NEAR EAST UNIVERSITY

Faculty of Engineering

Department of Electrical and Electronic Engineering

PHOTOELECRIC EFFECT AND LIGHT DETECTOR

Graduation Project
EE-400

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Special thanks to the Özgür C. Özerdem for his helps. And thanks to Faculty of Engineering for having such a good computational and electronical environment.

I also want to thank to my friends in Near East University:Special thanks to Ali for helping computer side of my project, Nedim, Mehmet, Gokhan, Hakan, Sercan.

Finally, I want to thank to the each person of the famıly of Near East Unıversıty for this education fhich they gave.

ABSTRACT

By the time passed, human being has more need to electrical devices in every kind of work. Also the Light Detector is one of these electrical devices which is a part of my project subject. Light detector is based on the Photoelectric Effect of light. These devices that are related to light and electrical effects describe the light's role in our life. These effects;

The main objective of this thesis is to provide a knowledge about light detector and photoelectric effects of light by describing the components of light detector and how the light is existed by electrically.

For this purpose I examined that Photoelectric Effect is connected with Quantum theory, Partical Wave Duality, Einstein's Theory and other theories. Therefore I examined Light Detector is connected with Photo Transistor Devices, Photo diode and definition of Detector and Light.

This project presents a practical electrical project,building a light detector circuit and emphasizing the importance of Light in our life.

INTRODUCTION

Photoelectric Effect and Light Detector, which are the subject of my project, are important for past, present and will be in future in our life. If I want give an example for light's place in our life, even a human's eye detects the colour of light and works like a Light Detector.

Another point that is important in our life is, the energy in Photons that is the description of Photoelectric Effect.

The Purpose of this project is design, build and test a Light Detector Circuit with its basic elements. This Thesis consists of the introduction, five chapters and conclusion.

The first chapter will discuss components which will be used in building the circuit of the Light Detector. The characteristic, properties and functions will also be discussed. Also this chapter describes and gives brief explanation about a circuit which works when light is received to LDR.

Chapter two will discuss the relations between Photoelectric Effect and Photon, Electron, Quantum mechanics.

Chapter three will discuss the definition of Photoelectric Effect, its growth to nowadays and also explains the relation Photon energy and Light energy.

Chapter four will discuss light and detector in forming of a Light Detector and specifications of a Light Detector.

Chapter five will discuss the different Light Detectors and their specifications that are being used nowadays.

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CHAPTER I
THE DEVICES USED FOR BUILDING A LIGHT DETECTOR

1.1. RESISTORS

The resistor is probably the most common and well known of all electrical components. Their uses are many, they are used to drop voltage, limit current, attenuate signals, act as heaters, act as fuses, furnish electrical loads and divide voltages.

Resistors have numerous characteristics which determine their accuracy when used. Each will effect the accuracy to a greater or lesser extent depending on the application. Some of these characteristics are, Tolerance at DC, Temperature Coefficient of Resistance (TCR), Frequency Response, Voltage Coefficient, Noise, Stability with Time and Load, Temperature Rating, Power Rating, Physical Size, Mounting Characteristics, Thermocouple Effect, and Reliability.

1.1.1. RESISTOR TERMS AND ABBREVIATIONS

1.1.1.1. Resistor Tolerance

Resistor Tolerance is expressed as the deviation from nominal value in percent and is measured at 25oC only with no appreciable load applied. It will change depending on the other conditions when in use.

1.1.1.2. Temperature Coefficient of Resistance

The Temperature Coefficient of Resistance (TCR) is expressed as the change in resistance in ppm (.0001%) with each degree of change in temperature Celsius (Co). This change is not linear with the TCR the lowest at +25oC and increasing as the temperature increases (or decreases). It can be either a bell shaped curve or an S shaped curve. It is treated as being linear unless very accurate measurements are needed, then a temperature correction chart is used. Normally a resistor with a TCR of 100 ppm will change 0.1% over a 10 degree change and 1% over a 100 degree change. The expression of ppm , one part in a million is similar to percent or 1 part in 100 (or percentile)

1.1.1.3. Frequency Response

Frequency Response is the change in resistance with changes in frequency and is more difficult to measure. Where exact values are needed, these changes can be plotted but not very accurately, and normally in db change. These measurements can be made with a Boonton RX Meter which is designed for measuring low Q circuits.

1.1.1.4. Voltage Coefficient

The Voltage Coefficient is the change in resistance with applied voltage and is associated with Carbon Composition Resistors and Carbon Film Resistors. It is a function of value and the composition of the carbon mixture used in the manufacture of these resistors.

1.1.1.5. Thermocouple Effect

The Thermocouple Effect is due to the Thermal emf generated by the change in the temperature at the junction of two dissimilar metals. This emf is due to the materials used in the leads or in the case of Wirewound Resistors the resistive element also. This can be minimized by keeping both leads at the same temperature.. The resistive element (the wire) of wirewound resistors is designed with a low thermal emf, but some of the wire used for high TCR resistors will have a much larger thermal emf.

1.1.1.6. Stability

Stability is the change in resistance with time at a specific load, humidity level, stress, and ambient temperature. The lower the load and the closer to +25oC the resistor is maintained, the better the stability. Humidity will cause the insulation of the resistor to swell applying pressure (stress) to the resistive element causing a change. Changes in temperature alternately apply and relieve stresses on the resistive element thus causing changes in resistance.

Reliability is the degree of probability that a resistor (or any other device) will perform it's desired function. There are two ways of defining Reliability. One is Mean Time Between Failures (MTBF) and the other is Failure Rate per 1,000 hours of operation. Both of these means of evaluating reliability must be determined with a specific group of tests and a definition of what is the end of life for a device, such as a maximum change in resistance or a catastrophic failure (short or open).

1.1.1.7. Temperature Rating

Temperature rating is the maximum allowable temperature that the resistor may be used. There are generally two temperatures for example, a resistor may be rated at full load up to +85oC derated to no load at +145oC. This means that with certain allowable changes in resistance over life the resistor may be operated at +85oC with it's rated power.

1.1.1.8. Power Rating

Power ratings are based on physical size, allowable change in resistance over life. thermal conductivity of materials, insulating and resistive materials, ambient operating conditions.

It is important that all of the above characteristics be considered when selecting a particular style and tolerance for each application.

1.1.2. TYPES OF MOUNTING AND PHYSICAL SIZES

1.1.3.1. RESISTOR SIZES

Resistors are available in almost any size ranging from 0.065 inches diameter by .125 inches long to 12 inches in Diameter to several feet high (for very high voltage resistors). They come in almost any shape that is imaginable. The most common form is cylindrical with leads coming out either end. They can be manufacture in custom shapes to fit the available space when quantities justify.

1.1.3.2. RESISTOR TYPES

1.1.3.3. PRECISION WIREWOUND

The Precision Wirewound is a highly accurate resistor with a very low TCR and can be accurate within .005%. A temperature coefficient of resistance (TCR) of as little a 3 part per million per degree Celsius (3ppm/oC) can be achieved. However these components are too expensive for general use and are normally used in highly accurate DC applications. The frequency response of this type is not good. When used in an rf application all Precision Wirewound Resistors will have a low Q resonant frequency.

The power handling capability is very small. These are generally used in highly accurate DC measuring equipment, and reference resistors for voltage regulators and decoding networks.

The accuracy is maintained at 25oC(degrees Celsius) and will change with temperature. The maximum value available is dependent upon physical size and is much lower than most other types of resistor. Their power rating is approximately 1/10 of a similar physical size in a carbon composition. They are rated for operation at +85oC or +125oC with maximum operating temperature not to exceed +145oC. This means that full rated power can be applied at +85 (125) oC with no degradation in performance. It may be operated above +125 (85) oC if the load is reduced. The derating is linear, rated load at +125(85) oC and no load at +145oC.. Precision Resistors regardless of type, are designed for maximum accuracy and not to carry power. The materials used in these resistors are highly stable heat treated materials that do change under extended heat and mechanical stress. The manufacturing processes are designed to remove any stresses induced during manufacture.

There is little detectable noise in this type of resistor. The stability and reliability of these resistors is very good and their accuracy can be enhanced by matching the absolute value and the temperature coefficient over their operating range to achieve very accurate voltage division.

1.1.3.4. NIST STANDARD

The NIST (National Institute of Standards and Technology) Standard can be as accurate as .001% with roughly the same TCR as Precision Wirewound Resistors and are very stable. These are used as a standard in verifying the accuracy of resistive measuring devices. They are normally the Primary Standards of a company's test lab.

Normally, a standard will take about 3 years to stabilize and becomes morestable with time unless it has had excessive power applied or has been dropped. These standards are generally stored in an oil bath at +25oC

These resistors are furnished in a totally enclosed metal case and for values above 1 ohm, this enclosure is filled with mineral oil (other type of oil may contain additives that can cause corrosion in later life). The values below 1 ohm may be built in an enclosure that is perforated and these must be submersed in oil. If power is applied without it being submersed, the Standard will be ruined.

All NIST Type Standards are equipped with provisions for two, three, or four terminal measurements. The applied power is calculated and the temperature of the Standard is monitored during test. These Standards are rated for operation at room temperature only but their other characteristics are the same as Precision Wirewound Resistors.

1.1.3.5. POWER WIREWOUND RESISTORS

Power Wirewound Resistors are used when it is necessary to handle a lot of power. They will handle more power per unit volume than any other resistor. Some of these resistors are free wound similar to heater elements. These require some form of cooling in order to handle any appreciable amount of power. Some are cooled by fans and others are immersed in various types of liquid ranging from mineral oil to high density silicone liquids. Most are wound on some type of winding form. These winding forms vary. Some examples are ceramic tubes, ceramic rods, heavily anodized aluminum, fiberglass mandrels, etc.

To achieve the maximum power rating in the smallest package size, the core on which the windings are made must have a material with high heat conductivity. It may be Steatite, Alumina, Beryllium Oxide, or in some cases hard anodized .There is a group of these called "Chassis Mounted Resistors"

The small power resistor can serve a two fold purpose, that is to fulfill it's purpose as a resistor and act as a heater in an enclosure. Some users have used them in crystal ovens to maintain the crystal at the desired temperature. It makes a reasonably cheap off the shelf heater that comes in a variety of wattage's , sizes and values.

These resistive elements are placed in a ceramic shell (boat) and an highly filled cement is used to fasten these in the boat. The filler often used in the cement is a ceramic material with high heat conductivity. These are very inexpensive, no effort is made to achieve tight tolerances, low TCRs, and the range of values is extremely limited. They are often found as surge resistors in TVs and other electronic /electrical equipment. Their main selling point is low cost. They are often sold with an enamel coating for a low power precision wirewound resistor that is even lower in cost.

1.1.3.6. FUSE RESISTORS

Fuse Resistors serve a dual purpose, a resistor and a fuse. They are designed so that they will open with a large surge current. The fusing current is calculated based on the amount of energy required to melt the resistive material .These resistors will normally run hotter than a normal precision or power resistor so that a momentary surge will bring the resistive element up to fusing temperature. Some designs create a hot spot inside the resistor to assist in this fusing. Calculations are made and samples are produced to verify the calculations. The major unknown is the heat transfer of the materials, which can be quite significant for pulse of long duration, and is very difficult to calculate.

Mounting of these devices is critical because it will effect the fusing current. These are quite often made to mount in fuse clips for more accurate fusing characteristics.

1.1.3.7. CARBON COMPOSITION

Carbon composition resistors were once the most common resistor on the market. They still have a very large market and prices are highly competitive. They are made from carbon rods cut in the appropriate length then molded with leads attached. The mix of the carbon can be varied to change the resistivity for the desired values.

High values are much more readily available. Very low values are more difficult to achieve. A 5% tolerance is available. This is usually done by measuring and selecting values. Normal tolerances without measurement and selection is in the area of 20%.

These resistors also has a voltage coefficient. That is the resistance will change with applied voltage, the greater the voltage, the greater the change. In addition to a power rating, they also have a voltage rating . The power capability in relation to physical size is greater than Precision Wirewounds but less than Power Wirewounds.

1.1.3.8. CARBON FILM RESISTORS

Carbon Film Resistors have many of the same characteristics as carbon composition resistors. The Carbon Film Resistor is made by coating ceramic rods with a mixture of carbon materials. This material is applied to these rods in a variety of means, the one most familiar to me are dipping, rolling, printing , or spraying the rods in the appropriate solution. The frequency response of this type of resistor is among the best, far better than Wirewounds, and much better that carbon composition. The wirewound resistors are inductive at lower frequencies and values and somewhat capacitive at higher frequencies regardless of value. Also wirewound resistors will have a resonant frequency. Carbon Composition Resistors will be predominately capacitive .

1.1.3.9. METAL FILM RESISTORS

Metal Film resistors are the best compromise of all resistors. They are not as accurate and have a higher temperature coefficient of resistance and are not as stable as Precision Wirewounds. Metal film resistors are manufactured by an evaporation/deposition process. That is the base metal is vaporized in a vacuum and deposited on a ceramic rod or wafer. Several attempts have been made to vaporize low TCR materials and deposit on these substrates, but to my knowledge, these attempts have not been successful. The very low TCR resistive materials are heat treated to achieve the resistivity and low TCR. This is not compatible with an evaporation process.

The frequency characteristics of this type are excellent and better than Carbon Films. The one area that carbon films exceed metal films is the maximum values. Carbon films can achieve higher maximum values than any other group.

1.1.3.10. FOIL RESISTORS

Foil resistors are similar in characteristics as metal films. Their main advantages are better stability than metal films and lower TCRs. They have excellent frequency response, low TCR, good stability, and very accurate. This type can be used as strain gauges, strain being measured as a change in the resistance. When used as a strain gauge, the foil is bonded to a flexible substrate that can be mounted on a part where the stress is to be measured.

1.1.3.11. FILAMEN

The Filament Resistors are similar to the Bathtub Boat Resistor except they are not packaged in a ceramic shell (boat). The individual resistive element with the leads already crimped is coated with an insulating material.

1.1.3.12. POWER FILM RESISTORS

Power film resistors are similar in manufacture to their respective metal film or carbon film resistors. They are manufactured and rated as power resistors, with the power rating being the most important characteristic.

1.2. CAPACITORS

Capacitors come in a various assortment of shapes sizes and colours,from round fat things to round thin things and round long things to round short things and square things to rectangular things, green, yellow, grey. The first type is the Electrolytic type. Two forms of this are avaliable. The first is a round upright type with two legs coming out of it's base and the other is a flat type which has one leg coming from each end. It is important that these legs are connected the correct way round to positive and negative. We can find the negative leg on the upright type by looking at the side of the capacitor for a (-) negative sign or a black strip. The leg nearest this is negative. On the flat type, there is a black band around one end. This is the negative end.

Capacıtors are figures under unit:

uF=Microfarads, nF=Nanofarads and pF=Picofarads.To translate between the four, here is how you do it. The highest value to the lowest value avaliable.

1 F = 1,000,000 uF or 1,000,000,000 nF or 1,000,000,000,000 pF

1 uF = 1,000 nF or 1,000,000 pF

1 nF = 1,000 pF

1 pF = 1 pF

The tolerance of the capacitor is not normally needed and so hardly ever printed. However, the voltage that is written on it MUST be higher than the power applied to it.

The other type of capacitor is the disc ceramic. This is as it states a disc, most times coloured in a dark orangy brown colour. Their physical shape is round, ranging from 2 millimeters in diameter to 1 centimeter. .

1.2.1. DIFFERENT CAPACITOR

Silver Mica capacitors- Very stable both in the frequency and temperature domain, these capacitors are some of the highest quality capacitors available. Their values range from around 1 pF up to a few thousand pico farads. They are useful for coupling and filter networks or circuits that require high precision. They are also used in high precision timing circuits.

Polypropylene capacitors- Also of high quality, these capacitors are quite temperature stable. They are useful in circuits up to and include the VHF ranges. Their values start where the silver micas leave off and extend up to about one microfarad. They are commonly used for coupling and filter networks, as well as timing circuits. picofarad up to several microfarad. The X7R types we carry are of very high quality and can be used in non-critical timing as well as coupling circuits.

Electrolytic capacitors- These have the largest capacitance value of all capacitors. Primarily used for filtering and decoupling of power supplies. They are polarity sensitive and should be used accordingly.

Tantalum capacitors- These offer the highest capacity for a given size. Usually used for filtering or decoupling. Somewhat expensive and not very tolerant of temperature.

Polyester film capacitors- These capacitors come in a wider value range than the polypropylene caps. They are not as temperature stable as the silver mica or polypropylene caps so their use should be limit to non critical circuits.

Ceramic capacitors- The most common type of capacitors. Ceramic caps are commonly used for decoupling or bypassing.

1.2.2 TESTING PRECAUTIONS

WARNING: make sure the capacitor is discharged! This is both for your safety and the continued health of your multimeter.

A pair of 1N400x diodes in parallel with opposite polarities may help protect the circuitry of a DMM. Since a DMM doesn't supply more than .6 V generally on ohms ranges, the diodes will not affect the readings but will conduct should you accidentally put the meter across a charged cap or power supply output.

They won't do much with a charged 10 F capacitor or high current supply where you forgot to pull the plug but may save your DMM's LSI chip with more modest goof-ups.

This approach cannot be used with a typical analog VOM because they usually supply too much voltage on the ohms ranges. However, my 20 year old analog VOM has something like this across the meter movement itself which has saved it more than once.

1.2.2.1 Testing capacitors with a multimeter

Some DMMs have modes for capacitor testing. These work fairly well to determine approximate uF rating. However, for most applications, they do not test at anywhere near the normal working voltage or test for leakage. However, a VOM or DMM without capacitance ranges can make certain types of tests.

For small caps (like .01 uf or less), about all you can really test is for shorts or leakage. (However, on an analog multimeter on the high ohms scale you may see a momentary deflection when you touch the probes to the capacitor or reverse them. A DMM may not provide any indication at all.) Any capacitor that measures a few ohms or less is bad. Most should test infinite even on the highest resistance range.

For electrolytics in the uF range or above, you should be able to see the cap charge when you use a high ohms scale with the proper polarity - the resistance will increase until it goes to (nearly) infinity. If the capacitor is shorted, then it will never charge. If it is open, the resistance will be infinite immediately and won't change. If the polarity of the probes is reversed, it will not charge properly either - determine the polarity of your meter and mark it - they are not all the same. Red is usually **negative** with VOMs, for example. Confirm with a marked diode - a low reading across a good diode (VOM on ohms or DMM on diode test) indicates that the positive lead is on the anode (triangle) and negative lead is on the cathode (bar).

If the resistance never goes very high, the capacitor is leaky.

The best way to really test a capacitor is to substitute a known good one. A VOM or DMM will not test the cap under normal operating conditions or at its full rated voltage. However, it is a quick way of finding major faults.

A simple way of determining the capacitance fairly accurately is to build a 555 oscillator. Substitute the cap in the circuit and then calculate the C value from the frequency. With a few resistor values, this will work over quite a wide range.

Alternatively, using a DC power supply and series resistor, capacitance can be calculated by measuring the rise time to 63% of the power supply voltage from T=RC or C=T/R.

1.3. POTENTIOMETER:

There are many instances where only a portion of an output voltage from a signal source is needed. If we allowed the full output voltage from a home CD player to be driven into the input of an amplifier, the amplifier would play at or near full power at all times. This would become quite annoying in a very short period of time. To reduce the overall volume, we need to allow only a fraction of the full signal through to the amplifier. To control the level of the signal, we use a potentiometer. A potentiometer (also know as a 'pot') is a modified resistor. Potentiometers can be used to allow a change in the resistance in a circuit or as a variable voltage divider (in the case of a volume control). If you have a rotary volume control on your TV or radio, it is (more than likely) a potentiometer being used as a variable voltage divider. A potentiometer generally has 3 terminals. 2 of the terminals are connected to the opposite ends of a resistive element. The 3rd terminal (usually, is physically in-between the other 2 terminals) is called the wiper. The wiper is a contact (actually, generally many very small contacts) that slides along the resistive element.

If your volume control clicks and steps the volume up or down with each click, it's probably a rotary encoder (a switch), not a potentiometer.

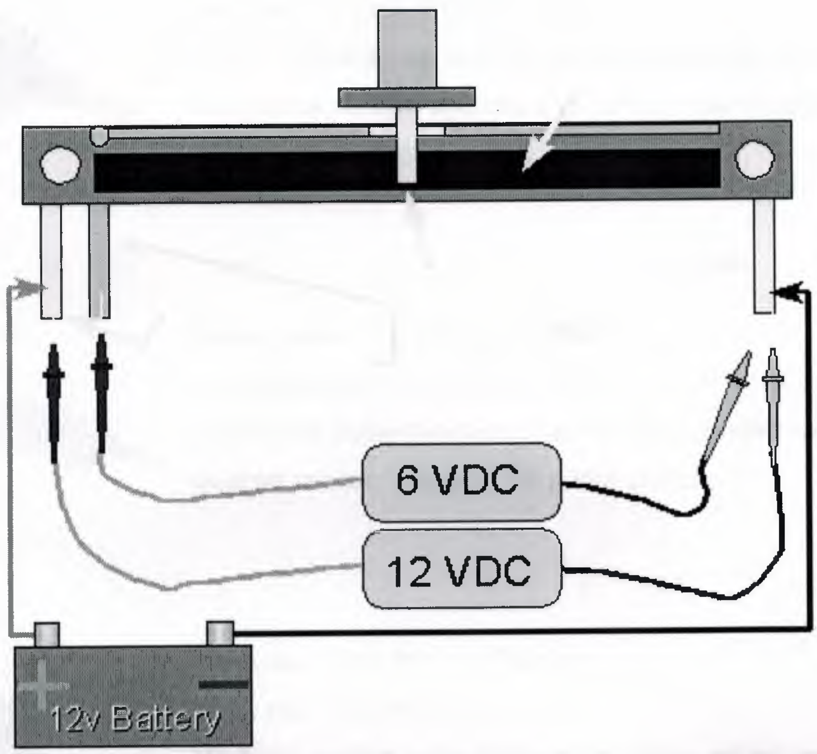
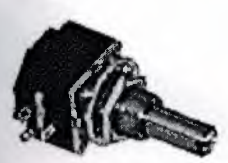


Figure 1.1 Voltage Control Potentiometer

1.3.1.TYPES OF POTANSIOMETERS

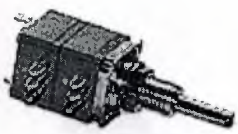
Custom Potentiometer



Series 70 - metal shaft and bushing

Series 72 - plastic shaft and bushing

5/8" square ModPot cermet, carbon, and conductive plastic panel potentiometers. Modular construction, multiple sections and concentric shafts. Rotary and push-pull switch options.



Series 388 - Conductive Plastic

Series 389 - Thick-Film Cermet

1/2 in. square, up to 8 modules, stackable potentiometers. Countless design options available, now including center and multiple detents.

Series 388MPLC - Conductive Plastic

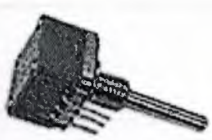
Series 389MPLC - Thick-Film Cermet

Motorized potentiometer (up to four ganged units) with a geared motor, coupled by a slip clutch.

Series 308 - Conductive Plastic

Series 309 - Thick-Film Cermet

Modular sealed potentiometers. Many rotary and push-pull switch options.

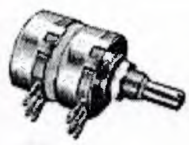


Series 408 - Conductive Plastic

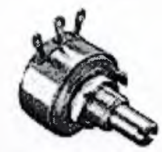
Series 409 - Thick-Film Cermet

High-performance sealed potentiometer, designed to meet wave soldering applications. Many rotary and push-pull switch options.

Series 580X - Low cost, for high volume applications. Conductive Plastic, up to 8 sections with a single shaft. Smooth feel, high rotational life, quiet electrical output. Metric dimensions. ISO 9001 Certified.



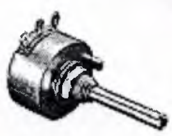
Series KK - Commercial version of the MilSpec 2RV7 potentiometer, with additional configuration options. A triple section model, Series KKK, is also available.



Series N - Commercial version of the MilSpec RV2 potentiometer, with additional configuration options.

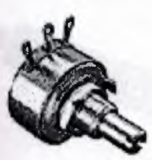
Series S - Commercial version of the MilSpec RV6 potentiometer, with additional configuration options.

Series SPR - Commercial version of the MilSpec RV8 potentiometer, with additional configuration options.

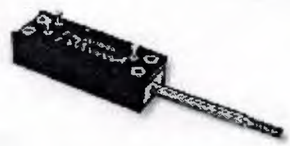


Series T - Commercial version of the MilSpec RV5 potentiometer, with additional configuration options

Stock MIL Spec Potentiometer

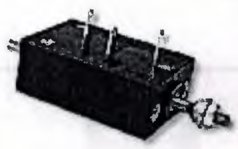


Series RV2 potentiometers are suitable for both military and commercial applications.

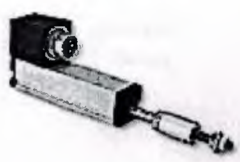


LCP12 & LW12 For General Purpose Applications. LCP12 has a conductive plastic element, LW12 has a wirewound element.

LCP12Y Mounting Flexibility. Conductive Plastic. Spherical ball bearings.



LCP15 Plug-on Terminals. Conductive Plastic. Bronze Bearings



LCP18UC Universal Conductor. Conductive Plastic. Adjustable Cleats

LCP20 & LW20 All Metal Housing. LCP20 has a conductive plastic element, LW20 has a wirewound element.

LCP30 Mounting Cleats. Conductive Plastic. Waterproof Connector.

LCPL Open Frame. Conductive Plastic.

LWR10 & LO10 Space Saver
Wirewound. LO10 is oil-filled.

LWR20 & LO20C Waterproof Connector
Wirewound. LO20C is oil-filled.

Designer Series

Contemporary Series

Regent Series

Industrial Series

Military Series

Traditional Series

Push-Fit Control Knobs

Push-Fit Control Knobs with Caps

Dual Concentric Knobs & Caps

Sliders

Collet Knobs & Caps

Switch Buttons

1.4. LIGHT EMITTED DIODE

LED's-are special diodes that emit light when connected in a circuit. They are frequently used as "pilot" lights in electronic appliances to indicate whether the circuit is closed or not. A a clear (or often colored) epoxy case enclosed the heart of an LED, the semi-conductor chip.

The first LEDs bright enough to use in outdoor applications were aluminum gallium arsenide (AlGaAs). These red LEDs appeared as high mount stop lights on automobiles and in a limited number of traffic lights. Today the US exit sign market has been almost completely transformed from incandescent sources to LEDs. A 1998 Lighting Research Center survey of exit sign sales representatives found that about 80 percent of exit signs being sold in the United States use LEDs as the primary light source. .

The two wires extending below the LED epoxy enclosure, or the "bulb" indicate how the LED should be connected into a circuit. The negative side of an LED lead is indicated in two ways: 1) by the flat side of the bulb, and 2) by the shorter of the

Two wires extending from the LED. The negative lead should be connected to the negative terminal of a battery. LED's operate at relative low voltages between about 1 and 4 volts, and draw currents between about 10 and 40 milliamperes. Voltages and currents substantially above these values can melt a LED chip.

In the absence of a large enough electric potential difference (voltage) across the LED leads, the junction presents an electric potential barrier to the flow of electrons. Region, the two charges "re-combine".

Each time an electron recombines with a positive charge, electric potential energy is converted into electromagnetic energy. For each recombination of a negative and a positive charge, a quantum of electromagnetic energy is emitted in the form of a photon of light with a frequency characteristic of the semi-conductor material elements. Only photons in a very narrow frequency range can be emitted by any material. LED's that emit different colors are made of different semi-conductor materials, and require different energies to light them.

1.4.1.What Causes the LED to Emit Light and What Determines the Color of the Light?

When sufficient voltage is applied to the chip across the leads of the LED, electrons can move easily in only one direction across the *junction* between the *p* and *n* regions. In the *p region* there are many more positive than negative charges. In the *n region* the electrons are more numerous than the positive electric charges.

When a voltage is applied and the current starts to flow, electrons in the *n region* have sufficient energy to move across the junction into the *p region.* Once in the *p region* the electrons are immediately attracted to the positive charges due to the mutual Coulomb forces of attraction between opposite electric charges. When an electron moves sufficiently close to a positive charge in the *p region*, the two charges "re-combine".

Each time an electron *recombines* with a positive charge, electric potential energy is converted into electromagnetic energy. For each recombination of a negative and a positive charge, a quantum of electromagnetic energy is emitted in the form of a photon of light with a frequency characteristic of the semi-conductor material (usually a combination of the chemical elements gallium, arsenic and phosphorus). Only photons in a very narrow frequency range can be emitted by any material. LED's that emit different colors are made of different semi-conductor materials, and require different energies to light them.

1.4.2. How Much Energy Does an LED Emit?

The electric energy is proportional to the voltage needed to cause electrons to flow across the p-n junction. The different colored LED's emit predominantly light of a single color. The energy (E) of the light emitted by an LED is related to the electric charge (q) of an electron and the voltage (V) required to light the LED by the expression: E = qV Joules. This expression simply says that the voltage is proportional to the electric energy, and is a general statement which applies to any circuit, as well as to LED's. The constant q is the electric charge of a single electron, -1.6×10^{-19} Coulomb.

1.4.3. Finding the Energy from the Voltage

Suppose that you have a red LED, and the voltage measured between the leads of is 1.71 Volts. So the Energy required to light the LED is E = qV or $E = -1.6 \times 10^{-19}$ (1.71) Joule, since a Coulomb-Volt is a Joule. Multiplication of these numbers then gives $E = 2.74 \times 10^{-19}$ Joule.

1.4.4. Finding the Frequency from the Wavelength of Light

The frequency of light is related to the wavelength of light in a very simple way. The spectrometer can be used to examine the light from the LED, and to estimate the peak wavelength of the light emitted by the LED. But we prefer to have the frequency of the peak intensity of the light emitted by the LED. The wavelength is related to the frequency of light by, where c is the speed of light (3×10^{8} m/s) and λ is the wavelength of light read from the spectrometer (in units of nanometers or 10^{-9} meters).. The corresponding frequency at which the red LED emits most of its light is or 4.55×10^{14} Hertz. The unit for one cycle of a wave each second (cycle per second) is a Hert

1.4.5. LED LAMPS

Figure 1.2 Led Lamps

Light Emitting Diode (LED) Lamps have inherent characteristics assuring high reliability and a compatibility with low current electronic drive circuits.

LEDs have advantages and disadvantages when compared with other light sources such as incandescent or neon lamps. The advantages are small size, low power consumption, low self-heating, high reliability, they can be switched on and off quickly, and they are resistant to shock and vibration. The features that sometimes can be considered disadvantages are the narrow viewing angle, near monochromatic light, limited wavelength selection, and they require a limiting resistor with a voltage drive.

1.4.5.1. Principles of Operation

LEDs are formed from various doped semiconductor materials in the form of a P-N diode junction. When electrical current passes through the junction in the forward direction, the electrical carriers give up energy proportional to the forward voltage drop across the diode junction, which is emitted in the form of light. The amount of energy is relatively low for infrared or red LEDs. For green and blue LEDs which are produced from higher forward voltage materials, the amount of energy is greater. LED Device Structure

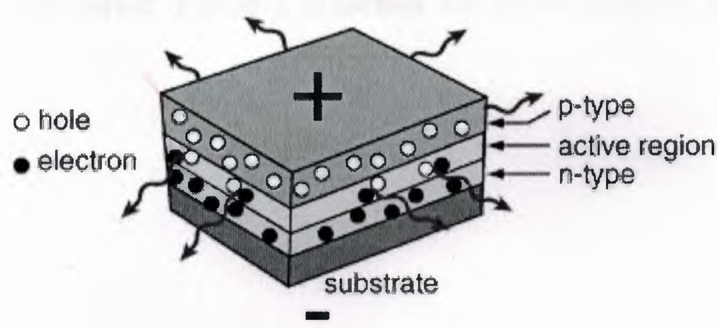


Figure 1.3. Led Device Structure

Since the device is being used in the forward biased mode, once the voltage applied exceeds the diode forward voltage; the current through the device can rise exponentially. Very high currents would damage the device which is why a current limiting resistor must be added in series with the LED when driven from a voltage source.

The amount of light emitted by an LED is proportional to the amount of current passing through the device in the forward bias direction. As the current is varied, the output of the light will vary in a similar fashion. By modulating the current flowing through the LED, the light output can be modulated to produce an amplitude modulated optical signal which can be used to communicate information through free space (i.e. TV remote control).

If the voltage source is applied in the reverse direction, the P-N junction will block current flow until the voltage applied exceeds the devices ability to block the current. At that point, the device junction will break down, and if there is no current limit device in the circuit, the LED will be destroyed. The typical value of maximum reverse voltage is five volts.

1.4.5.2. Construction and Operation

The semiconductor material is typically a very small chip or die, which is mounted onto a lead frame and encapsulated in a clear or diffused epoxy. The shape of the epoxy and the amount of diffusing material in the epoxy control the angle of emission of the light output. Figure 1 illustrates the construction of a common LED package.

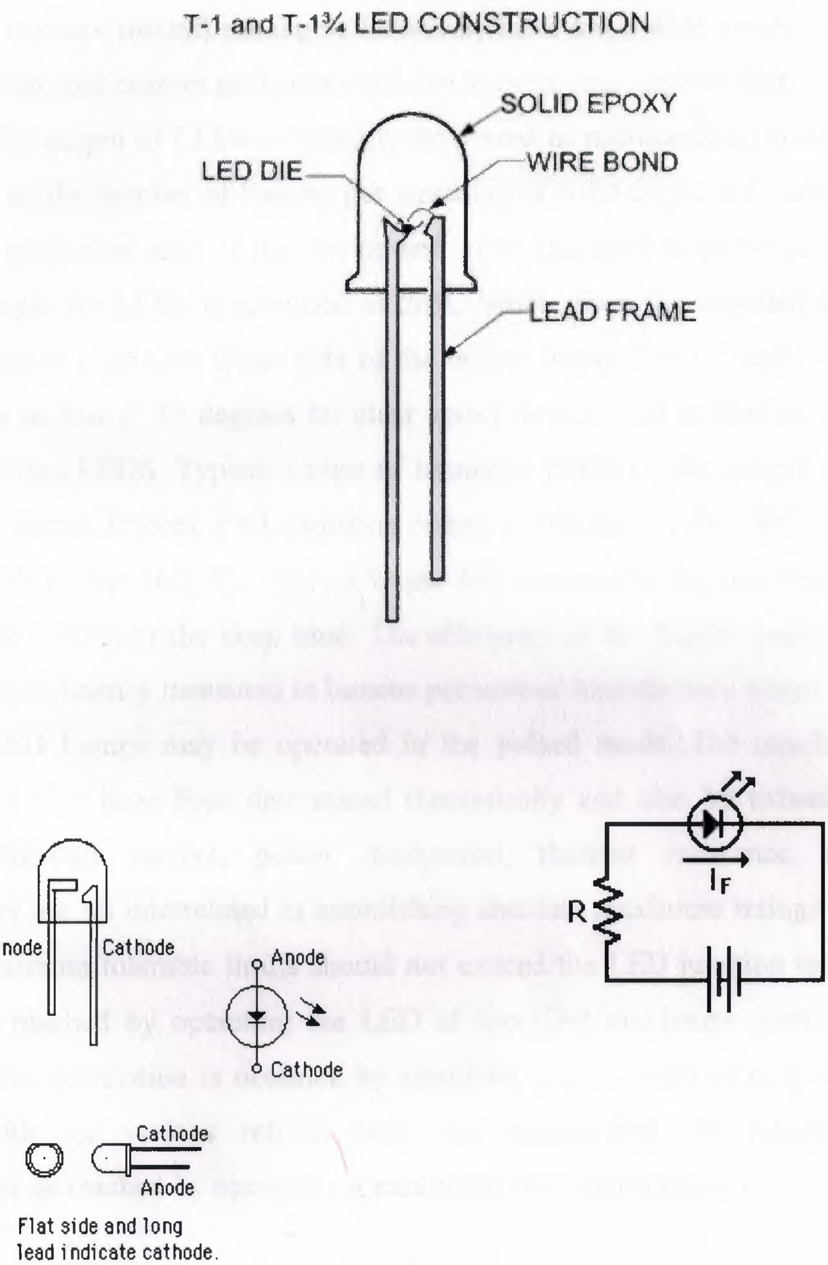


Figure 1.4. Led Construction

Many of our LEDs incorporate high efficiency chips mounted into T-1, T-1¾ and SMT (surface mount) packages. However, there are a wide variety of right angle, multi-package and custom packages available to meet your requirement.

The output of LEDs is typically expressed in millicandela (mcd). The candela is defined as the number of lumens per steradian of solid angle. It is usually measured along the projection axis of the device and gives the eye's response to the light. The viewing angle for LEDs is specified as 2q½, which gives the included angle between the ½ intensity points on either side of the output beam. For T-1 and T-1 3/4 devices this can be as low as 10 degrees for clear epoxy devices and as high as 60 degrees for highly diffused LEDS. Typical values of luminous intensity can exceed 1,000 mcd for the higher output devices. Peak radiation output is available at 940, 880, 700, 660, 625, 620, 610, 595, 590, 565, 555, 525, 470 and 430 nanometers ranging from the infrared through the visible to the deep blue. The efficiency of the higher output devices now exceeds the efficiency measured in lumens per watt of incandescent lamps.

LED Lamps may be operated in the pulsed mode. The absolute maximum ratings of LEDs have been determined theoretically and also by extensive reliability testing. Forward current, power dissipation, thermal resistance, and junction temperature are all interrelated in establishing absolute maximum ratings. In the pulsed mode, maximum tolerable limits should not exceed the LED junction temperature that would be reached by operating the LED at specified maximum continuous forward current. This correlation is obtained by establishing combinations of peak current and pulse width for various refresh rates and maintaining the maximum junction temperature as reached by operation at maximum continuous current.

1.4.5.3. Drive circuits

The drive circuits for LEDs must provide sufficient voltage to overcome the forward voltage drop of the diode junction, while controlling the current to the correct value for the specific device. The most common circuit to accomplish this is a voltage source which is significantly higher than the diode forward voltage drop and a series current limiting resistor. Several configurations are shown in the following diagram. Use Ohms law to calculate the resistor value depending on the LED chosen, the voltage source, and the maximum continuous current rating.

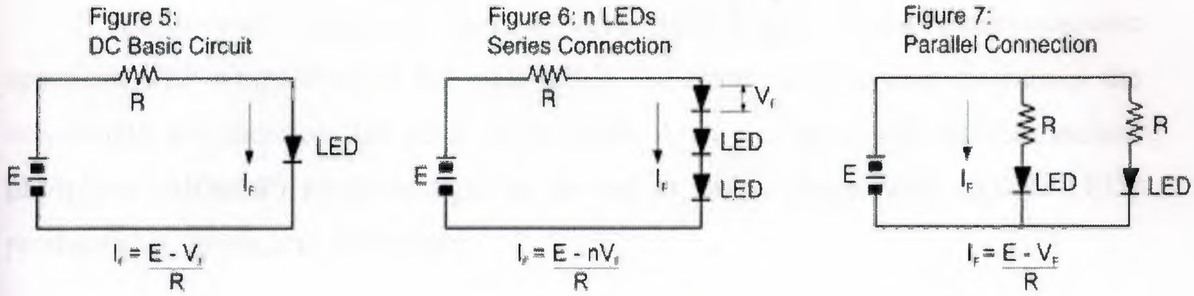


Figure 1.5. Led Voltage Source

Everyone is familiar with light-emitting diodes (LEDs) from their use as indicator lights and numeric displays on consumer electronics devices. New LED materials and improved production processes have produced bright LEDs in colors throughout the visible spectrum, including white light, with efficacies grater that incandescent lamps. These brighter, more efficacious, and colorful LEDs move LED technology into a wider range of lighting applications.

Already a leading light source for exit signs and developing as a popular source for traffic signals, LEDs also appear in display, decorative, and transportation applications, with plenty of opportunity for expansion. Small, lightweight, durable, and with long life, LEDs have the long-term potential to be the source of choice in many applications, from automotive brake lights to task lights.

Light is generated inside the chip, a solid crystal material, when current flows across the junction of the different materials. The light-generating chip is quite small, typically 0.25 millimeters square. The plastic encapsulate and lead frame occupy most of the volume.

Manufacturing LEDs involves a process known as epitaxy in which crystalline layers of different semiconductor materials are grown on top of one another. Advances in epitaxial crystal growth processes have enabled the use of LED materials for colors that previously could not be made with high enough purity and structural precision. The technique of chemical vapor deposition from metal organic precursors enables the cost-effective production of nitrides of the group-III metals from the periodic table, including aluminum gallium indium nitrides. Highly efficient indium gallium nitride (InGaN) blue LEDs result from this process.

LEDs emit energy in narrow wavelength bands of the electromagnetic spectrum. The composition of the materials in the semiconductor chip determines the wavelength and therefore the color of the light. A chip of aluminum gallium indium phosphide (AlGaInP) produces light in the red to amber range, while InGaN LEDs produce blue, green, and white light.

1.5. LIGHT DEPENDENT RESISTORS

LDRs or Light Dependent Resistors are very useful especially in light/dark sensor circuits. Normally the resistance of an LDR is very high, sometimes as high as 1000 000 ohms, but when they are illuminated with light resistance drops dramatically.

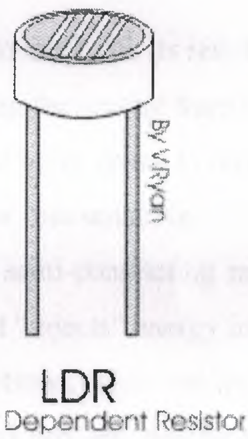


Figure 1.6. LDR

The animation opposite shows that when the torch is turned on, the resistance of the LDR falls, allowing current to pass through it.

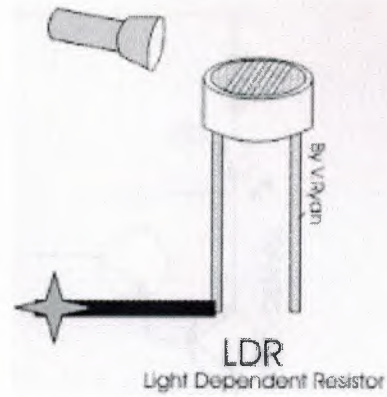


Figure 1.7. LDR Turn On Animation

When the light level is low the resistance of the LDR is high. This prevents current from flowing to the base of the transistors. Consequently the LED does not light.

However, when light shines onto the LDR its resistance falls and current flows into the base of the first transistor and then the second transistor. The LED lights.

The preset resistor can be turned up or down to increase or decrease resistance, in this way it can make the circuit more or less sensitive.

A light dependent resistor is a semi-conducting material (rather like Silicon). By shining a light onto an LDR, the light "injects" energy into the semiconductor which is absorbed by co-valently bonded electrons. This energy breaks the bonds between atoms. The electrons become delocalised and are free to move within the LDR. This leads to a larger current (smaller resistance) flowing in the semiconductor.

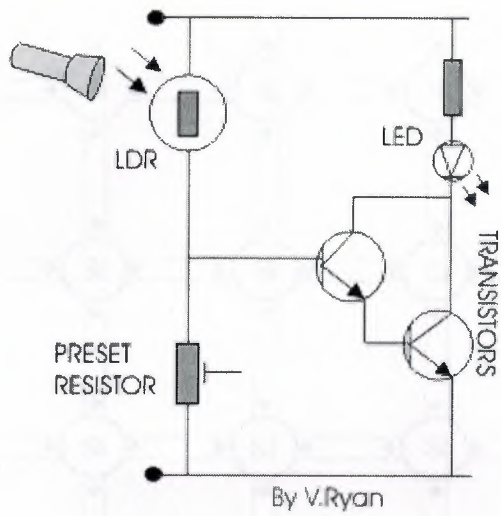


Figure 1.7. This is an example of a light sensor circuit :

When the light level is low the resistance of the LDR is high. This prevents current from flowing to the base of the transistors. Consequently the LED does not light.

However, when light shines onto the LDR its resistance falls and current flows into the base of the first transistor and then the second transistor. The LED lights.

The preset resistor can be turned up or down to increase or decrease resistance, in this way it can make the circuit more or less sensitive

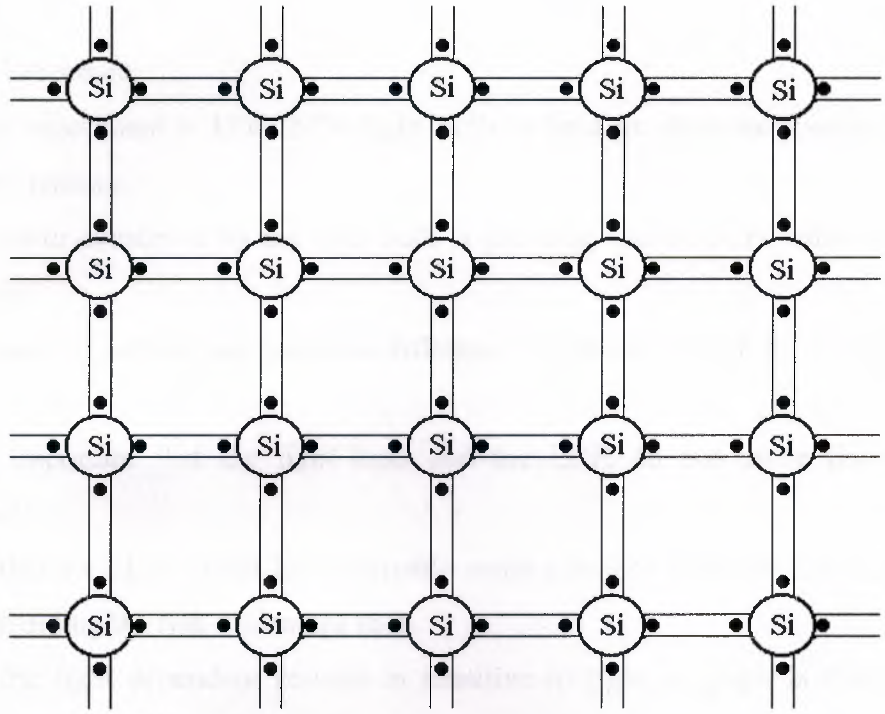


Figure 1.9. Semiconductor LDR

Thus the resistance of a Light Dependent Resistor decreases with increasing Illumination. This is used in cricket light metres and burglar alarms etc.

Measurement of the conduction characteristic of a Light Dependent Resistor

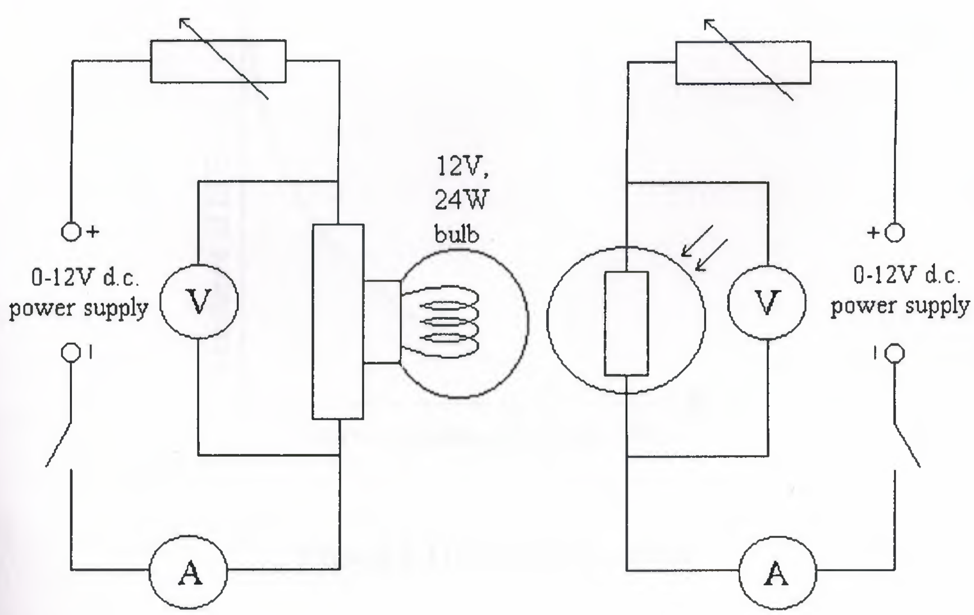


Figure 110.

Procedure:

(i)In this experiment a 12V, 24W light bulb is held as close as possible to a light dependent resistor.

(ii)The power consumed by the light bulb is gradually increased in order to change its brightness.

(iii)Readings of current and potential difference are recorded both for the bulb and the LDR.

(iv)It is important that the light bulb and the LDR do not move throughout the experiment.

(v)Note that the LDR circuit has a variable resistor in it to limit the current through it, thereby avoiding the risk of damage to it.

(vi) As the light dependent resistor is sensitive to light, a graph is then plotted of Resistance of the LDR on the y-axis against power consumed by the light on the x-axis.

Note that 1mV = /1000V and than 1 A = 1/1,000,000A.

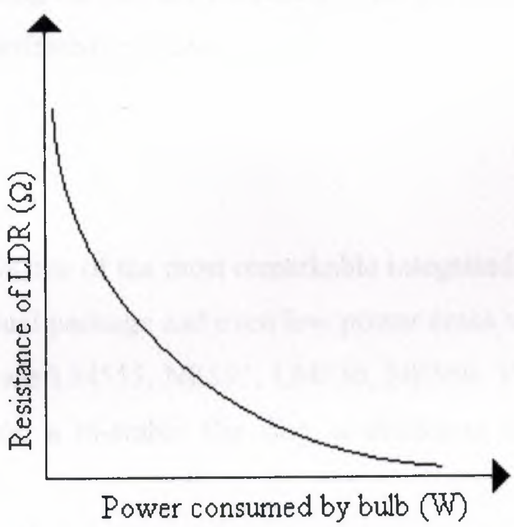


Figure 1.11. Schematic Graph:

1.5.1.Photoresistor

(Redirected from Light-dependent resistor)

A photoresistor is an electronic component whose resistance decreases with increasing incident light intensity. It can also be called a light-dependent resistor (LDR), or photoconductor.

A photoresistor 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.
A photoelectric device can be either intrinsic or extrinsic. In intrinsic devices, the only available electrons are in the valence band, and hence the photon must have enough energy to excite the electron across the entire bandgap. Extrinsic devices have impurities added, which have a ground state energy closer to the conduction band - since the electrons don't have as far to jump, lower energy photons (i.e. longer wavelengths and lower frequencies) are sufficient to trigger the device.

1.5.2.Applications

Photoresistors come in many different types. Inexpensive cadmium sulfide (CdS) ones can be found in many consumer items such as camera light meters, clock radios, security alarms and street lights. At the other end of the scale, Ge:Cu photoconductors are among the best far-infrared detectors available, and are used for infrared astronomy and infrared spectroscopy.

1.6. 555 TIMER

The 555 timer is one of the most remarkable integrated circuits ever developed. It comes in a single or dual package and even low power cmos versions exist ICM7555. Common part numbers are LM555, NE555, LM556, NE556. The 555 timer consists of two voltage comparators, a bi-stable flip flop, a discharge transistor, and a resistor divider network.

Philips describe their 555 monlithic timing circuit as a "highly stable controller capable of producing accurate time delays, or oscillation. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For a stable operation as an oscillator, the free running frequency and the duty cycle are both accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output structure can source or sink up to 200mA."

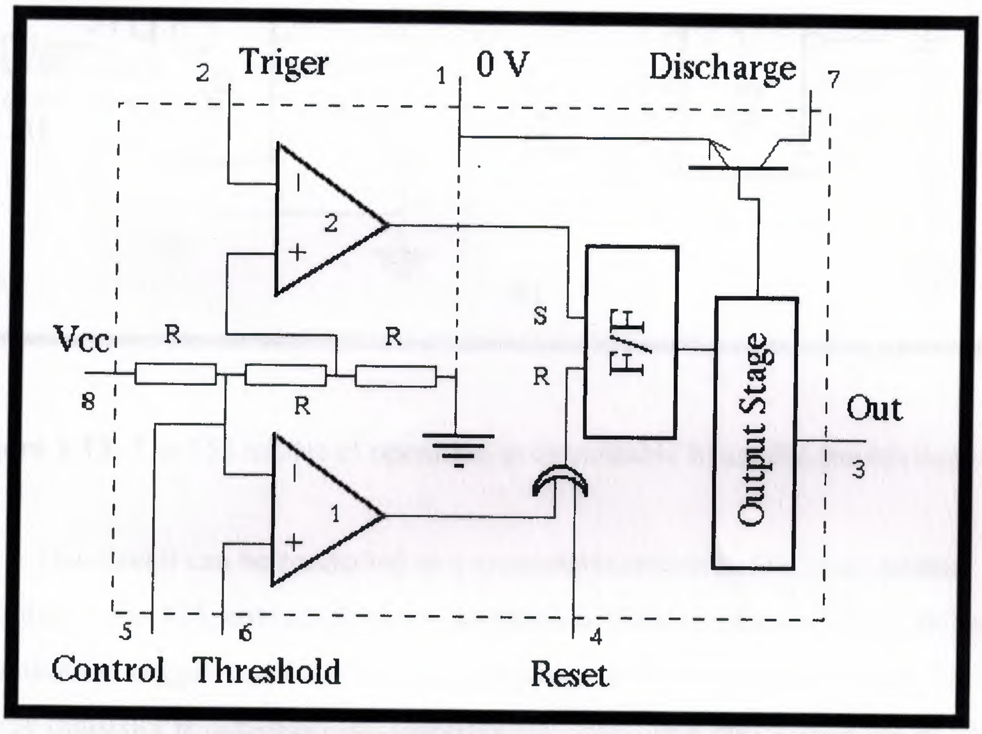


Figure 1.12: The 555 internal circuit

The 555 circuit is consisted by two comparators, one ohmic ladder one flip-flop and a discharging transistor.

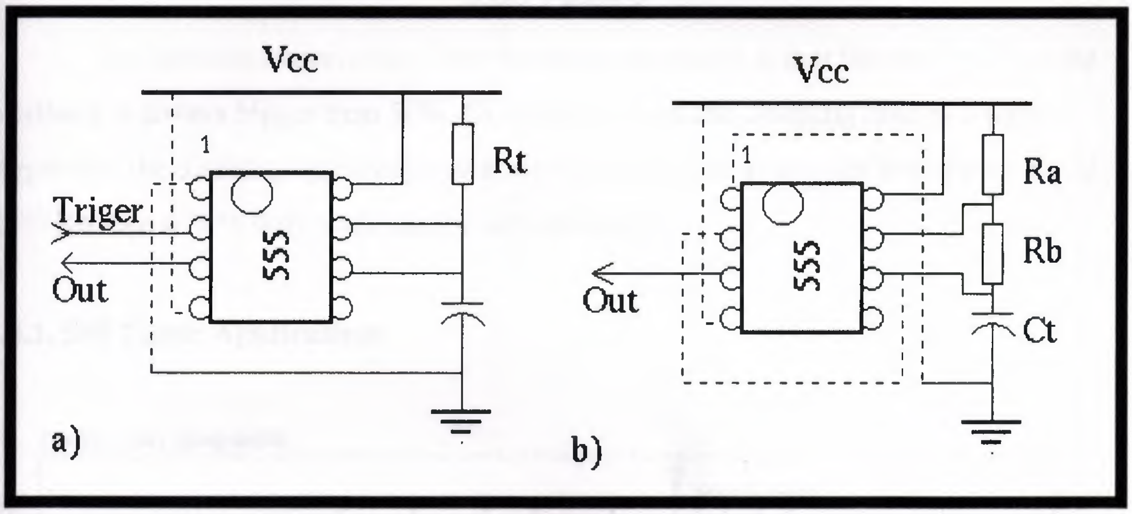


Figure 1.13: The 555 modes of operation a) monostable b) astable (multivibrator).

This circuit can be connected as a monostable multivibrator or an astable multivibrator. The 555, connected as a monostable is shown in figure 1.1a. In this mode of operation the *trigger* input sets the flip flop which drives the output to *high.* The discharge transistor is turned off and therefore the capacitor *Ct* is charged via *Rt.* When the voltage on the capacitor (*Ct*) reaches the control voltage, which is defined by the three resistor voltage divider (*Vcont=2/3 Vcc*), the flip-flop is resetted. This turns the discharge transistor on, which discharge the capacitor. Thereafter the circuit can be charged again by a new pulse at the *trigger* input. The timed period is given by the equation:

$$T=1.1\,Rt*Ct$$

Were *T* is the output pulse *high* period, *Ct* the charging capacitance measured in Farads and *Rt* the charging resistor in Ohms.

If the circuit is connected as an astable multivibrator (figure 1.1b), the comparator 2 of figure 1.1 sets the flip-flop, when the voltage on the capacitor *Ct* falls below *1/3Vcc*, while the comparator 1 resets the flip-flop when the voltage on the capacitor becomes bigger than *2/3Vcc.* In this case the discharging transistor is turned *on*, which discharge the time capacitor *Ct* via *Rb.*

This allows the use of the 555 as an oscillator (figure 1.1b) The time at the *high* (or charging) period is given by the equation:

$$Th=0.7(Ra+Rb)Ct$$

While the time for the low period is given by the equation:

$$Tl=0.7Rb*Ct$$

The obvious observation from the above equations is that the duty cycle of the oscillator is always bigger than 50%. Or in other words the charging time is always bigger that the discharging period, since $Ra+Rb>Rb$ taken in account that $Ra>0$. Yet if Ra>>Rb then a 50% duty cycle can be approximated.

1.6.1. 555 Timer Applications

EQUIVALENT SCHEMATIC

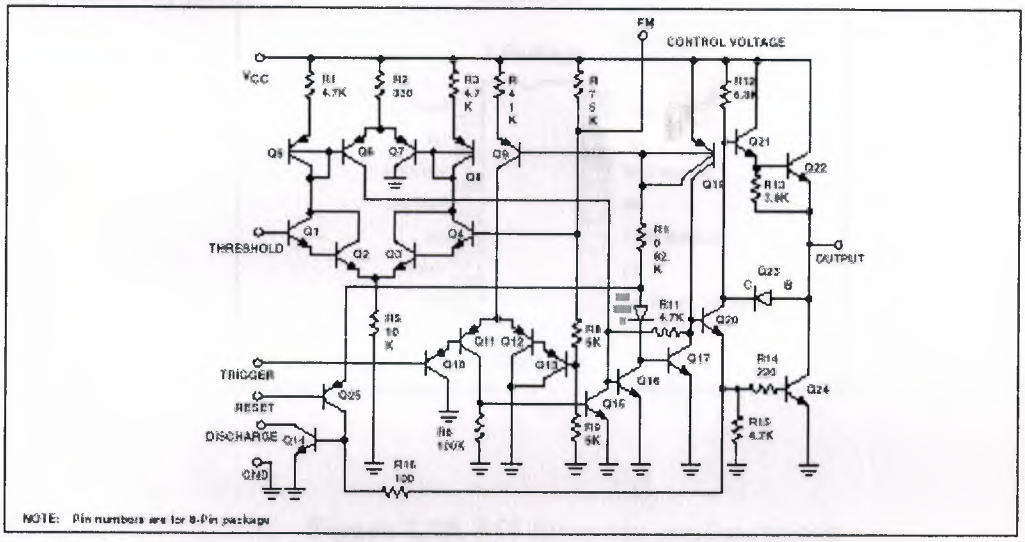


Figure 1.14

Applications include precision timing, pulse generation, sequential timing, time delay generation and pulse width modulation (PWM).

1.6.2. Pin configurations of the 555 timer

Here are the pin configurations of the 555 timer in figure 1 below.

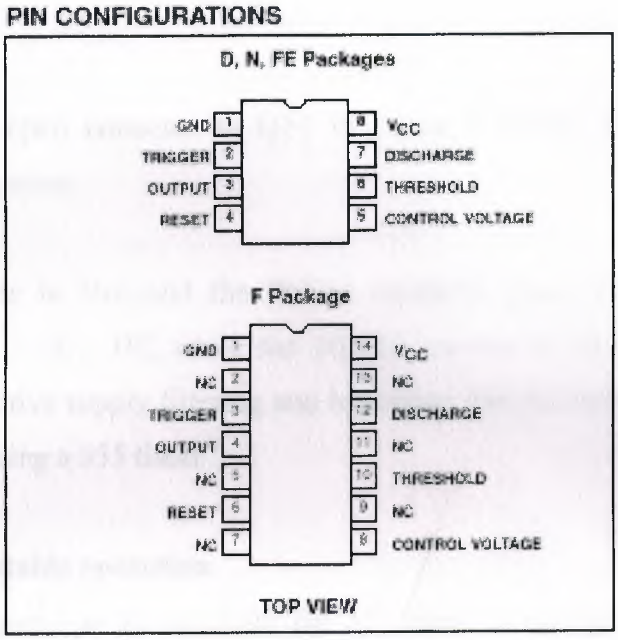


Figure 1.15. 555 timer pin configurations

1.6.3. Pin Functions - 8 pin package

Ground (Pin 1)

Not surprising this pin is connected directly to ground.

Trigger (Pin 2)

This pin is the input to the lower comparator and is used to set the latch, which in turn causes the output to go high.

Output (Pin 3)

Output high is about 1.7V less than supply. Output high is capable of Isource up to 200mA while output low is capable of Isink up to 200mA.

Reset (Pin 4)

This is used to reset the latch and return the output to a low state. The reset is an overriding function. When not used connect to V+.

Control (Pin 5)

Allows access to the 2/3V+ voltage divider point when the 555 timer is used in voltage control mode. When not used connect to ground through a 0.01 uF capacitor.

Threshold (Pin 6)

This is an input to the upper comparator. See data sheet for comprehensive explanation.

Discharge (Pin 7)

This is the open collector to Q14 in figure 4 below. See data sheet for comprehensive explanation.

V+ (Pin 8)

This connects to Vcc and the Philips databook states the ICM7555 cmos version operates 3V - 16V DC while the NE555 version is 3V - 16V DC. Note comments about effective supply filtering and bypassing this pin below under "General considerations with using a 555 timer"

1.6.4. 555 timer in astable operation

When configured as an oscillator the 555 timer is configured as in figure 2 below. This is the free running mode and the trigger is tied to the threshold pin. At power-up, the capacitor is discharged, holding the trigger low. This triggers the timer, which establishes the capacitor charge path through Ra and Rb. When the capacitor reaches the threshold level of 2/3 Vcc, the output drops low and the discharge transistor turns on.

There are difficulties with duty cycle here and I will deal with them below. It should also be noted that a minimum value of 3K should be used for Rb.

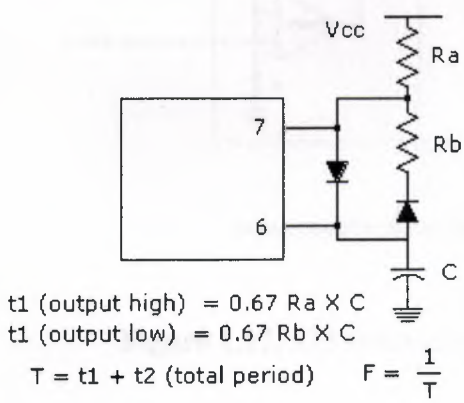


Figure 1.16. Modified duty cycle in astable operation

Here two signal diodes (1N914 types) have been added. This circuit is best used at Vcc = 15V.

1.6.5. 555 timer in monostable operation

Another popular application for the 555 timer is the monostable mode (one shot) which requires only two external components, Ra and C in figure 3 below. Time period is determined by 1.1 X Ra C.

General considerations with using a 555 timer

Most devices will operate down to as low as 3V DC supply voltage. However correct supply filtering and bypassing is critical, a capacitor between .01 uF to 10 uF (depending upon the application) should be placed as close as possible to the 555 timer supply pin. Owing to internal design considerations the 555 timer can generate large current spikes on the supply line.

While the 555 timer will operate up to about 1 Mhz it is generally recommended it not be used beyond 500 Khz owing to temperature stability considerations.

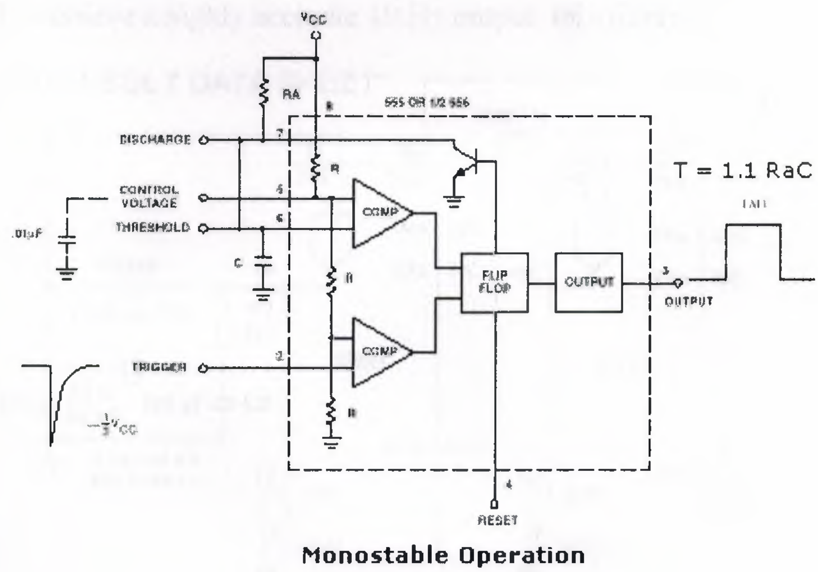


Figure 1.17. 555 timer in monostable operation

1.6.6. External components when using a 555 timer

Care should be taken in selecting stable resistors and capacitors for timing components in the 555 timer. Also the data sheet should be consulted to determine maximum and minimum component values which will affect accuracy. Capacitors must be low leakage types with very low Dielectric Absorption properties. Electrolytics and Ceramics are not especially suited to precision timing applications.

1.6.7. Very low frequency timing

There have been a few people who have written to me about problems in using the 555 timer in very low frequency applications. One particular case was at 10 Hz:

The 74HC/HCT4060 are 14-stage ripple-carry counter/dividers and oscillators with three oscillator terminals (RS, RTC and CTC), ten buffered outputs (Q3 to Q9 and Q11 to Q13) and an overriding asynchronous master reset (MR).

The oscillator configuration allows design of either RC or crystal oscillator circuits. The oscillator may be replaced by an external clock signal at input RS. In this case keep the other oscillator pins (RTC and CTC) floating.

One device is capable of dividing by Q13 (that's Philips notation for 14 as they consider Q0 as a valid first number division).

To achieve a highly accurate 10 Hz output this(figure):

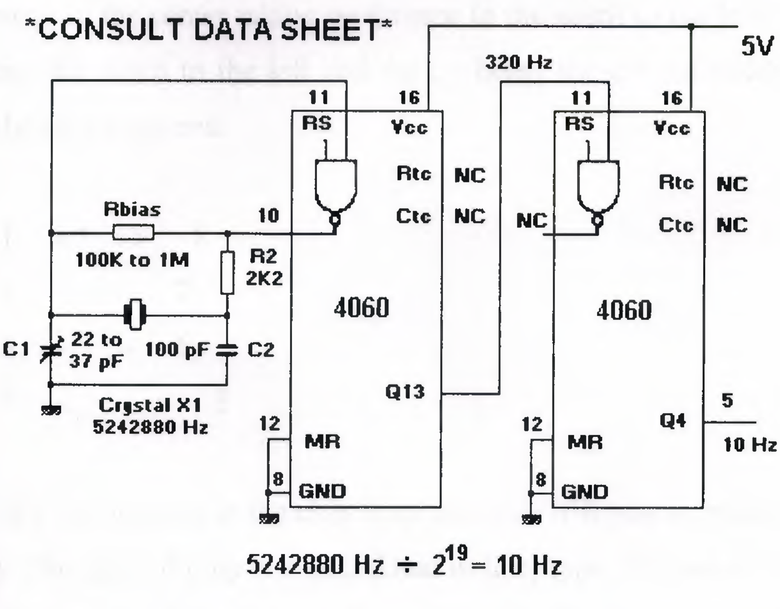


Figure 1.18. 74HC/HCT4060

14-stage ripple-carry counter/dividers used to achieve 10 Hz output

To some people the confusing part is Philips use the system of Q0, Q1, Q2.., Q12 and Q13. So Q13 is actually the 14th stage and Q4 is actually the 5th stage. Adding the two together, 14 + 5 = 19 (oh duh), means if we successively divided 5242880 by 2 for nineteen times we will get down to 10 Hz.

Several points to bear in mind:

maximum clock frequency is a very generous 80+ Mhz

1.6.8. IC CHIPS

Computer chips are now getting so advanced, it is hard to keep up with them. There are now a few optical chips, unfortunately these require a fair amount of technology to change an electrical signal to a light signal then back again. Very effective over long distances,

Some computer chips, do certain jobs, for example, analogue to digitalconverters, Eproms (Erasible Programmable Read Only Memory), Timers, Operational amplifiers, Audio amplifiers, Opto Isolators, Decade counters, Darlingtons and a whole host of others for various purposes.

The top or pin one of the IC is found by looking for a notch cut out from the top center of the chip at either end or by a notch to the left of the chip at one end, with the cut out notch in the center taking preferance to the notch to the left, as in this example, the * being the notch to the left and the :_: being the cut out notch. All other similar notches should be ignored.

```
   _ _
1  -:*:_: :-  8
2  -:     :-  7
3  -:     :-  6
4  -:_____:-  5
```

We are looking at the chip from above as if it was a circuit with the legs away from you. This type of chip is a DIL (Dual in line) type. Pin one is to the top left where both notches are, pin 2,3 and 4 run down that side of the chip, then pin 5 is opposite pin 4, pin 5,6,7 and 8 then run up that side of the chip. The pins run in a similar way on all other chips for example pin 1 to pin 7 would be on the left hand side, pin 8 to 14 on the right and so on....

IC chips are made of silicon (sand) and different types of conductive material.

The silicon chip is connected to the outside legs by thin slivers of wire, finer than a human hair. These are connected to the silicon chip and the legs not by soldering, but by sound. A high frequency 'noise' bonds the wire to the silicon or the leg. It melts it on to it to a tiny fraction of the wires thickness. There are other facts to a chip. These are their power comsumption, and their current limitations and breakdown features. Again, all chips are different, but there are two or three things that remain the same. There are IC's that require a large amount of current or voltage for them to work. These are the older type of TTL74, 74LS and 74ALS series chips, each requiring less as you come down the line. The newer faster 74HC and 74HCT series, and another type of chip. of chips. They range from the 4000 range onwards. These are VERY sensitive to static electricity from our body or other sources.

CHAPTER II

EXPLANATION OF PHOTON, ELECTRON AND QUANTUM THEORY

2.1. PHOTON

In some ways, visible light behaves like a wave phenomenon, but in other respects it acts like a stream of high-speed, submicroscopic particles. Isaac Newton was one of the first scientists to theorize that light consists of particles. Modern physicists have demonstrated that the energy in any electromagnetic field is made up of discrete packets. The term photon (meaning "visible-light particle") has been coined for these energy packets. Particle-like behavior is not restricted to the visible-light portion of the electromagnetic radiation spectrum, however. Radio waves, infrared rays, visible light, ultraviolet rays, X rays, and gamma rays all consist of photons, each of which contains a particular amount of energy that depends on the wavelength.

Photons travel through empty space at a speed of approximately 186,282 miles (299,792 kilometers) per second. This is true no matter what the electromagnetic wavelength. In media other than a vacuum, the speed is reduced. For example, visible light travels more slowly through glass than through outer space. Radio waves travel more slowly through the polyethylene in a transmission line than they do through the atmosphere. The ratio of the speed of the photons in a particular medium to their speed in a vacuum is called the velocity factor. This factor is always between 0 and 1 (or 0 and 100 percent), and it depends to some extent on the wavelength.

The shorter the wavelength of an electromagnetic disturbance, the more energy each photon contains. In fact, this relationship is so precise that a mathematical formula applies. If e represents the energy (the unit of measurement is the joule) contained in each photon and s represents the electromagnetic wavelength (in meters), then

$$e = hc / s$$

where h is Planck's constant (approximately equal to 6.626 times 10^{-34} joule-second) and c is the speed of electromagnetic-field propagation in the medium in question (approximately 2.998 times 10^{8} meters per second in a vacuum). A simpler formula applies to frequency. If f represents the frequency of an electromagnetic field (in hertz), then

$$e = hf$$

The energy contained in a single photon does not depend on the intensity of the radiation. At any specific wavelength -- say, the wavelength of light emitted by a helium-neon laser -- every photon contains exactly the same amount of energy, whether the source appears as dim as a candle or as bright as the sun. The brilliance or intensity is a function of the number of photons striking a given surface area per unit time.

2.1.1. Mass of a Photon

Does the photon have mass, after all it has energy and energy is equivalent to mass?

This question comes up in the context of wondering whether photons are really "massless," since, after all, they have nonzero energy and energy is equivalent to mass according to Einstein's equation $E=mc^2$. The problem is simply that people are using two different definitions of mass. The overwhelming consensus among physicists today is to say that photons are massless. However, it is possible to assign a "relativistic mass" to a photon which depends upon its wavelength. This is based upon an old usage of the word "mass" which, though not strictly wrong, is not used much today. See also the Faq article Does mass change with velocity?.

The old definition of mass, called "relativistic mass," assigns a mass to a particle proportional to its total energy E, and involved the speed of light, c, in the proportionality constant:

$$m = E / c^2. \qquad (1)$$

This definition gives every object a velocity-dependent mass.

The modern definition assigns every object just one mass, an invariant quantity that does not depend on velocity. This is given by

$$m = E_0 / c^2, \qquad (2)$$

where E_0 is the total energy of that object at rest.

The first definition is often used in popularizations, and in some elementary textbooks. It was once used by practicing physicists, but for the last few decades, the vast majority of physicists have instead used the second definition.The "relativistic mass" is never used at all. Note, by the way, that using the standard definition of mass, the one given by eqn (2), the equation "$E = m c^2$" is not correct. Using the standard definition, the relation between the mass and energy of an object can be written as

$$E = m c^2 / \mathrm{sqrt}(1 - v^2/c^2), \qquad (3)$$

or as

$$E^2 = m^2 c^4 + p^2 c^2, \quad (4)$$

where v is the object's velocity, and p is its momentum.

In one sense, any definition is just a matter of convention. In practice, though, physicists now use this definition because it is much more convenient. The "relativistic mass" of an object is really just the same as its energy, and there isn't any reason to have another word for energy: "energy" is a perfectly good word. The mass of an object, though, is a fundamental and invariant property, and one for which we do need a word.

The "relativistic mass" is also sometimes confusing because it mistakenly leads people to think that they can just use it in the Newtonian relations

$$F = m a \quad (5)$$

and

$$F = G m_1 m_2 / r^2. \quad (6)$$

In fact, though, there is no definition of mass for which these equations are true relativistically: they must be generalized. The generalizations are more straightforward using the standard definition of mass than using "relativistic mass."

Oh, and back to photons: people sometimes wonder whether it makes sense to talk about the "rest mass" of a particle that can never be at rest. The answer, again, is that "rest mass" is really a misnomer, and it is not necessary for a particle to be at rest for the concept of mass to make sense. Technically, it is the invariant length of the particle's four-momentum. (this eq) For all photons this is zero. On the other hand, the "relativistic mass" of photons is frequency dependent. UV photons are more energetic than visible photons, and so are more "massive" in this sense, a statement which obscures more than it elucidates.

2.1.2. PHOTON ENERGY

Photon Energy is the powerful new energy that will replace electricity in the new millennium. It's a free energy source and nobody can monopolize it. Its outer edge or belt has already reached Earth's atmosphere and is affecting not only Earth but many planets in the solar system. Photon Energy is light energy, and it permeates the Earth in waves. It has the power to extend human life because its molecular structure realigns the human body into a lightbody. Photon Energy vibrates at a very high frequency, and confers the power of instant manifestation of thought. Therefore, it is essential to maintain clarity and purity of thought by practicing daily meditation, being in the "now," and staying heart-centered.

2.1.3. PHOTON BELT EMITTING JAGGED WAVES

The jagged energy patterns (peaks and valleys) are due to the warbling of the Earth and how the Photon Energy will impact the planet. The Photon Energy Belt is closer to the Earth plane than we in the Guidance Realm anticipated. Short bursts of energy are being emitted from the Belt (the outside edge of the Photon Energy is called the Belt Oftentimes, when a burst of energy hits the Earth plane, it causes an out-flux of energy behind it and that's how the waving sensation (peaks and valleys) is created. As the short burst of energy waves through the Earth plane, it pulls the energy that's behind it, and that's how you get what feels like a dry spell, or an out-flux of energy, which normally follows it. This out-flux of energy is chaotic, or mis-aligned energy, because its power is reduced.

2.2. ELECTRON

An electron is a negatively charged subatomic particle. It can be either free (not attached to any atom), or bound to the nucleus of an atom. Electrons in atoms exist in spherical shells of various radii, representing energy levels. The larger the spherical shell, the higher the energy contained in the electron.

In electrical conductors, current flow results from the movement of electrons from atom to atom individually, and from negative to positive electric poles in general. In semiconductor materials, current also occurs as a movement of electrons. But in some cases, it is more illustrative to envision the current as a movement of electron deficiencies from atom to atom. An electron-deficient atom in a semiconductor is called a hole. Holes "move" from positive to negative electric poles in general.

The charge on a single electron is considered as the unit electrical charge. It is assigned negative polarity. The charge on an electron is equal, but opposite, to the positive charge on a proton or hole. Electrical charge quantity is not usually measured in terms of the charge on a single electron, because this is an extremely small charge. Instead, the standard unit of electrical charge quantity is the coulomb, symbolized by C, representing about 6.24×10^{18} electrons. The electron charge, symbolized by e, is about 1.60×10^{-19} C. The mass of an electron at rest, symbolized m_e, is approximately 9.11×10^{-31} kilogram (kg). Electrons moving at an appreciable fraction of the speed of light, for example in a particle accelerator, have greater mass because of relativistic effects.

2.2.1. Electron Volts

For instance, the electric charge of an electron is -e [where e is the charge of a proton, defined in Eq. (2)]. An ELECTRON VOLT (eV) is the kinetic energy gained by an electron [or any other particle with the same size charge] when it is accelerated through a one volt (1 V) electric potential. Moving a charge of 1 C through a potential of 1 V takes 1 J of work (and will produce 1 J of kinetic energy), so we know immediately from Eq. (2) that

$$1\ \mathrm{eV} = 1.60217733(49) \times 10^{-19}\ \mathrm{J}$$

This is not much energy if you are a toaster, but for an electron (which is an incredibly tiny particle) it is enough to get it up to a velocity of 419.3828 km/s, which is 0.14% of the speed of light! Another way of looking at it is to recall that we can express temperature in energy units using Boltzmann's constant as a conversion factor. You can easily show for yourself that 1 eV is equivalent to a temperature of 11,604 degrees Kelvin or about 11,331 °C. So in the microscopic world of electrons the eV is a pretty convenient (or ``natural'') unit. But not in the world of toasters and light bulbs. So let's get back to ``conventional'' units.

A convenient energy unit, particularly for atomic and nuclear processes, is the energy given to an electron by accelerating it through 1 volt of electric potential difference. The work done on the charge is given by the charge times the voltage difference, which in this case is:

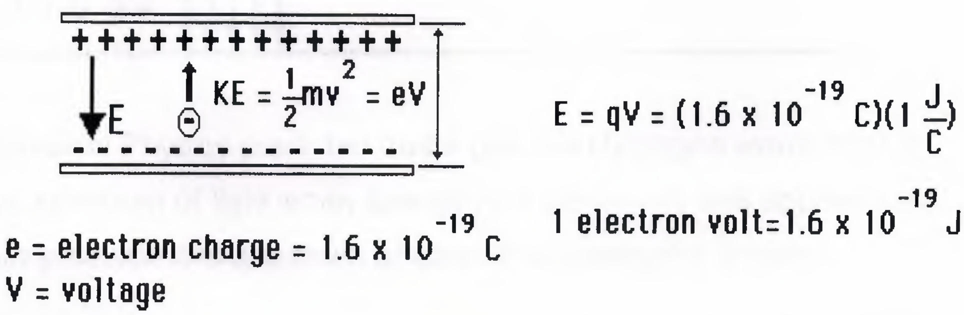
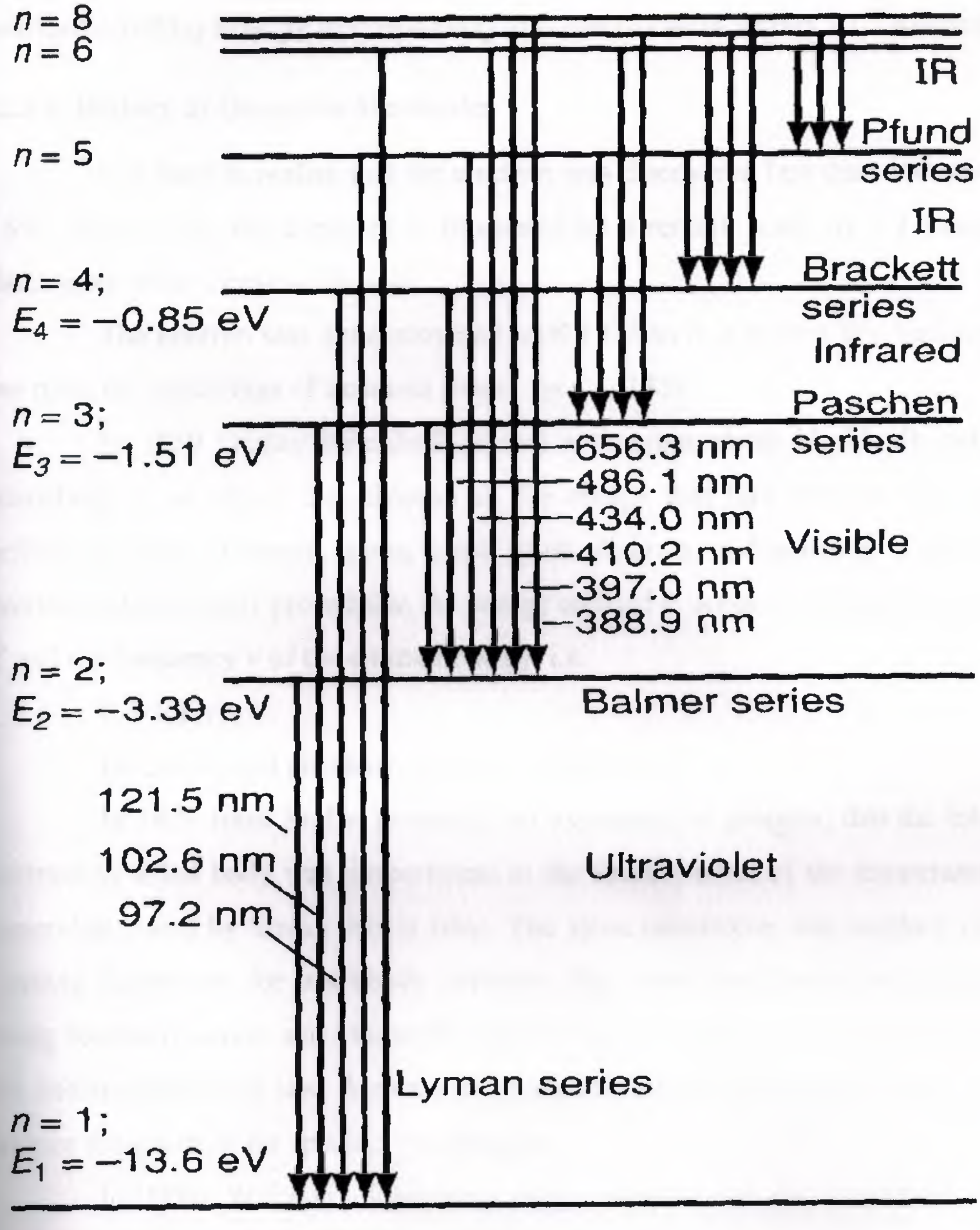


Figure 2.1. The abbreviation for electron volt is eV.

2.3. QUANTUM THEORY



Classical Physics predicted that a gas like Hydrogen would emit a continuous spectrum of light when Energy (like electricity) was applied – *but instead, an emission line spectrum of specific wavelengths is seen.*

Niels Bohr - The electron in Hydrogen can only occupy fixed energy levels. Electrons absorb fixed amounts (quanta) of energy and emit quanta of electromagnetic radiation when they drop to a lower energy level, as predicted by Planck's formula Δ **E = hν** (h is Planck's constant 6.62 x 10^{-34} Joules• sec.)(ν is frequency).

Bohr was able to explain the emission spectrum of Hydrogen and predicted lines in the UV and IR; but electrons cannot orbit an atomic nucleus without emitting energy and spiraling into the nucleus within 10^{-11} second.

2.3.1. History of Quantum Mechanics

It is hard to realise that the electron was discovered less than 100 years ago in 1897. That it was not expected is illustrated by a remark made by J J Thomson, the discoverer of the electron. He said;

The neutron was not discovered until 1932 so it is against this background that we trace the beginnings of quantum theory back to 1859.

In 1859 Gustav Kirchhoff proved a theorem about blackbody radiation. A blackbody is an object that absorbs all the energy that falls upon it and, because it reflects no light, it would appear black to an observer. A blackbody is also a perfect emitter and Kirchhoff proved that the energy emitted E depends only on the temperature T and the frequency v of the emitted energy, i.e.

E = J(T,v).

He challenged physicists to find the function J.

In 1879 Josef Stefan proposed, on experimental grounds, that the total energy emitted by a hot body was proportional to the fourth power of the temperature. In the generality stated by Stefan this is false. The same conclusion was reached in 1884 by Ludwig Boltzmann for blackbody radiation, this time from theoretical considerations using thermodynamics and Maxwell's electromagnetic theory. The result, now known as the Stefan-Boltzmann law, does not fully answer Kirchhoff challenge since it does not answer the question for specific wavelengths.

In 1896 Wilhelm Wien proposed a solution to the Kirchhoff challenge. However although his solution matches experimental observations closely for small values of the wavelength, it was shown to break down in the far infrared by Rubens and Kurlbaum.

Kirchhoff, who had been at Heidelberg, moved to Berlin. Boltzmann was offered his chair in Heidelberg but turned it down. The chair was then offered to Hertz who also declined the offer, so it was offered again, this time to Planck and he accepted.

Rubens visited Planck in October 1900 and explained his results to him. Within a few hours of Rubens leaving Planck's house Planck had guessed the correct formula for Kirchhoff's J function. This guess fitted experimental evidence at all wavelengths very well but Planck was not satisfied with this and tried to give a theoretical derivation of the formula. To do this he made the unprecedented step of assuming that the total energy is made up of indistinguishable energy elements - quanta of energy. He wrote

Experience will prove whether this hypothesis is realised in nature

Planck himself gave credit to Boltzmann for his statistical method but Planck's approach was fundamentally different. However theory had now deviated from experiment and was based on a hypothesis with no experimental basis. Planck won the 1918 Nobel Prize for Physics for this work.

In 1901 Ricci and Levi-Civita published Absolute differential calculus. It had been Christoffel's discovery of 'covariant differentiation' in 1869 which let Ricci extend the theory of tensor analysis to Riemannian space of n dimensions. The Ricci and Levi-Civita definitions were thought to give the most general formulation of a tensor. This work was not done with quantum theory in mind but, as so often happens, the mathematics necessary to embody a physical theory had appeared at precisely the right moment.

In 1905 Einstein examined the photoelectric effect. The photoelectric effect is the release of electrons from certain metals or semiconductors by the action of light. The electromagnetic theory of light gives results at odds with experimental evidence. Einstein proposed a quantum theory of light to solve the difficulty and then he realised that Planck's theory made implicit use of the light quantum hypothesis. By 1906 Einstein had correctly guessed that energy changes occur in a quantum material oscillator in changes in jumps which are multiples of $\hbar v$ where $\hbar$ is Planck's constant and v is the frequency. Einstein received the 1921 Nobel Prize for Physics, in 1922, for this work on the photoelectric effect.

In 1913 Niels Bohr wrote a revolutionary paper on the hydrogen atom. He discovered the major laws of the spectral lines. This work earned Niels Bohr the 1922 Nobel Prize for Physics. Arthur Compton derived relativistic kinematics for the scattering of a photon (a light quantum) off an electron at rest in 1923.

However there were concepts in the new quantum theory which gave major worries to many leading physicists. Einstein, in particular, worried about the element of 'chance' which had entered physics. In fact Rutherford had introduced spontaneous effect when discussing radio-active decay in 1900.

There are therefore now two theories of light, both indispensable, and - as one must admit today despite twenty years of tremendous effort on the part of theoretical physicists - without any logical connection.

In the same year, 1924, Niels Bohr, Kramers and Slater made important theoretical proposals regarding the interaction of light and matter which rejected the photon. Although the proposals were the wrong way forward they stimulated important experimental work. Niels Bohr addressed certain paradoxes in his work.

(i)How can energy be conserved when some energy changes are continuous and some are discontinuous, i.e. change by quantum amounts.

(ii) How does the electron know when to emit radiation.

Einstein had been puzzled by paradox (ii) and Pauli quickly told Niels Bohr that he did not believe his theory. Further experimental work soon ended any resistance to belief in the electron. Other ways had to be found to resolve the paradoxes.

Up to this stage quantum theory was set up in Euclidean space and used Cartesian tensors of linear and angular momentum. However quantum theory was about to enter a new era.

The year 1924 saw the publication of another fundamental paper. It was written by Satyendra Nath Bose and rejected by a referee for publication. Bose then sent the manuscript to Einstein who immediately saw the importance of Bose's work and arranged for its publication. Bose proposed different states for the photon. He also proposed that there is no conservation of the number of photons. Instead of statistical independence of particles, Bose put particles into cells and talked about statistical independence of cells. Time has shown that Bose was right on all these points.

Work was going on at almost the same time as Bose's which was also of fundamental importance. The doctoral thesis of Louis de Broglie was presented which extended the particle-wave duality for light to all particles, in particular to electrons. Schrödinger in 1926 published a paper giving his equation for the hydrogen atom and heralded the birth of wave mechanics. Schrödinger introduced operators associated with each dynamical variable.

The year 1926 saw the complete solution of the derivation of Planck's law after 26 years. It was solved by Dirac. Also in 1926 Born abandoned the causality of traditional physics. Speaking of collisions Born wrote

Heisenberg wrote his first paper on quantum mechanics in 1925 and 2 years later stated his uncertainty principle. It states that the process of measuring the position x of a particle disturbs the particle's momentum p, so that

$$Dx\,Dp \geq \hbar = h/2$$

where Dx is the uncertainty of the position and Dp is the uncertainty of the momentum. Here h is Planck's constant and $\hbar$ is usually called the 'reduced Planck's constant'. Heisenberg states that the nonvalidity of rigorous causality is necessary and not just consistently possible.

Heisenberg's work used matrix methods made possible by the work of Cayley on matrices 50 years earlier. In fact 'rival' matrix mechanics deriving from Heisenberg's work and wave mechanics resulting from Schrödinger's work now entered the arena. These were not properly shown to be equivalent until the necessary mathematics was developed by Riesz about 25 years later.

Also in 1927 Niels Bohr stated that space-time coordinates and causality are complementary. Pauli realised that spin, one of the states proposed by Bose, corresponded to a new kind of tensor, one not covered by the Ricci and Levi-Civita work of 1901. However the mathematics of this had been anticipated by E Cartan who introduced a 'spinor' as part of a much more general investigation in 1913.

Dirac, in 1928, gave the first solution of the problem of expressing quantum theory in a form which was invariant under the Lorentz group of transformations of special relativity. He expressed d'Alembert's wave equation in terms of operator algebra.

The uncertainty principle was not accepted by everyone. Its most outspoken opponent was Einstein. He devised a challenge to Niels Bohr which he made at a conference which they both attended in 1930. Einstein suggested a box filled with radiation with a clock fitted in one side. The clock is designed to open a shutter and allow one photon to escape. Weigh the box again some time later and the photon energy and its time of escape can both be measured with arbitrary accuracy. Of course this is not meant to be an actual experiment, only a 'thought experiment'.

Niels Bohr is reported to have spent an unhappy evening, and Einstein a happy one, after this challenge by Einstein to the uncertainty principle. However Niels Bohr had the final triumph, for the next day he had the solution. The mass is measured by hanging a compensation weight under the box. This is turn imparts a momentum to the box and there is an error in measuring the position. Time, according to relativity, is not absolute and the error in the position of the box translates into an error in measuring the time.

Although Einstein was never happy with the uncertainty principle, he was forced, rather grudgingly, to accept it after Bohr's explanation.

In 1932 von Neumann put quantum theory on a firm theoretical basis. Some of the earlier work had lacked mathematical rigour, but von Neumann put the whole theory into the setting of operator algebra.

Louis de Broglie (French 1924) – determined that matter has wave properties. Electrons have a dual wave-particle nature. Electrons should be considered as waves confined to a space around the atomic nucleus.

This discovery led to the invention of the first electron microscope by the German physicist Ernst Ruska in 1933.

2.3.2. De Broglie's Relationship

DERIVATION:

$E = h\nu$ (Planck's theorem) $v = \lambda\, \nu$ (wavelength x frequency = velocity

$$\nu = \frac{v}{\lambda}$$

$$E = \frac{hv}{\lambda}$$ SUBSTITUTING:

$$mv^2 = \frac{hv}{\lambda}$$ $E = mv^2$ SUBSTITUTING:

SOLVING FOR λ

$$\lambda = \frac{hv}{mv^2} = \frac{h}{mv}$$ De Broglie's Relationship

Wavelength = Planck's constant divided by momentum

CHAPTER III
THE PHOTOELECTRIC EFFECT

3.1. OVERVİEW

An unusual phenomenon was discovered in the early 1900's. If a beam of light is pointed at the negative end of a pair of charged plates, a current flow is measured. A current is simply a flow of electrons in a metal, such as a wire. Thus, the beam of light must be liberating electrons from one metal plate, which are attracted to the other plate by electrostatic forces. This results in a current flow.

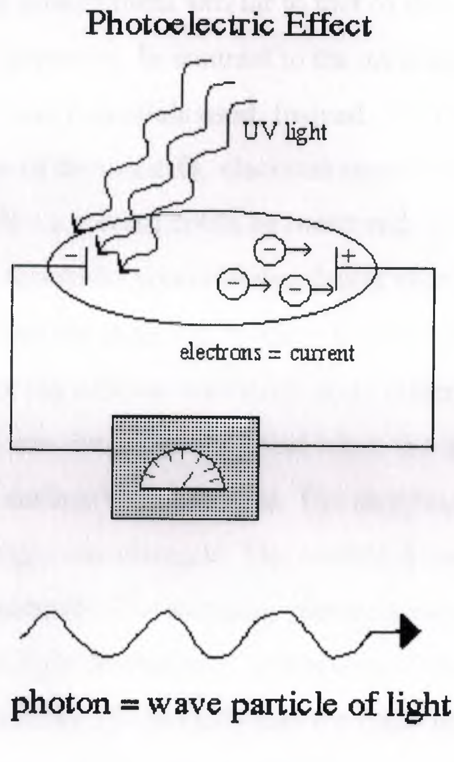


Figure 3.1. Photoelectric effect

In classical physics, one would expect the current flow to be proportional to the strength of the beam of light (more light = more electrons liberated = more current). However, the observed phenomenon was that the current flow was basically constant with light strength, yet varied strong with the wavelength of light such that there was a sharp cutoff and no current flow for long wavelengths.

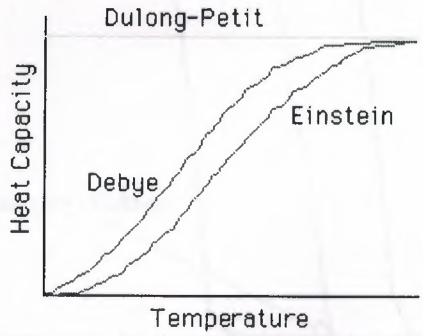


Figure 3.2. heat-temp rate

An experimental arrangement similar to that of the cathode ray tube, scientists had observed another phenomenon. In contrast to the cathode ray tube, the cathode was not heated nor were large bias potentials used. Instead, it was found that when light impinged upon the surface of the cathode, electrons could be ejected from the cathode and picked up by the anode - a current could be measured. If an opposing bias voltage was established, a certain threshold potential was found above which no current would be measured. This was called the stopping voltage. It was determined that the stopping voltage was different when the cathode was made from different materials. But what was particularly troubling was the effect observed when the wavelength and intensity of the light which struck the surface were changed. The stopping potential did not change when the intensity of the light was changed. The current, however, did increase with increasing incident light intensity. The stopping potential increased when the wavelength of the incident light decreased. Furthermore, as the light intensity decreased, the current also dropped - nevertheless the onset of the current from the time the light first hit the surface was always instantaneous.

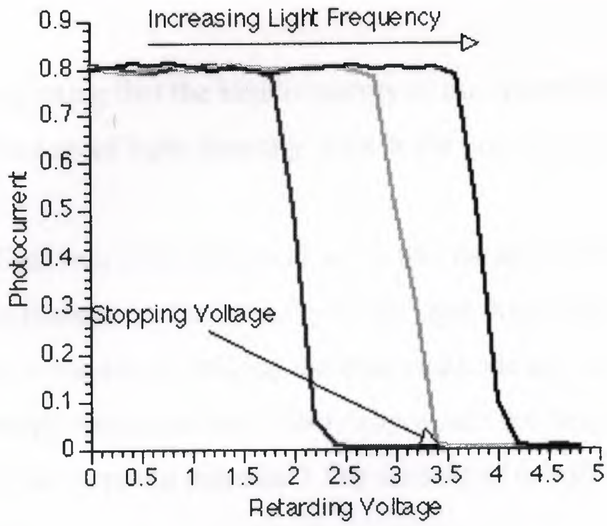


Figure 3.3 current-voltage rate with respect of light frq.

This graph shows the typical results of an experiment. For a given light frequency and a particular metal for the cathode, the photocurrent is constant until a large enough retarding potential prevents the ejected electrons from reaching the anode. This potential is called the stopping potential and just matches the kinetic energy of the ejected electrons. When a higher energy light source is used (greater frequency, shorter wavelength), the ejected electrons possess a greater kinetic energy and so the stopping potential is correspondingly larger.

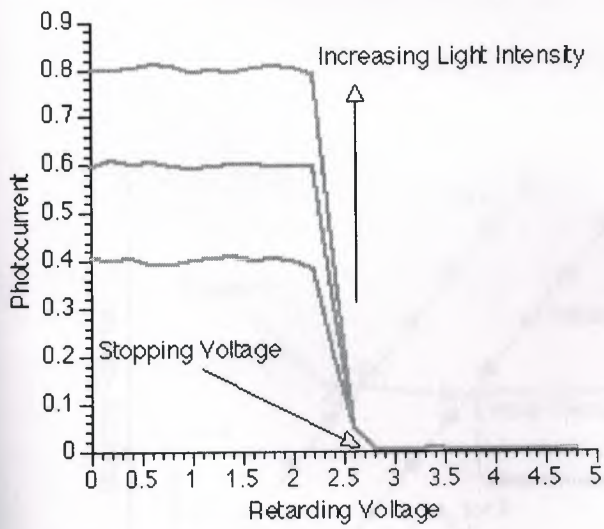


Figure 3.4. current-voltage rate with respect of light intensity

This graph shows how the photocurrent increases when the light intensity increases but the wavelength is held constant. The stopping potential is the same however, suggesting that the kinetic energy of the ejected electrons is the same and hence independent of light intensity. This is the opposite of what would be expected classically.

If light was of the classical wave-like nature, we would expect a time lag which would increase as the intensity of the light decreased. The total energy would be spread across a wavefront striking the entire cathode and nothing could happen until sufficient energy were absorbed. Also, why would the frequency of the light make a difference to the stopping potential? The amount of energy in a wave is carried by its amplitude.

Here is a plot of the measured stopping potentials obtained for several light frequencies for two different metals. The slope of this plot is the same in both cases and is equal to Planck's constant h. The x-intercept corresponds to the lowest frequency light that is able to eject electrons for each metal. This frequency times Planck's constant is the work function of the metal, peculiar for each metal, and represents the amount of energy necessary for an electron to "climb" out of bulk metal materials.

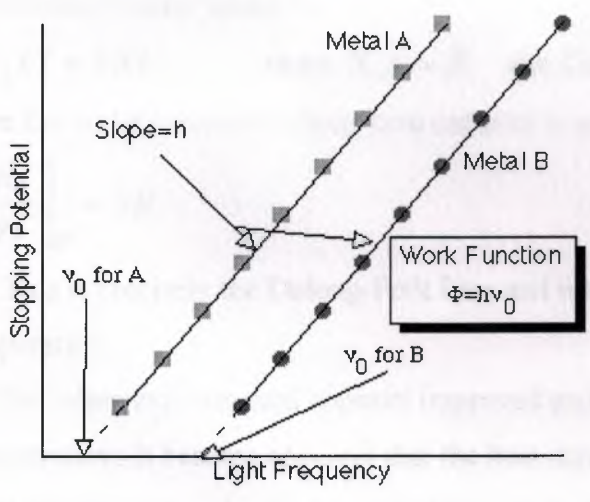


Figure 3.3.

It was Einstein who, in 1905, took Planck's quantum hypothesis and applied it the photoelectric effect and showed how the consideration of the structure of matter has having quantized energy levels accounted precisely for these observations. This was a tremendous boost to the integrity of the quantum concept. In its interesting to note that it was this concept for which Einstein was awarded the Nobel Prize, and not for his work in relativity - something he developed the same year and for which he now is more well-known.

During the early part of the nineteenth century, studies on the heat capacity of materials tended to indicate that it was a rather uninteresting property, somewhat independent of temperature. These results, arising mainly because of a rather limited experimental temperature range and by working around room temperature and above, gave rise to the Dulong-Petit law, which referred to the constant pressure heat-capacity as being approximately constant at about 26.8 J/K mol. The constant volume heat capacity is even more nearly the same for all elements, since the difference done in expansion pV work in the constant pressure case adds additional minor variations. Lewis and Gibson (1917) measured the constant volume heat capacities and noted that they were all within 1.5% of 24.69 J/K mol for elements heavier than potassium and for which data were available.

This can be readily seen from classical physics where the equipartition theorem would assign a vibrational energy of 3kT to each atom in a solid. For N atoms, this would give 3NkT for the total vibrational energy. The molar internal energy arising from vibrational motion would be

$$\overline{U} = 3N_A kT = 3RT \qquad \text{since } N_A k = R \quad \text{the Gas Constant}$$

From here the molar constant volume heat capacity is easily predicted to be

$$\overline{C}_V = \left[\frac{\partial \overline{U}}{\partial T}\right]_V = 3R$$

This is precisely the Dulong-Petit Law and readily shows its independence from temperature.

But when experimental apparati improved and measurements were made for lower temperatures it became apparent that the heat capacity actually drops with decreasing temperature and in fact approaches zero at absolute zero temperature. Einstein first tackled this problem by invoking Planck's quantum ideas. He suggested that each atom was an oscillator of frequency ν and then asserted that any oscillation would have to be an integer multiple nhν. From this he calculated the molar vibrational energy and, by differentiating with respect to T, arrived at what is known as the Einstein Formula.

$$\overline{C}_V = 3R\left[\frac{h\nu}{kT}\left(\frac{e^{\frac{h\nu}{2kT}}}{e^{\frac{h\nu}{kT}}-1}\right)\right]$$

At high temperatures, you can expand the exponentials and see how the expression reduces to the Dulong-Petit Law. But at low temperatures it indeed approaches zero as observed. Numerical agreement is not excellent, however, and Peter Debye produced a further correction by not assuming that all atoms had oscillated at the same frequency, but rather averaged over all frequencies present. This Debye Equation nicely predicts the observed experimental results, lending further credence to Planck's Quantum Hypothesis.

Einstein won the Nobel Prize for Physics not for his work on relativity, but for explaining the photoelectric effect. He proposed that light is made up of packets of energy called photons. Photons have no mass, but they have momentum and they have an energy given by:

Energy of a photon : E = hf

The photoelectric effect works like this. light of high enough energy on to a metal, electrons will be emitted from the metal. Light below a certain threshold frequency, no matter how intense, will not cause any electrons to be emitted. Light above the threshold frequency, even if it's not very intense, will always cause electrons to be emitted.

The explanation for the photoelectric effect goes like this: it takes a certain energy to eject an electron from a metal surface. This energy is known as the work function (W), which depends on the metal. Electrons can gain energy by interacting with photons. If a photon has an energy at least as big as the work function, the photon energy can be transferred to the electron and the electron will have enough energy to escape from the metal. A photon with an energy less than the work function will never be able to eject electrons.

Before Einstein's explanation, the photoelectric effect was a real mystery. Scientists couldn't really understand why low-frequency high-intensity light would not cause electrons to be emitted, while higher-frequency low-intensity light would. Knowing that light is made up of photons, it's easy to explain now. It's not the total amount of energy (i.e., the intensity) that's important, but the energy per photon.

When light of frequency f is incident on a metal surface that has a work function W, the maximum kinetic energy of the emitted electrons is given by:

$$KE_{max} = hf - W$$

Note that this is the maximum possible kinetic energy because W is the minimum energy necessary to liberate an electron. The threshold frequency, the minimum frequency the photons can have to produce the emission of electrons, is when the photon energy is just equal to the work function:

threshold frequency : $f_0 = W / h$

3.1.1. The Compton effect

Although photons have no mass, they do have momentum, given by:

momentum of a photon: $p = E / c = hf / c = h / \lambda$

Convincing evidence for the fact that photons have momentum can be seen when a photon collides with a stationary electron. Some of the energy and momentum is transferred to the electron (this is known as the Compton effect), but both energy and momentum are conserved in such a collision. Applying the principles of conservation of energy and momentum to this collision, one can show that the wavelength of the outgoing photon is related to the wavelength of the incident photon by the equation:

Compton effect : $\lambda' - \lambda = (h / mc)\,[1 - \cos\theta]$
where θ is the angle between the incident and outgoing photons,
and m is the mass of the electron.

3.1.2. Quantum mechanics and Photoelectric Effect

All these ideas, that for very small particles both particle and wave properties are important, and that particle energies are quantized, only taking on discrete values, are the cornerstones of quantum mechanics. In quantum mechanics we often talk about the wave function (Ψ)of a particle; the wave function is the wave discussed above, with the probability of finding the particle in a particular location being proportional to the square of the amplitude of the wave function.

The most dramatic prediction of Maxwell's theory of electromagnetism, published in 1865, was the existence of electromagnetic waves moving at the speed of light, and the conclusion that light itself was just such a wave. This challenged experimentalists to generate and detect electromagnetic radiation using some form of electrical apparatus. The first clearly successful attempt was by Heinrich Hertz in 1886. He used a high voltage induction coil to cause a spark discharge between two pieces of brass, to quote him, "Imagine a cylindrical brass body, 3 cm in diameter and 26 cm long, interrupted midway along its length by a spark gap whose poles on either side are formed by spheres of 2 cm radius." The idea was that once a spark formed a conducting path between the two brass conductors, charge would rapidly oscillate back and forth, emitting electromagnetic radiation of a wavelength similar to the size of the conductors themselves.

To prove there really was radiation emitted, it had to be detected. Hertz used a piece of copper wire 1 mm thick bent into a circle of diameter 7.5 cms, with a small brass sphere on one end, and the other end of the wire was pointed, with the point near the sphere. He added a screw mechanism so that the point could be moved very close to the sphere in a controlled fashion. This "receiver" was designed so that current oscillating back and forth in the wire would have a natural period close to that of the "transmitter" described above. The presence of oscillating charge in the receiver would be signaled by a spark across the (tiny) gap between the point and the sphere (typically, this gap was hundredths of a millimeter). The experiment was very successful - Hertz was able to detect the radiation up to fifty feet away, and in a series of ingenious experiments established that the radiation was reflected and refracted as expected, and that it was polarized. The main problem - the limiting factor in detection -- was being able to see the tiny spark in the receiver. In trying to improve the spark's visibility, he came upon something very mysterious. To quote from Hertz again (he called the transmitter spark A, the receiver B): "we occasionally enclosed the spark B in a dark case so as to more easily make the observations; and in so doing we observed that the maximum spark-length became decidedly smaller in the case than it was before. On removing in succession the various parts of the case, it was seen that the only portion of it which exercised this prejudicial effect was that which screened the spark B from the spark A. The partition on that side exhibited this effect, not only when it was in the immediate neighbourhood of the spark B, but also when it was interposed at greater distances from B between A and B. A phenomenon so remarkable called for closer investigation."

Hertz then embarked on a very thorough investigation. He found that the small receiver spark was more vigorous if it was exposed to ultraviolet light from the transmitter spark. It took a long time to figure this out - he first checked for some kind of electromagnetic effect, but found a sheet of glass effectively shielded the spark. He then found a slab of quartz did not shield the spark, whereupon he used a quartz prism to break up the light from the big spark into its components, and discovered that the wavelength which made the little spark more powerful was beyond the visible, in the ultraviolet.

3.1.2.1. Hallwachs' Simpler Approach

The next year, 1888, another German physicist, Wilhelm Hallwachs, in Dresden, wrote:

"In a recent publication Hertz has described investigations on the dependence of the maximum length of an induction spark on the radiation received by it from another induction spark. He proved that the phenomenon observed is an action of the ultraviolet light. No further light on the nature of the phenomenon could be obtained, because of the complicated conditions of the research in which it appeared. He then describes his very simple experiment: a clean circular plate of zinc was mounted on an insulating stand and attached by a wire to a gold leaf electroscope, which was then charged negatively. The electroscope lost its charge very slowly. However, if the zinc plate was exposed to ultraviolet light from an arc lamp, or from burning magnesium, charge leaked away quickly. If the plate was positively charged, there was no fast charge leakage. (We showed this as a lecture demo, using a UV lamp as source.)

Although Hallwach's experiment certainly clarified the situation, he did not offer any theory of what was going on.

In fact, the situation remained unclear until 1899, when Thomson established that the ultraviolet light caused electrons to be emitted, the same particles found in cathode rays. His method was to enclose the metallic surface to be exposed to radiation in a vacuum tube, in other words to make it the cathode in a cathode ray tube. The new feature was that electrons were to be ejected from the cathode by the radiation, rather than by the strong electric field used previously.

By this time, there was a plausible picture of what was going on. Atoms in the cathode contained electrons, which were shaken and caused to vibrate by the oscillating electric field of the incident radiation. Eventually some of them would be shaken loose, and would be ejected from the cathode. It is worthwhile considering carefully how the number and speed of electrons emitted would be expected to vary with the intensity and color of the incident radiation. Increasing the intensity of radiation would shake the electrons more violently, so one would expect more to be emitted, and they would shoot out at greater speed, on average. Increasing the frequency of the radiation would shake the electrons faster, so might cause the electrons to come out faster. For very dim light, it would take some time for an electron to work up to a sufficient amplitude of vibration to shake loose.

In 1902, **Lenard** studied how the energy of the emitted photoelectrons varied with the intensity of the light. He used a carbon arc light, and could increase the intensity a thousand-fold. The ejected electrons hit another metal plate, the collector, which was connected to the cathode by a wire with a sensitive ammeter, to measure the current produced by the illumination. To measure the energy of the ejected electrons, Lenard charged the collector plate negatively, to repel the electrons coming towards it. Thus, only electrons ejected with enough kinetic energy to get up this potential hill would contribute to the current. Lenard discovered that there was a well defined minimum voltage that stopped any electrons getting through, we'll call it V_{stop}. To his surprise, he found that V_{stop} did not depend at all on the intensity of the light! Doubling the light intensity doubled the number of electrons emitted, but did not affect the energies of the emitted electrons. The more powerful oscillating field ejected more electrons, but the maximum individual energy of the ejected electrons was the same as for the weaker field.

But Lenard did something else. With his very powerful arc lamp, there was sufficient intensity to separate out the colors and check the photoelectric effect using light of different colors. He found that the maximum energy of the ejected electrons did depend on the color --- the shorter wavelength, higher frequency light caused electrons to be ejected with more energy. This was, however, a fairly qualitative conclusion --- the energy measurements were not very reproducible, because they were extremely sensitive to the condition of the surface, in particular its state of partial oxidation. In the best vacua available at that time, significant oxidation of a fresh surface took place in tens of minutes.

In the above figure, the battery represents the potential Lenard used to charge the collector plate negatively, which would actually be a variable voltage source. Since the electrons ejected by the blue light are getting to the collector plate, evidently the potential supplied by the battery is less than V_{stop} for blue light. the wire the direction of the electric current in the wire.

3.1.2.2. Einstein Suggests an Explanation

In 1905 Einstein gave a very simple interpretation of Lenard's results. He just assumed that the incoming radiation should be thought of as quanta of frequency hf, with f the frequency. In photoemission, one such quantum is absorbed by one electron. If the electron is some distance into the material of the cathode, some energy will be lost as it moves towards the surface. There will always be some electrostatic cost as the electron leaves the surface, this is usually called the work function, W. The most energetic electrons emitted will be those very close to the surface, and they will leave the cathode with kinetic energy

$$E = hf - W$$

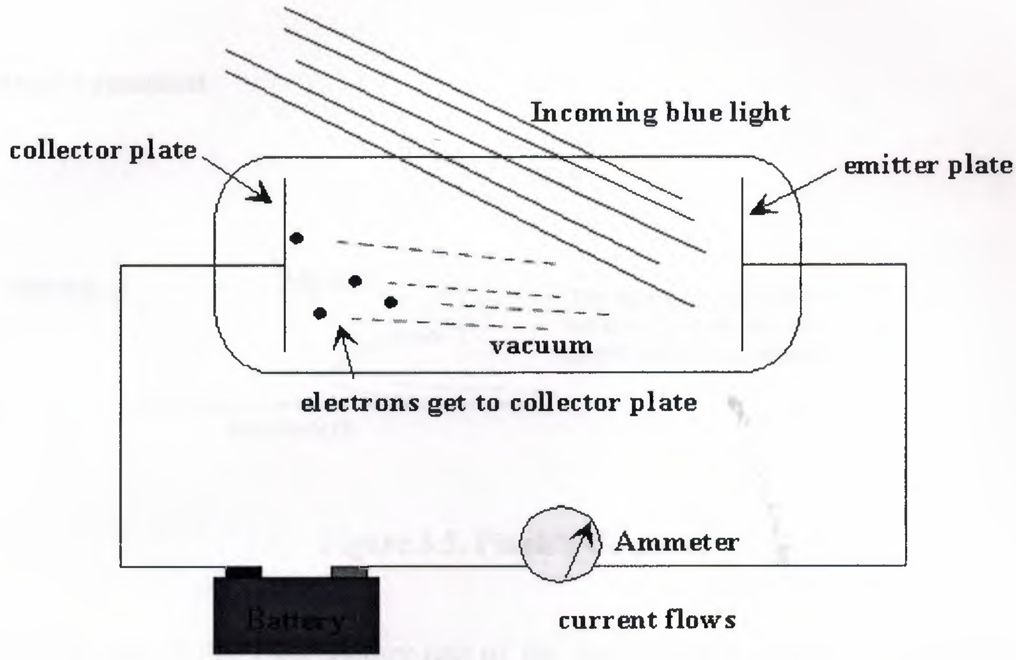


Figure 3.6. Battery Represent of Potential

On cranking up the negative voltage on the collector plate until the current just stops, that is, to V_{stop}, the highest kinetic energy electrons must have had energy eV_{stop} on leaving the cathode. Thus,

$$eV_{stop} = hf - W$$

Thus Einstein's theory makes a very definite quantitative prediction: if the frequency of the incident light is varied, and V_{stop} plotted as a function of frequency, the slope of the line should be h/e.

It is also clear that there is a minimum light frequency for a given metal, that for which the quantum of energy is equal to the work function. Light below that frequency , no matter how bright, will not cause photoemission.

3.1.2.3. Millikan's Attempts to Disprove Einstein's Theory

This is a completely different way to measure Planck's constant. The American experimental physicist Robert Millikan, who did not accept Einstein's theory, which he saw as an attack on the wave theory of light, worked for ten years, until 1916, on the photoelectric effect. He even devised techniques for scraping clean the metal surfaces inside the vacuum tube. For all his efforts he found disappointing results: he confirmed Einstein's theory, measuring Planck's constant to within 0.5% by this method. One consolation was that he did get a Nobel prize for this series of experiments.

3.1.3. Planck's constant

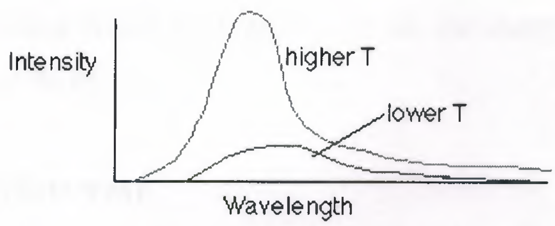


Figure 3.5. Plank's Constant

At the end of the 19th century one of the most intriguing puzzles in physics involved the spectrum of radiation emitted by a hot object. Specifically, the emitter was assumed to be a blackbody, a perfect radiator. The hotter a blackbody is, the more the peak in the spectrum of emitted radiation shifts to shorter wavelength. Nobody could explain why there was a peak in the distribution at all, however; the theory at the time predicted that for a blackbody, the intensity of radiation just kept increasing as the wavelength decreased. This was known as the ultraviolet catastrophe, because the theory predicted that an infinite amount of energy was emitted by a radiating object.

Clearly, this prediction was in conflict with the idea of conservation of energy, not to mention being in serious disagreement with experimental observation. No one could account for the discrepancy, however, until Max Planck came up with the idea that a blackbody was made up of a whole bunch of oscillating atoms, and that the energy of each oscillating atom was quantized. That last point is the key : the energy of the atoms could only take on discrete values, and these values depended on the frequency of the oscillation:

Planck's prediction of the energy of an oscillating atom : $E = nhf$ ($n = 0, 1, 2, 3 ...$)

where f is the frequency, n is an integer, and h is a constant known as Planck's constant. This constant shows up in many different areas of quantum mechanics.

Planck's constant : $h = 6.63 \times 10^{-34}$ J s

The spectra predicted for a radiating blackbody made up of these oscillating atoms agrees very well with experimentally-determined spectra.

Planck's idea of discrete energy levels led Einstein to the idea that electromagnetic waves have a particle nature. When Planck's oscillating atoms lose energy, they can do so only by making a jump down to a lower energy level. The energy lost by the atoms is given off as an electromagnetic wave. Because the energy levels of the oscillating atoms are separated by hf, the energy carried off by the electromagnetic wave must be hf.

3.1.4. Particle wave

The probability of finding a particle at a particular location, then, is related to the wave associated with the particle. The larger the amplitude of the wave at a particular point, the larger the probability that the electron will be found there. Similarly, the smaller the amplitude the smaller the probability. In fact, the probability is proportional to the square of the amplitude of the wave.

3.1.5. Particle-Wave Duality

In 1905 Einstein went further and suggested that light itself could behave like little particles or quanta, with energy proportional to the frequency (the colour) of the light. These particles of light are what we now call photons. Einstein's suggestion went straight to the heart of Quantum Theory, and began to expose the fundamental conceptual difficulties associated with it. Indeed it was for this work that he was awarded the Nobel prize in 1921.

During the 19th century experimental and theoretical work on light had demonstrated - apparently conclusively - that light was a wave. The key experimental evidence for this is the observation of interference. If you drop a pebble into a still pond, you see circular wavelets spreading out. Drop another pebble in nearbye, and the two s interfere where they overlap. Where the crest of one and the trough of another coincide, they cancel to leave the water undisturbed. At neighbouring places the cancellation is less perfect, and elsewhere the peaks or troughs of the two waves coincide and reinforce each other. Exactly this type of interference pattern can be observed with light, and it can only be explained by a wave theory.

If light behaves like little particles there is a difficulty in accounting for interference phenomena. But even worse, from the point of view of classical physics, streams of electrons, neutrons, and even atoms produce similar interference patterns. So particles show wave-like behaviour, and light, according to Einstein, shows particle-like behaviour. This is the famous problem of particle-wave duality.

The de Broglie wavelength

In 1923, Louis de Broglie predicted that since light exhibited both wave and particle behavior, particles should also. He proposed that all particles have a wavelength given by:

de Broglie wavelength : $\lambda = h / p$

Note that this is the same equation that applies to photons.

de Broglie's prediction was shown to be true when beams of electrons and neutrons were directed at crystals and diffraction patterns were seen. This is evidence of the wave properties of these particles.

Everything has a wavelength, but the wave properties of matter are only observable for very small objects.

The two-slit interference experiment

It is worth examining interference in more detail, and the simplest demonstartion of it is the two-slit interference experiment. Feynman said that this is

a phenomenon which has in it the heart of Quantum Mechanics. In reality, it contains the only mystery.

Here a source of light shines on a screen in which have been cut two vertical slits, A and B. Light which passes through the slits is detected on a distant screen. We might expect the illumination on the detector screen to consist of two paler patches where light from only one slit falls, and a brighter panel in the centre (in the region between a and b in the diagram) where the two beams overlap:

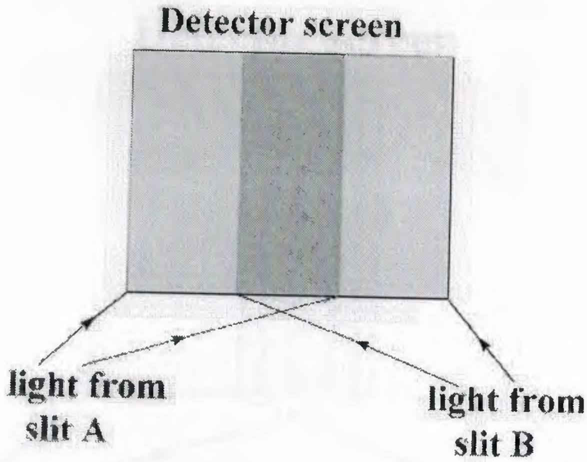


Figure 3.8. Detector Screen

In fact we see a pattern of light and dark vertical stripes in the central region. This is the 2-slit interference pattern:

The interference pattern is easily understood if we think of waves from the two slits reaching the same point on the detector and interfering. But it would not be expected for streams of particles. Each particle would go through one slit or the other, and we should expect an increased number of particles to arrive in the central area of the detector. But the detection of one particle cannot be cancelled out by the arrival of another. So the minima - the dark stripes - of the pattern cannot be explained in terms of particles.

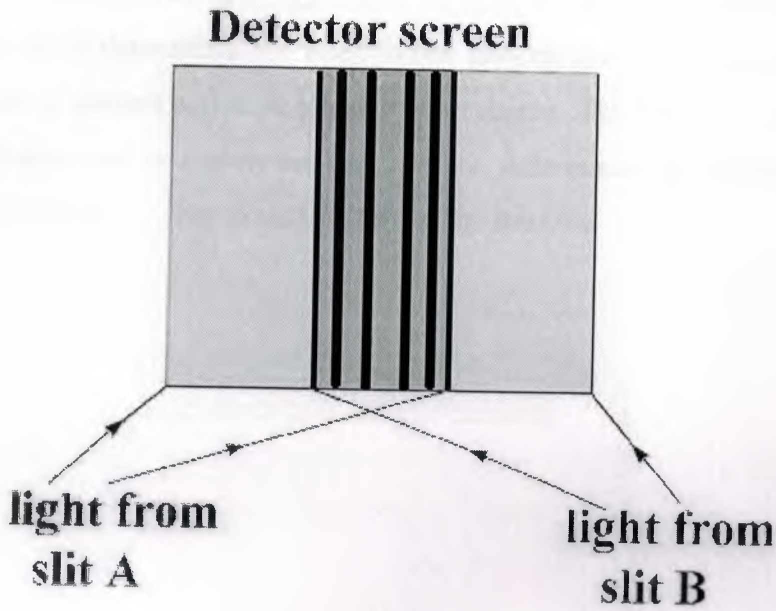


Figure 3.7. Detector Screen

Even worse, if we reduced the intensity of the source sufficiently we can arrive at *a situation where only one particle at a time arrives on the detector. In this situation* what we see on the detector is surprising: Each particle that arrives produces a spot on the screen. So the detector sees the arriving light as individual particles. When only a few particles have arrived it looks as though the pattern of arrival points is random, but eventually, when enough points have been collected, we see that the interference pattern appears. It is made up of a very large number of separate spots, each marking the arrival of a particle.

Since the pattern can be built up with particles going through the apparatus one at a time, the path of each individual particle must be constrained so that it avoids arriving at an interference minimum. If we close slit B, to try and establish which regions of the pattern are due to particles going through slit A, the pattern vanishes and particles begin to arrive at minima - points which they would be unable to reach if both slits were open. It seems that in some way the path of a particle passing through one slit A say - is affected by whether or not the other slit - which it DOESN'T pass through - is open or not!

To explain the two-slit experiment we need a wave to be associated with each particle. This wave determines the interference pattern, and constrains the path of the particle so that it doesn't arrive at interference minima. The intensity of this quantum mechanical wave over a region on the detector determines the probability that the particle will arrive there - this should be zero at the minima.

CHAPTER IV

LIGHT DETECTOR AND FORMATION

4.1. DETECTOR

When we talk about a "light detector", we are referring to any instrument that detects electromagnetic radiation. For example, your eye is a type of light detector. It detects white visible light, which contains all the colors of the rainbow from red to violet.

But, remember how we said that some light is "invisible" to the human eye? Well, to detect this type of radiation, we need different detectors to be able to "see" the radiation. X-ray machines, radios, cell phones, and even your television (unless you have cable) are all types of light detectors.

4.1.1. Infrared Radiation

Infrared radiation is what we like to describe as heat. We can't see infrared waves, but we can feel them. Our body gives off heat, so it is an emitter of infrared radiation.

The range of infrared wavelengths is about sub-millimeters to micrometers (the size of a bacteria).

4.1.2. The Visible Spectrum

Visible light is the light that we can see, and thus is the only light detectable by the human eye. White light is visible light, and it contains all the colors of the rainbow, from red to violet. The range of visible wavelengths is 400 to 700 nanometers.

Ultraviolet light is the radiation from the sun that causes a sunburn when you have been outside too long on a sunny day. But, watch out! The range for ultraviolet light is 10^{-8} to 10^{-10} meters.

Gamma rays are the most energetic light waves found on the electromagnetic spectrum. We can find Gamma rays released in nuclear reactions and particle collisions. The range for a gamma ray is in picometers (10^{-12} meters).

4.2. DEFINITION OF LIGHT

Light is simply a name for a range of electromagnetic radiation that can be detected by the human eye.

Electromagnetic radiation has a dual nature as both particles and waves. One way to look at it is as changing electric and magnetic fields which propagate through space, forming an electromagnetic wave. This wave has amplitude, which is the brightness of the light, wavelength, which is the color of the light, and an angle at which it is vibrating, called polarization.

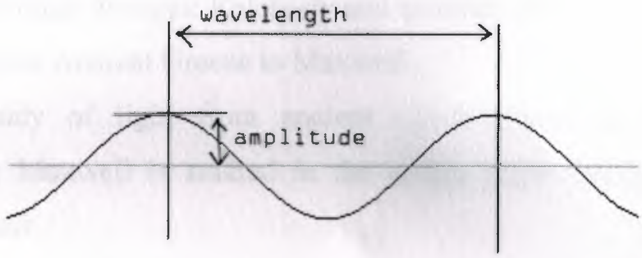


Figure 4.1. Polarization of Light

This was the classical interpretation, crystallized in Maxwell's Equations, which held sway until Planck, Einstein and others came along with quantum theory. In terms of the modern quantum theory, electromagnetic radiation consists of particles called photons, which are packets ("quanta") of energy which move at the speed of light. In this particle view of light, the brightness of the light is the number of photons, the color of the light is the energy contained in each photon, and four numbers (X, Y, Z and T) are the polarization.

Both of them, actually. It turns out electromagnetic radiation can have both wave-like and particle-like properties as demonstrated in experiments such as the dual slit experiment. In this exploration of light, we will primarily take the wave viewpoint as it is a more useful description of the everyday properties of light, but keep in mind that both viewpoints are valid, and sometimes we will use the quantum viewpoint too.

On to the numbers! Light ranges from wavelengths of 7x10-5 cm (red) to 4x10-5 cm (violet) and (like all electromagnetic radiation) travels at the speed of light, 299,792,458 meters per second or 186,282 miles per second. (Interesting fact: the speed of light is actually defined to be 299,792,458 meters per second and scientists combine this with the definition of a second to create the definition of a meter! As stated at the 17th General conference on weights and Measures, "The meter is the length of the path traveled by light in a vacuum during a time interval of 1/299,792,458 of a second.")

The frequency (number of wavelengths per second) of a light wave may be calculated using the equation c=ln where l is the wavelength, n is the frequency and c is the speed of light. In quantum theory, a photon has energy equal to hn, where h is Plank's constant and n is the frequency of the light in classical theory.

4.3. HISTORY OF LIGHT DETECTOR

Light through the ages: Relativity and quantum era .

Light from Ancient Greece to Maxwell .

The study of light from ancient Greek times up to the revolutionary breakthrough by Maxwell is studied in the article Light through the ages: Ancient Greece to Maxwell.

Maxwell can be thought of as the person who completed the classical description of light, and also as the person who began the modern developments.

He wrote an article for Encyclopaedia Britannica in 1878 in which he described how light is propagated as a transverse wave, and that its consists of electromagnetic radiation with specific wavelengths.

There certainly were extreme difficulties with the idea, as Maxwell was well aware, for to carry such high frequency vibrations as light the substance needed to be incredibly rigid, yet the earth, moon and other planets passed through this rigid material as if it were not there.

However, in his 1878 Encyclopaedia Britannica article Maxwell proposed an experiment to determine the velocity of the earth through the aether using light in the following way.

Split a ray of light, suggested Maxwell, and send the two resulting rays at right angles to each other.

Although he could detect no difference in the time taken by the two rays of light, this was put down to his experiment not being accurate enough or that the earth dragged the aether with it in much the same way that it drags the atmosphere.

This was so accurate that when it failed to show any difference in the time taken by the two rays of light, it could no longer be put down to experimental error.

Of course the result of the Michelson-Morley experiment is totally incomprehensible if one thinks in a classical way about light travelling.

It gets back to the detector in the same length of time irrespective of whether the detector is moving or not.

FitzGerald explained the failure of the Michelson-Morley experiment in 1889 by suggesting that a moving object is foreshortened in the direction of travel.

The amount of this foreshortening for an object moving with velocity v was sqrt (1 - v2/c2), where c is the velocity of light.

Of course this is very close to 1 for velocities v which are small compared to that of light but it explained the results of the experiment by foreshortening the instruments while still allowing there to be an aether through which light travelled at a fixed velocity.

Lorentz, independently, made a similar suggestion to FitzGerald and worked out the full implications of it in 1904 giving transformations which would describe the way that light would look to observers moving relative to each other.

Einstein published the special theory of relativity in the following year which is based on the remarkable suggestion that the speed of light remains constant for all observers independent of their relative velocities.

However it had its origin from the time that Einstein was a boy when he tried to imagine what would happen if he were moving at the same speed as a beam of light.

Of course if the notion that the speed of light is the same for all observers seems hard to understand, then so would the classical view which would suggest that if one could travel faster than light then one could set out on a journey and arrive soon enough to be able to look back and see oneself setting out! .

In 1915 Einstein published the general theory of relativity which predicted the bending of rays of light passing through a gravitational field.

In 1926 Michelson carried out his last and most accurate experiment to determine the velocity of light.

Using a light path of length 35 km from the Mount Wilson observatory to the telescope on Mount San Antonio, he found the value of 299,796 km per sec.

Another important development in the understanding of light, namely the development of quantum theory, had taken place over this same period of time, roughly 1880 to 1926.

Lord Rayleigh made an important contribution to light in 1899 when he explained that the sky is blue, and sunsets are red, because blue light is scattered by molecules in the earth's atmosphere.

He did not believe in the physical reality of the light quanta, there was far too much evidence that light was a transverse wave for him to change to a corpuscular theory on account of this.

Planck thought of his quanta as a mathematical way round the problem of blackbody radiation, rather than thinking that light was actually composed of particles.

A second problem also led to a quantum theory of light, and this time to a belief in the physical reality of the quanta.

Heinrich Hertz discovered the photoelectric effect, so called because it was caused by light rays, in 1887.

He observed that when that ultraviolet light was shone onto metallic electrodes the voltage required for sparking to take place was lowered.

In 1900 Philipp Lenard, a student of Hertz, showed that the photoelectric effect was caused by electrons, which had been discovered by J J Thomson three years earlier, being ejected from the surface of a metal plate when it was struck by light rays.

In 1905 Einstein explained the photoelectric effect by showing that light was composed of discrete particles, now called photons, which are essentially energy quanta.

The wave theory of light, which had totally triumphed over the corpuscular theory, could not explain this effect.

Bose published his paper Planck's Law and the Hypothesis of Light Quanta in 1924 which derived the blackbody radiation from the hypothesis that light consisted of particles obeying certain statistical laws.

Not only could photons of light behave like waves, suggested de Broglie, but so could other particles such as the electron.

In 1927 de Broglie's claim that electrons could behave like waves was experimentally verified and, in the following year, Bohr put forwards his complementarity principle which stated that photons of light (and electrons) could behave either as waves or as particles, but it is impossible to observe both the wave and particle aspects simultaneously.

In 1927 Heisenberg put forward his uncertainty principle which states that there is a limit to the precision with which the position and the momentum a particle of light can be known.

It attempted to explain the dual wave-particle duality of light which, in the words of Baierlein [1]:- .

The main idea of the Copenhagen interpretation is the collapse of the wave function, namely that observing light waves makes them collapse into particles.

The clearest example of how this works is to look again at Thomas Young's experiment of passing rays of light through two parallel slits and observing the interference patterns on a screen behind (see the article Light through the ages: Ancient Greece to Maxwell).

This is a classical demonstration of the wave nature of light.

Even more strange is the fact that it we put a detector on one of the slits to tell us whether the photon goes through that slit or the other one then the interference pattern vanishes.

The nature of light really is strange! But this behaviour is not limited to photons of light far, as de Broglie predicted, electrons behave in exactly the same way.

It now appears that we, as observers, affect the way that light behaves.

This will lead us to deep philosophical questions and eventually we will be forced to ask whether the universe only exits because there are intelligent beings to observe it.

The Copenhagen interpretation is in trouble from experimental evidence too, for recent subtle experiments have managed to create a situation where photons of light behave both as waves and particles at the same time contrary to Bohr's complementarity principle.

But we are getting too deeply into modern day physics and away from the history, so let us end our look at the dual wave-particle nature of light here.

There has been one other important development in the theory of light in the 20th century which we no not want to examine in too much detail, as it also takes us too deeply into physics, but needs to be mentioned in an article on the history of light.

This is the development of lasers, an acronym of "light amplification by stimulated emission of radiation".

The basic concept goes back to Einstein in 1916 when he showed that if an atom is excited so that it moves to a higher energy level, then if light falls on the atom at the instant it is moving to the higher energy level, then it emits radiation that is in phase with the wave that stimulated it and so amplifies that wave.

It was many years after Einstein discovered the principle of stimulated emission before it became possible to built a device which would produce such a coherent beam of light.

C H Townes, J P Gordon and H J Zieger built a device at Columbia University in 1953 which used ammonia to produce a coherent beam, not of light at optical wavelengths, but of microwave radiation.

In 1958 A L Schawlow and C H Townes described how a device might amplify light by stimulated emission and the first such device was built in 1960 at the Hughes Research Laboratories by T H Maiman using a rod of ruby.

4.4. A LIGHT DETECTOR

The Visible Haze Sensor requires a light detector to measure the intensity of the sunlight which gets through the haze. There are many combinations of light sources and detectors you could explore. This suggests the possibility of an extension to study detectors in detail. Here you will consider only one; a photoresistor. In this activity, you will gain a sense it works, and its light detecting capability.You should use LED's of different colors, and an incandescent (flashligh) bulb to investigate the properties of this detector.

Materials

- Photoresistor
- LED's of sevral colors
- Incandescent bulb
- Multimeter
- Battery
- Resistors, 330 ohm and 100 ohm.

We will need the volt-ohmmeter for measuring the electrical response of the detector. We will need a battery. If you use a battery for the incadescent lamp, be sure to match the voltage requirements of the bulb and battery. For instance, if the lamp needs 3 V, use a pair of 1.5 V batteries (A, C, or D). The simplest strategy might be to use a 9 V lamp and battery. We will need a 100 ohm and 330 ohm resistor. A breadboard would be helpful, too.

Connections for the light sources.

If our incadescent light needs a battery, you can connect it directly to the batttery for which it is rated. The LEDs, on the other hand, should NOT be connected directly to a battery. If we try this, you will fry the LED. You need a resistor in series to limit the current. Try a 330 ohm resistor first. If the LED is too dim, then use a 100 ohm resistor.

4.4.1. LED Light Source

A LED will only pass current in one direction. If we cannot light our LED, try reversing its leads. Most LEDs have one lead longer than the other. The shorter lead should be connected to the negative terminal of the battery.

4.4.2. LED Connections for the Detector.

A photoresistor changes resistance depending on the light falling on it. To use it, simply attach its leads to a volt ohmmeter and set the meter to measure ohms.

Testing the Detector

Try out our detector on the various light sources. Be sure the detector "sees" only the light source and is not illuminated by room lighting or another source. We might do this by making your observations in a light-tight box, or by turning off room lights. Measure the response of the detector at the same distance from each source. Then double the distance. This should (if the detector has a linear response) result in one-quarter the amount of light falling on the detector

4.4.3. THE WORKING OF A LIGHT DETECTOR

In radio, the information that is to be transmitted to a distant receiver is placed on a high frequency alternating current that acts as a carrier for the information. To convey the information, the carrier signal must be modulated in some fashion. Most radio systems either vary the amplitude (amplitude modulation, AM) or the frequency (frequency modulation, FM) of the carrier. To extract the information from the carrier at the receiver end, some kind of detector circuit must be used.

In optical communications a light source forms the carrier and must also be modulated to transmit information. Virtually all present optical communications systems modulate the intensity of the light source. Usually the transmitter simply turns the light source on and off. To decode the information from the light pulses, some type of light detector must be employed. The detector's job is to convert the light signals, collected at the receiver, into electrical signals. The electrical signals produced by the detector's optical energy to electrical energy conversion are much easier to demodulate than pure light signals.

As discussed in the section on light theory, although light is a form of energy, it is the intensity or power of the light that determines its strength. Therefore, the real job of the light detector is to convert light power into electrical power, independent of the energy of the transmitted light pulses. This relationship also implies that the conversion is independent of the duration of the light pulses used. This is an important concept and is taken advantaged of in many of the systems that follow.

4.5. The Silicon PIN Photo Diode

There are many kinds of light detectors, such as a "photo transistor", "photo cells" and "photo resistors" but there are only a few devices that are practical for through-the-air optical communications. Although these circuits worked after a fashion, they could have functioned much better if the design had used a different detector. From the list of likely detectors, only the silicon "PIN" photodiode has the speed, sensitivity and low cost to be a practical detector. For this reason virtually all of the detector circuits described in this book will call for a PIN photodiode.

As the letters PNP and NPN designate the kind of semiconductor materials used to form transistors, the "I" in the "PIN" photodiode indicates that the device is made from "P" and "N" semiconductor layers with a middle intrinsic or insulator layer.

Most PIN photodiodes are made from silicon and specific response curves. Look carefully at the curve. Note that the device is most sensitive to the near infrared wavelengths at about 900 nanometers. Also notice that the device's response falls off sharply beyond 1000 nanometers, but has a more gradual slope toward the shorter wavelengths, including the entire visible portion of the spectrum. In addition, note that the device's response drops to about ½ its peak at the visible red wavelength (640 nanometers. Fortunately, most IR light emitting diodes (LEDs) and infrared lasers do indeed emit light at or near the 900nm peak, making them ideal optical transmitters of information.

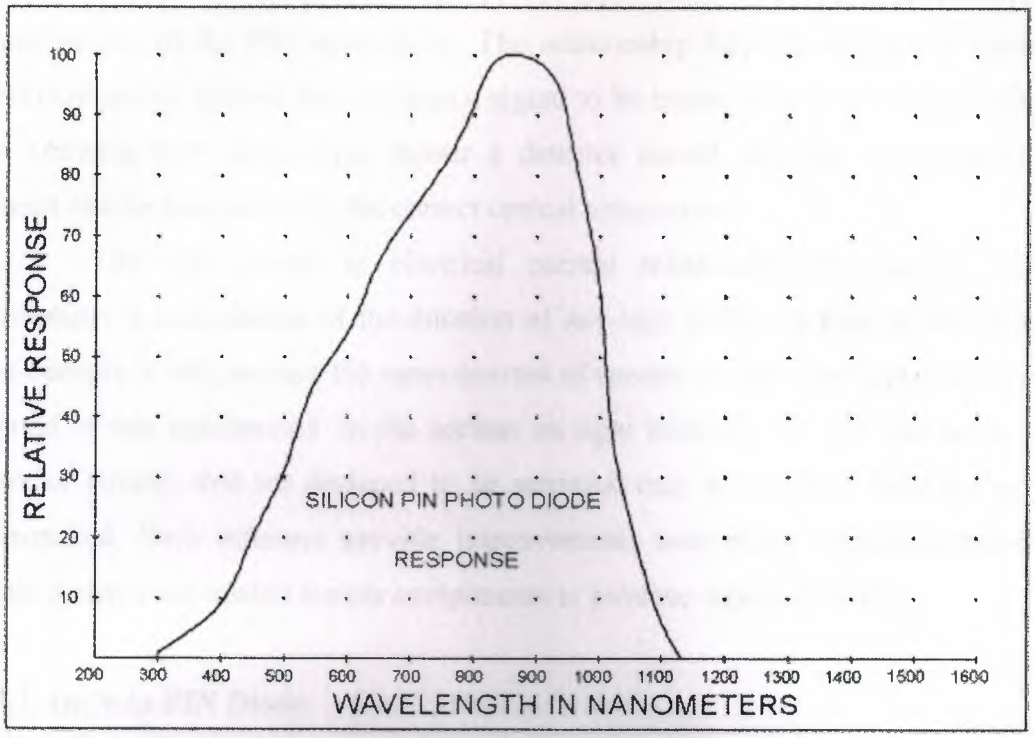


Figure 4.2. Response Of Silicon Photo Diode

The PIN photo detector behaves very much like a small solar cell or solar battery that converts light energy into electrical energy. Like solar cells, the PIN photodiode will produce a voltage (about 0.5v) in response to light and will also generate a current proportional to the intensity of the light striking it. However, this In the reversed biased mode, the PIN detector is biased by an external direct current power supply ranging from a few volts to as high as 50 volts. When biased, the device behaves as a leaky diode whose leakage current is dependent on the intensity of the light striking the device's active area. It is important to note that the intensity of a light source is defined in terms of power, not energy. When detecting infrared light at its 900 nanometer peak response point, a typical PIN diode will leak about one milliamp of current for every two milliwatts of light power striking it (50% efficiency).

For most devices this relationship is linear over a 120db (1 million to one) span, ranging from tens of milliwatts to nanowatts. Of course wavelengths other than the ideal 900 nanometer peak will not be converted with the same 50% efficiency. If a visible red light source were used the light to current efficiency would drop to only 25%.

The current output for light power input relationship is the most important characteristic of the PIN photodiode. The relationship helps to define the needs of a communications system that requires a signal to be transmitted over a certain distance. By knowing how much light power a detector circuit requires, a communications system can be designed with the correct optical components.

The light power to electrical current relationship also implies that the conversion is independent of the duration of any light pulse. As long as the detector is fast enough, it will produce the same amount of current whether the light pulse lasts one second or one nanosecond .İn the section on light receivers we will use some unique detector circuits that are designed to be sensitive only to the short light pulses being transmitted. Such schemes provide improvements over many existing commercially made systems and enable simple components to produce superior results.

4.5.1. InGaAs PIN Diode

Silicon is not the only material from which to make a solid-state light detector. Other photodiodes made from Gallium and Indium semiconductors work well at longer infrared wavelengths than silicon devices. These devices have been used for many years in optical fiber communications systems, which rely on longer wavelengths. Glass optical fibers operate more efficiently at these longer wavelengths. The curve shown below is the typical response for this device but peak can be shifted slightly as needed. As shown in the curve (Figure 2a-1), an InGaAs photodiode's response includes only some of the wavelengths that a silicon photodiode covers small active areas.

4.5.2. Typical PIN Diode Specifications

Package: PIN silicon photodiodes come in all sizes and shapes. Some commercial diodes are packaged in special infrared (IR) transparent plastic. The plastic blocks most of the visible wavelengths while allowing the IR light to pass. The plastic appears to be a deep purple color when seen by our eyes but it is nearly crystal clear to infrared light. Some of these packages also place a small plastic lens in front of the detector's active area to collect more light. As long as the modulated light being detected is also IR either the filtered or the unfiltered devices will work.

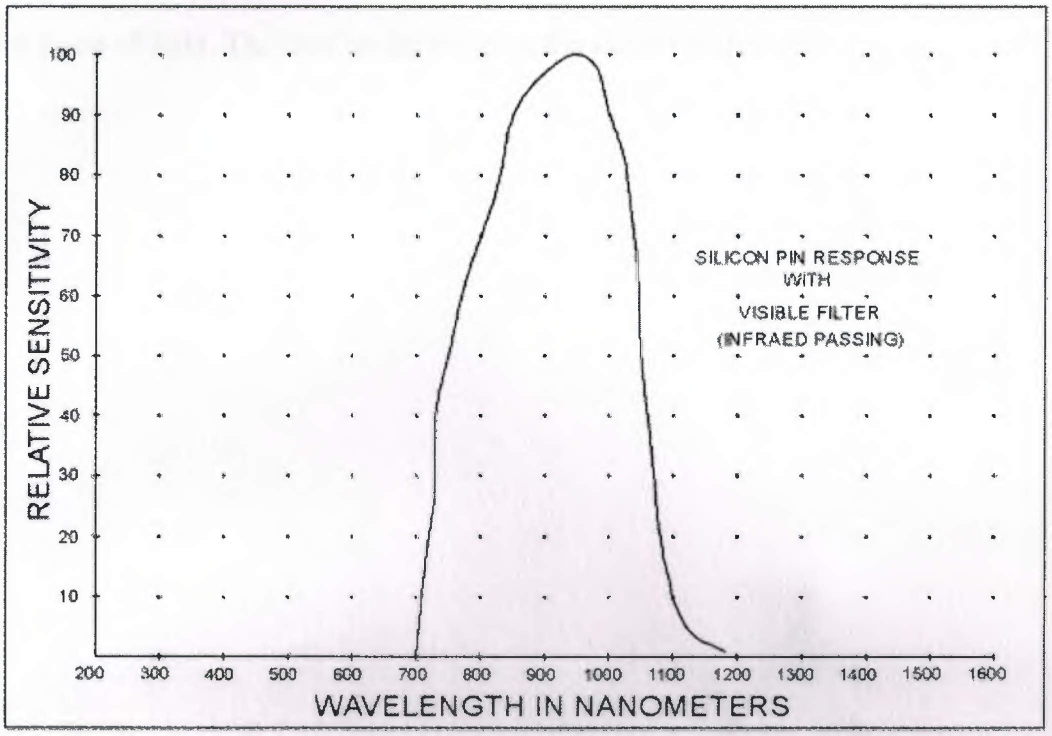


Figure 4.3. **Silicon Pin Response With Visible Filter**

Active Area: There will usually be an active area specification for PIN photodiodes. This corresponds to the size of the actual light sensitive region, independent of the package size. PINs with large active areas will capture more light but will always be slower than smaller devices and will also produce more noise. However, if a small device contains an attached lens it will often collect as much light as a much larger device without a lens. But, the devices with attached lenses will collect light over narrower incident angles (acceptance angle). Flat surface devices are usually used if light must be detected over a wide area. For most applications either style will work. For high speed applications a device with a small active area is always recommended. However, there is a tradeoff between device speed and the active area. For most long-range applications, where a large light collecting lens is needed, a large area device should be used to keep the acceptance angle from being too small. Small acceptance angles can make it nearly impossible to point the receiver in the right direction to collect the light from the distant transmitter.

Response Time: All PIN photodiodes will have a response time rating that is usually listed in nanoseconds. The rating defines the time the device needs to react to a short pulse of light. The smaller the number, the faster the device.

CHAPTER V

OTHER IMPORTANT LIGHT DETECTORS

5.1. PHOTO TRANSISTOR

Most phototransistors will have response times measured in tens of microseconds, which is some 100 times slower than similar PIN diodes. Such slow speeds reduce the usefulness of the device in most communications systems. They also have the disadvantage of having small active areas and high noise levels. You will often find them being used for simple light reflector and detector applications that do not rely on fast light pulses. But, overall, they are a poor substitute for a good PIN diode when connected to well designed receiver circuit

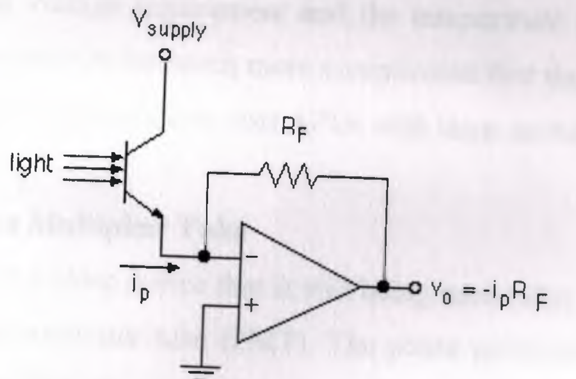


Figure 5.1. photo transistor amplification

This amplification gives the photo transistor much more light sensitivity than a standard PIN diode. But, with the gain comes a price. The photodiode/transistor connection dramatically slows down the otherwise fast response time of the diode inside..

Avalanche Photo Diode: Although the silicon PIN detector is the most universal device for nearly all optical communications applications, there are a few other devices worth mentioning. Once such device is an "APD" or avalanche photodiode. An APD is a special light detecting diode that is constructed in much the same way as a PIN photodiode. Unlike a PIN diode, that only needs a bias of a few volts to function properly, an APD is biased with voltages up to 150 volts. When light strikes the device it leaks current in much the same way as a typical PIN diode, but at much higher levels. Unlike a PIN diode that may produce only one microamp of current for two microwatts of light, an APD can leak as much as 100 microamps for each microwatt (x100 gain). This gain factor is very dependent on the bias voltage used and the APDs operating temperature. Some systems take advantage of these relationships and vary the bias voltage to produce the desired gain. When used with narrow optical band pass filters and laser light sources APDs could allow a through-the-air system to have a much higher light sensitivities and thus longer ranges than might otherwise be possible with a standard PIN device. However, in systems that use LEDs, the additional noise produced by the ambient light focused onto the device cancels much of the gain advantage the APD might have had over a PIN. Also, most commercial APDs have very small active areas, making them very unpopular for through-the-air applications. They are also typically 20 times more expensive than a good PIN photodiode. Finally, the high bias voltage requirement and the temperature sensitivity of the APD causes the detector circuit to be much more complicated that those needed with a PIN. Still, as the technology improves, low cost APDs with large active areas may become available.

5.2. Photo Multiplier Tube

An older device that is still being used today to detect very weak light levels is the photo multiplier tube (PMT). The photo multiplier is a vacuum tube that operates somewhat like an avalanche photodiode. Light striking a special material called a "photo cathode" forces electrons to be produced. A high voltage bias between the cathode and a nearby anode plate accelerates the electrons toward the anode. The high speed electrons striking the first anode causes another material coated on the anode to produce even more electrons. Those electrons are then accelerated toward a second anode. The process is repeated with perhaps as many as ten stages.

This high gain makes the PMT the most light sensitive device known. They are also fast. Some will have response times approaching good PIN diodes. However, the PMT has several drawbacks. It is a physically large device. Also, since it is made of glass, it is much more fragile than a solid state detector.

Also, the high voltage bias, that is required, makes the supporting circuits much more complicated. In addition, because of the very high gains available, stray light must be kept to very low levels. The ambient light associated with a through-the-

Figure 2c-1.) Finally, PMTs are usually very expensive. Still, PMTs do have rather large active areas. If used with visible wavelength lasers and narrow optical filters, a PMTs large active area could allow a receiver system to use a very large light collecting lens. If optimized, such a system could yield a very long range. But overall, a PMTs disadvantages far outweigh their advantages in most applications.

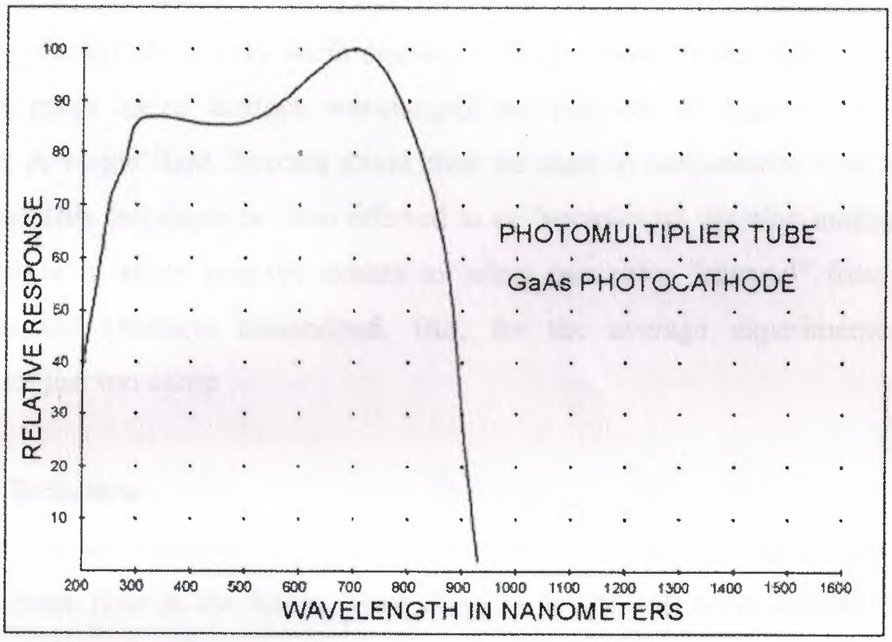


Figure 5.3.**Photomultiplier Tube GaAs Photocathode**

5.3. Optical Heterodyning

Another detector scheme, that has already been demonstrated in the laboratory and may someday be available to the experimenter, is "optical heterodyning". The scheme doesn't actually use a new detector but rather a new way of processing the light with an existing detector. Students of electronics should be familiar with the classical super-heterodyne technique used in most radio receivers. In brief, this method mixes the frequencies from the incoming radio signal with another fixed local oscillator frequency. The result is both a sum and difference family of frequencies that can be more easily amplified and used to separate the desired signal from the background noise and interference. This same principle has now been applied in the realm of optical frequencies.

To make the optical heterodyne concept work, special lasers must be used that have been carefully constructed to emit light of very high purity. The light from these lasers is very nearly one single wavelength of light. When the light from two of these lasers that emit light of slightly different wavelengths, is focused onto a detector, the detector's output frequency corresponds to a sum and difference of the two wavelengths. In practice, the light from a nearby laser produces light with a slightly different wavelength than the distant transmitter laser. As in the radio technique, optical heterodyning should allow very weak signals to be processed more easily and should also permit many more distinct wavelengths of light to be transmitted without interference. A single light detector could then be used in conjunction with multiple laser sources. This technique is often referred to as "wavelength division multiplexing" and could allow a single receiver system to select one color "channel" from among several thousand channels transmitted. But, for the average experimenter, such techniques are just too comp

5.4. Future Detectors

Experimental research in optical computers may lead to some useful light detectors at some time in the future. Most likely, a device will be developed that will amplify light somewhat like a transistor amplifies current. Such a device would use some kind of external light that would be modulated by the incoming light. Perhaps light emitted from a constant source would be sent through the device at one angle and would be modulated by the much weaker light striking the device at another angle. Since these devices would use only light to amplify the incoming light, without an optical to electrical conversion, they should be very fast and might have large active areas. Such detectors may eventually allow individual photons to be detected, even at high modulation rates. If these advanced detectors do become available, then many optical through-the-air communications systems could be designed for much longer ranges than now possible. Perhaps the combination of higher power light sources and more sensitive light detectors will allow a future system to be extended by a factor of 100 over what is now possible.

In addition to the above "all optical" detector there may be other kinds of detectors developed that work on completely different concepts. Some experiments on some special materials suggest that an opto-magnetic device might make a nice detector. Such a device produces a magnetic field change in response to incident light.

A coil wrapped around the material might be used to detect the small change in the field and thus might allow small light levels to be detected.

5.5. Detector Noise

Unlike fiber optic communications, through-the-air systems collect additional light from the environment. Light from the sun, street lights, car head lights and even the moon can all be focused onto the detector. The stray light competes with the modulated light from the distant transmitter. If the environmental light is sufficiently strong it can interfere with light from the light transmitter. As indicated above, the light striking the detector produces a DC current proportional to the light intensity. But, within the DC signal produced there is also some broadband AC noise components. The noise produces random electrical signal fluctuations. The background static you often hear on an AM radio when tuned between stations is one example of noise. Fortunately, the magnitude of the AC noise seen in an optical receiver is small but it can still be high enough to cause problems. The noise has the effect of reducing the sensitivity of the detector, during high ambient light conditions. As will be discussed in the section on light receiver circuits, some tricks can be employed to lessen the amount of noise that would otherwise be produced at the detector from ambient light. But, as long as there is extra light focused onto a detector there will always be noise

The equation shown in Figure 2d describes how the detector noise varies with ambient light. The relationship follows a square root function. That means if the ambient light level increases by a factor of four, the noise produced at the detector only doubles. This characteristic both helps and hurts a light receiver circuit, depending on whether the system is being used during the light of day or during the dark of night. The equation predicts that for high ambient daytime conditions, you will have to dramatically reduce the amount of ambient light striking the detector in order to see a significant reduction in the amount of noise produced at the detector circuit. The equation also describes that under dark nighttime conditions, the stray light has to dramatically increase in order to produce a sizable elevation in noise. If the system must work during both day and night, it will have to contend with the worst daytime noise conditions. Conversely, some light receivers could take advantage of the low stray light conditions found at night and produce a communications system with a much longer range than would be otherwise possible if it were used during daylight.

5.6. Minimum Detectable Light Levels

The weakest modulated light signal that can be detected by a typical PIN diode will be dependent on several factors. The most important factor is the noise produced by the detector. As discussed above, the detector noise is very dependent on the amount of extra light striking the detector. For most medium speed applications, the weakest modulated light signal that can be detected is about 0.1 nanowatts. But, such a sensitivity can only be achieved under very dark conditions, when virtually no stray light is focused onto the detector. In many daytime conditions the ambient light level may become high enough to reduce the minimum detectable signal to about 10 nanowatts. However, to insure a good communications link you should plan on collecting enough light so the signal of interest, coming from the distant transmitter, is at least 10 times higher in amplitude than the noise signal. This rule-of-thumb is often referred to as a minimum 20db signal to noise ratio (SNR).

5.7. LIGHT-SCATTERING DETECTOR

The evaporative light detection system has revolutionized the analysis of lipids by HPLC since its introduction around 1980. This type of detector works by measuring the light scattered from the solid solute particles remaining after nebulization and evaporation of the mobile phase. For native lipids (not derivatized), the light-scattering detector (ELSD) is far more useful for on-line lipid quantification than the commonly used UV detector.

An updated bibliography of papers relevant to various applications of light-scattering detection to the analysis of lipids is given below :

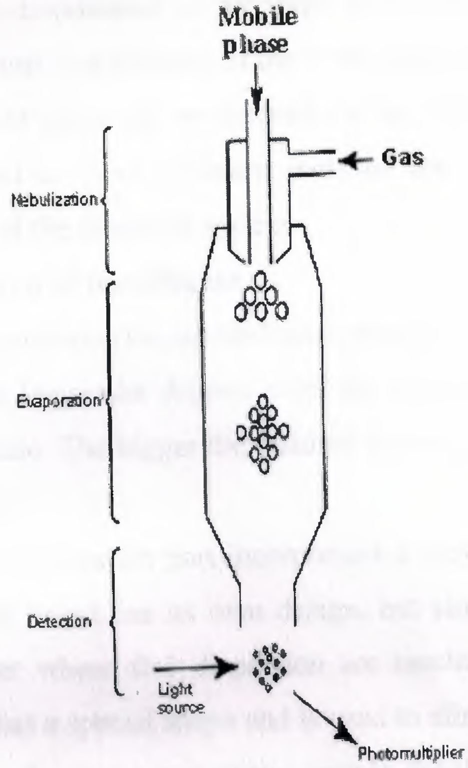


Figure 5.4. Light Scattering Detector

5.7.1. PRINCIPLE OF THE LIGHT-SCATTERING DETECTOR

This type of detector can be used for all solutes having a lower volatility than the mobile phase. Semi-volatile solutes can be detected due to the relatively low temperatures at which new generations of instruments can operate. For the majority of non-volatile solutes, the detection limits reach frequently the nanogram range per injection.

In the ELSD, the mobile phase enters the detector, is evaporated in a heated device and the remaining solute is finally detected by the way it scatters light. The intensity of the light scattered from solid suspended particles depends on their particle size. Therefore, the response is dependent on the solute particle size produced. This, in turn, depends on the size of droplets generated by the nebulizer and the concentration of solute in the droplets. The droplet size produced in the instrument nebulizer depends on the physical properties of the liquid and the relative velocity and flow-rates of the gas and liquid stream. The importance of all these parameters emphasizes the need for careful design and rigorous optimization of the instrument parts.

Three important steps can be defined during the working of the instrument, steps which are located in three different parts of the detector: the nebulizer, the evaporation chamber and the detection system.

1- Nebulization of the effluent

This first step transforms the whole liquid phase flowing from the HPLC column into fine droplets. The larger the droplet size, the higher the temperature needed to evaporate the liquid phase. The bigger the residual solute particles, the more intense the scattered light will be.

In general, the nebulization part incorporates a Venturi-type flow of gas around the eluent inflow. Each brand has its own design, but similar to that found in atomic absorption spectrometer where fine dispersion are needed. In some instruments, the nebulization chamber has a special shape and is used to eliminate the biggest droplets of solvent, thus removing the water part of the sample droplets, in others all the column effluent passes into the next part (evaporation zone).

2- Evaporation of the effluent

This second step begins when the droplets are carried by the gas flow into the heated area located before the detection chamber. Each brand has its own design for this zone and the efficiency of the required evaporation depends on the shape of the tube and the needed temperature. The solvent is completely removed to produce particles of solutes without solvation or even droplets of pure solutes. Practically, a temperature in the range 40-60°C is sufficient to evaporate solvents used in HPLC of lipids where high percentages of water or polar solvents are frequently used.

3- Detection

The sample particles pass through a flow cell where they are hit with an incident light beam, the amount of light scattered being measured using a photomultiplier and an electronic device. In some instrument a secondary gas inlet is used to concentrate the particles in the center of the detection chamber.

5.7.2. CHARACTERISTIC PROPERTIES OF SCATTERING DETECTOR

5.7.2.1. Low background signal

ELSD has a very low background signal since there is no light scattered from the light source by the evaporated solvent. Thus, there is no solvent peak which may hide the detection of trace components eluting at the beginning of the chromatogram. Of course clean solvents must be used. The detector can be used with any solvent or mixture of solvents as long there are volatile. The choice of the evaporation temperature is important and must be adjusted by trial and error with repeated injections of a known amount of solute.

5.7.2.2. Reproducibility

If physical conditions of the analysis are maintained constant (flow rate, gas pressure, temperature, quality of the eluent, sample volume), the reproducibility of the ELSD is very good. For cholesterol in the µg range, we have observed a relative standard deviation of the signal of about 1%.

5.7.2.3. Low band broadening

The transit time in the instrument being short, there is a very small band broadening effect. Choosing a small time constant for the response signal allows the detection of tiny solute mass.

5.7.2.4. Detector response and quantification

It is currently considered that the linearity of the signal with respect to sample size is an important mathematical condition. Fortunately, the new graphical softwares allow the user of an ELSD to consider equally a linear, a logarithmic or another type or response.

Indeed, analysts have described with ELSD the response to a range of lipid masses as linear, sigmoidal, logarithmic or quadratic. These types of response are frequently obtained at the lower range of the scale while a linear response is observed at increasing concentrations. It is noticeable that this behaviour is mainly dependent of the design of the instrument and also of the type of lipid detected. As the flow of the nebulizer and the temperature of the evaporation chamber influence the signal-mass relationship, an optimization of the detector parameters may be tried. Calibration should be made with lipid standards as close as possible in composition to the lipids analyzed.

5.8. PRACTICAL CONSIDERATIONS

5.8.1. Solvent quality

The solvent quality is of prime importance to get the lowest background signal. Don't forget that the detector sensitivity is related to the ratio signal/noise. Don't choose a solvent for ELSD as for UV or fluorescence detection. The residue after evaporation is the most important criteria and this quality must be always lower than 1 mg/l. We daily observed that HPLC-grade solvents have this specification. Solvents used or solvent mixtures must be filtered through compatible sub-micron filters (0.4 or 0.2 μm). If possible samples must also be filtered with special filters before injection. When possible, the use of solvents "for residue analysis" is recommended, they are known to contain less than 5 mg impurities per liter.

5.8.2. Solvent modifiers

A common way to modify the pH value of the final solvent mixture is to add solvent modifiers. It is possible to use volatile acids, bases and salts but trials are needed to choose the most efficient modifier for the separation. Use the lowest modifier concentration compatible with reliable results. To acidify, use of formic, acetic, trifluoroacetic and nitric acids are possible. To basify, use ammonia, triethylamine and pyridine. To increase ionic strength, it is possible to add ammonium bicarbonate or acetate, if necessary in combination with the above-mentioned acids or bases. Practically, we use no more than 0.1 ml acidic or basic modifier per liter of solvent.

5.8.3. Gas cleanliness

Nitrogen is sometimes preferred for safety reasons but clear compressed air is most frequently used. In all cases, the instrument exhaust must be connected to a fume hood. If the air compressor is oil-lubrified, a charcoal column followed by a sub-micron particle filter must be inserted in the air line before entering the ELSD

5.8.4. Internal standards

To ensure accuracy and precision in the analysis of lipid components with the ELSD, as with other detectors, a calibration against well-defined lipid standards is necessary.

It remains possible to include in the sample a defined and well separated compound as an internal standard. As an example, cholesterol was used for phospholipid quantification. This approach allows the correction of detector drift in between day measurements but after calibration with a known standard mixture corresponding to the separated compounds.

In the PL-ELS 1000 (Polymer Laboratories), new features are found including a high efficiency nebulizer design and low volume/low dispersion evaporation system (straight evaporation chamber). The instrument is said to have a superior baseline stability and very good reproducibility and sensitivity.

5.9. NTE3036 Phototransistor Silicon NPN Photo Darlington Light Detector

The NTE3036 is a silicon NPN photo Darlington light detector in a TO18 type package designed for use in applications such as industrial inspection, processing and control, counter, sorters, switching and logic circuit or any design requiring very high radiation sensitivity at low light levels.

Popular TO18 Type Hermetic Package for Easy Handling and Mounting Sensitive Throughout Visible and Near Infrared Spectral Range for Wider Application

- Minimum Light Current: 12mA ,H = 0.5mW/cm2
- External Base for Added Control
- Absolute Maximum Ratings: (TA = +25°C unless otherwise specified)
- Collector–Base Voltage, VCBO 50V
- Collector–Emitter Voltage, VCEO
- Emitter–Base Voltage, VEBO
- Light Current, IL 250mA
- Total Device Dissipation (TA = +25°C), PD 250mW
- Derate Above 25°C 1.43mW/°C
- Operating Junction Temperature Range, TJ –65° to +200°C
- Storage Temperature Range, Tstg –65° to +200°C
- Electrical Characteristics: (TA = +25°C unless otherwise specified)
- TA = +25°C unless otherwise specified)
- Parameter Symbol Test Conditions Min Typ Max Unit

5.9.1. Static Characteristics

- Collector Dark Current ICEO VCE = 10V, H ~ 0 – 10 100 nA
- Collector–Base Breakdown Voltage V(BR)CBO IC = 100μA 50 100 – V
- Collector–Emitter Breakdown Voltage V(BR)CEO IC = 100μA 40 80 – V
- Emitter–Base Breakdwon Voltage V(BR)EBO IE = 100μA 10 15.5 – V
- Electrical Characteristics (Cont'd): (TA = +25°C unless otherwise specified)
- Parameter Symbol Test Conditions Min Typ Max Unit

5.9.2. Optical Characteristics

Light Current IL VCC = 5V, RL = 10., Note 1 12 20 – mA

Collector–Emitter Saturation Voltage VCE(sat) IL = 10mA, H = 2mW/cm2 at 2870°K – 0.6 1.0 V

Photo Current Rise Time tr RL = 10., IL = 1mA Peak, Note 2 – 15 100 μs

Photo Current Fall Time tf RL = 10., IL = 1mA Peak, Note 2 – 65 150 μs

Note 1. Radiation flux density (H) is equal to 0.5mW/cm2 emitted from a tungsten source at a color temperature of 2780°K.

Note 2. For unsaturated response time measurement, radiation is provided by pulse GaAs (gallium–arsenide) light emitting diode (. 0.9μm) with a pulse width equal to or greater than 500μs,

IL = 1mA peak

CONCLUSION

The Light Detector is based on Photoelectric Theory and is a Detector that is dependent to light. The detector's work is to convert the light signals collected at the receivers into electrical signal. A light source forms, the carrier and must be transmission information. The light Detectors which's most important property is their sensitivities to light are related with devices like Light Dependent Resistor and Light Emitted Diode.

The Photoelectric Effect works like this, light of high enough energy on to a metal electron will be emitted from the metal. To explain for the photoelectric effect. It is taken a certain energy to eject on electron from a metal surface. Einstein's Theory is the best theory that describes Photoelectric Effect.

The Detectors in the future perhaps may be the combination of higher power night sources and more sensitive light detectors will allow a future system.The future Detectors, in spite of the detectors are being used today like Photo Transistors, Photon Multiplier Tube and Photo Diode will be much more sensitive to light.

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