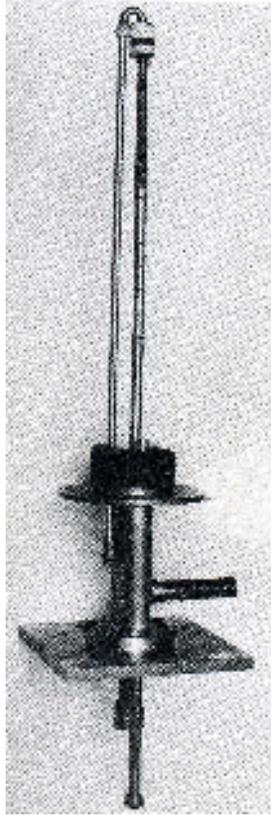


# Photo Detectors



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## Introduction

Photo detectors are used primarily as an optical receiver to convert light into electricity. The principle that applies to photo detectors is the photoelectric effect, which is the effect on a circuit due to light. Max Planck In 1900 discovered that energy is radiated in small discrete units called quanta; he also discovered a universal constant of nature which is known as the Planck's constant. Planck's discoveries lead to a new form of physics known as quantum mechanics and the photoelectric effect  $E = h\nu$  which is Planck constant multiplied by the frequency of radiation. The photo electric effect is the effect of light on a surface of metal in a vacuum, the result is electrons being ejected from the surface this explains the principle theory of light energy that allows photo detectors to operate. Photo detectors are commonly used as safety devices in homes in the form of a smoke detector, also in conjunction with other optical devices to form security systems.

## Photo detector:

A photo detector operates by converting light signals that hit the junction to a voltage or current. The junction uses an illumination window with an anti-reflect coating to absorb the light photons. The result of the absorption of photons is the creation of electron-hole pairs in the depletion region. Examples of photo detectors are photodiodes and phototransistors. Other optical devices similar to photo detectors are solar cells which also absorb light and turn it into energy. A similar but different optical device is the LED which is basically the inverse of a photodiode, instead of converting light to a voltage or current, it converts a voltage or current to light.

## Photodiodes:

A commonly used photo detector is the photodiode. A photodiode is based on a junction of oppositely doped regions (pn junction) in a sample of semiconductor. This creates a region depleted of charge carriers that results in high impedance. The high impedance allows the construction of detectors using silicon and germanium to operate with high sensitivity at low temperatures. The photodiode functions using an illumination window (Figure 1), which allows the use of light as an external input. Since light is used as an input, the diode is operated under reverse bias conditions. Under the reverse bias condition the current through the junction is zero when no light is present, this allows the diode to be used as a switch or relay when sufficient light is present.

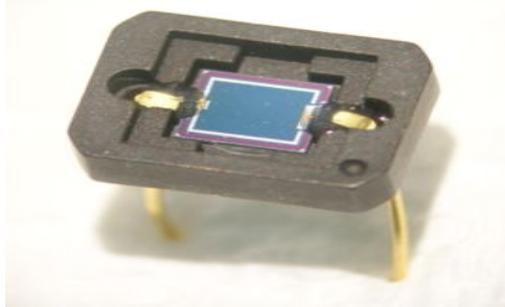


Figure 1 photo diode with illumination window as shown.

Photodiodes are mainly made from gallium arsenide instead of silicon because silicon creates crystal lattice vibrations called phonons when photons are absorbed in order to create electron-hole pairs. Gallium arsenide can produce electron-hole pairs without the slowly moving phonons; this allows faster switching between on and off states and GaAs also is more sensitive to the light intensity. Once charge carriers are produced in the diode material, the carriers reach the junction by diffusion. Important parameters for the photodiode include quantum efficiency, current and capacitance which will be covered in the equations section.

### PIN Photodiode

Another type of photodiode is the PIN photodiode; this photodiode includes an intrinsic layer in between the P and N type materials. The PIN must be reverse bias due to the high resistivity of the intrinsic layer; the PIN has a larger depletion region which allows more electron-hole pairs to develop at a lower capacitance. The illumination window for a PIN is on the P-side of the diode because the mobility of electrons is greater than holes which results in better frequency response. The larger breakdown voltage in comparison to the PN photodiode allows it to be used with a biased voltage of approximately 100 which results in a fast response time by the equation below.

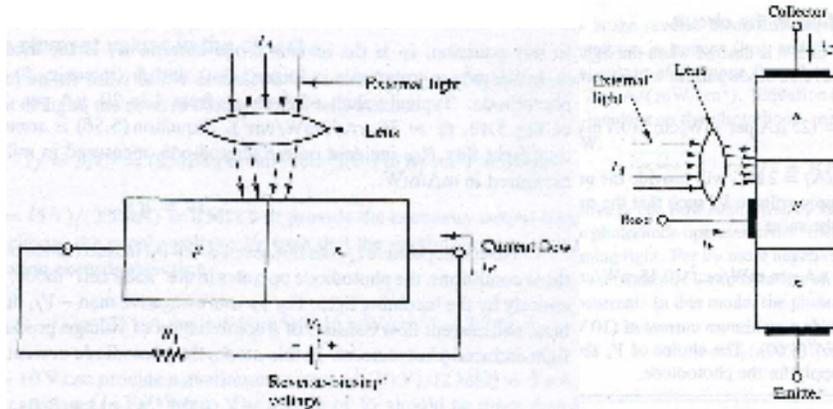
$$\tau_{PIN} = \frac{\ell^2}{\mu(V_0 + V_b)} \tau_{PIN} \text{-Response time of PIN photodiode}$$

### Avalanche Photodiode

An Avalanche photodiode is operated at reverse bias close to the breakdown, which causes photo excited charge carriers to accelerate in the depletion region and produce additional carriers by avalanching. The avalanche photodiodes are good for fiber optic systems that require low light levels with quantum efficiency larger than 100%.

### Phototransistor

Phototransistor is similar to the photodiode except an additional n-type region is added to the photodiode configuration. The phototransistor includes a photodiode with an internal gain. A phototransistor can be represented as a bipolar transistor that is enclosed in a transparent case so that photons can reach the base-collector junction. The electrons that are generated by photons in the base-collector junction are injected into the base, and the current is then amplified. Since phototransistor detection is on the order of the photodiode they can not detect light any better than a photodiode. The draw back of a phototransistor is the slower response time in comparison to a photodiode. The figure below shows the relationship between a photodiode and phototransistor.



PN Photodiode

NPN Phototransistor

Photodiode Equations:

The conductivity of photodiodes is as follows:

$\sigma = \sigma_{th} + \sigma_{ph}$  The value  $\sigma_{th}$  is the thermal conductance and is also referred to as dark current when no light hits the junction. The photodiode conductivity  $\sigma_{ph}$  can be represented by the electron hole charge carrier concentrations:  $\sigma_{ph} = q(\mu_n n + \mu_p p)$

Current density

$$J_x = qn_0 \langle v_x \rangle = \sigma \epsilon_x$$

Quantum Efficiency

By looking at the diffusion of charge carriers into the depletion region shown by:

$$\frac{dn}{dt} = D_n \frac{d^2n}{dx^2} - \frac{n}{\tau_n} + g \quad g - \text{Photo-excitation} \quad \tau_n - \text{electron lifetime}$$

The quantum efficiency for steady state (dn/dt=0) can be derived:

$$\frac{d^2n}{dx^2} - \frac{n}{L^2} + \frac{g}{D} = 0 \quad g \text{ in this equation is the photo generated charge carriers}$$

The quantum efficiency after numerous derivations is in the form:

$$\eta = \frac{2b}{e^{c/L} + e^{-c/L}} = b \operatorname{sech} \left( \frac{c}{L} \right),$$

b – The fraction of incident photons available to produce charge carriers

c – The flux of charge carriers

Current

The total current in the junction is  $I = I_p - I_n$  and can be represented as:

$$I = \left[ qA \left( \frac{D_n^p}{L_n^p} p_n + \frac{D_p^n}{L_p^n} n_p \right) \right] (e^{qV_b/KT} - 1)$$

The term in the square bracket represents the

saturation current  $I_0$ .

### Capacitance

The width of the depletion regions for the p and n type materials are:

$$w_p = \left[ \frac{2\epsilon N_D (V_0 - V_b)}{qN_A (N_A + N_D)} \right]^{1/2}, \quad w_n = \left[ \frac{2\epsilon N_A (V_0 - V_b)}{qN_D (N_A + N_D)} \right]^{1/2}$$

The Total width of the depletion region is the sum of the n and p type materials:

$$w = w_p + w_n = \left[ \frac{2\epsilon (N_A + N_D) (V_0 - V_b)}{qN_A N_D} \right]^{1/2}$$

The Junction Capacitance can now be obtained as:

$$C_J = \epsilon \frac{A}{w} = \epsilon_r \epsilon_0 \frac{A}{w}$$

### Applications of Photo Detectors

- Photo detectors are used in various different applications such as radiation detection, smoke detection, flame detection and to switch on relays for street lighting.
- The circuits that use photodiodes use either normally closed or normally open contacts depending on the desired operation.
- In a smoke detector circuit the photo diode is attached to a relay switch, this switch is normally closed and attached to the fire alarm. When the photo diode conducts it picks up the relay switch, this causes the normally closed switch to open preventing the alarm from activating. When the photo diode fails to conduct, the normally closed contact activates the alarm.
- Photo diodes are also used in modern oil burning furnaces as a safety feature. The photo diode is comprised of lead sulphide and is used to detect the flame from the boiler, in the event that the flame goes out or fails to occur the photo diode opens the circuit, cutting power to the motor and step up transformer.
- Another commonly used application is street lights. The photo diode in the circuit uses switch-on relays to turn on the street lights when the diode fails to conduct and turns the lights off with when sufficient light is present.
- Another application is the AFM (Atomic Force Microscope), a laser beam is projected from a laser diode onto the back of the cantilever, and the beam is then reflected to a photodiode. The position of the beam of light on the diode gives the (x,y,z) position of the material as the probes of the cantilever scraps across the surface of the material. This gives a three dimensional representation of the surface being scanned.
- Photodiodes are also used with lasers to form security system. When the light projected by a laser to the photodiode is broken a security alarm is tripped.