikipedia

Some Humphry Davy facts:

- Davy started out as an apprentice to an apothecary, but he was dismissed after his experiments led to explosions.
- Michael Faraday worked as Davy's assistant for a while.
- In 1799, Davy discovered the intoxicating effect of nitrous oxide. This led to a brief fad of nitrous oxide parties.
- The British physician Peter Roget collaborated on the nitrous oxide experiments. Roget published the first Thesaurus in 1852.



Incandescent Lamp Efficiency



We have already learnt that incandescent lamps are inefficient at producing visible light, since most of the energy they radiate is at infra-red (IR) wavelengths.

Can we make electric lights that don't use incandescence?

Electric Lighting: Arc Lamps

The arc lamp makes light by using an electric discharge to ionize the air between two electrodes. The ionized air (a plasma) radiates light.

- The first arc lamp was demonstrated in 1809 by Sir Humphry Davy, using an electric discharge between charcoal electrodes.

Pictures from Wikipedia

Davy mounted his electrodes horizontally, and because heat rises, the arc formed in an arch shape. He called the light an "arch lamp", which has lead to the name "arc lamp".

By the late 1800's, arc lamps were used in many cities for street lighting.

Gas Vapour Arc Lamps

Arc lamps containing specific gases do not produce a continuous spectrum of light, but rather the ionized gas "plasma" emits light at specific wavelengths.

Picture from Wikipedia

Neon lamps were invented in 1911 by Georges Claude (1870-1960), a French engineer and chemist.

Emission spectra of neon gas

Gas discharge spectra images taken from http://astro.u-strasbg.fr/~koppen/discharge/

Other Common Gas Vapour Arc Lamps

Mercury vapour lamps produce bluish-green light and are often used for street lights.

- They emit a lot of UV light, but this can be blocked by using a glass cover over the quartz bulb.
- Fluorescent lamps are low pressure mercury lamps, in which a phosphorescent coating is used to absorb the UV light, and re-emit it in the visible colour band.

Low pressure sodium lamps emit a dull yellow colour. They are typically used for street lights.

- They produce light at two spectral lines at 589.0 and 589.6 nm.
- These wavelengths are near the peak colour vision sensitivity for humans, and so sodium lamps are very efficient light sources.

How Bright Can You Make a Light?

The Vortek lamp was invented by University of British Columbia researchers in 1975.

- Measuring 11 cm long, a 300 kW Vortek arc lamp puts out 120 kW of visible light from a 12,000 K plasma.

More than twice the surface temperature of the sun !!!

How bright is it?

- A single Vortek lamp can light an entire sports stadium !!
- In a search a rescue demonstration, a single lamp lit up a 1.6 km wide area !!

Due to their very high brightness and power needs, they have never found wide commercial usage for lighting. Vortek lamps are often used in furnaces to very rapidly heat the surface of objects.

- Objects placed a hand's breadth from a Vortek lamp can quickly heat to 3000°C.

Efficiency of Electric Light Sources

The efficiency of common types of electric light sources is shown below.

- Incandescent sources are low efficiency.
- Halogen incandescent lamps are more efficient, since the filament is hotter and so produces more light in the visible part of the spectrum.
- Fluorescent, LED, and sodium lamps are the most efficient.

Light Source	Luminous efficiency
60 W tungsten incandescent	2.1%
100 W tungsten incandescent	2.6%
Quartz halogen	3.5%
Compact fluorescent	8 - 11%
White LED	1.5 - 22%
Low pressure sodium lamp	15 - 29%

← ← ←

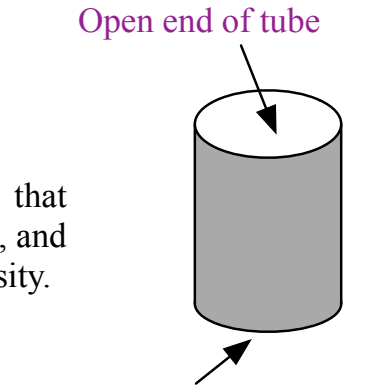
These light sources are more efficient because they radiate more energy at visible wavelengths.

Measuring the Efficiency of Electric Light Sources

Incandescent Lamp vs. LED

In today's lab you will compare the efficiency of an incandescent lamp to a light emitting diode (LED).

You will build a simple light meter that gathers light from a single light source, and uses a light sensor to measure its intensity.



Determining the efficiency of each light:

- Measure the total electrical energy used by the light source. You can do this by using the power equation P = V x I.
- Compare the measured power to the amount of visible light coming out of the light.

Measuring "Visible Light" Intensity

Since you want to make a light meter that accurately measures light seen by humans, you want to measure "visible light" intensity.

- The visible light spectra is the wavelengths that our eyes can see.
- For example, if you use a light sensor that also responds to infra-red light, you will get incorrect intensity measurements since we can't see those wavelengths.

What type of light sensor do we need?

In order to answer this question, we need to learn:

- What wavelengths our eyes can see efficiently.
- How semiconductor light sensors work.

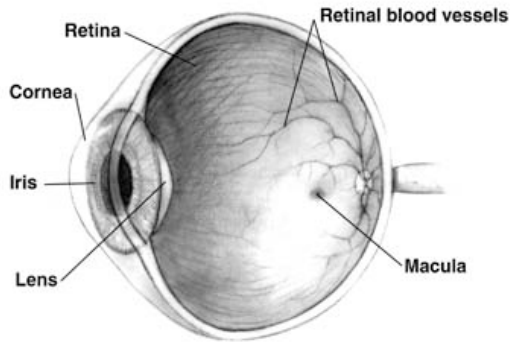
Human Vision

Human Vision Cells

Humans need to be able to see in a wide range of light levels.

Light Intensity	Example
0.001 Lux	Typical starlight
0.3 Lux	Full moon
50 - 200 Lux	Typical living room
300 - 500 Lux	Typical office
1,000 Lux	Overcast day
10,000 Lux	Daylight
50,000 - 100,000 Lux	Direct sunlight

10 lux is about equal to the illuminance from 1 candle seen from one foot away.



Picture from Wikipedia

We are able to see such a large range of intensities by using two types of visual sensor cells.

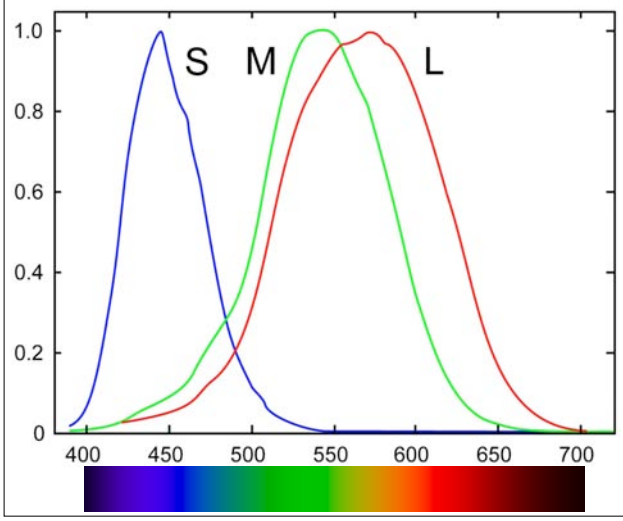
- Rods are used for night vision.
- Cones are used for day vision.

Cone Cells

The human eye has ~ 7 million cone cells.

- Humans have three types of cone cells, each with a specific pigment sensitive to a specific colour spectra. Their maximum absorption occurs approximately at 424 nm (blue), 530 nm (Bluish-Green), and 560 nm (Yellowish-Green).

Colour blindness is caused by reduced sensitivity in (or absence of) one or more of the three types cone cells.



Graph showing the normalized sensitivity of the three types of cones cells as a function of light wavelength.

Picture from Wikipedia

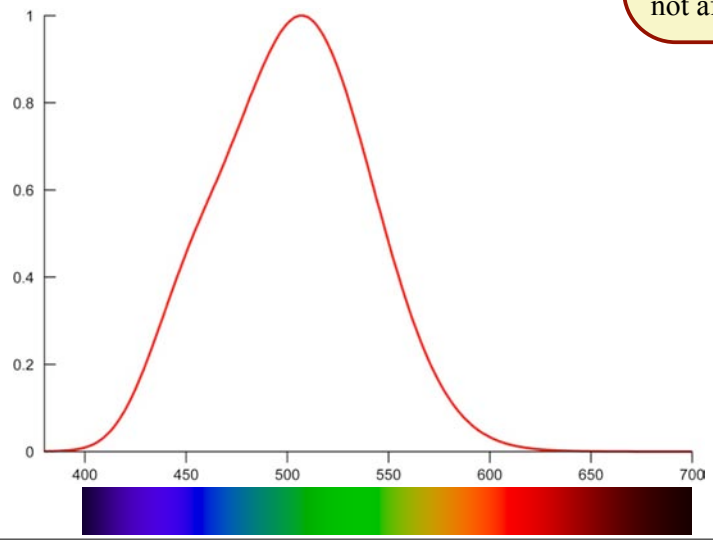
Rod Cells

The human eye has ~ 100 million rod cells.

- Rod cells are not sensitive to different colours.
- Rods see red light very poorly.

There is colour at night. You just can't see it.

This is why using red light at night does not affect your night vision much.



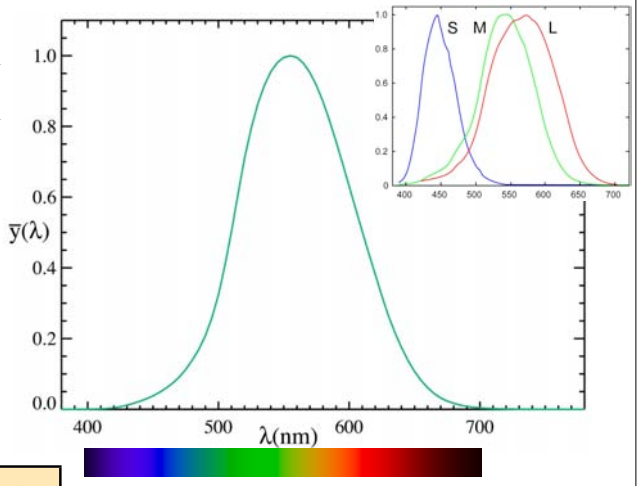
Graph showing the normalized sensitivity of rod cells as a function of light wavelength.

Picture from Wikipedia

Light Source Efficiency & Human Vision

The peak daylight wavelength sensitivity of our eye can be found by considering an average of the combined spectral sensitivities of the cone cells in our eyes.

- This peak occurs at about 555 nm (yellowish-green colour).



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Low pressure sodium lamp	15 - 29%

Sodium lamps are very efficient because their light (589.0 nm and 589.6 nm) is near the peak wavelength sensitivity of human vision.

Semiconducting Materials,

Light Measurement Devices,

&

Light Emitting Diodes

Semiconductors

Semiconductors are materials who's electrical resistivity lies between that of a good conductor (such as copper) and an insulator (such as glass).

- Copper's resistivity: $\rho = 1.7 \times 10^{-8}$ Ωm
- Silicon resistivity: $\rho =$ ~ 1000 Ωm
- Glass resistivity: $\rho = 10^{10} - 10^{14}$ Ωm

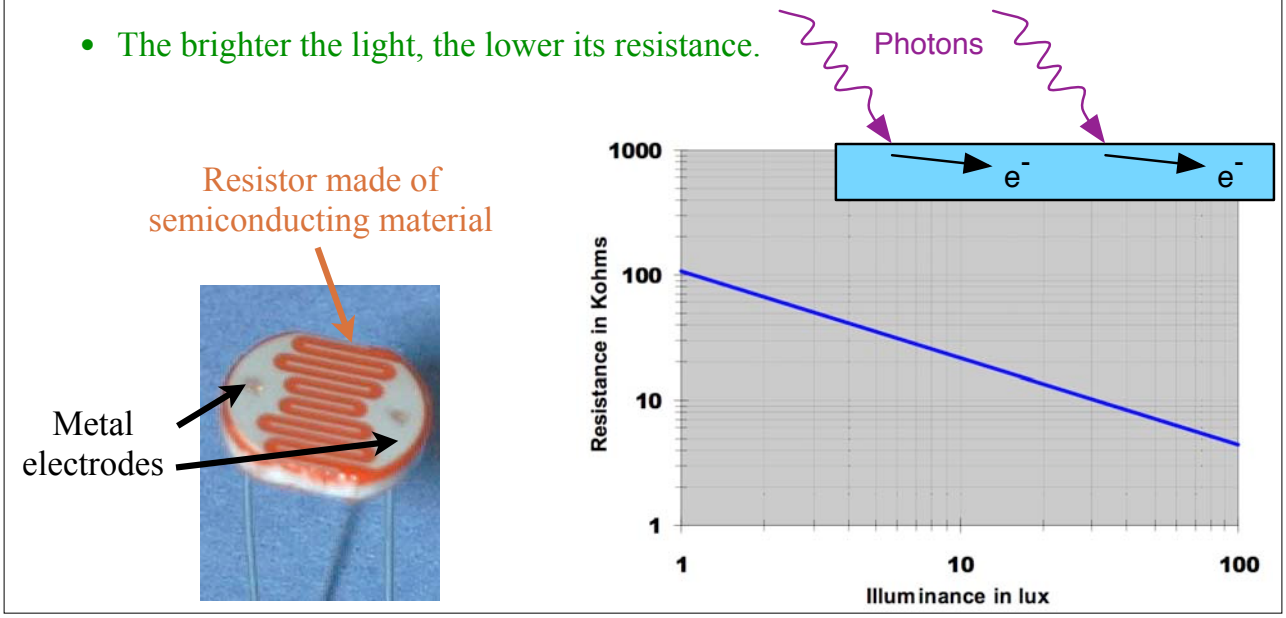
Semiconductor devices can be made to switch from electrically insulating to electrically conducting, by application of external voltages, or energy such as light incident on their surface.

- Semiconductor devices are the foundation of modern electronics, because of this ability to control or switch current flow.

Photoresistors

A photoresistor is a resistor is made of a semiconducting material. Its electrical resistance varies as the intensity of light shining on it changes.

- When photons of sufficient energy strike it, the energy absorbed releases electrons, which increases its conductivity.
- The brighter the light, the lower its resistance.



Photons & Quantum Mechanics

A photoresistor is a resistor is made of a semiconducting material. Its electrical resistance varies as the intensity of light shining on it changes.

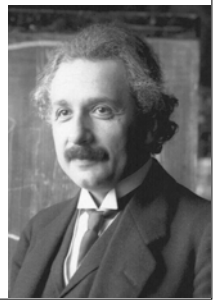
- **When photons of sufficient energy** strike it, the energy absorbed releases electrons, which increases its conductivity.

?? What does "photons of sufficient energy" mean ??

It requires a photon of a certain minimum energy to release an electron.

- A photon's energy is proportional to its frequency. *Energy ∝ frequency*
- It does not matter how many photons you have (how bright the light is), each photon itself must have enough energy to free an electron.

This concept was explained in 1905 by Albert Einstein (1879 - 1955). Einstein extended Planck's concept of energy quantization to light (electromagnetic waves), and said it was made up of photons of individual energies.

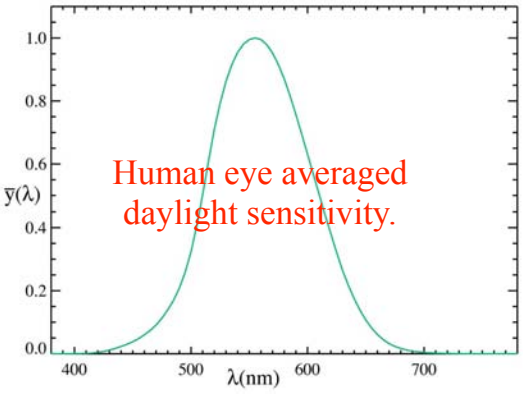


CdS Photoresistor Based Light Meter

In today's lab you will use a cadmium sulfide (CdS) photoresistor to make a light meter. You will use it to compare the efficiency of an incandescent bulb versus an LED.

CdS photoresistors are sensitive to light from 400 - 800 nm, with a peak around 500 - 600 nm, which is similar to the human eye.

- They are used in many applications such as light sensors in street lamps, light meters in cameras, and security alarms.



Since the CdS photoresistor has a similar spectral response as the human eye, it is a good choice to evaluate the efficiency of light sources.

Diodes

Diodes are an electrical device through which electric current only flows one way.

- They are made from semiconducting materials, such as silicon.

Circuit symbol for a diode 

Diodes have many uses in electric circuits, as well as optical uses.

Light emitting diodes (LED's) are used as light sources.

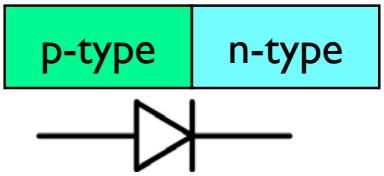
Diodes can be used as light detectors and solar cells.

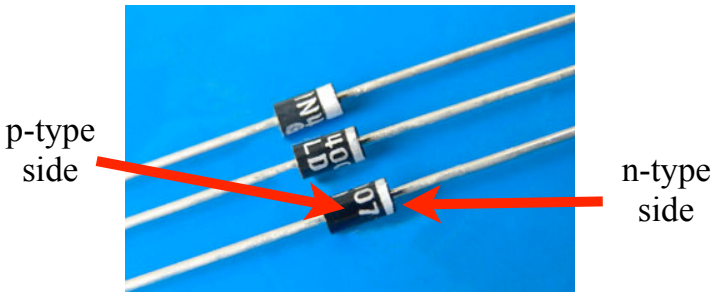
Picture from Wikipedia

Diode Construction

A basic silicon diode is composed of two regions.

- In one region, atoms which have 3 valence electrons (1 less than silicon) are added. This is called the p-type region.
- In the other region, atoms which have 5 valence electrons (1 more than silicon) are added. This is called the n-type region.

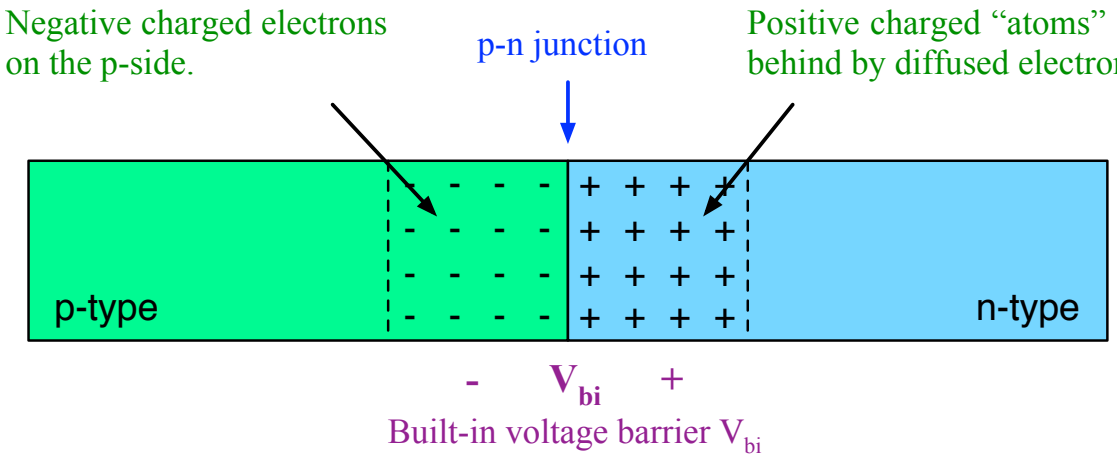




Diode Operation

Because of the unequal concentration of electrons in the n-type and p-type regions, when they are placed in contact, electrons near the junction spread out (diffuse).

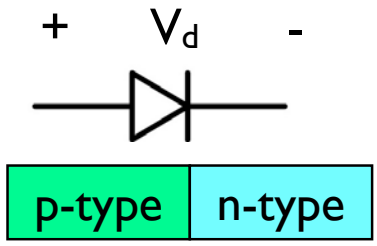
- This creates a charge separation at the junction between these two regions.
- This charge separation acts a voltage barrier.

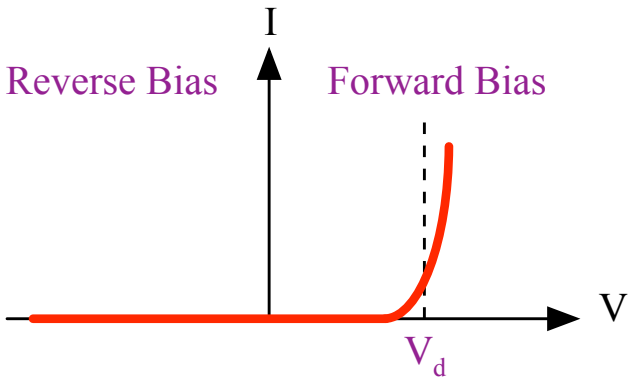


Diode Operation

The barrier potential V_{bi} opposes the flow of electrons across the diode.

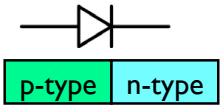
- This barrier lowers if the p-type side is connected to a more positive voltage than the n-type side. This is called *forward bias* condition.
- This barrier raises if the p-type side is connected to a more negative voltage than the n-type side. This is called *reverse bias* condition.



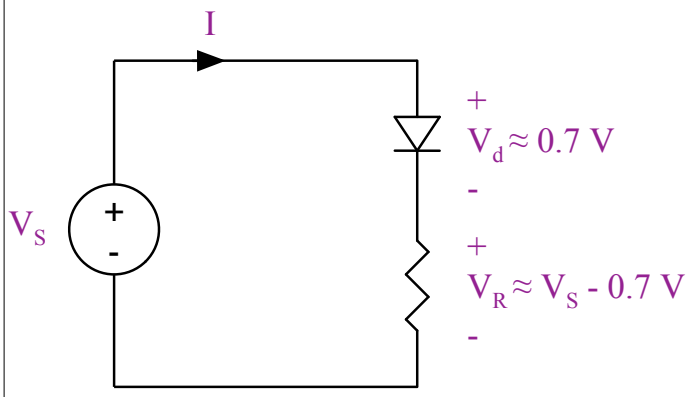


In a silicon diode, significant current can flow across the diode if the forward bias voltage is $V_d \approx 0.6$ - 0.7 V. This can be thought of as a "turn-on" voltage.

Diode in a Circuit



Forward bias condition

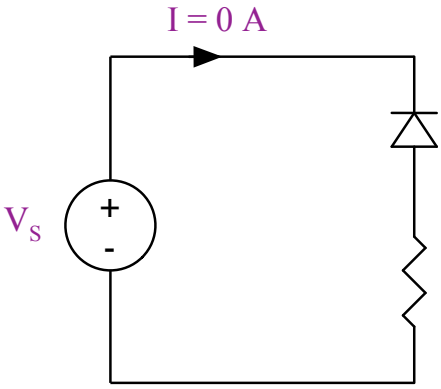


P-type side higher voltage than n-type side.

Diode uses ≈ 0.7 V to turn-on.

Current flows in circuit.

Reverse bias condition



P-type side lower voltage than n-type side.

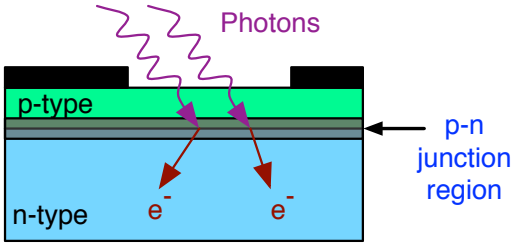
Diode is off.

No current flows in circuit.

Photodiodes and Solar Cells

Photodiodes are used as light detectors. They have a window in their package so light can enter.

- When photons of sufficient energy strike the p-n junction region, electrons are released.



Picture from Wikipedia

If the diode has no bias voltage across it, the generated charge carriers have nowhere to go, and a "photovoltaic" voltage builds up across the diode.

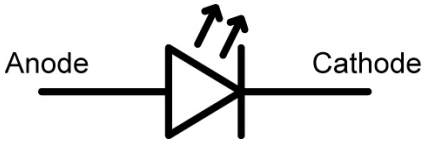
- This voltage can be used to drive a circuit.
- A solar cell (photovoltaic cell) is essentially a large photodiode.

Light Emitting Diodes

An LED is a type of semiconductor diode that emits light when electrons flow across it.

- They use very little energy, and have very long lifetimes.
- The colour of the light, and the efficiency of light generation, depends on the semiconductor material that the LED is made of.

Circuit symbol for an LED

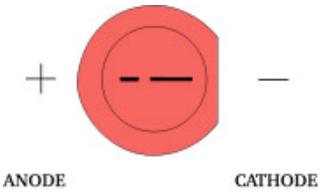


LED Operation

When an LED is forward biased, electrons flowing across the p-n junction release energy in the form of light (a photon). This is called electroluminescence.

- The forward bias turn-on voltage (V_d) for LEDs is around 1 - 3 volts, depending on the LED.

Electroluminescence was discovered by Henry Joseph Round (1881 - 1966) in 1907, while he worked at the Marconi Company developing cat's whisker detectors (a simple diode) for crystal radios.



The round head of the LED has a flat side, which indicates which side should contact the lower potential.

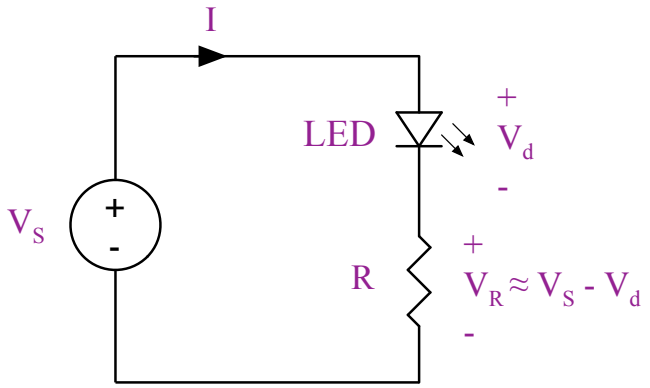
LED in a Circuit

When you put your LED in a circuit, you must make sure you limit the amount of current passing through it.

- The LED you are using today will be damaged if over 30 mA of current passes through it.

You limit the current by putting a resistor in series with the LED.

- As a simple assumption, assume the LED has no resistance when it is on, and so the resistor R is what limits the current I.



$$I = \frac{V_R}{R} = \frac{V_S - V_d}{R}$$

which simplifies to

$$I = \frac{V_S}{R} \quad \text{if } V_d << V_S$$

Important Things To

Remember

Important Points

Low pressure sodium lamps are very efficient because they emit light near the peak sensitivity of human colour vision.

Fluorescent lamps are mercury vapour lamps which use a phosphorescent coating to convert the UV light into visible light.

In a photoresistor, the resistance of the semiconducting material reduces when it is hit by photons of sufficient energy. And the brighter the light, the greater the reduction of resistance.

Silicon diodes need a forward bias voltage of 0.6 - 0.7 V to enable significant current flow.

In a circuit, a forward biased diode can be approximately modelled as a voltage drop of 0.7 volts.