Radiation Sensors :

The sensors which are developed to detect the emissions from matter. The fundamental law on which Some of these sensors are based is the photoelectric effect.

Radiation energy propagating through space in quanta when collides with matter, certain integral number of quanta called photons are emitted, reflected, absorbed depending on the material characteristics.

If the photon energy $h\nu$ (h is planck's constant and ν is the frequency of radiation), then

$$h\nu = \frac{1}{2}mv^2 + \phi e.$$

Where

→ $\frac{1}{2}mv^2$ is energy of the electron emitted from the atom of the matter by the impact of photon,

→ ϕe is the energy required to release the electron (e is the charge of electron, ϕ = work function of material)

The Kinetic energy of the photoelectron is dependent only on the incident photon energy which is transmitted to the electron When the photon energy hits the electron, two situations arises, they are :

→ The incident energy is sufficient to transfer the electron into a vacant conductivity level and not beyond. This process leads to increased photoelectric Conductance.

→ If the incident energy $h\nu$ is high enough, it causes the electron to be detached and emitted from the material.

Radiation sensors are also called as photosensors or photosensistors, optical or photonic sensing. The types of radiations known are infrared, ultraviolet, visible, photon-type, x-rays, and nuclear radiations such as β- and γ-rays.

The earlier classification of radiation sensors are:

(i) The photoelectric cell such as photoemissive cell,
ii) The photoemf cell such as photovoltaic cell,
iii) The photoconductive cell such as light sensitive resistors.

* The photosensistor is a combination of two electrodes in an electrolyte. and according to radiation ranges, frequency, or wavelength, the electrodes change in size and shape and the electrolyte changes to gas, liquid, or solid.

Basic characteristics :

The important characteristics that are need to be considered for photodetectors are

i) work function
ii) quantum yield and quantum voltage
iii) spectral sensitivity and spectral threshold
iv) time lag
v) drift, fatigue
vi) Static and dynamic responses
vii) Linearity.

i) Work function :

Work function is a physical constant for a given material and is usually expressed in electron volts and it is denoted by ϕ.. The energy E which is spent in overcoming the surface attractive forces is given by

$$E = \phi e$$

e is the electronic charge.

For metallic elements., the work function is observed to be smaller for higher atomic number, like for caesium has the smallest value, 1.54 eV. So, for photodetectors, alkali metals make a good choice, where alkali metals are electropositive and loose electrons easily, this makes them vulnerable to the atmospheric state that contain electronegative oxygen or hydroxyl ions. These are only as surface layer on metal plates of higher work functions. Thus Na, K, Rb, cs layers are laid on Ag, Be, Ta, Ni, Al, Cu, Ca, Ca, Zr, W plates.

The alkali metals have a single electron on the outermost orbit so a low work function is enough to dislodge from an atom. When the number of electrons on outermost orbit increases, then the metal has higher work function.

ii) Quantum yield and quantum voltage :

It is a ratio of number of electrons emitted by sensistor cathode to the number of photons it receives for the purpose. At any wavelength λ, the number of electrons emitted can be given by a number 6.242×10^{18} ζ. ζ is sensitivity. and a flow of 6.242×10^{18} electrons is required to produce 1A current.

To free an electron an energy,

$$E_\lambda = \frac{12395}{\lambda} \text{ eV} = \frac{1.9857 \times 10^{-8}}{\lambda} \text{ ergs}$$

is required, and one watt (10^7 ergs/s) of power would release

$$\frac{10^7 \times 10^8}{1.9857} \lambda = 5.036 \times 10^{14} \lambda \text{ electrons/s.}$$

producing a current of $\frac{(5.036 \times 10^{14})\lambda}{(6.242 \times 10^{18})}$ A/W.

The quantum yield is, however,

$$Q_y = \frac{6.242 \times 10^{18} J}{5.036 \times 10^{14} \lambda} = \frac{12395 J}{\lambda}$$

The energy that a photoelectron acquires by the impact of a photon is expressed as quantum voltage. The maximum kinetic energy it can have after escape from the surface is

$$E_m = E_\lambda - \phi$$

The threshold wavelength is then defined as the one for which $E_m = 0$. The value of the quantum voltage is

$$E_\lambda = \frac{h\nu}{e} = \frac{hc}{\lambda \cdot e} = \frac{1.2395}{\lambda} \text{ eV}$$

The photoelectric effect occurs at $E_\lambda > \phi$, indicates colour of the radiation, for visible light, for green radiation, $\lambda = 0.546$ μm

Element	Work function (eV)	Ionization potential
Cs	1.54	3.87
K	1.8	4.32
Na	1.94	5.12
Rb	2.15	4.16
Li	2.21	5.37
Sr	2.3	5.67
Ca	2.51	6.09

iii) Spectral Sensitivity and Spectral Threshold :

When the electron velocity is zero, $v = 0$ which occurs at absolute zero from the product value of $h\nu$, then the electron escape from metal surface is possible with radiation if

$$h\nu > \phi e$$

and a threshold frequency is obtained as

$$\nu_0 \geq \frac{\phi e}{h}$$ and the wavelength is

$$\lambda_0 \leq \frac{hc}{\phi e}$$

c is the velocity of light, then

$$\lambda_0 = \frac{1.2395}{\phi}\ \mu m$$

for caesium $\lambda_0 = 0.8045\ \mu m$.

The photoelectric emission from metal surface occurs if the wavelength of incident radiation is less than threshold frequency wavelength. The amount of emission is proportional to the intensity of incident radiation.

The spectral sensitivity of photosensistors higher than threshold frequency is a function of incident radiation.

Element	Atomic weights	λ_p (μm)
Li	6.94	0.4050
Na	22.997	0.4190
K	39.096	0.4400
Rb	85.48	0.4730
Cs	132.91	0.5390

iv) Time Lag :

Time lag for photosensistors obviously varies over a wide rang. It is very small, of the order of 10^{-8}s in photo-emissive cells and quite large, of order of 5×10^{-2}s. in light sensitive resistors..

For gas-filled photocells, the time lag is of order of 10^{-5}s. The time response characteristics of the photosensistor becomes

$$y = y_0 (1 - e^{-\alpha t})$$

y_0 and α are constants, α is large for photoemissive cells, medium for photovoltaic cells, small for photoresistor types.

v) Drift, fatigue :

When the incident radiation is fluctuating at a frequency larger than 100Hz, the response of the detector does not follow the fluctuations faithfully. This is prominent in LDRs, and it is called as dynamic fatigue. For a steady high energy incidence, the photodetector output is not always with respect to input and it is called as static fatigue

Drift is the transient response change during a short period after the cell is irradiated, is more common in photovoltaic cells

vi) Static and Dynamic Response :

Static response is the ratio of the output to the input for steady illumination. it is called as Static sensitivity.

$$S_{st} = \frac{i_a}{\phi_l} \qquad i_a \text{ is anode current.}$$

The dynamic response is given by dynamic sensitivity

$$S_{dy} = \frac{\partial i_a}{\partial \phi_l} = \frac{\partial i}{\partial t} \Big/ \frac{\partial \phi_l}{\partial t}$$

vii) <u>Linearity</u> :

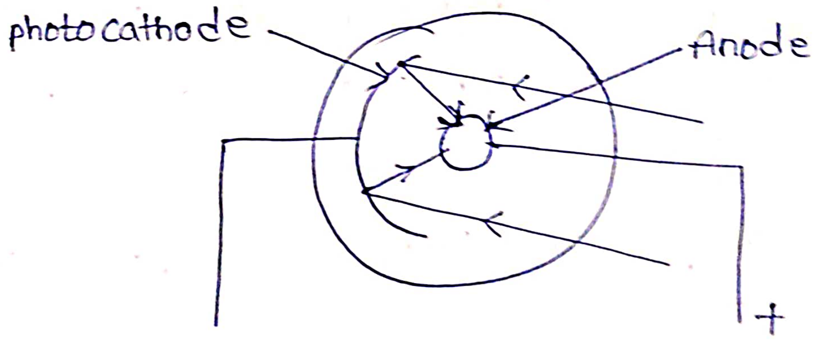
The linearity in response of a photosensistors is not ideal particularly in loaded condition. The photovoltaic cell produces a voltage and the linearity between this voltage V and incident light flux ϕ_l is ideal. However, for photoemissive cells, the linearity is much better at $R = R_0 e^{-\beta l}$.

<u>Types of Photosensistors/Photodetectors</u> :

i) Photoemissive cells and photomultipliers.
ii) Photovoltaic cells including photodiodes.
iii) Photoconductive cells and light detecting resistors.

(i) The Photoemissive cell and the photomultiplier :

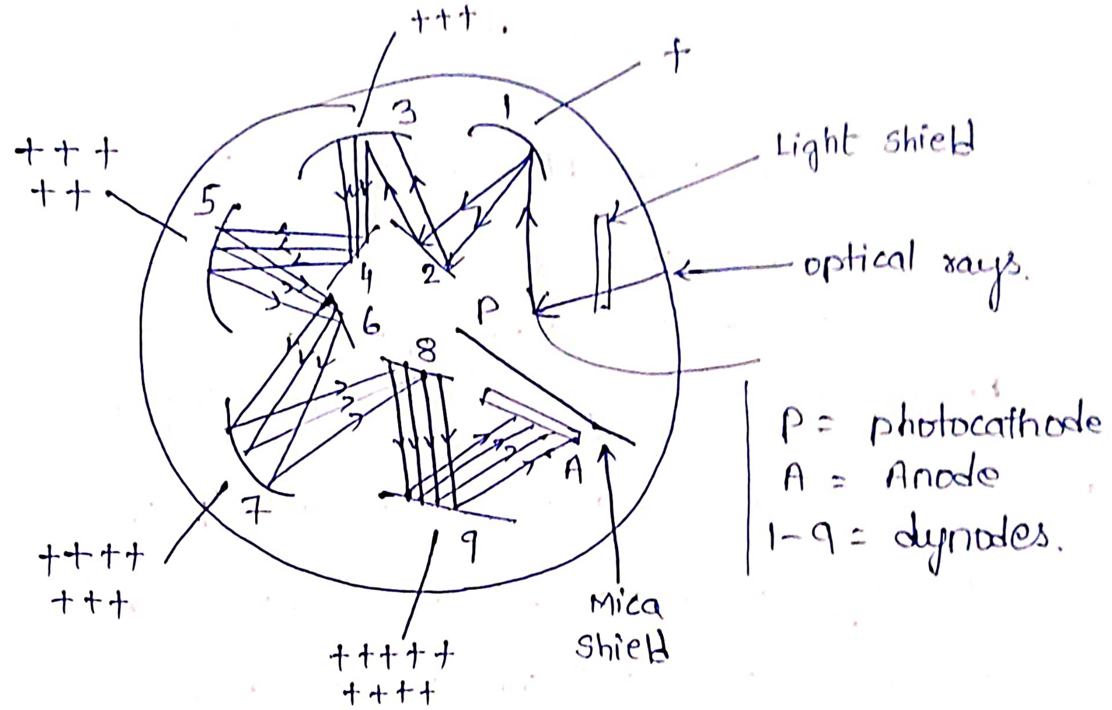
This type of radiation sensor shows an external effect when a photoelectric cell consists of a pair of electrodes separated by a rare gas or vacuum as shown in figure.



A basic photoemissive cell

Light is made to fall on a properly coated photocathode to have very low work function which releases electrons which are attracted towards the anode.

The external circuit is connected with a resistance so that the change in current indicates the intensity of optical radiation falling on the cathode. The current with a single pair of electrodes is very small and photomultiplication process is incorporated at large current output. The technique takes advantage of secondary emission of elections and for this, a number of electrodes called dynodes are used which are secondary emitters of electrodes.



A photomultiplier

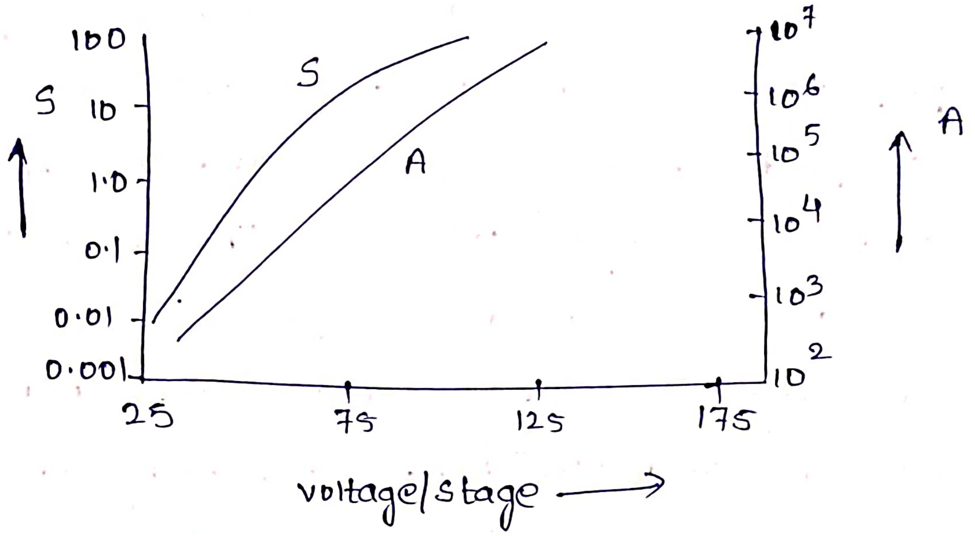
All electrodes are kept at a higher potential for elections to be attracted by it. The use of nine to eleven such dynodes is shown in above figure.

Light shield is actually a grill connected to photocathode and in this way the electrode assembly is electrostatically completed. Optical radiation reaches the photocathode P through this shield and elections liberated from photocathode at first attracted to dynode 1. These electrons by impact on dynode 1, release a number of secondary elections. Like this successive impacts occur on other dynodes increasing electrons exponentially and at the end this stream of elections are collected by the anode. A and an external load may now be connected to it to produce the output current I given by

$$I = I_p K^n$$

I_p is the initial primary photoelectric current
K is a constant dependent on dynode
n is number of stages.

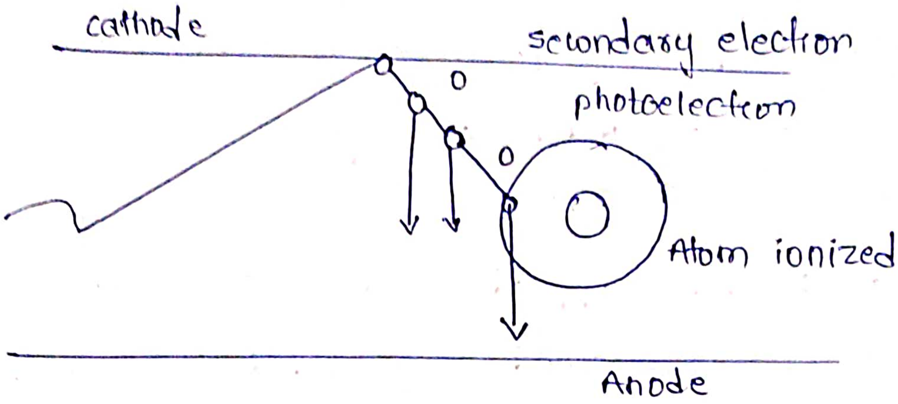
The potential different applied between successive stages is about 100-130 volts. A mica shield is provided between photocathode and subsequent multiplying stages for isolation to prevent spurious election emission. The typical current sensitivity/amplification characteristics of a photomultiplier is shown in figure



The vacuum photoemissive cell has a variation when it is filled with an inert gas at a very low pressure. With a potential between cathode and anode exceeding a certain critical value for filling gas, the photoelection emitted, gets accelerated and ionizes a gas atom into another election and a positive ion.

The positive space charge close to the photocathode may induce secondary election emission from it which partly neutralizes the positive ions.

A part of these secondary electrons with some photoelectrons and 'gas-ionized' electrons move towards anode to form photo-electric current.



photocurrent generation mechanism.

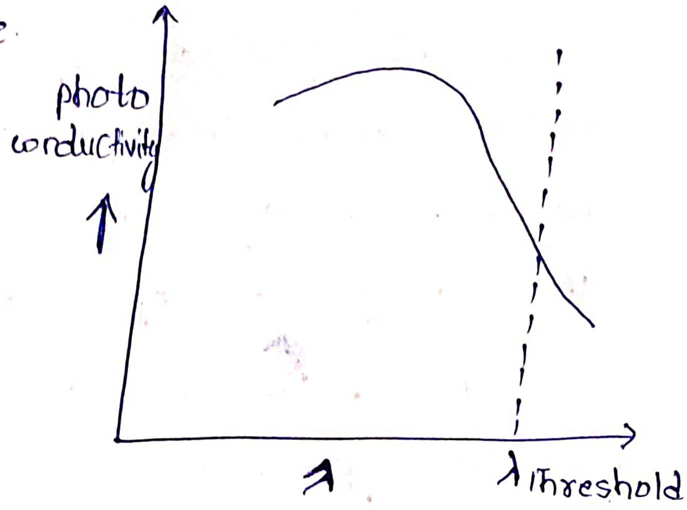
ii) The Photoconductive cell :

In intrinsic semiconductors thermal energy can cause a small proportion of valence band electrons to first conduction band. The holes produced in this process and the free electrons so produced, move in crystal lattice resulting in a kind of conduction. If this conduction occurs due to photons then it is called as photoconductivity. ∴ it occurs when sufficient number of electrons shift into the conduction band after being irradiated by photons changing the conductivity of the material. These devices include photoresistors or Light dependent resistors (LDR)

The LDR :

The photoconductivity occurs when the photon energy is sufficient to shift the electrons, and the photoconductivity appears to change below a certain wavelength, and a sharp cut-off is likely to be observed when the photonic energy is equal to the semiconductor energy gap.

The width of the energy gap fluctuates as a result of thermal vibrations within the lattice. However, the photons of lower energy pass through the material without having to part with their energy such as germanium is used to make lenses for such radiations



Semiconductor	Doping material	Maximum value of λ (μm)
Germanium	gold	9
Germanium	mercury	15
Germanium	copper	29
Ge - Silicon	gold	14
Ge - Silicon	zince	16

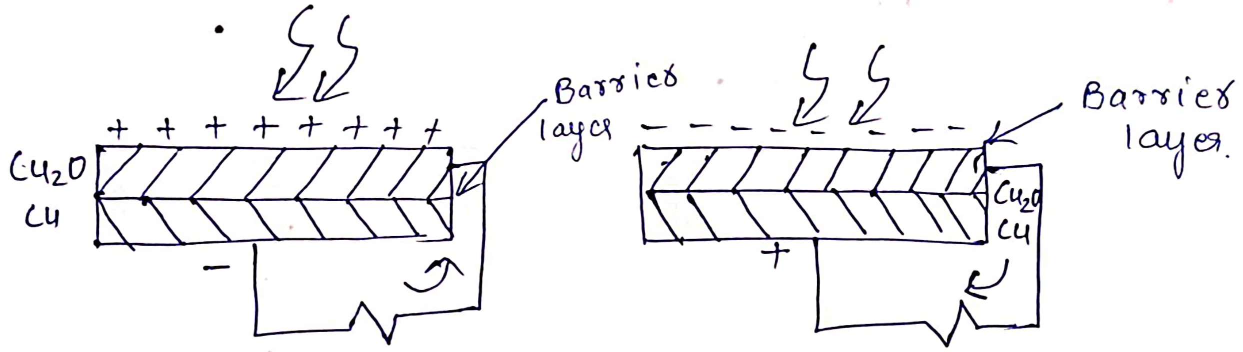
ii) photovoltaic and photojunction cells :

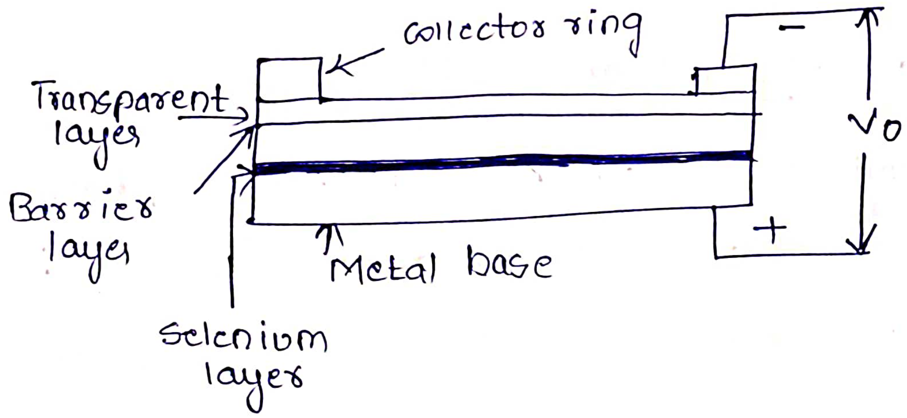
The photovoltaic cell which is made of photoemf cell, consists of a layer of a semiconductor on a metal disc. A thin translucent or transparent layer of a precious metal is sputtered on top.

The incident radiation on top layer passes through it and absorbed by the upper surface of the semiconductor and electrons are freed. These electrons flow away from or towards the incident radiation depending on type of cell.

There are two types of photocells (i) backwall type in which the electrode exposed to the incident radiation becomes positive and ii) frontwall type where it becomes negative. The barrier layer is the interface of electrodes at which the charges develop and move.

Based on the choice of material, the photocells are of two types. (i) uses copper oxide on cuppor (ii) uses Selenium on metal base as shown in figure.



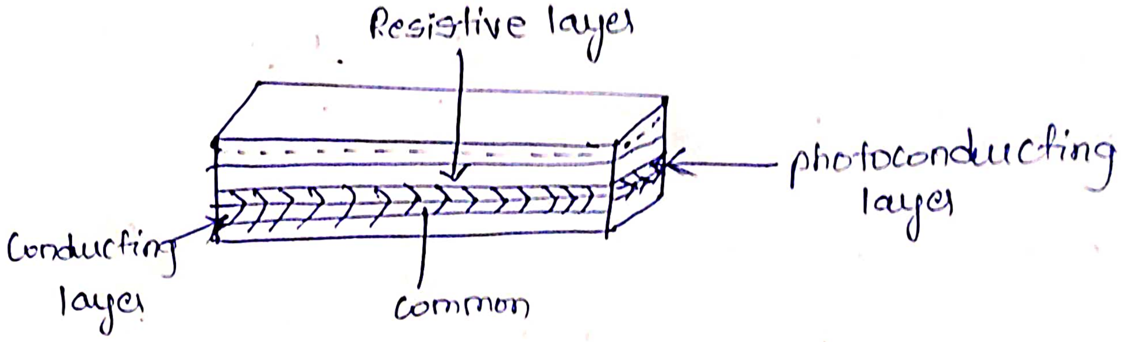


The selenium cell characteristics are very close to that of human eye. Pure selenium is a p-type semiconductor, the metal base aluminium or brass. Selenium film coating is heated converting it to Crystalline state. Cadmium is diffused in selenium to form p-n junction as cadmium oxide forms n-type layer. This layer is called barrier layer.

If the p-n junction is in forward bias, it is used as electrical circuit and photo-irradiation has no control on its current. If the diode is reverse biased, small leakage current due to intrinsic carrier could flow. Now with photo-irradiation, the rate of generation of intrinsic carrier is enhanced with increasing illumination. This occurs in photodiodes and are called as photojunction cells.

Position sensitive cell:

These cells are designed to conduct based on the position of the resistive layer to the conductive layer, through the photoconductor using the position of illumination



This structure is comprised of three layers.

a) highly resistive layer
b) photoconductive layer
c) Conductive layer on an isulating substrate.

Any bright spot, depending upon the position would result a differential signal based on obtained position.

Phototransistors and photoFETs :

These are made to amplify the photodiode current and a large output is derived.. In phototransistors the base collector junction can be considered as photodiode so that the leakage current is a function of illumination.

In case of photoFETs, the irradiated junction produces a leakage current $I_G + I_p$. the sum of normal gate current and photocurrent.

Photocouplers are used for electrical isolation by optical means often use photodetectors and a photothyristor. This consists of an LED and a photocell in a light-tight encapsulation. These photocouplers are specified by the current transfer ratio (CTR) which is the ratio of output current (I_2) to the input (I_1) currents.

X-Ray and Nuclear Radiation sensors.:

These are high energy radiations compared to optical range of radiations, and have different units of measurements for their energy content at different parameters. For example Roentgen is a measure of intensity of the radiation in air, and is defined as the charge, per cc of air at 0°c at 1 atm pressure.

Radiation damage that occurs due to X- Rays, γ-rays is called relative biological effectness (RBE) and it is denoted by R.

Types of X-ray and nuclear radiation sensors are

i) Geiger-Muller counter
ii) Proportional counter
iii) Scintillation counter
iv) Ionization chamber
v) Electron multiplier tubes.
vi) Non-dispersive detectors.

The nuclear emissions from radioisotopes are

i) α - particles
ii) β - particles.
iii) γ - rays.

These are ionizing radiations and neutrons and X-Rays are ionizing radiation but not nuclear in nature.

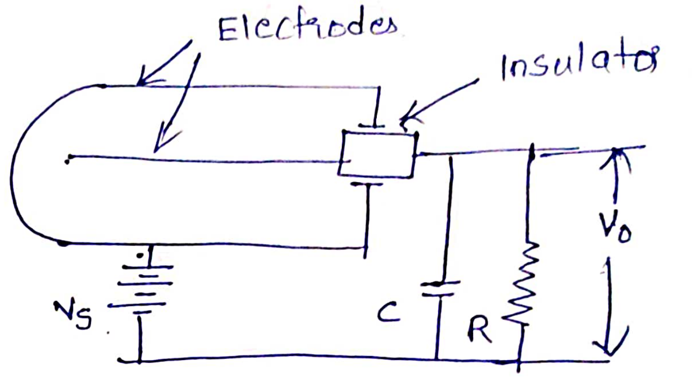
The non-ionizing radiations comprise of

i) UV-visible-IR optical types
ii) Extremely low frequency, radio-frequency, microwave

Ionizing Radiation	characteristics	Detectors
α-particles (He^{++})	Positively charge, highly ionizing, low penetration discrete energy levels.	Ionization chamber, proportional counter, Scintillation counter Semiconductors, plastic films
β-particles (e^-, e^+)	electrons and positrons, more penetration than α and continuous energy	Geiger-Muller counter, plastic films, proportional counter, Scintillation counter
γ-rays & X-rays	Penetrating electromagnetic types	Geiger-Muller (X-rays), photon-spectrometer, Proportional counter
Neutrons (n)	Indirectly ionizing	p-n junction diode, etched tracker films,

Ionization chamber :

The basic gas-filled detector chamber is designed by a central electrode is kept separated from the chamber, which is also an electrode, by an insulator. A supply voltage of V_S is impressed between the electrodes through a resistance R in parallel with a capacitor.



$$V_0 = \frac{q}{C}$$

This charge C results in the emission of three types of ions in the chamber, these are electrons, positive ions, and negative ions. The time for an ion to be picked by any of the electrode is much smaller than its RC product. and produces a voltage V_o. When the voltage increases, electrons are accelerated to acquire higher energy to produce a secondary ionization.

In ionization chamber, this secondary ionization makes a recombination of ions and is proportional to the product of positive and negative charge densities. e_{d+} and e_{d-}.

$$\frac{de_{d+}}{dt} = \frac{de_{d-}}{dt} = \rho e_{d+} e_{d-}$$

ρ is the recombination coefficient and has a value of 10^{-6} to 10^{-5} for gases. As electrons are faster than ions they constitute main current in the chamber and the drift velocity is given by

$$v_{\pm} = (\mu \pm)\left(\frac{E_f}{P}\right)$$

For large specific ionization, pulse type measurement is made with information on

i) number of ionizing particles
ii) time intervals between incidences of ionizing particles
iii) energy distribution

Proportional Counters:

These are more sensitive in nature and often used used for weak α- and β-particle sources and X-Rays. These are gas filled chambers and the gas multiplication increases the pulse size through this increase causes primary ionization. The gas multiplication varies between 10^3 and 10^4 to around 10^5 - 10^6.

From the counter chamber design data, applied field; number of ion pairs produced, pressure, mobility of ions, pulse size, ion collection time, can be determined.

The pulse size is given by

$$V_p(t) = \frac{n_0 e}{c}\left[-\frac{\ln(d_o/d_n)}{\ln(d_o/d_c)} + \frac{\ln(d_o/d_p)}{\ln(d_o/d_c)}\right]$$

$$\doteq -\frac{n_0 e}{c}\left[\frac{\ln(d_p/d_n)}{\ln(d_o/d_c)}\right]$$

d_c - diameter of collecting electrode.
d_o - diameter of outer electrode
d_p - distance of positive ion from central axis
d_n - distance of negative ion from central axis.
n_0 - number of ion-pairs produced
c - chamber capacitance

velocity of positive ions is given by

$$v_+ = \frac{d}{dt}(dp) = \mu_+ \left(\frac{E_f}{p}\right) = \mu_+ \frac{V_s}{p d_p \ln(d_o/d_c)}$$

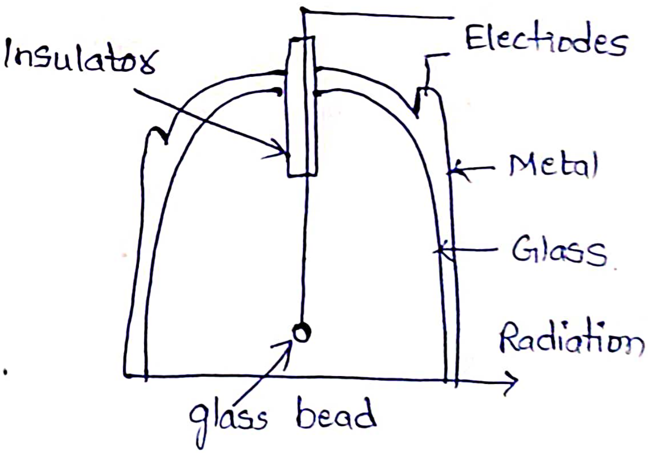
V_s is the supply voltage to the electrodes.

Geiger Counters:

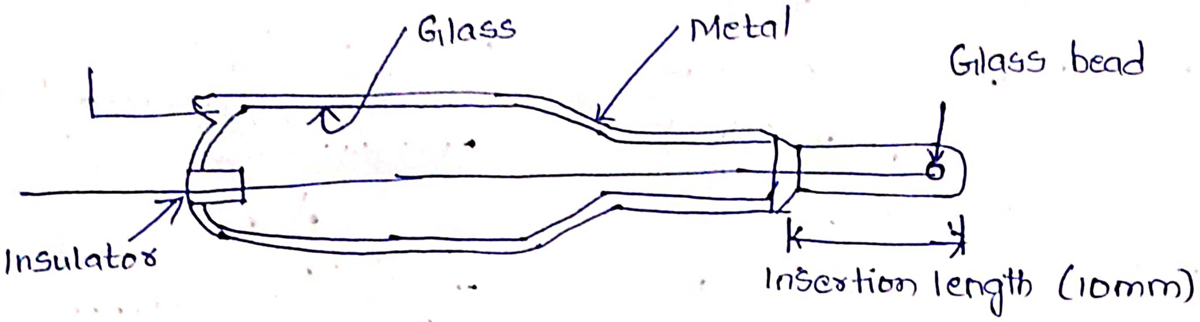
It is the most commonly used gas-filled counters named as Geiger-Muller counter or GM counter. It can measure all types of radiations with high sensitivity and large output. There are widely three types of GM counters.

(i) The end-window type
(ii) The cylindrical type
iii) The needle type

In the end-window type, a metal-coated glass tube of cylindrical form has a thin tungsten wire of 0.002-0.01 cm diameter passing through the centre acting as collector electrode with the body as other. This is usually made of mica sheet of a thickness less than the 1 mg/cm². To avoid spark over the central electrode, it terminates into a glass bead and the radiation is received by the end-window



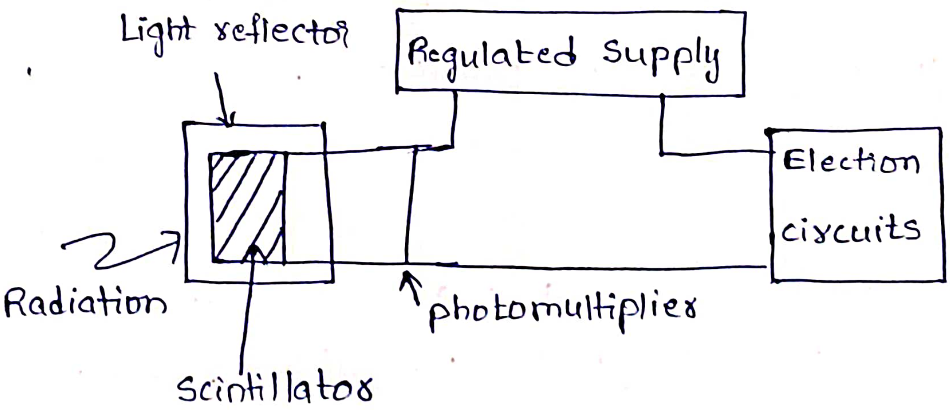
In the cylindrical GM counters, radiation is received by the side walls. This also, works for a needle type GM counter, where insertion in a narrow channel is required. The GM counter uses a gas at a low pressure of about 0.1-0.15 Kg/cm² that consists of 90% inert gas such as Ar and Ne, and 10% ethyl alcohol or organic vapours like methane. This mixture ensures transit through electrons only.



Scintillation Detectors:

Scintillations are the flashes or very short duration light pulses produced when a single crystals of organic or inorganic materials, activated glasses / Liquids or plastic flours when they they receive high energy radiation. and these materials are scintillators

This detectors basically consists of a scintillator, a photo multiplier that converts light flashes into electrical pulses, and other electronic circuits such as amplifier, pulse shaper, scaler.



If the radiation energy received by the crystal is E, the number of photoelectrons produced is n and is given by

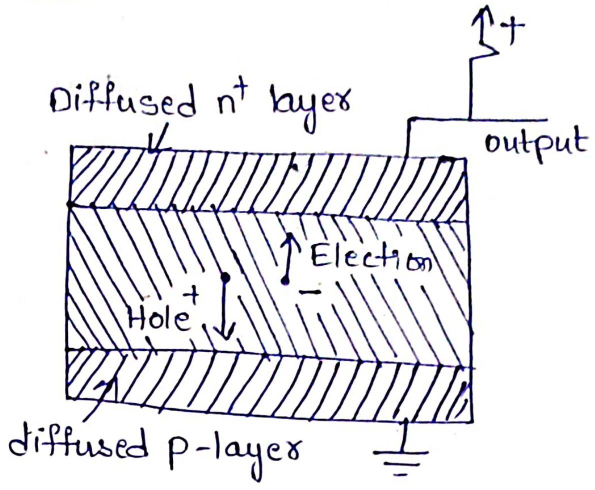
$$n = K_1 K_2 E$$

K_1 is dimensional constant

$$K_2 = f_a f_\lambda f_c f_e$$

Solid State Detectors :

These are based on the semiconductor based detection, Ge and Si have been best-suited and detects all kinds of radiations. Other materials like cadmium telluride (CdTe), mercuric iodide (HgI_2), mercuric sulphide. (HgS) gallium arsenide (GaAs), Silicon Carbide (SiC) are also used to detect radiations.



The semiconductor forces a current to flow in the external circuit. The maximum fraction of energy that is transferred to the election is given by

$$\frac{E_m}{E} = 4m$$

E_m is maximum energy transferred
E is energy of ionizing particle
m is election to particle mass ratio M_e/M_p.

For high energy detectors, the donors or acceptors should be completely compensated in p-type or n-type silicon or germanium.

Plastic film and Luminescent Detectors :

High energy ionizing particles are known to cause damage to the molecules of polycarbonates, So. polycarbonate films irradiated with such particles leave tracks of damage which may be narrow or broad and these films are studied under microscopes for strength of ionization radiation.

Thermoluminescent property of certain materials such as flourites and ceramics is sometimes used for radiation detectors.. LiF, CaF_2 both activated with Mn. can detect x-rays, γ-rays. β-rays, elections and even neutrons.

Fibre optic sensors :

Optical fibres are basically considered as communication channel and sometimes affected by external parameters/stimuli such as temperature, acoustic vibration, magnetic field and many more. These fibre optic sensors are classified into two groups.

1) Active - The fibre is exposed to energy source that effects the measurand and a consequent change in the optical propagation in the fibre is detected and related to the measurand.

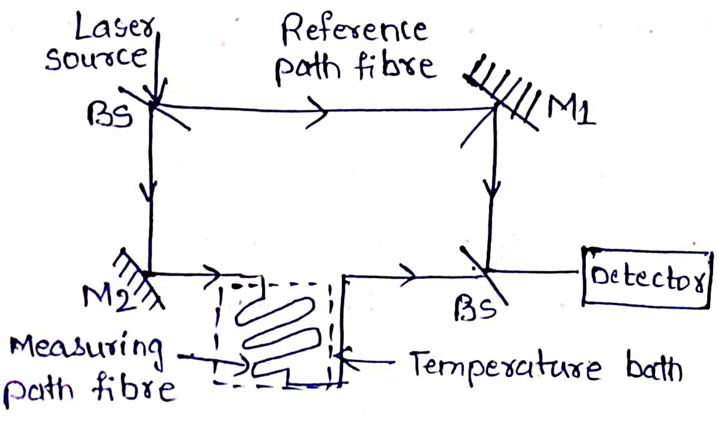
2) Passive - Light transmitted through a fibre at input end, and is modulated by a conventional optical sensor and this light is propagated through a second fibre called output fibre and detected corrected with the measurand.

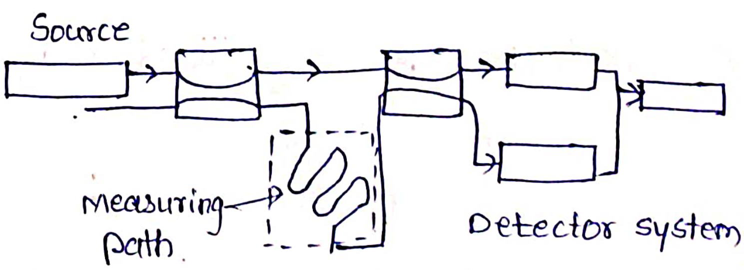
There multiple types of fibre optic sensors namely.

i) Temperature sensors
ii) Liquid level sensing.
iii) Fluid Flow sensing
iv) Microbend Sensors.

Temperature Sensors :

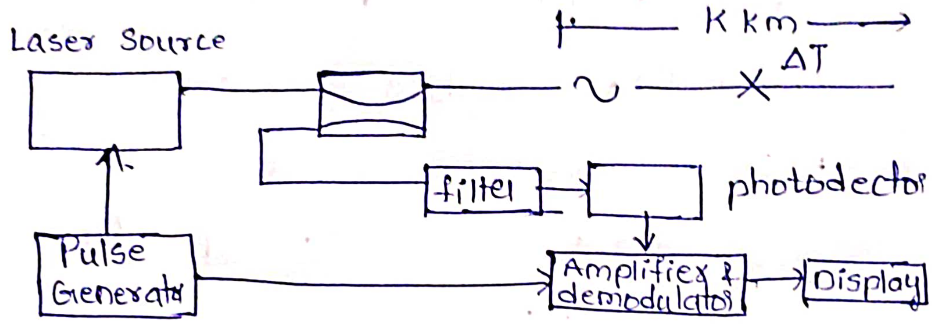
Two identical optical fibres are used to propagate radiation from a source say, a laser source and a fibre as medium with temperature different than that of other, the optical outputs from two fibres would have a phase difference which is a function of difference in temperature.





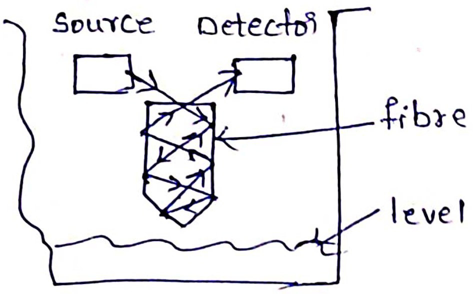
These sensors use He-Ne laser as source and the first one uses Mach-Zender interferometer as the detector while second uses a Michelson interferometer. The beam-splitter (BS) and mirrors(M) in the first case have been dispensed with using fibre couplers in the second.

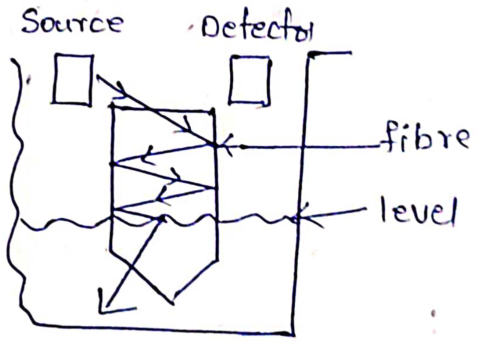
Optical fibre can be used for distributed temperature sensing. optical pulse from a pulsed laser source is sent along a fibre over a distance covering a few kilometers.



Liquid Level Sensing:

Fibre optics works on the principle of total internal reflection, if the light is incident in a proper angle. if the fibre is placed in a liquid medium of different refractive index. it is possible that light refracts into liquid and total internal reflection inside fibre stops. stopping light propagation into it..





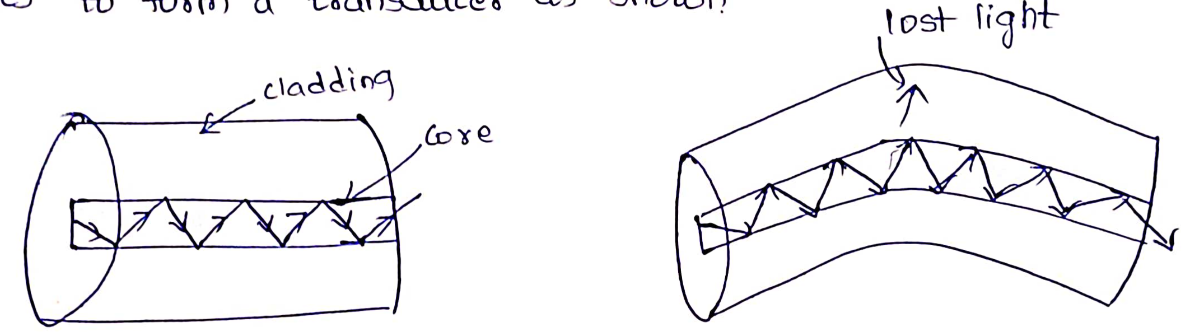
This principle is utilized in measuring liquid level at specific values The bottom end of fibre is shaped like a prism so that the, with large difference in refractive indices of fibre and medium like air, there is internal reflection and light travels to be detected as shown. When liquid level rises to cover the bottom of the fibre, light refracts into the liquid and the detector fails to show any output.

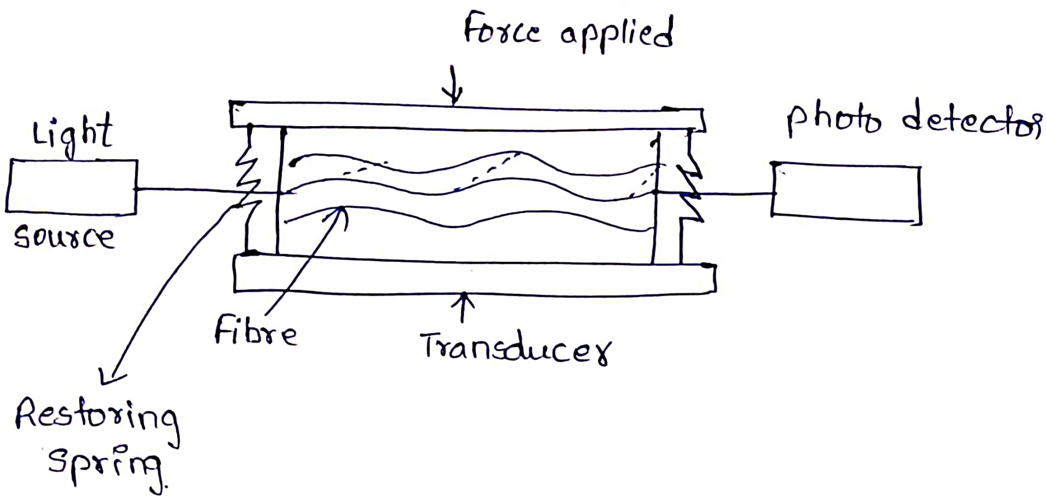
Fluid Flow sensing :

The fluid flow rate is sensed by an optical fibre mounted transversely in a pipeline through which it flows. This is done by a fibre, mounted across the flow, vortex shedding occurs in channel and fibre vibrates, which in turn, causes phase modulation of optical carrier wave propagating through fibre. The vibration frequency is proportional to the flow rate.

Microbend Sensors :

Acoustic pressure sensing can be done by the microbending of a multimode fibre. The optical fibre is placed in two corrugated plates to form a transducer as shown





Applied forces causes microbending in the fibre. Consequently more light is lost and the receiver detector indicates less intensity. A calibration of force in terms of the intensity of detected light may also be made