Subdivision of radiation detection.

(a) Methods based on the detection of free charges carriers.
- can be solid, liquid & gas.
- can detect the ± ve charge particle (α, β)
- can also detect the neutral particle (n, γ)
- Exp. → Ionization chamber, proportional counter, Geiger Muller counter and semiconductor detector.

(b) Methods based on the light sensing.
- Can be solid, liquid and gases.
- Can detect charged or uncharged particle.
- Exp- Scintillation counters & Cerenkov detector.

(c) Methods based on visualization of tracks of the radiation
- can be solid, liquid & gases.
- can be used mostly for charged particles
- Exp - Wilson cloud chamber, bubble chamber, nuclear emulsion plates, spark chamber and solid state track detectors.

We will discuss only 'a' & 'b'

Detector for Nuclear Radiations

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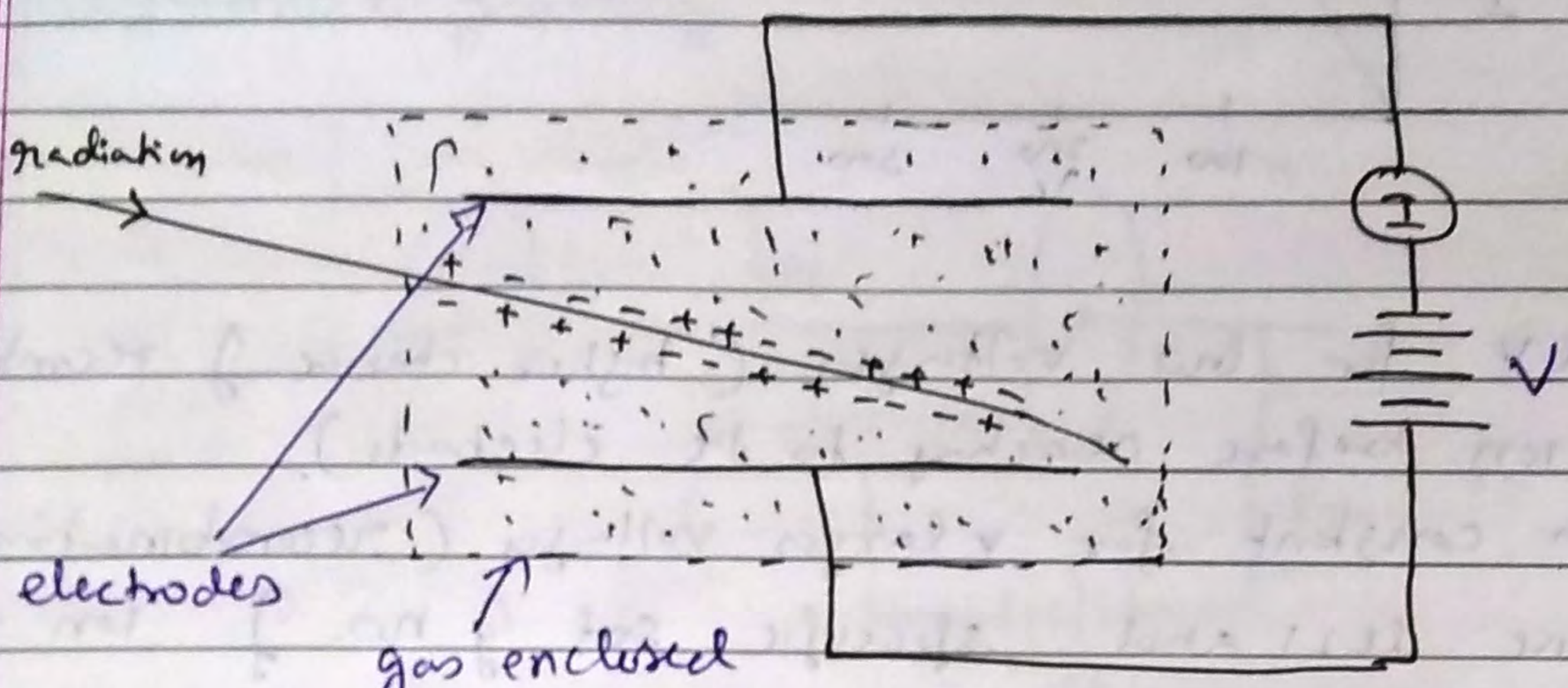
Date

Gas detectors

1) Ionization Chamber



When an energetic heavy charged particle moves through a substance, it loses engy by repeated ionizing collisions with the atomic electrons in the substance. In each such collision, a pair of positive ion & negative ions ~~electron~~ is produced. The negative ions are generally electrons. This ionization process is called primary ionization. The positive and negative electrodes placed within a detector attract the oppositely charged ions produce in the medium b/w them which gives rise to ~~the~~ an ionizing current.

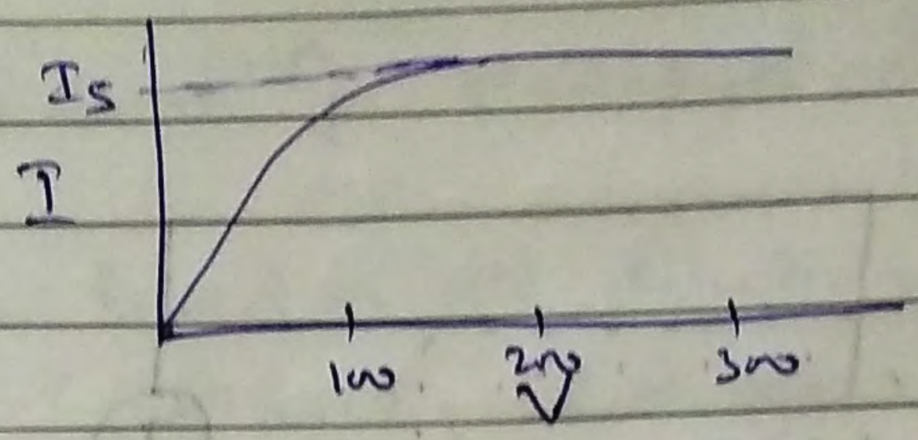
no. of ion pairs formed = $n = \frac{E}{W}$

E ⇒ engy of incident radiation.
W ⇒ engy required to form one ion-pair in a particular medium.
W is typically 25 ~ 35 eV/ion.

So if 1MeV particle enters a medium of W = 25 eV/ion

then $n \Rightarrow \frac{E}{W} \Rightarrow \frac{1MeV}{25 eV/ion} \Rightarrow 40K$ ions.

variation of ion current and voltage is as shown.



→ $I \propto V$ for low voltages (higher chance of recombination of ion before reaching to the electrode).

→ I is constant for larger voltages. (recombination become less and specific no. of ion reaches to the electrodes. or larger fraction of the ions reaches the electrodes.

$a = \frac{F}{m} = \frac{Ed}{m}$

drift velocity of ion. $v_d = \frac{s}{t} = \frac{1/2\, at^2}{t} \Rightarrow \frac{1}{2} at \Rightarrow \frac{1}{2} \frac{Ed}{m}$

$\Rightarrow \frac{1}{2} \frac{eE}{m} t$

$= \frac{1}{2} \frac{eE}{m} : \lambda/c$

$t = \lambda/c$

not so imp but to understand.

$t \Rightarrow$ mean time
$\lambda =$ mean free path
$c =$ mean thermal velocity

$v = kE$

$k =$ ionic mobility

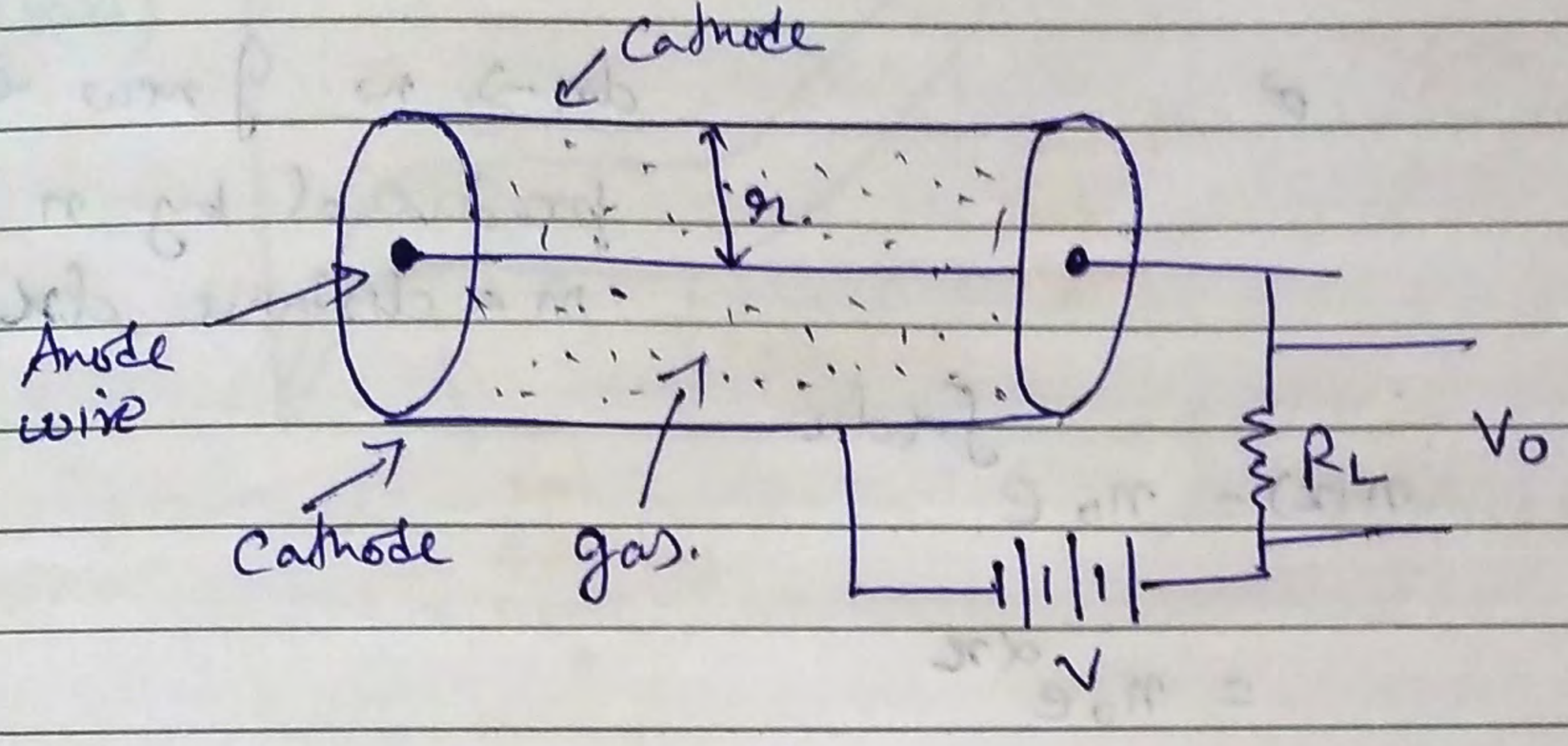
So total current $\Rightarrow I \Rightarrow ne(v_i + v_e)$

$\Rightarrow neE(k_i + k_e)$

$= ne(k_i + k_e) \frac{V}{d}$

2. Proportional Counter

Typically proportional counter are constructed with the cylindrical geometry.



electric field $$E(r) = \frac{V}{r \ln(b/a)}$$

b = cathode inner radius (~ 1.0 cm)
a = anode wire radius (~ 0.005 cm)
V_2 applied voltage. ($a > 2000$ V.)

So the typical electric field near the anode wire will be $\sim 10^6$ V/m.

Due to this large field; large no. of secondary ionization process can occur and resulting into an avalanche formation and increases the no. of ion pairs(s) before getting collected at the electrodes. This increases the amplitude of output pulse V_0.
The increase in ion pair formation is also called ~~gas~~ amp gas amplification.

The fractional increase in the no. of electrons per unit length is goremed by the townsend eq.

$$\frac{dn}{n} = \alpha dx$$

$\alpha \Rightarrow$ Townsend coefficient

$dn \rightarrow$ no. of new electron produced by n electrons in a distance dx

$$n(x) = n_0 e^{\int \alpha dx}$$

$$= n_0 e^{\alpha x}$$

gas amplification factor. M

$$Q = n_0 e M$$

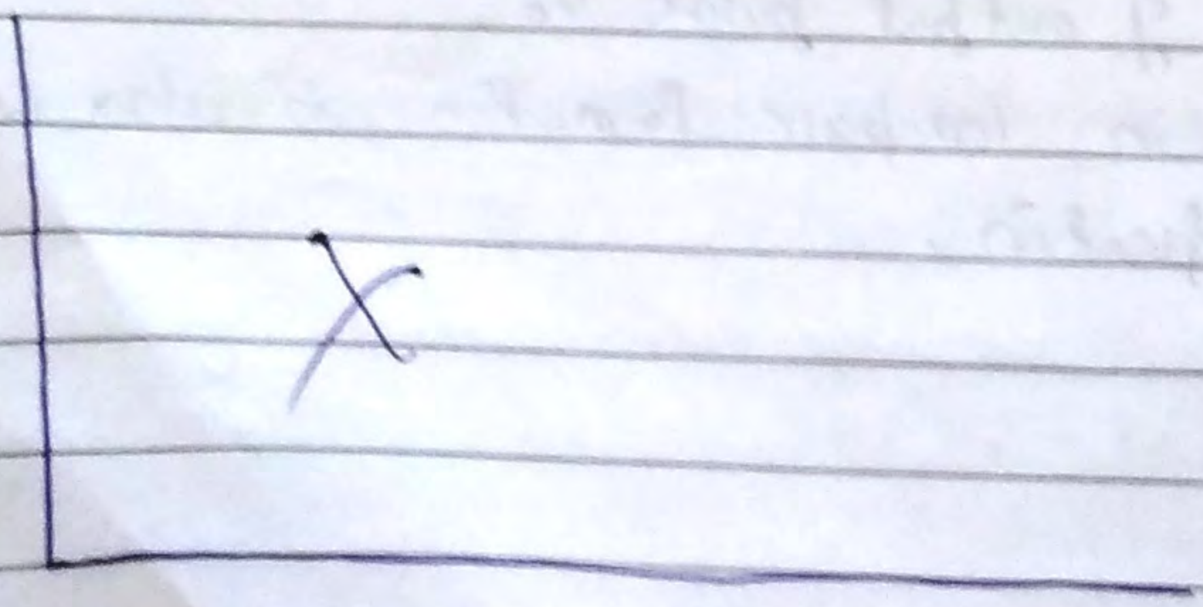
Q = total charge produced

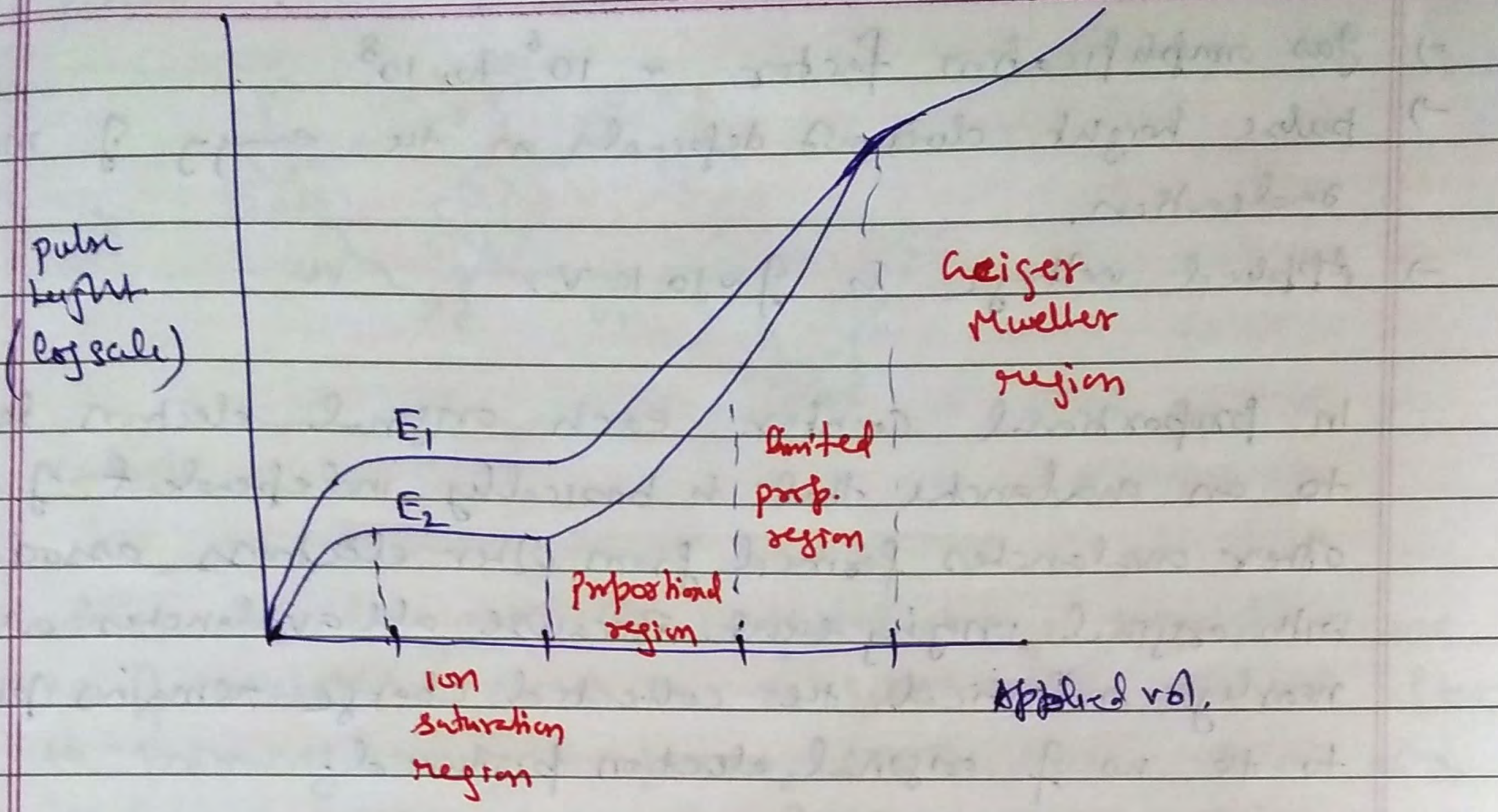
n_0 = no charge produced by primary ionization

also $M = \frac{n(x)}{n_0} = e^{\alpha x}$ or $e^{\int \alpha dx}$

typically gas amplification factor for proportional counter is $\sim 10^2$ to 10^4

variation of pulse height (V_0) and applied voltage for gas detector.





E_1 & E_2 are energy of different incident particle

We can see that in ionization and proportional region the pulse height at the output is proportional to the energy of incident particle. But in GM region irrespective of incident energy the pulse height at output is same.

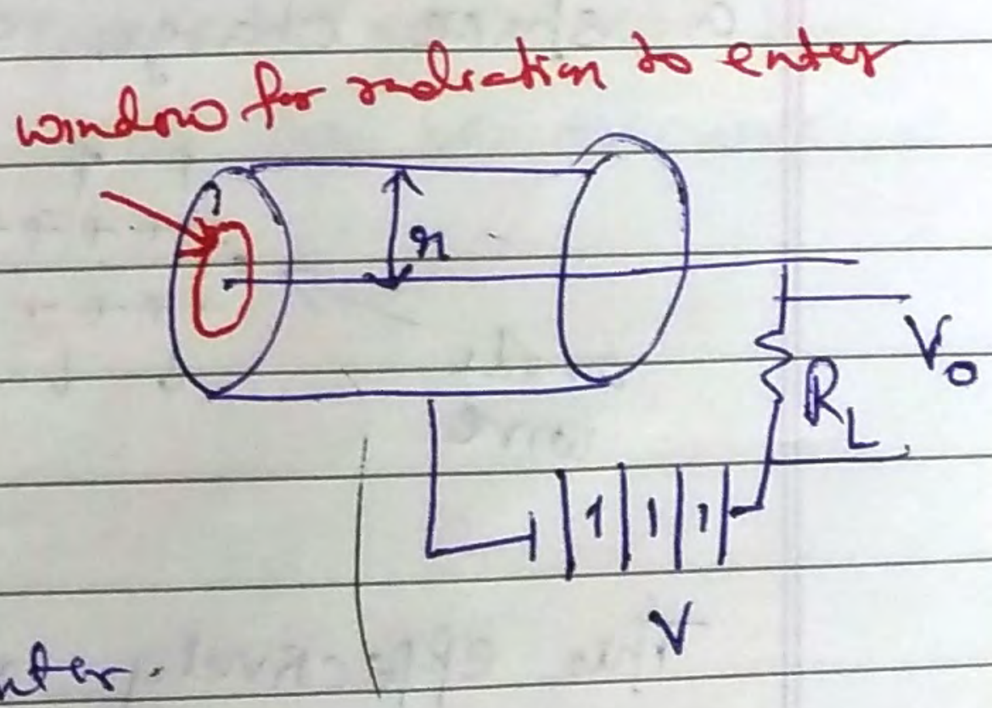
3) Geiger - Mueller Counter or GM Counter.
Müller.

Cylindrical geometry.

$$E(r) = \frac{V}{r \ln(b/a)}$$

basic.

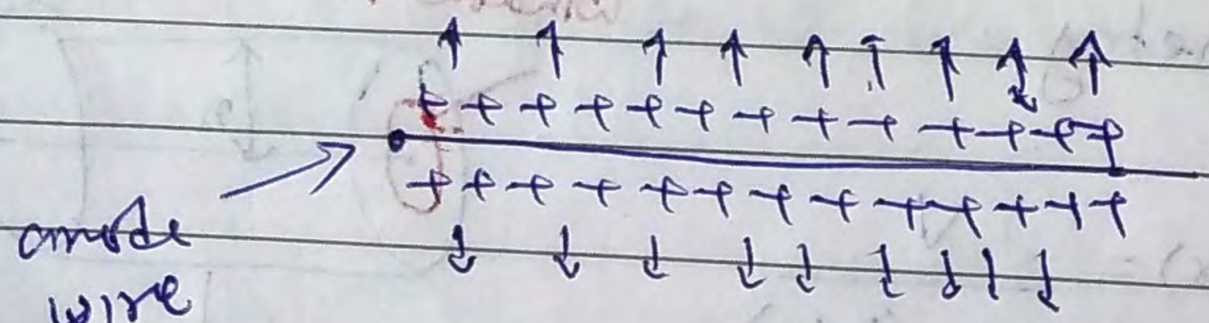
Some diff from proportional counter.



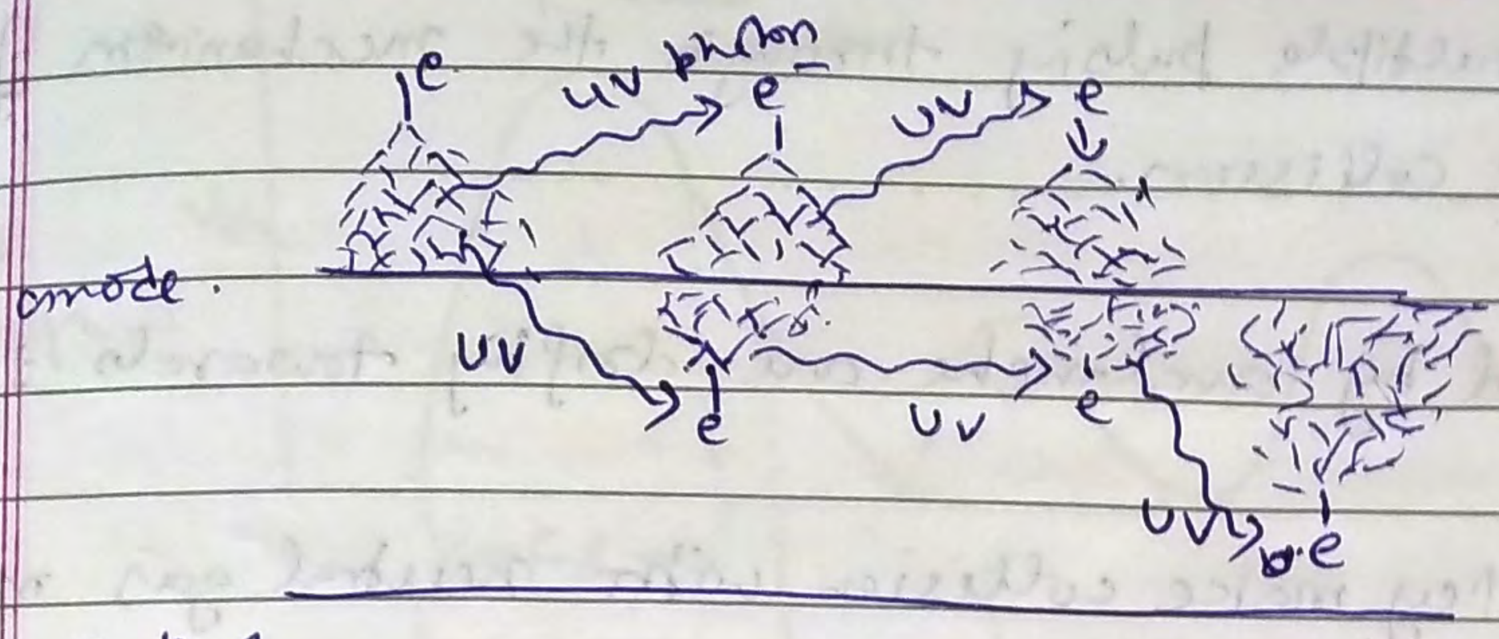
→ Gas amplification factor ~ 10^6 to 10^8
→ pulse height does not depends on the energy of incident radiation.
→ Applied voltage is ~ 10 kV.

In proportional counter each original electron leads to an avalanche that is basically independent of all other avalanches formed from other electrons associated with original ionizing event. Because all avalanches are nearly identical the collected charge remains proportional to the no of original electron produced.

In GM counter under a proper condition a situation is created in which one avalanche can itself trigger a second avalanche at a different position within the GM tube. So in principle an exponentially growing no of avalanche could be created within a very short time (1μs) These give rise to a dense envelope of elec- ion pairs) immediately surrounding the central wire throughout the entire length of anode. The electrons are very light and quickly collected by the anode wire. The ions are massive and take time to move towards the cathode so they get accumulated around the anode wire, producing a space charge sheath surrounding the anode.



This effectively reduce the electric field near the anode which lower the gas multiplication and hence the Geiger discharge process stops.



Cathode

Since for termination of Geiger discharge requires same no of avalanches event in the tube to be created after the primary ionization process, All the pulse form as a of Geiger Müller tube are of same amplitude regardless of the no. of original primary ion pairs formed.

Quenching of the discharge.

Why Quenching (Stopping) is required.

One After the termination of avalanche process the positive ions have started drifting towards the cathode and become neutralized (takes 10^{-4}–10^{-3} sec), but during their travel they can be accelarated and strike the cathode with enough energy to release electrons and to begin the process again of avalanche again without any incoming radiation. This will give rise to an false output pulse. So to avoid this we require quenchig of the discharge.

Methodes of quenching.

1) Internal Quenching.
Adding 5- to 10 % quenching gas with active gas in the GM tube.

This prevent multiple pulsing through the mechanism of charge transfer collission.

steps:

→ +ve ions formed by avalanche are drifting towards the cathode.

→ during drift they make collision with neutral gas molecules of quenching gas.

→ because of difference in the ionization energy (primary gas and quench gas molecules), there will be a tendency to transfer the +ve charge to the quench gas.

→ Due to this all the primary gas molecules are neutralized before reaching to cathode.

→ It means the gas molecules reaching to the cathode surface are quench gas molecules.

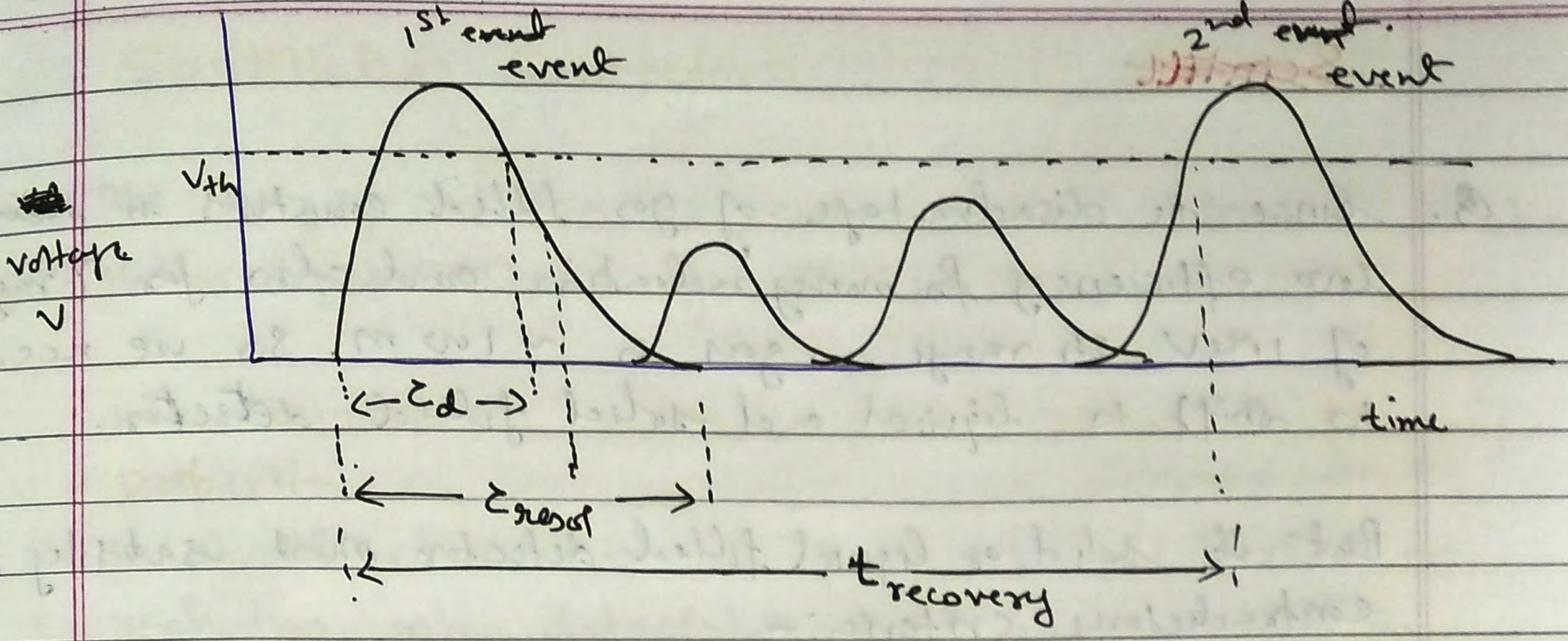
→ When these quench gas molecules are neutralized at the cathode surface, the excess energy (released during this process) may go into disassociation of the more complex quench gas molecules in preference to liberating a free electron from the cathode surface.

Example of quench gas → ethyl alchol, ethyl formate.)

2) Quenching can also be done by reducing the applied voltage for a fixed time after each pulse, that is too low to support any gas amplification.

Dead time of GM Counter. (τ_d)

This is defined as the time interval b/t the production of the initial pulse and the initiation of the second Geiger discharge.



Resolving time ($\tau_{resol.}$) a little longer then τ_d

Recovery time ($\tau_{recovery}$) the time interval after which the counter return to its orginal state to produce the full sized pulse again

$$N = \frac{n}{1 - n\tau_d}$$

N = actual rate of arrival of ionizing particles

n = counting rate of counter

So no. of particle missed by the counter per second

$$= N n \tau_d = N - n$$

because $n\tau_d$ time the ~~dead~~ counter is a unable to respond to the particle n per second.

~~Scintt~~

Q. Since the disadvantage of gas filled counters is their low efficiency for many radiation and also for X-rays of 1 MeV its range in gas is ~ 100 m. So we need to shift to liquid and solid filled detectors.

But the solid or liquid filled detector must satisfy two contradictory criteria:-

1) Material must be able to support large electric field, so e & ions pairs can be collected into an electronic pulse, no current must flow in the absence of radiation.

2) e & ion pairs must be able to travel easily through the material (ions travels like hole)

Materials that satisfy above criteria are semiconductor and also scintillators (but in diffrent way).

Scintillation Detectors

The ionizing radiation in certain matrial produce scintillation light instead of elec-ion pairs.

Idea scintillation material should posses the following properties

1) It should convert the KE of the charged particle or γ-radiation into detectable light quanta with a high scintillation efficiency.

2) This conversion should by linear - light yield should be proportional to deposited engy over as wide a range as possible.

3) The medium should be transparent to the wavelength of its own light emission for good collection of light quanta.

4) The decay time of the induced luminescence should be short so that fast signal pulse can be generated.

5) The material should be of good optical quality and subjected to manufacture in sizes large enough to be of interest as a particle detector.

6) its index of refraction should be near that of glass (1.5) to permit efficient coupling of the scintillation light to a photomultiplier tube or other light sensor

The process of scintillation

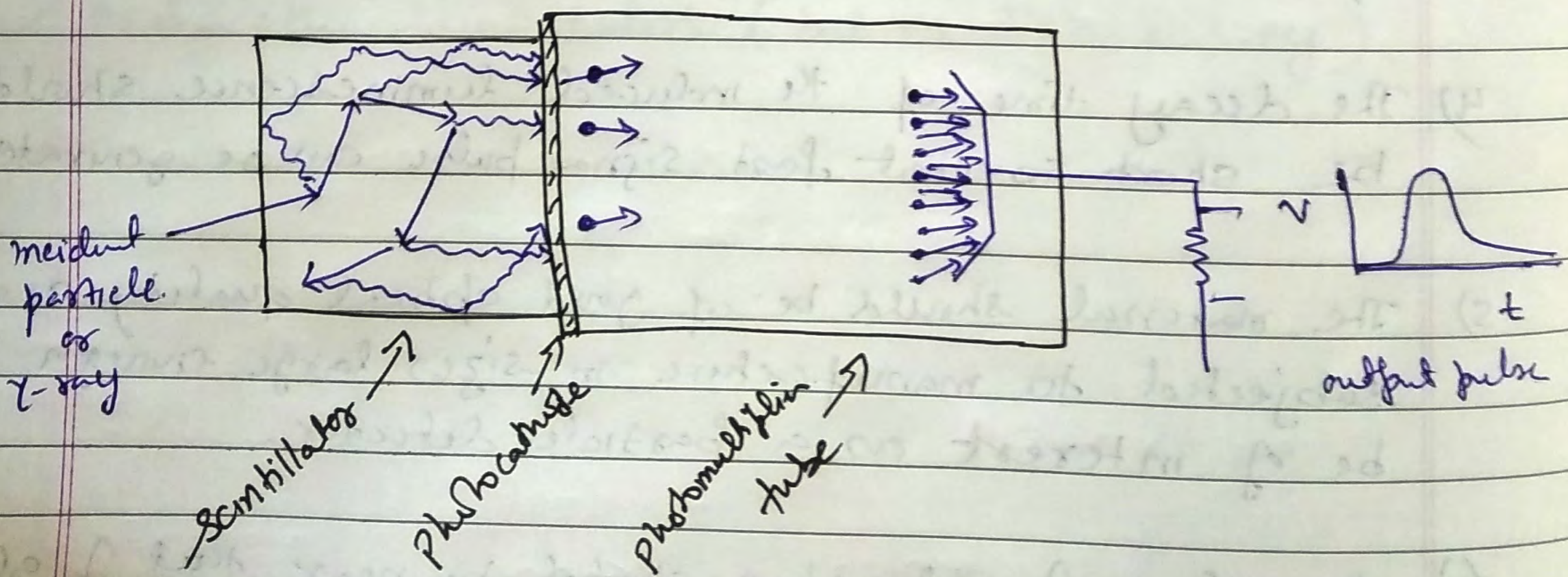
1) The incident radiation enters a detector and suffer large no of interactions, which results in the raising of the atoms to excited states

2) The excited states rapidly emit visible (or near-visible) light quanta. The material is said to be fluoresce.

3)

3) The light strikes a photosensitive surface, releasing at most one photoelectron per photon.

4) These secondary electrons are then multiplied, accelerated and formed into the ~~on~~ output pulse in the photo-multiplier tube (PMT)



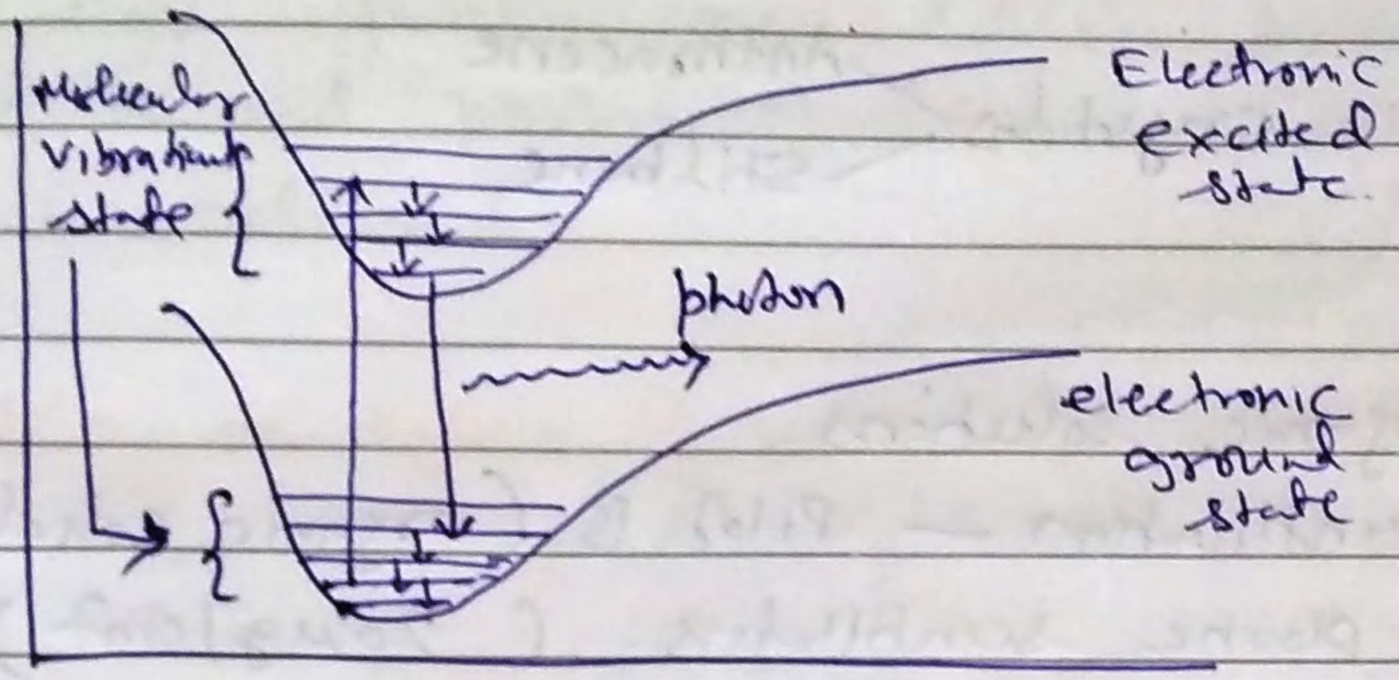
Scintillation detector.

Type of Scintillator

1) Organic Scintillators

a) Mechanism of Scintillation

transition composed of electronic & vibrational excitation states



electronic excitation state ~ 10eV

vibrational state ~ 0.1eV

electrons which are involved in the transition are those which do strongly take part in bonding. such as π electrons

→ The incoming radiation interacts with many molecules, losing a few eV at each interaction as it excites the molecules.

→ Many possible vibrational states can be excited

→ These vibration state in (in Electronic excited state) decay quickly (1 ps) to the lowest vibrational state of the electronic excited state.

→ Now this can go to one of the vibrational state of ground electronic ground state (10 ns) by emitting a photon.

→ finally molecule can get go to the lowest vibrational state in the electronic ground state.

According to Boltzmann distribution, it is unlikely to find any population of the vibrational states above

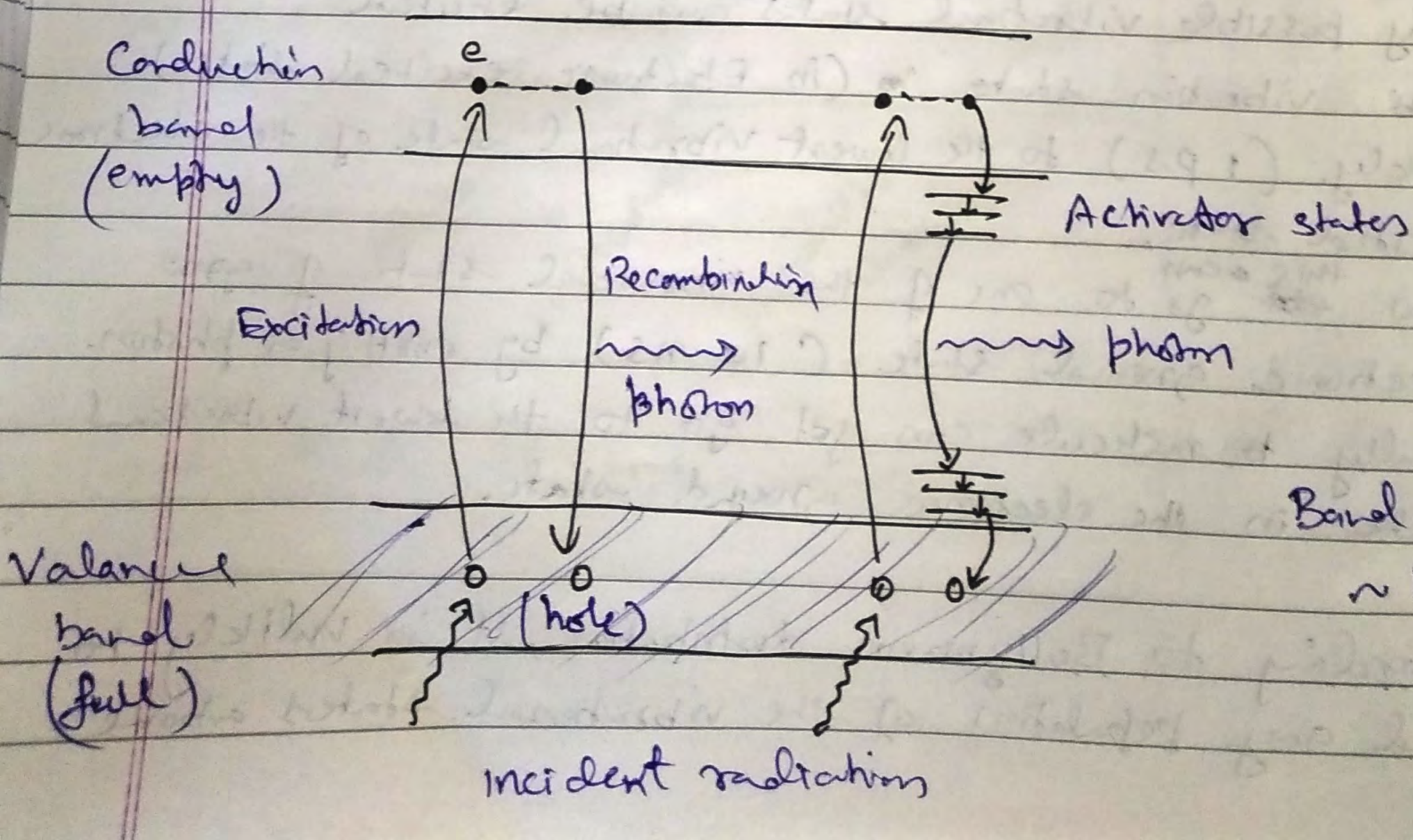
the electronic ground state. Thus only one of the many emitted photon transition has any probability to be absorbed.

(b) Examples or types of organic Scintillation

1) Pure organic crystals — Anthracene, Stilbene
2) liquid organic solutions
3) Plastic Scintillation — Pilot B (organic solvent)
4) Thin film plastic scintillators. ($20 \mu g/cm^2$)
5) Loaded organic scintillators. — lead or Tin added to common plastic scintillators up to a concentration of 10% by weight. This increases the high Z-elements that have better photoelectric conversion for gamma rays.

2) Inorganic Scintillators.

(a) Scintillation mechanism



Simple process of excitation of electron from valence band to conduction band and then recombination after electron drop back to hole in valance band by emitting a photon of energy equal to band gap of the inorganic scintillator. due to radiation

Some time impurities are added forming activator state and photon of lesser energy than band gap is released.

b) Examples or types of inorganic scintillators.

1) Alkali Halide
   - NaI (Tl) — 415 nm — λ of photon
   - CsI (Tl) — 540 nm
   - CsI (Na) — 420 nm

2) Unactivated fast inorganic
   - BaF_2 — 220 nm
   - BaF_2 — 310 nm
   - CsI — 305 nm
   - CsI — 450 nm

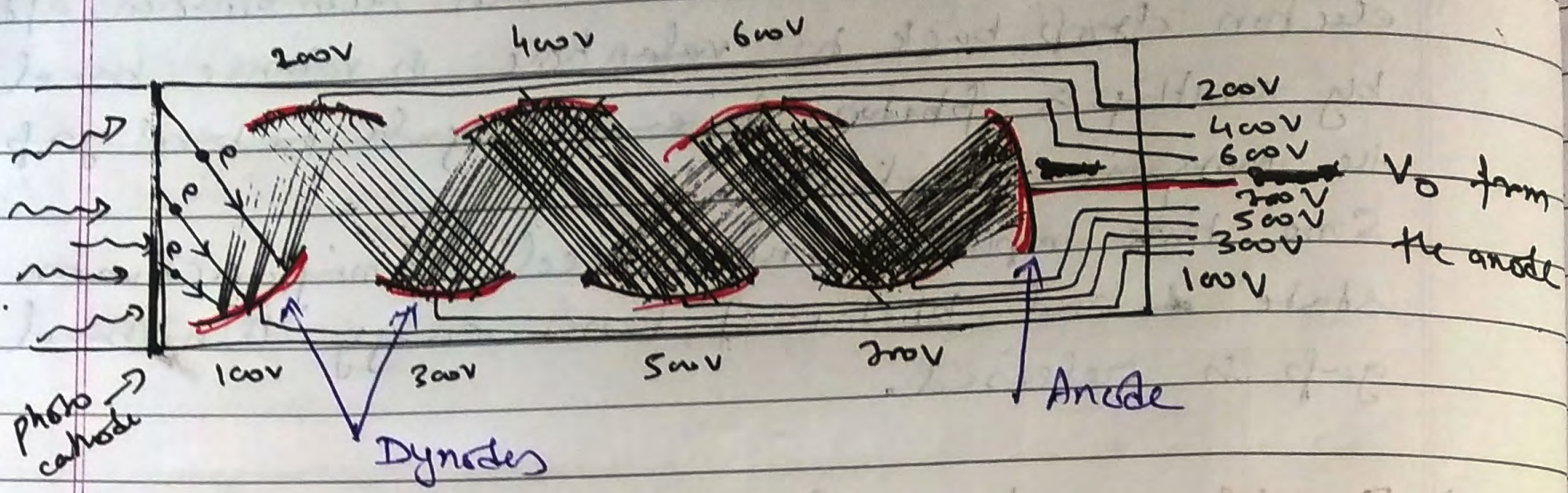
3) other Slow inorganic
   - BGO — 480 nm — $Bi_4Ge_3O_{12}$
   - $CdWO_4$
   - ZnS(Ag)
   - CaF_2(Eu)

4) Cerium Activated fast inorganic
   - Gd_2SiO_5
   - $YAlO_3$
   - $Y_3Al_5O_{12}$
   - $Lu_2(SiO_4)O$
   - $LuAlO_3$

5) Glass Scintillators

6) Gas Scintillators
   - Xe — 325 nm
   - K — 318 nm
   - Ar — 250 nm
   - He — 390 nm
   - N — 390 nm

Photo-multiplier tube (PMT)



Each dynodes are at potential difference of 100V w.r.t each other.

- Dynodes are constructed of materials with high probability of secondary electron emission when it is hit by an electron having high energy.

Secondary electron emission takes around 2~3 eV.

So when the electrons from photocathode are accelerated by the dynodes at 100 V potential, and the electron hit the dynodes surfaces with K.E of 100 eV and secondary electron are released. These secondary electron now accelerated toward the 2nd dynode with potential of 200V and so on. till the electrons get multiplied and reaches to Anode.

Example. 1 from 1st dynode.

no of secondary electron per per primary electron $\Rightarrow \frac{100\ eV}{2\ eV}$ (KE of e hitting it / (energy need to release an secondary ele)

$= 50$

no. of secondary ele. from 2nd dynode per per primary electron $= \frac{50 \times 100}{2}$

$= 25\alpha$

so over all gain $= x^y$

$x \Rightarrow$ gain of each dynodes
$y =$ no. of dynode.

so if α is the initial primary & no. of electron then final total no. of electron collected at anode.

$$= \alpha x^y$$

Imp point :— linearity and stability to be maintained while multiply the electron in PMT. It mean the amplitude of the output pulse should be proportional to the original no. of scintillation events and thus in turn to the energy of incident particle.

Semiconductor Detectors

limitation of scintillation counters is their relatively poor energy resolution because of several chain of event occurs to produce the final pulse at output.

Semiconductor is answer to this or called solid state detectors.

→ Band gap of semiconductor $E_g \rightarrow$ 1 eV to 4 eV.

→ charge carriers in semicond. — intrinsic — pure semicond.
extrinsic — n-type
p-type

in intrinsic semiconductor $n_i = p_i$ (no. of electron / no. of hole)

in extrinsic semiconductor.

in n-type $n \simeq N_D$ no of donor impurities

in p-type $p \simeq N_A$ no. of acceptor impurities

electrical conductivity of doped semi is much higher than intrinsic semi

ex. for intrinsic Si $n_i = p_i = 10^{10} / cm^3$

if N_D - 2 atm / million Si

$$n \simeq N_D = 10^{17} / cm^3$$

then $np = n_i p_i$

$$p = \frac{n_i p_i}{n} \Rightarrow \frac{10^{10} \times 10^{10}}{10^{17}} = 10^3 / cm^3$$

so net charge carrier of doped Si ~ 10^{17} elec / cm^3
~ 10^3 hole / cm^3

for n-type { electron are called majority charge carriers.
hole are called minority charge carriers

for p-type { hole majority
electrons minority

mobility μ

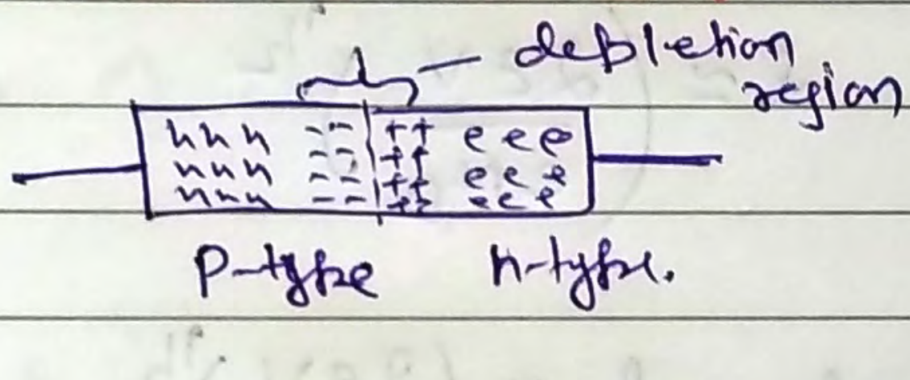
$$\mu_e = \frac{v_e}{\mathcal{E}} \qquad v_e = \text{drift velocity of ele.}$$

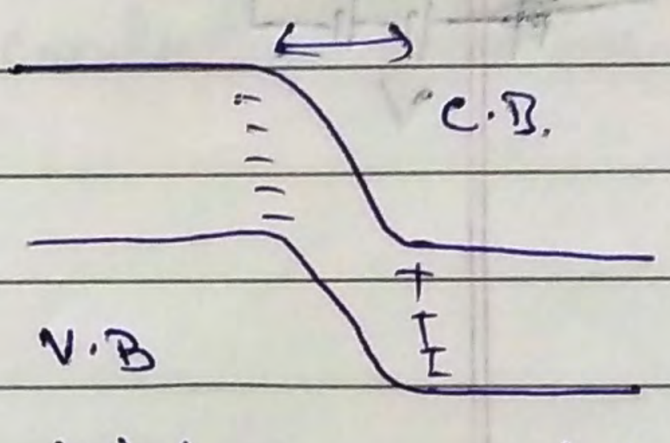
$$\mu_h = \frac{v_h}{\mathcal{E}} \qquad v_h = \text{drift velocity of hole}$$

Resistivity intrinsic $\rho = \frac{1}{e n_i (\mu_e + \mu_h)}$

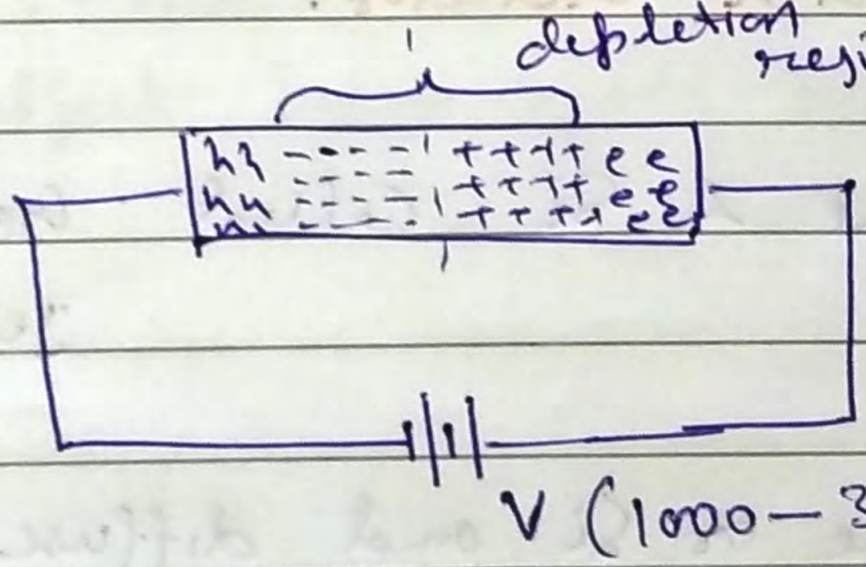
n-type $\rho = \frac{1}{e N_D \mu_e}$

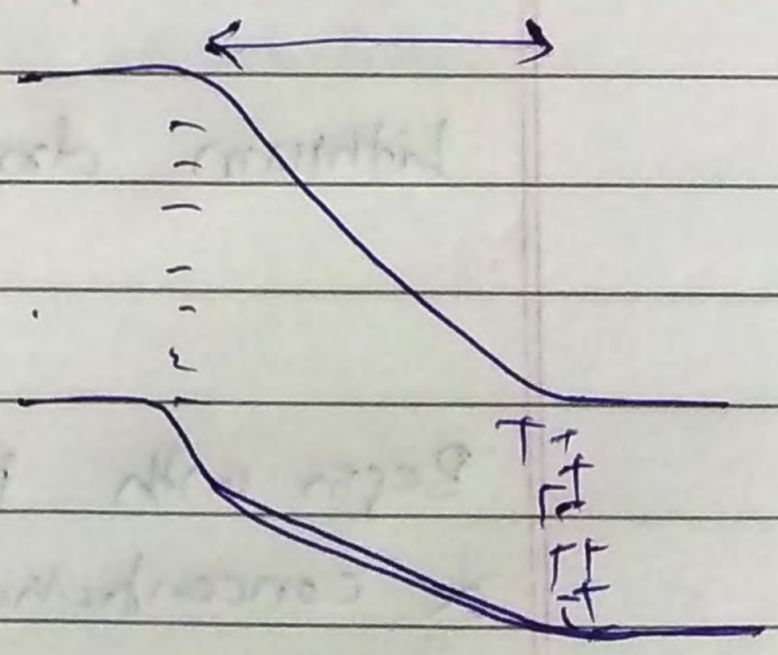
PN Junction diode as detector.





in Reverse bias condition





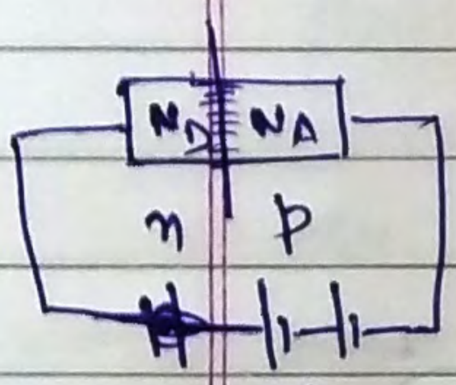
When Radiation enters the depletion region it creates e-h pairs very similar to the primary ionizing process in ionization chamber. PN junction diode is operated at very large reverse bias voltages and there e-h are collected collected in the form of reverse bias current.
This current is proportional to the energy of incident radiation

Why large voltage is applied in reverse bias

1) it increases the magnitude of the electric field in the depletion region, making charge collection more efficient.

2) it increases the dimension of the depletion region which increases the sensitive volume of the detector.

Size of depletion region. d



$$d \simeq \left(\frac{2\varepsilon V}{eN_A}\right)^{1/2} \qquad N_D >> N_A$$

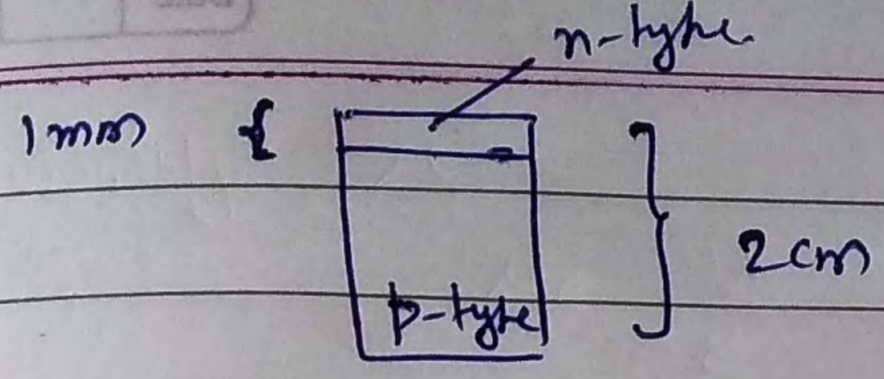
$$d \simeq \left(\frac{2\varepsilon V}{eN_D}\right)^{1/2} \qquad N_A >> N_D$$

or generalized $d \simeq \left(\frac{2\varepsilon V}{eN}\right)^{1/2}$ ε - dielectric const

Examples of Semiconductor detectors.

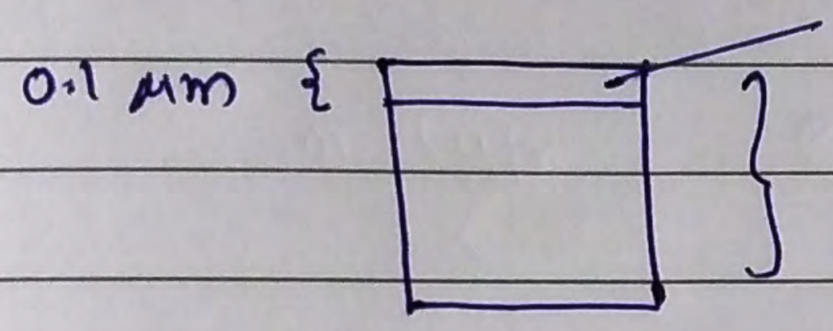
Lithium drifted Ge & Si called Ge(Li) & Si(Li)
jelly silly

Begin with p-type Ge or Si and diffuse into its surface a concentration of Li atoms, which tend to form a donor states and thereby create a thin n-type region. Under reverse bias and slightly higher temp, Li drift into p-type region, making quite large depletion region. These detectors are kept at 77K temp to stop the further migration of Li from its doped lattice site.



Ge(Li) & Si(Li) are good for γ-ray of 100 KeV

But for α-particle of 5 MeV range is less than 1mm in Si & Ge. So we need n-type or p-type thickness ~ μm. such detector are called surface-barrier detector.



extremely thin p-type layer is etched or deposited on n-type surface of Si.

→ time of collection of charges in semiconductor detector is of the order of 10-100 ns.

advantage

→ more efficient
→ high sensitivity
→ more denser and compact.
→ linear response over a wide range of energy and good output pulse having better energy resolution.