Radiation detectors and signal processing

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During the past fifty years radiation detectors and the related signal processing techniques have recorded a remarkable evolution, as requested by the increasing demand of sensitivity and accuracy set by physics, by several other sciences like biology, chemistry and medicine and also by a number of industrial applications.

Such an evolution has been of fundamental importance in the history of nuclear and elementary particle physics of the past few decades, as pointed out by the fact that in 1992 the Nobel Prize for Physics was conferred to George Charpak of CERN, a scientist whose dominant contribution has been in the field of radiation detectors.

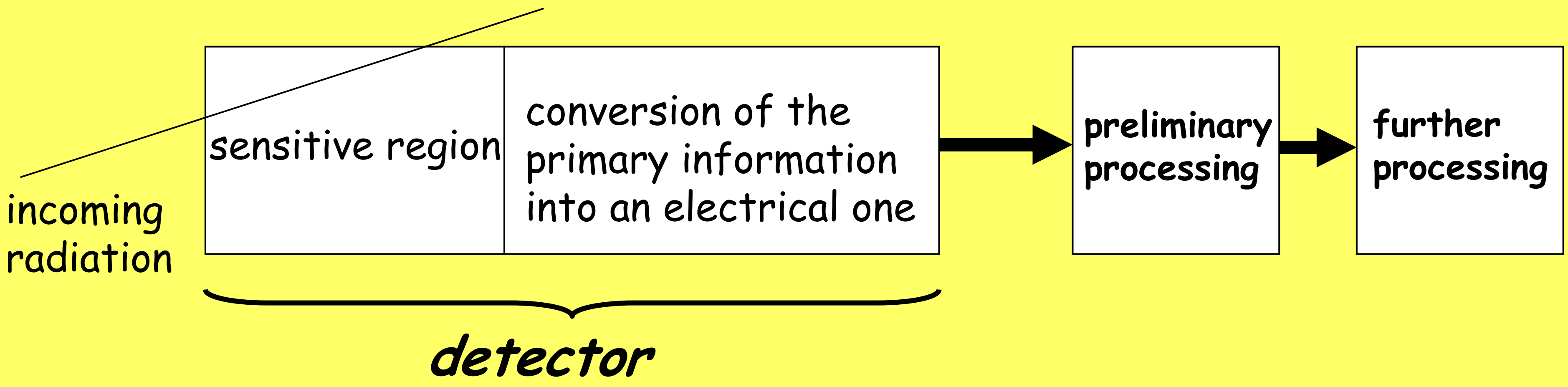
In the following lectures we shall focus on detectors that are able to recognize single events. Historically the first detector of this nature was the Geiger counter, as invented by Geiger and Rutherford in 1908. The Geiger-Mueller counter in the version we are familiar with nowadays was actually an improvement introduced in 1947.

With the increasing complexity of the functions requested to arrive at the final information, after some preliminary processing, the intervention of computers to deal with the information provided by the detector became essential.

Nowadays, a group of experimental physicists wishing to join an experiment must be knowledgeable about detectors and signal processing and it may even be requested to contribute with a detection system. For this reason a background on detectors is absolutely essential.

For reasons of speed of operation and for the sake of alleviating the complexity of the intermediate steps preceding the computer operation, the detector must either yield a primary physical quantity of electrical nature or, if the primary physical quantity is not of electrical nature, the detector must be be associated to a device able to convert it into an electrical signal.

According to the previous considerations, a radiation detector should be thought of as a part of a system which can be represented as in the figure below.



The more common detection principles are:

- **IONIZATION** – The energy released by the incoming radiation in the sensitive region of the detector gives rise to ionization processes with the creation of charge carriers of opposite sign (electron-ion pairs in gaseous or liquid media, electron-hole pairs in a solid-state medium). The primary physical quantity is of electrical nature. Therefore, no conversion process is needed.

- **SCINTILLATION** – The energy released in a sensitive region made of particular materials has the effect of exciting metastable states in their molecules. Their return to the fundamental state is accompanied by the emission of a short flash of light. In this case the primary physical quantity resulting from the interaction of the incoming radiation with the sensitive region is not of electrical nature. It is a bunch of photons, which requires a photodetector to convert it into an electrical signal.

❖ **CHERENKOV EFFECT** – Is the emission of light which occurs in a transparent medium when a charged particles travels through it at a speed higher than the speed of light in that medium. It is a process which has a threshold in the particle speed and as such it has several important application. The primary physical quantity is not of electrical nature and therefore, like in the case of the scintillation-based detectors, a conversion process is required to pass from the light signal into an electrical one. The conversion is realized by a photodetector.

❖ **BOLOMETRIC DETECTION** – This principle has the advantage of avoiding the partition of the energy released by the radiation into competing processes that are detected separately, like for instance coexisting ionization and scintillation. The bolometric approach consists in detecting the heat transferred by the interaction of the radiation with the sensitive region by measuring the temperature variation in that region. The primary physical quantity is a temperature variation, which requires a conversion device to be transformed into an electrical signal.

DETECTION BASED UPON SUPERCONDUCTIVE EFFECTS

Consider an STJ (superconductive tunneling junction) made of two superconductive layers separated by a very thin insulating layer. The energy deposited by a particle or by a photon absorbed in one of the superconducting layers breaks the Cooper pairs existing there giving origin to excited states called ***quasi-particles***.

A small bias voltage applied to the insulating layer causes the quasi-particles to cross the insulator by tunneling. The resulting current is proportional to the energy deposited by the incoming particle or photon.

As the energy required to break a Cooper pair is small, of the order of 1 meV, the number of charge carriers made available at a given value of the energy deposited by the radiation is much larger than in any other type of ionization-based detector. For this reason the STJ detectors may lead to a high resolution in the energy measurements.

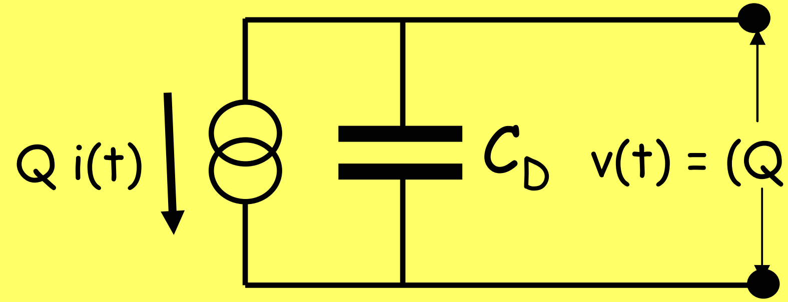
Types of information provided by a radiation detector

Radiation detectors associated with the suitable signal processors can perform the following functions:

- ❖ Measurement of the energy released by the radiation in the sensitive volume and energy-dispersive analysis.
- ❖ Definition of the instant at which the interaction of the radiation with the detector occurs (event timing).
- ❖ Position sensing, that is, definition of the coordinates of the interaction point.
- ❖ Event counting, or detecting the number of interactions in the sensitive volume occurring in a given time interval. This function provides information about the intensity of the radiation.

Before moving into the discussion about the specific detectors it is advisable to analyze a situation which will prove to be helpful in the understanding of the extent to which the features of a detector and the conditions set by the experiment affect the accuracy of a measurement.

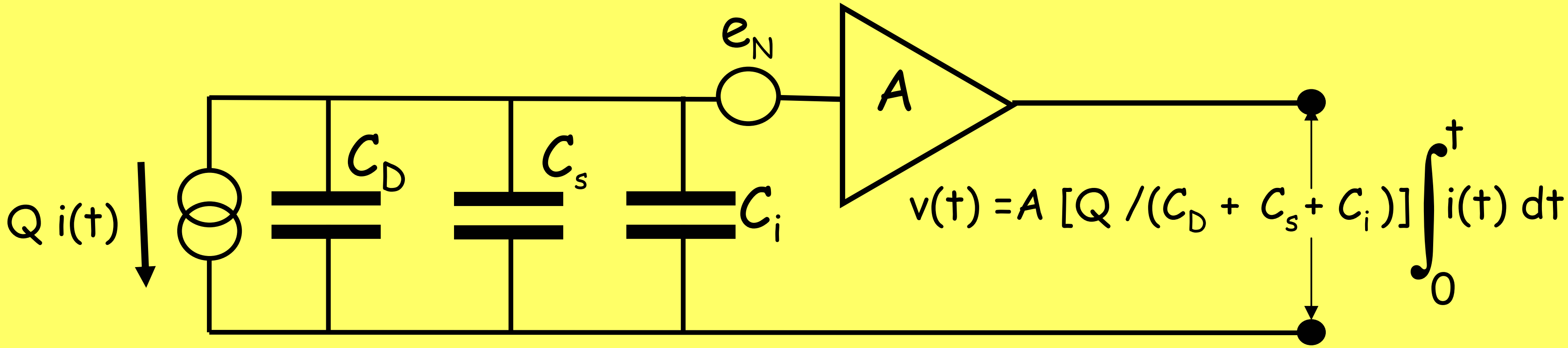
Most of detectors that are considered in this course can be modeled as a current source in parallel to a capacitance, as shown in the figure below.



$$v(t) = (Q / C_D) \int_0^t i(t)\, dt$$

In the figure Q is the charge associated with the current pulse i(t). In a linear detector, Q is proportional to the energy released by the radiation in the sensitive volume of the detector. The current pulse i(t) is assumed to be normalized to unit area, so that the integration of the detector signal carried out through the entire duration of i(t) would lead to the value of Q. In an oversimplified approach to the problem, we may think of integrating the detector signal across the detector capacitance C_D

This approach would make sense only if the detector capacitance is linear, that is, voltage-independent and reliable in value. Even if these conditions are met, however, the voltage signal appearing across the detector capacitance would be too small to be processed by the circuits that follow. Amplification is therefore required, as shown in the figure below.



C_s represents the total stray capacitance which appears between the detector terminals

C_i is the input capacitance of the amplifier.

A is the gain of the amplifier, which is represented as a noiseless block. Its noisy nature is accounted for by the input-referred voltage noise source e_N

In this oversimplified approach the current i(t) can be thought of as a rectangle of a finite duration t_D. The shorter is such a duration, the more suitable is the detector for operation on radiation of high intensity.

Therefore we can make the following considerations.

1 – The signal-to noise ratio in a detector charge measurement is affected by two parameters of the detector: its sensitivity dQ/dE where E is the energy released by the radiation and its capacitance C_D. The sensitivity dQ/dE determines the value of Q at a given value E of the energy released by the radiation in the detector.

2 – The signal-to noise ratio for a given energy release depends on the amplifier noise e. As it will be apparent throughout this course, effort aiming at reducing e becomes of paramount importance.

3 – The parameter t_D sets an upper limitation to the intensity of the radiation falling on the detector. The rate λ (s^{-1}) of events to be detected must be such that the average distance between two events, λ^{-1} be suitably larger (say, at least a a factor ten) than t_D .

Detectors based on ionization

Ionization as a detection principle is employed in the following types of detectors:

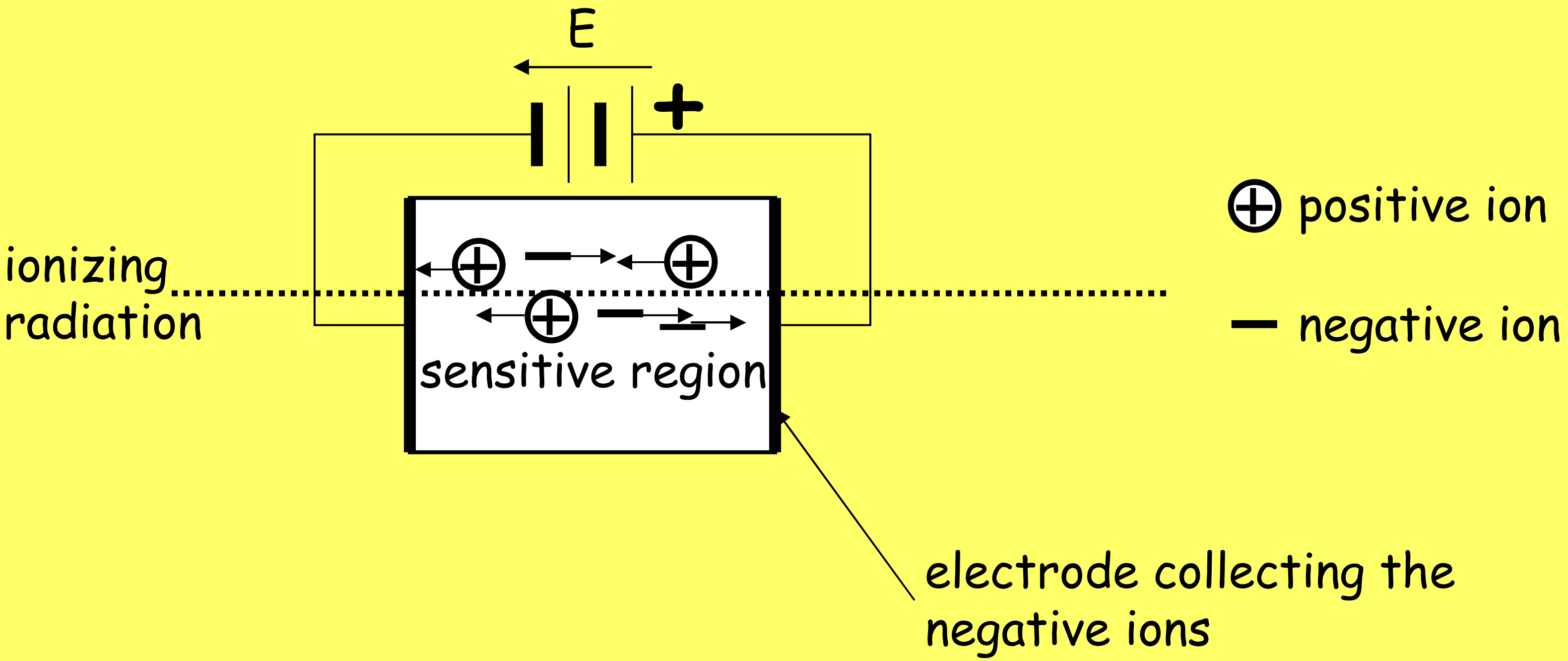
- Gas filled ionization chambers
- Cryogenic liquid ionization chambers
- Solid state detectors

Before the advent of solid state detectors, the gas filled ionization chambers have constituted the choice detectors for the energy spectrometry of the α particles emitted by natural radioactive materials. They have a remarkable importance, for instance, in the history of the nuclear physics of heavy nuclei. This must not give the wrong impression that nowadays the gas filled ionization chamber is an obsolete type of detector. LHC, the most advanced research unit ever developed by the physicists will employ in its luminosity monitor a gas filled ionization chamber.

The cryogenic liquid ionization chamber is at the basis of a large number of solutions in modern calorimetry.

Ionization is the basic detection principle in solid-state detectors, like ionization chambers employing insulators or P-N junctions in semiconductors.

THE FIGURE BELOW SHOWS THE GENERAL STRUCTURE OF A DETECTOR BASED ON IONIZATION AND EXPLAINS ITS OPERATION.



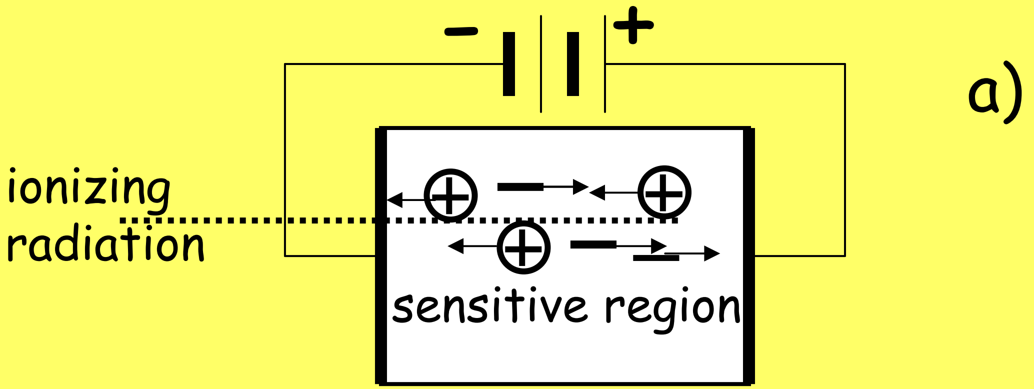
The electric field E established by the bias supply in the sensitive region implements a twofold function:

- ❖ it separates the ions of opposite charge preventing their recombination.
- ❖ it makes them drift toward the relevant collecting electrodes.

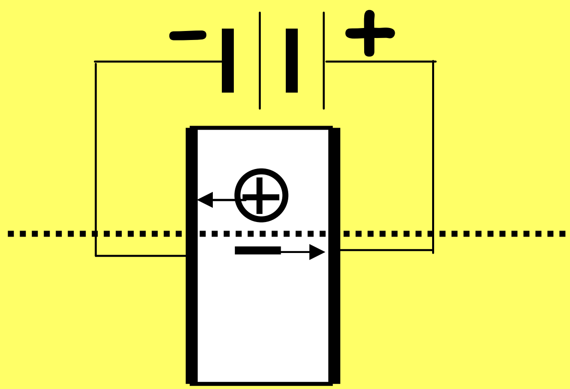
During their drift motion toward the collecting electrodes the carriers induce on them current signals. The charge associated with these signals is related to the energy released by the ionizing radiation in the sensitive region of the detector. Therefore, the measurement of the energy released in the active region of the detector implies a charge measurement.

In the previous example the ionizing radiation crosses the sensitive region without stopping. Therefore the energy released in the detector is smaller than the total energy of the radiation.

Here are two more examples. In case a) the ionizing radiation stops in the sensitive region and therefore the energy released equals the total energy of the incoming radiation. Case b) shows a detector featuring a very thin sensitive region. This type of detector is employed in the measurement of the specific energy loss dE/dx.



b) Very thin sensitive region for dE/dx measurements



In an ionization-based detector, a parameter of fundamental importance is the energy ε required to create an ion pair. For a given energy E released in the sensitive region, the number of ion pairs is:

$$N = E/\varepsilon$$

which shows that the smaller is ε, the larger is the number of ion pairs created in the detector for the same energy release. A large number of ion pairs means a large number of charge carriers drifting toward the electrodes and therefore a large charge associated with the induced current signals.

This is an important aspect in a detector which doesn't have an internal charge multiplication mechanism, like the gas filled ionization chambers, the ionization chambers employing liquids and the solid-state detectors. Indeed:

- The larger is the charge associated with the signal delivered by the detector, the less subject it is to being deteriorated by unwanted external signals, like noise and deterministic disturbances.

- A larger charge makes the amplification process required to bring the detector signals to the level required by the further circuits easier. Amplification is a crucial step in detector signal processing.

The importance of a large number of free charge carriers in an ionization detectors emerges from the following consideration. The creation of carrier is a random process, so that the number N is subject to statistical fluctuations. This subject will be discussed in more detail later on. For the moment, just assume that N obeys a Poisson statistics. In this case the variance associated with N would be $N^{1/2}$. The relative variance, which expresses the linewidth or the resolution in an energy measurement where the average number of carriers made available by the incoming radiation is N, is

$$N^{1/2} / N = 1 / N^{1/2}$$

Here are some values of ε relevant to materials employed in different ionization detectors

In Argon, a typical filling gas for ionization chambers ε = **25** eV
In a semiconductor of a low energy gap, like Germanium, ε = 2.67 eV
For diamond, an insulator featuring a high energy gap, ε = 13. 2 eV

DETECTOR SIGNAL

As already pointed out, the detector information in contained in the current signals induced by the two types of carriers in their motion toward the relevant collecting electrodes.

IMPORTANT REMARK

Both carriers induce current signals on both electrodes. The two types of carriers induce on the same electrode signals of the same polarity. For instance, electrons induce a negative signal on the electrode at positive voltage, toward which they drift. Positive ions induce on the same electrode a signal which is also negative. This because, they have a positive charge, but their velocity is opposite to that of the electrons.

IONIZATION DETECTORS WHERE THE SENSITIVE REGION IS GASEOUS.

Features of gas as a material filling the sensitive region

- The density is low, but can be increased by acting on the gas pressure.
- The gas is a medium which lends itself, in particular geometries creating regions of high electric field, to a reliable charge multiplication.
- The gas can be fluxed continuously, thereby restoring its initial conditions by removing the degradation which may occur in some special circumstances, like for instance, exposure to radiation.
- The drift velocity of the electrons in a gas like Argon is of the region of 1 cm/μs. That of the positive ions is up to three orders of magnitude higher. The drift velocity of electrons can be substantially raised by adding organic molecules to the filling gas. However, organic molecules may bring about unwanted side-effects.

DETECTORS UTILIZING THE IONIZATION IN A GASEOUS MEDIUM AS THE PRIMARY DETECTION PROCESS.

- The ionization chamber, where the charge available at the output is that created in the primary ionization process. As already pointed out, it was historically an important detector in the energy analysis of alpha particles.

- The proportional counter, where the charge available at the output is consistently larger than the initial ionization charge by virtue of a multiplication process in the gas. The proportional counter is still employed in the energy measurement of soft X rays. The multiplication process adopted in the proportional counter has opened-up the way to the Multiwire Proportional Chambers (MWPC) that played a very important role in the particle physics of the past few decades.

- The Geiger counter, which is based upon a geometrical configuration similar to that of the proportional counter. In the Geiger counter the operating conditions are such that the multiplication is so high to degenerate into a discharge. No information about the initial ionization charge is maintained. The function of the detector is just counting the single ionizing events occurring in a given time.

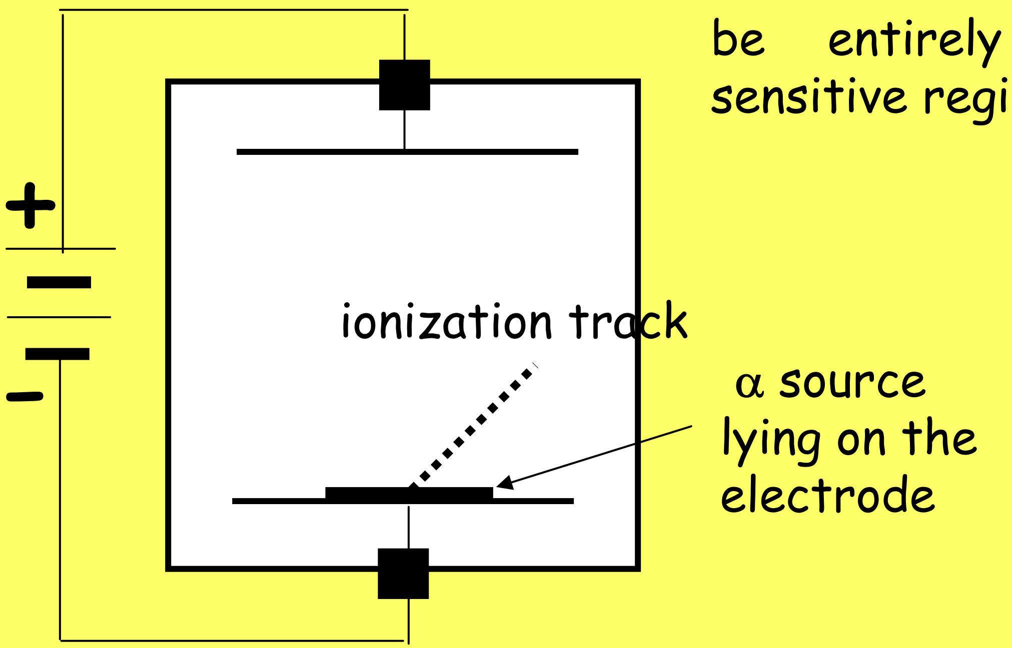
CHARACTERISTICS OF GASES AND GASEOUS MIXTURES FOR IONIZATION DETECTORS

Type of gas	Energy needed to create a pair (eV)	Electron drift velocity (cm/s) field 1kV/cm, P = 1 atm
Neon	36.2	---------
Argon	26.2	0.5×10^6
Argon+isobutane (70:30)		5×10^6
Argon+1% Nitrogen		2.3×10^6
Xenon	21.5	----------

The present study of the ionization detectors begins from the gas filled ionization chamber. The analysis of this detector is particularly instructive because of its comparatively simple structure, which allows the introduction of the mechanism of signal formation in a straightforward way. This mechanism can be next extended to the solid state detectors.

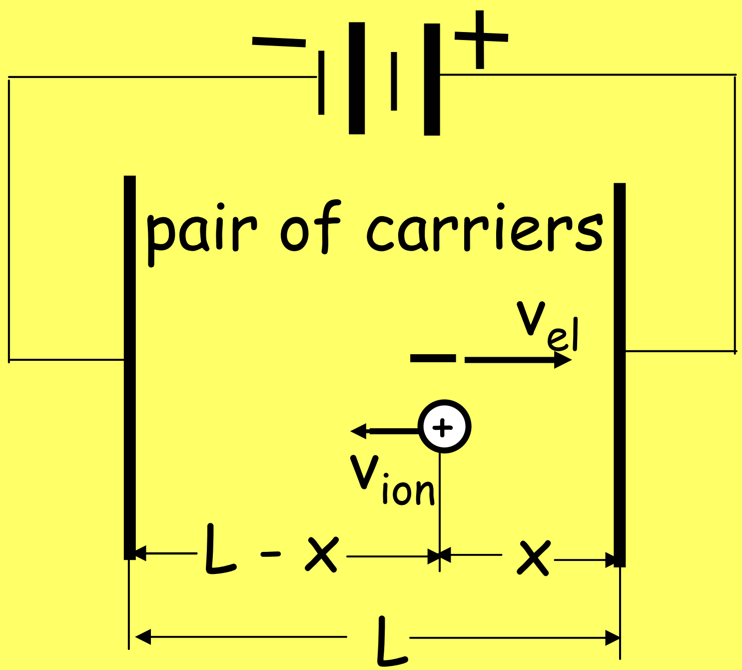
The figure shows a gas filled ionization chamber as it used to be employed in α particle spectrometry.

The ionization track is supposed to be entirely contained in the sensitive region.



The evaluation of the induced currents in an ionization chamber will be done, to begin with, in the simple case of a pair of carriers. The carriers move at a constant speed, as a combined effect of the electric field, which would tend to impose a constant acceleration and of the scattering by the molecules of gas. As a fundamental reading, refer to:

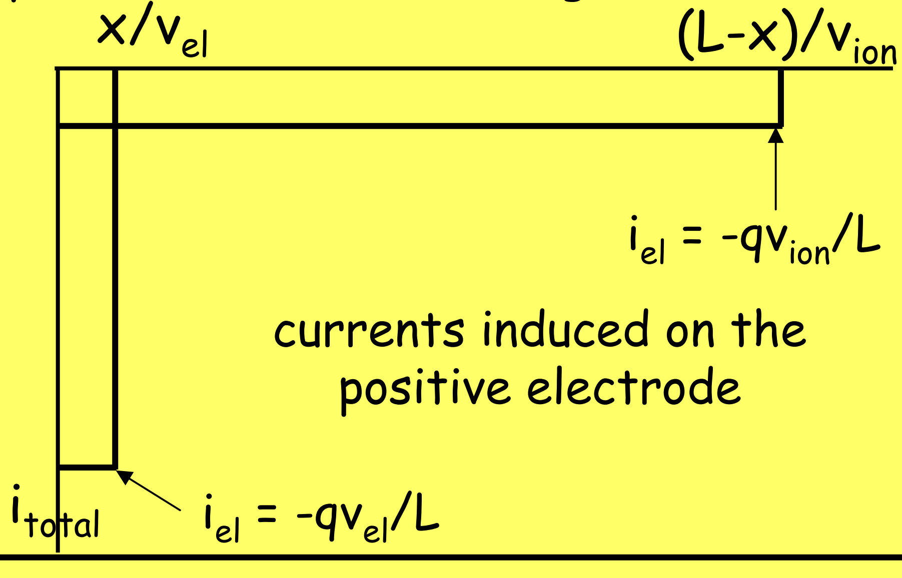
B. Rossi, H. Staub – Ionization Chambers and Counters- Mc Graw-Hill



The evaluation of the current induced by the pair of carriers on one of the electrodes, for example on the electrode at positive voltage, can be done by using Ramo's theorem. Ramo's theorem states that, *in the actual case of constant velocity v, the current induced on an electrode by a carrier* of charge q *is constant during its motion of and its value is given by:*

$$i = q\,\mathbf{v} \times E_{eff}$$

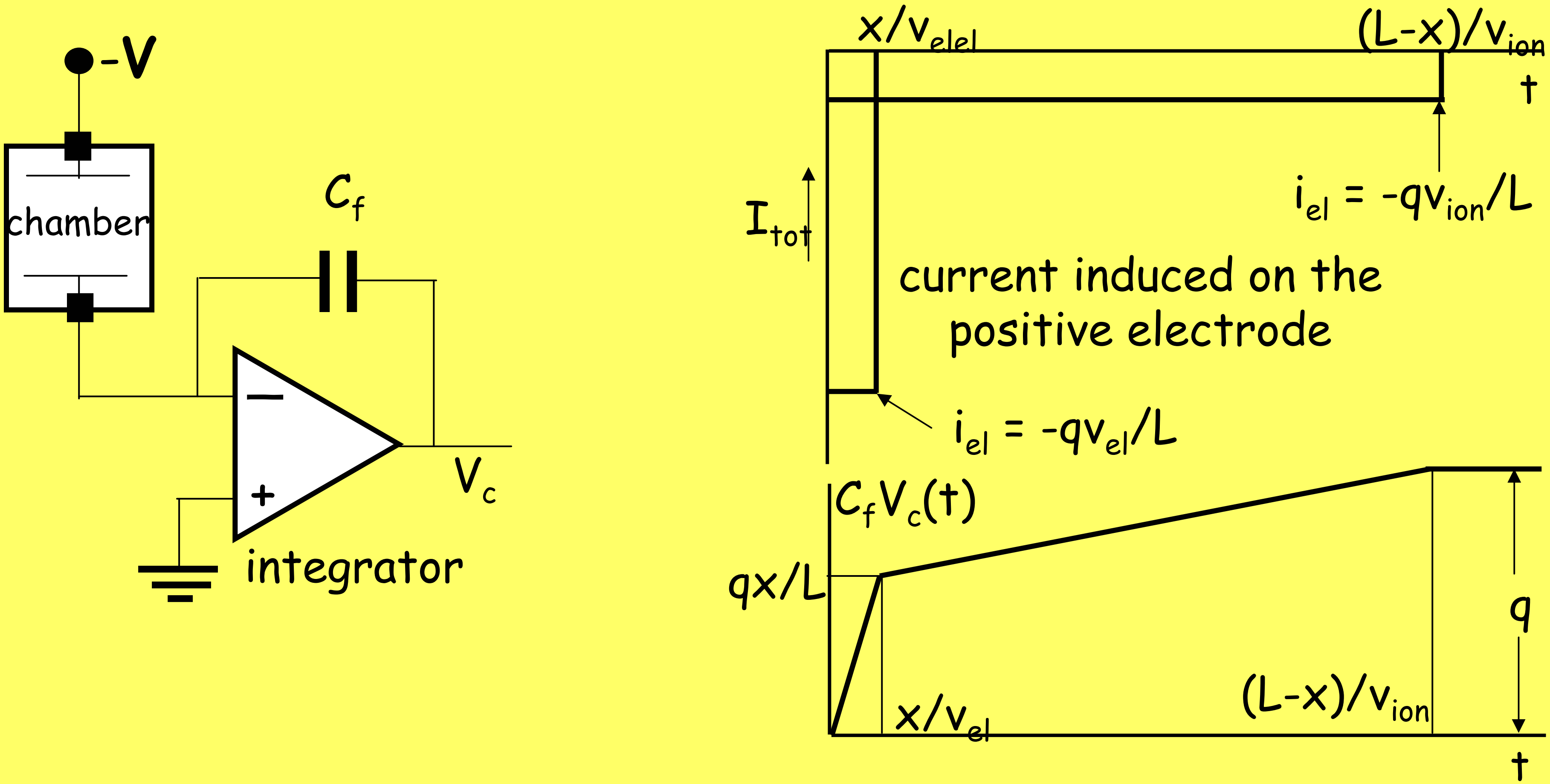
that is, it is determined by the scalar product of vectors **v** and $\mathbf{E}_{eff}$, where E_{eff} is the field obtained in the point where the pair is created by attributing a 1V potential to the collecting electrode and 0V to all the other electrodes.



Though very simple, the analysis of this situation is instructive as it points out that:

- **both carriers induce current on the electrode**
- **the induced currents have the same polarity because the carriers have opposite charges, but also velocities directed in opposite directions.**

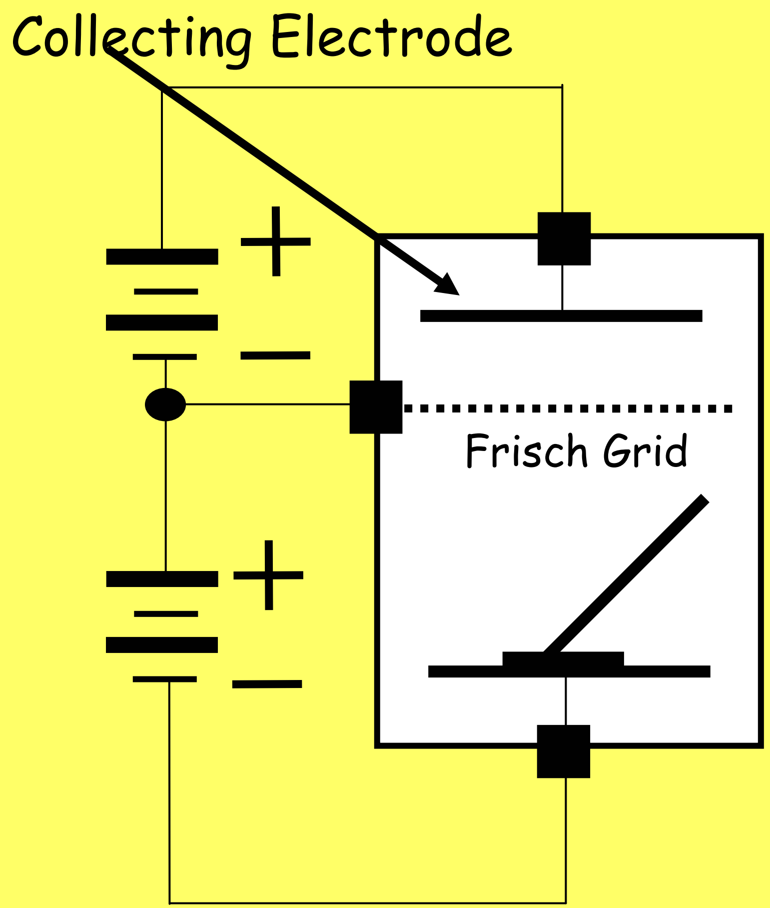
The charge induced on the positive electrode is obtained integrating the induced current. The diagram below shows how this integration is achieved by using an operational integrator.



The following remarks are of general validity and, as such, they' ll be extended to liquid and solid-state ionization chambers.

- Until the collection process of both carriers is completed, the charge induced charge depends on the position where the pair is created.
- Only when both carriers are collected the induced charge equals that of the carriers, q in our example.
- The evaluation of induced current and charge in the case of an extended track is done by repeating the calculation done in the case of a single pair, then applying the superposition principle.
- Therefore, also in the case of an extended track, the value of the induced charge equals that made available by the incoming radiation only when all carriers are collected.
- The previous consideration is essential in order to perform accurate energy measurements, as required by energy spectrometry.
- This means that the time of operation of an ionization detector in energy spectrometry is limited by the drift velocity of the slower carrier.

Fast Chamber



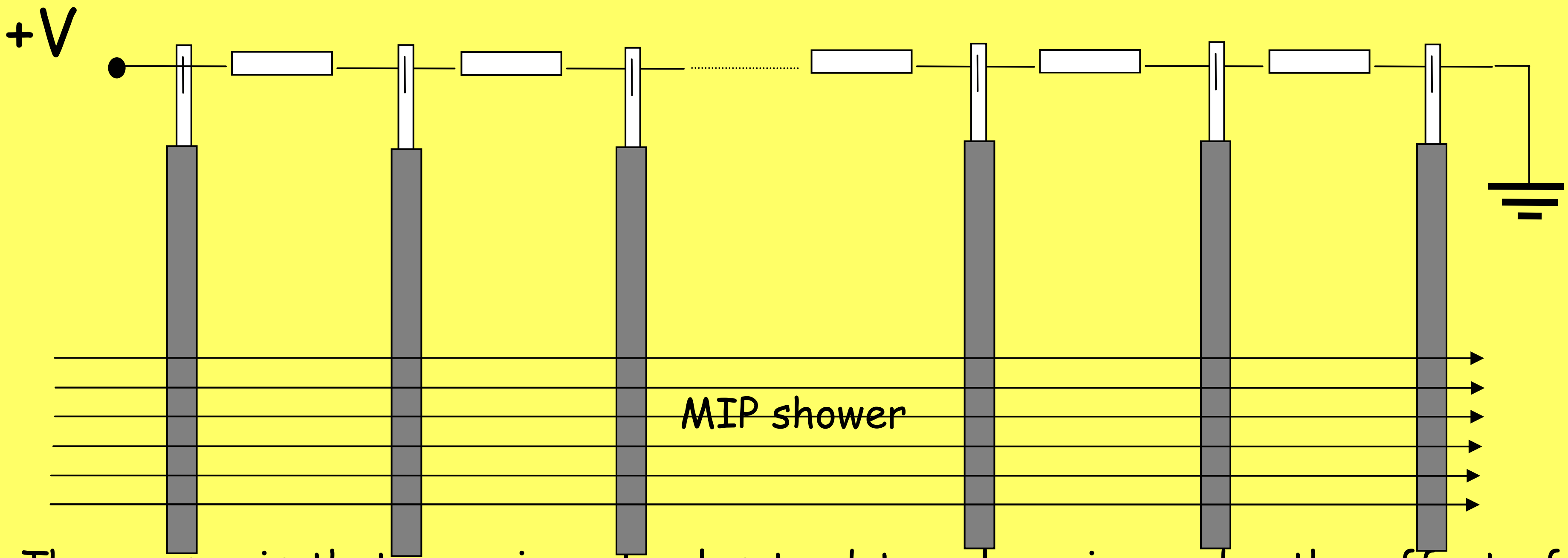
As an application example of the ionization chamber, the luminosity monitor of LHC will be described now. The luminosity monitor of LHC is based upon a nearly zero-angle detector aiming at measuring the energy deposited by showers of Minimum Ionizing Particles. The detector must comply with the following two requirements:

❖ be able to stand extremely high radiation doses, up to two or three orders of magnitude beyond those foreseen for detectors in the experiments.

❖ feature a response time compatible with the bunch crossing intervals at LHC, that are 25 ns.

The analysis of the radiation hardness characteristics of several possible solutions has led to conclude that the most suitable detector for the actual application was an ionization chamber where the filling gas is continuously fluxed.

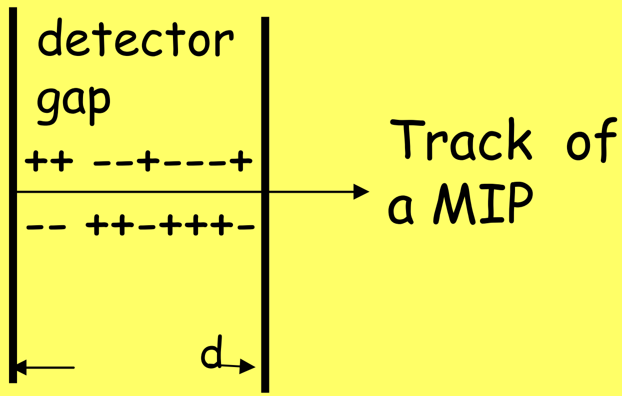
The problem was to make it as fast as required by the LHC time-scale. To solve it, the chamber was designed as the series connection of thin gaps, 0.5 mm each in the preliminary version, 1mm in the more recent design. Gas mixtures containing organic molecules to increase the drift velocity had to be discarded.

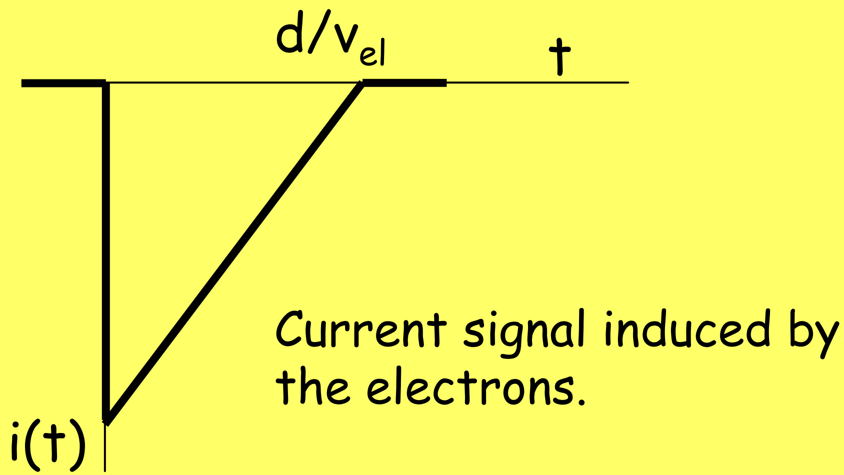


The reason is that organic molecules tend to polymerize under the effect of radiation which may impair the radiation resistance of the detector. On account of this, an inorganic filling gas, like Argon has been chosen as a basic component.

A thorough analysis on the data available for the drift velocity of electrons in gas mixtures has provided interesting data about mixtures of inorganic gases, like Argon to which a small fraction of Nitrogen is added. For instance, the drift velocity of electrons in a mixture of Ar + 2% N_2 reaches 3.2 cm/μs at a value of the electric field-to-pressure ratio of 1000V/cmxatm.

A slightly higher fraction of Nitrogen would result in a further increase in drift velocity.

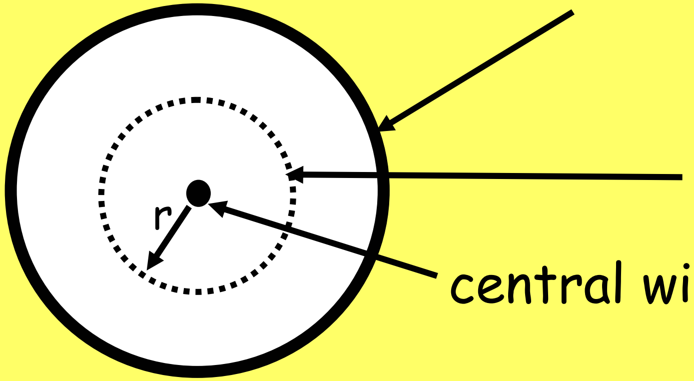




The figure on the left shows an ionization track extending across a detector gap with a uniform carrier density. The figure on the right shows the current induced on the electrode by the motion of the electrons. The positive ions are so slow that at such short times their contribution to the induced current has been neglected.

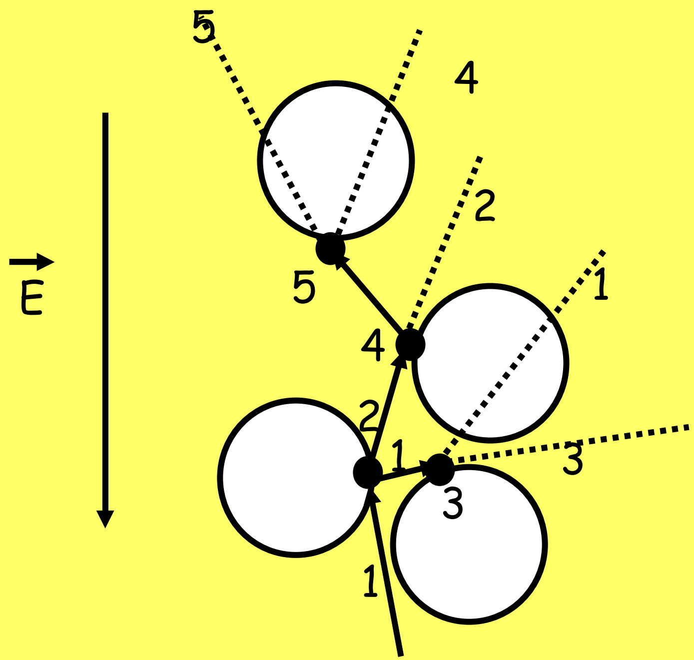
CHARGE MULTIPLICATION IN A GAS – THE PROPORTIONAL COUNTER

As anticipated, a reliable charge multiplication can be obtained in a gas, with the advantage of increasing the detector sensitivity dQ/dE. To achieve the charge multiplication, the parallel-plate geometry of the detector must be abandoned and the cylindrical structure shown in the figure must be adopted.

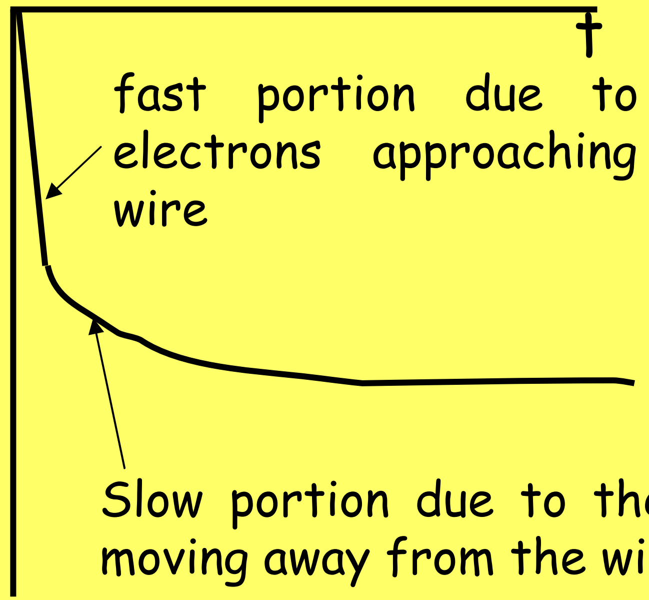


The electric field has a 1/r – dependence on the distance from the central wire. Gas multiplication is due to the accelerated electrons. It requires a sufficiently high electric field and therefore it takes place in a cylindrical layer around the central wire. Consequently it is fundamental that the central wire act as the anode.

MULTIPLICATION PROCESS



SHAPE OF THE ANODE SIGNAL IN THE PROPORTIONAL COUNTER



Charge induced on the anode

The charge multiplication has a remarkable importance in detector signal processing.

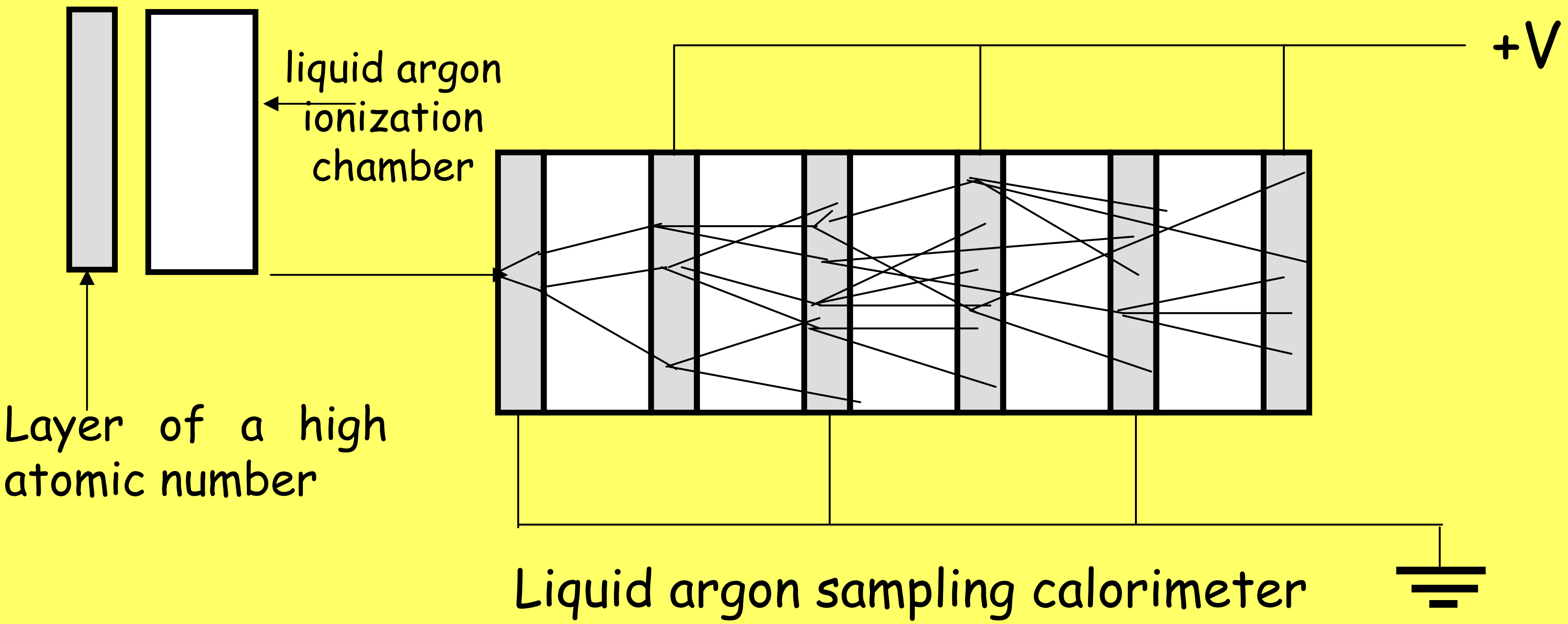
The increased sensitivity dQ/dE results in a considerably higher output charge for the same energy release and the same filling gas as compared to the case where it is absent, like in the ordinary ionization chamber where the charge available at the output is only that made available by the primary ionization process.

Values of the multiplication factor ranging between 10^3 and 10^4 are indeed readily achievable.

As already pointed out, this strongly attenuates the deteriorating effects due to noise and external disturbances on the detector charge and makes the signal amplification easier and less critical.

DETECTORS BASED UPON IONIZATION IN LIQUID MEDIA

Ionization chambers filled with cryogenic liquids, like liquid Ar, Liquid Kr, liquid Xe are detectors of great importance. As compared to the gas filled ionization chambers, the positive ions in a liquid can be considered virtually immobile, so that the induced current is evaluate taking into account only the contribution of the electrons.



The figure at the previous page shows the application of a liquid argon ionization chamber in a sampling calorimeter. Calorimeters are employed to measure the total energy of the incoming radiation.

As shown in the figure, in its basic structure, the sampling calorimeter can be thought of as a row of cells, each cell consisting of a layer made of a material of a high atomic number Z, followed by a volume filled with the liquid, where the ionization takes place. The incoming radiation creates showers in the layers, while the ionization process provides the energy sampling.

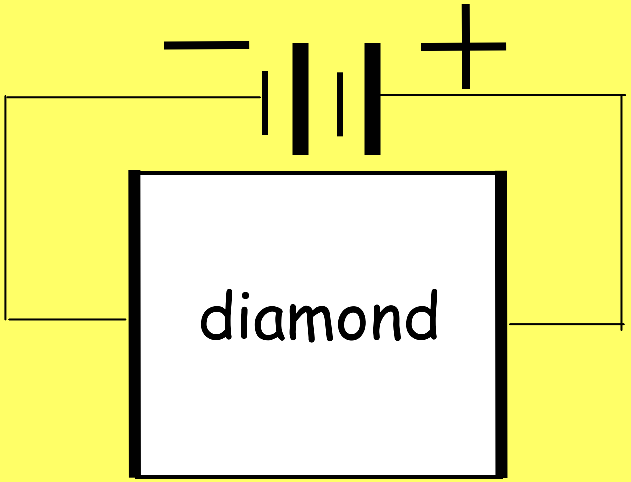
In some cases, like in the Atlas liquid Ar calorimeter the readout electrodes are thin copper layers kept by spacers halfway between two high Z layers.

The shape of the currents induced on the electrodes can be evaluated on the basis of the same criteria adopted in the gas-filled ionization chambers. It can be assumed that the density of electron-positive ion pairs is constant along the ionization tracks, so the induced currents have a triangular shape.

As already pointed out, in a cryogenic liquid, it is a reasonable assumption that the only the electrons contribute to the induced signals, because the positive ions in the liquid have a negligible mobility.

DETECTORS BASED UPON THE IONIZATION IN A SOLID MEDIUM

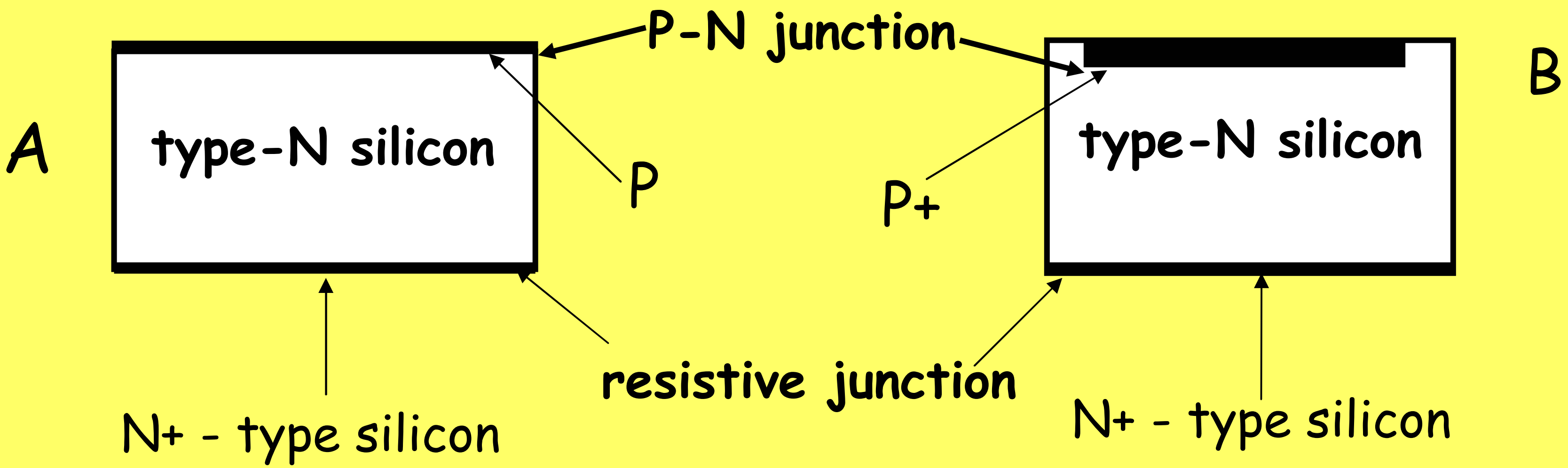
If the detecting medium is an insulator, the detector can be realized as a solid state ionization chamber. This is the case, for instance, of diamond. A diamond detector can be realized by evaporating the electrodes on the opposite faces of a slab of diamond.



If the material, instead, is a semiconductor, such a simple approach would fail. The reason is that in a semiconductor, which has a non negligible conductivity at room temperature, the current flowing under the effect of the applied voltage and its associated noise would mask the small current signals due to the particles.

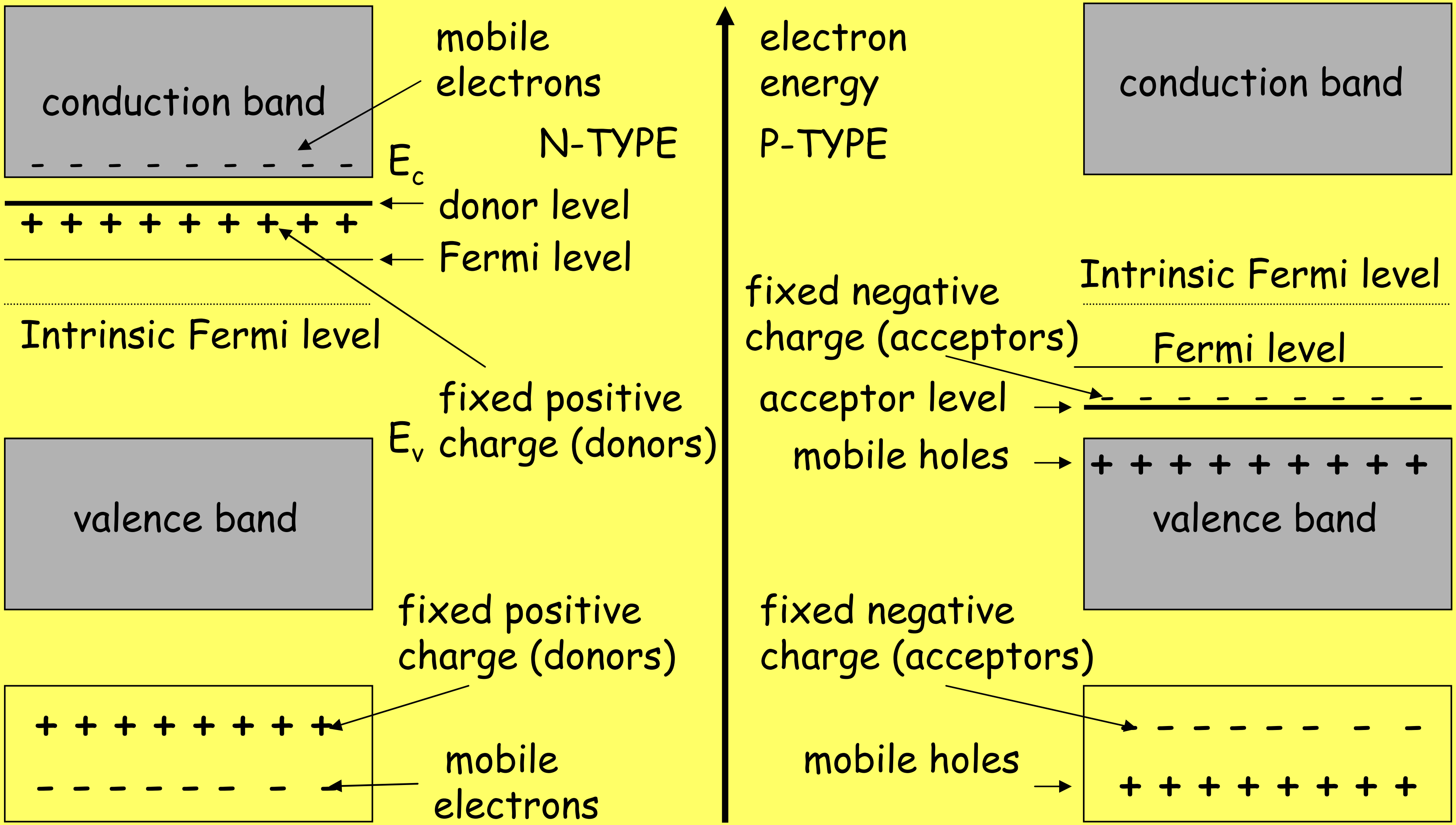
For this reason, detectors made of semiconductor materials of a comparatively small gap in their energy-band model, like Silicon or Germanium are realized as P-N junctions operated in the reverse bias mode. In this way the parasitic current can be kept at acceptably small values.

Structures of P-N silicon detectors

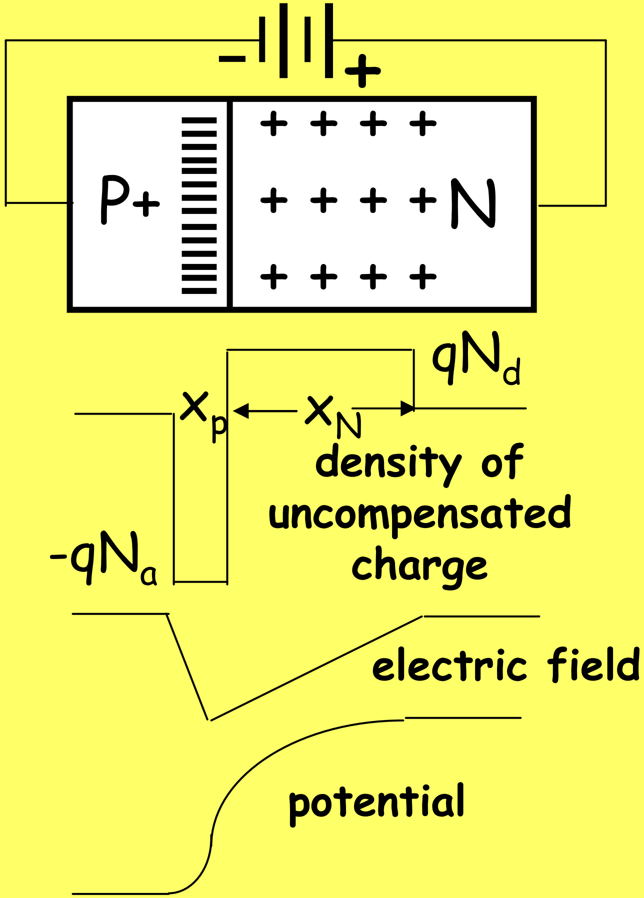


A: the junction is obtained by evaporating under vacuum a thin layer of gold

B: the junction is obtained by creating a P+ layer by ion implantation


conduction band
mobile electrons
E_c
N-TYPE
donor level
Fermi level
Intrinsic Fermi level
fixed positive charge (donors)
E_v
valence band
fixed positive charge (donors)
mobile electrons
electron energy
P-TYPE
conduction band
Intrinsic Fermi level
fixed negative charge (acceptors)
Fermi level
acceptor level
mobile holes
valence band
fixed negative charge (acceptors)
mobile holes

EXAMPLE: CASE OF ABRUPT P-N JUNCTION

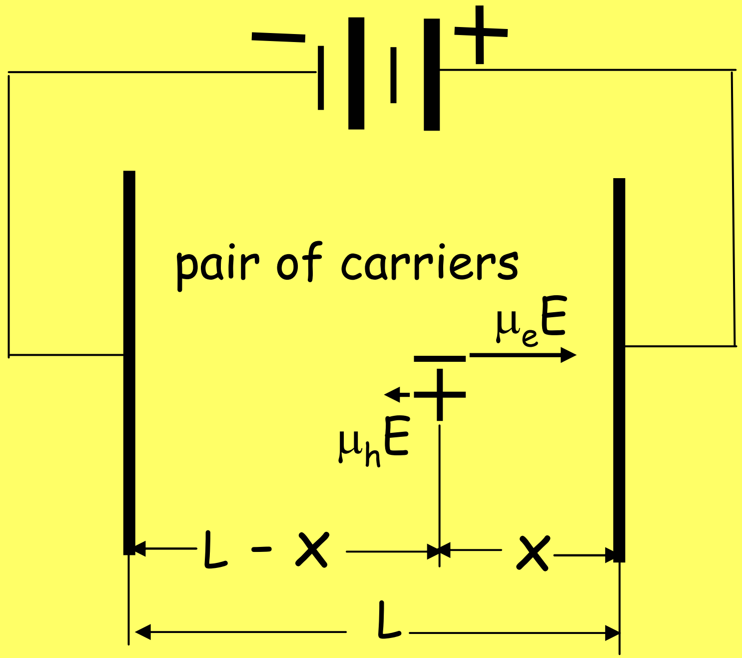


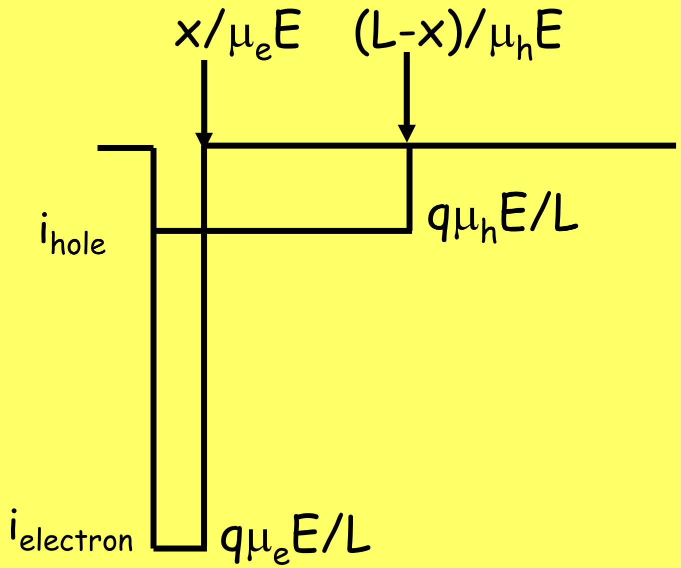
P+region: trivalent impurities (B) with density N_a- free carriers holes(+), ionized atoms with negative charge
N region: penthavalent impurities (As) with density N_d , free carriers electrons (-), ionized atoms with negative charge
Charge balance: $x_P N_a = x_N N_d$ which shows that the space charge region extends more deeply into the region of lower impurity density.
Case of N_a >> N_d, the depleted region extends almost entirely in the N region, $x_P \ll x_N$ and x_N is proportional to $(V/N_d)^{1/2}$

The evaluation of the shape of the induced signal in a semiconductor detector is still based on Ramo's theorem. As compared to the case of the gas-filled ionization chamber, the evaluation of the signal shape in a P-N junction is made more complicated by the fact that the electric field is not constant.

The calculation is done utilizing the concept of mobility μ.

μ = velocity/electric field is expresses in cm^2/Vxs.





CHARACTERISTICS OF MATERIALS OF MORE COMMON USE IN THE REALIZATION OF SOLID STATE DETECTORS

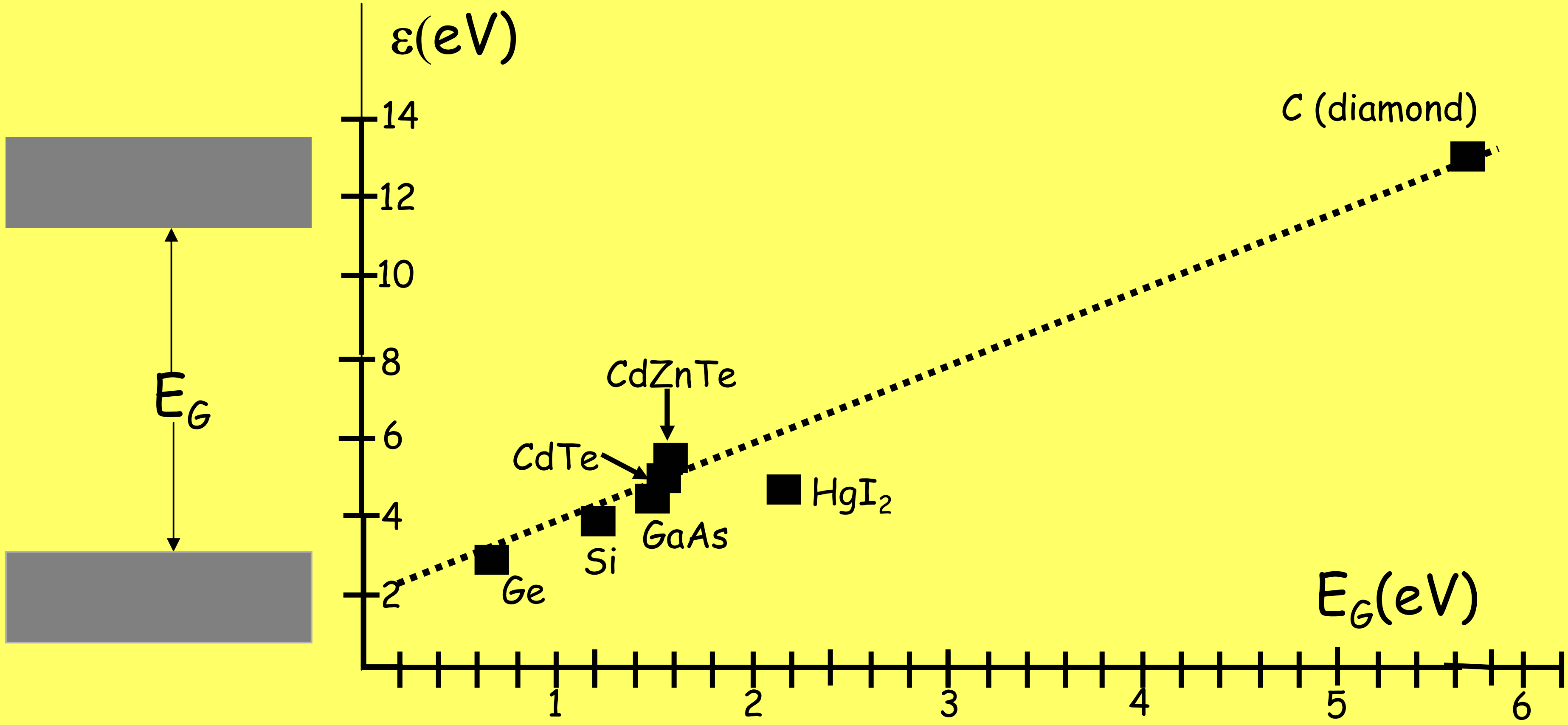
MATERIAL	E_G (eV)	μ_e (cm^2/Vxs)	μ_h (cm^2/Vxs)
Ge	0.72	3900	1900
Si	1.13	1400	480
GaAs	1.43	8000	400
CdTe	1.44	1100	100
CdZnTe	1.5 - 2.2	1350	120
CdSe	1.73	720	75
HgI_2	2.13	100	4
PbI_2	2.32	8	2
C	5.4	2200	1600

At the temperature of 77 K the mobilities of Ge and Si are higher.

Ge: $\mu_e = 3.6X10^4\ cm^2/Vxs$ $\mu_h = 4.\ 2X10^4\ cm^2/Vxs$

Si: $\mu_e = 2.3X10^4\ cm^2/Vxs$ $\mu_h = 1.1X10^4\ cm^2/Vxs$

Relationship between the energy gap E_G and the value of ε, the energy required to create an electron-hole pair in some solid materials of commonly employed in the realization of solid-state detectors.



IN THE CASE OF SOLID STATE DETECTORS, AS IN THE CASE OF GAS FILLED IONIZATION CHAMBERS,THE OPERATION TIME IS DETERMINED BY THE COLLECTION OF THE SLOWER CARRIERS.

ANOTHER IMPORTANT PARAMETER IS THE CARRIER LIFETIME τ; WHICH IS RELATED TO THE DEGREE OF PURITY OF THE MATERIAL. FOR INSTANCE, IN HIGH PURITY MATERIALS LIKE GERMANIUM AND SILICON, THE VALUES OF τ FOR BOTH CARRIERS CAN BE CONSIDERED TO HAVE SETTLED SINCE SEVERAL YERS IN THE MILLISECOND REGION.

FOR OTHER LESS PURE MATERIALS THEY ARE STILL IN THE MICROSECOND REGION.

THE MEAN FREE PATH BEFORE TRAPPING FOR ELECTRONS AND HOLES IS DEFINED BY THE FOLLOWING RELATIONSHIPS:

ELECTRON $\lambda_e = \mu_e \tau_e E$ ***HOLE*** $\lambda_h = \mu_h \tau_h E$

WHERE **E** IS THE ELECTRIC FIELD.

DOMAINS OF APPLICATION OF SOLID STATE DETECTORS MADE OF DIFFERENT MATERIALS

GERMANIUM – It is employed in high resolution gamma-ray spectrometry. Nowadays Ge detectors are realized as junction structures on High Purity material. Germanium detectors must operate at cryogenic temperature to reduce their leakage current. (They are ordinarily cooled with liquid Nitrogen, T=77 K)

Several structures: planar, coaxial cylindrical, well-type are available, sometimes of large dimensions (several centimeters in diameter and height).

In large coaxial and well-type detectors, despite the high mobility of the carriers which results from cryogenic operation, the following problems arise:

- long collection times, up to several hundreds of nanoseconds
- large variations in the shapes of the signals

Besides, the coaxial or well-type structures of large dimension have a comparatively high capacitance, in the 10-30 pF range.

SILICON – is the material which covers the largest variety of applications. The structure obtained by ion-implanting P impurities on a high resistivity N-type material has undergone a remarkable technological improvement in the early eighties when the planar process currently employed in microelectronics was introduced in the detector realization.

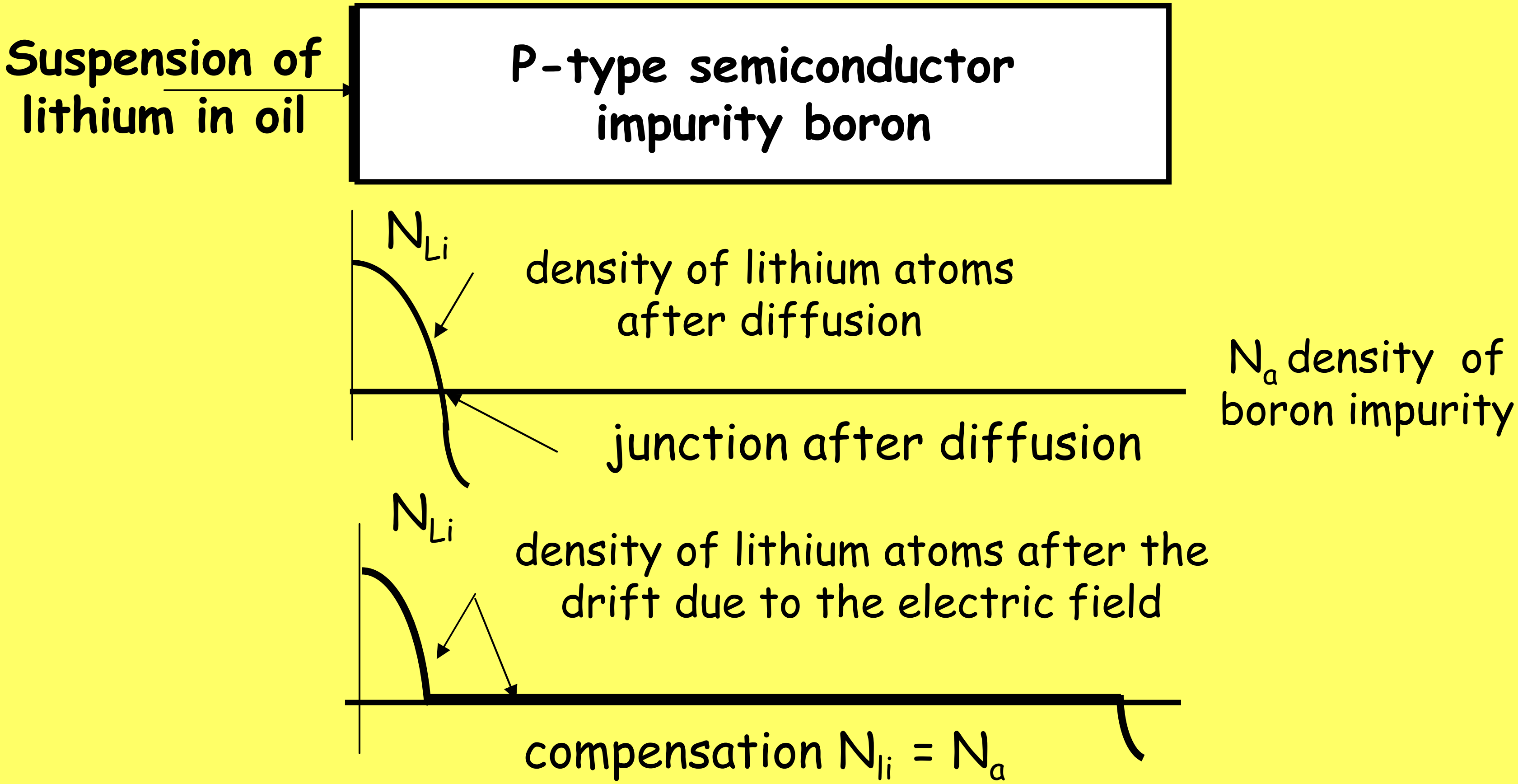
These structures have thicknesses ranging from tens of microns to a few millimeters and suit the following applications:

- spectrometry of charged particles (α and β) emitted by radioactive sources
- dE/dx measurements on minimum ionizing particles in particle physics

The same realization principle is employed in highly segmented detectors for position sensing (microstrip and pixel detectors).

WHEN A HIGH THICKNESS OF THE DELETED REGION, UP TO 1 cm IS REQUIRED IN A SILICON DETECTOR TO SUIT, FOR INSTANCE, THE X-RAY SPECTROMETRY AT ENERGIES UP TO ABOUT 100 KeV, A DIFFERENT APPROACH, CALLED LITHIUM DRIFT IS EMPLOYED.

THE PROCESS OF LITHIUM DRIFT IN SILICON IS USED TO OBTAIN LARGE THICKNESSES OF A NEARLY INTRINSIC MATERIAL



The lithium-drift silicon detector are employed in cryogenic conditions. They provide the most suitable solution for high resolution X-ray spectrometry. Their characteristics are:

• collection times in the 100 ns region

• small capacitance, of the order of 1pF, by virtue of the large thickness of the intrinsic region

• leakage currents around 1 pA due to the cryogenic operation and the energy gap higher than 1 eV.

CADMIUM TELLURIDE CdTe o CdZnTe

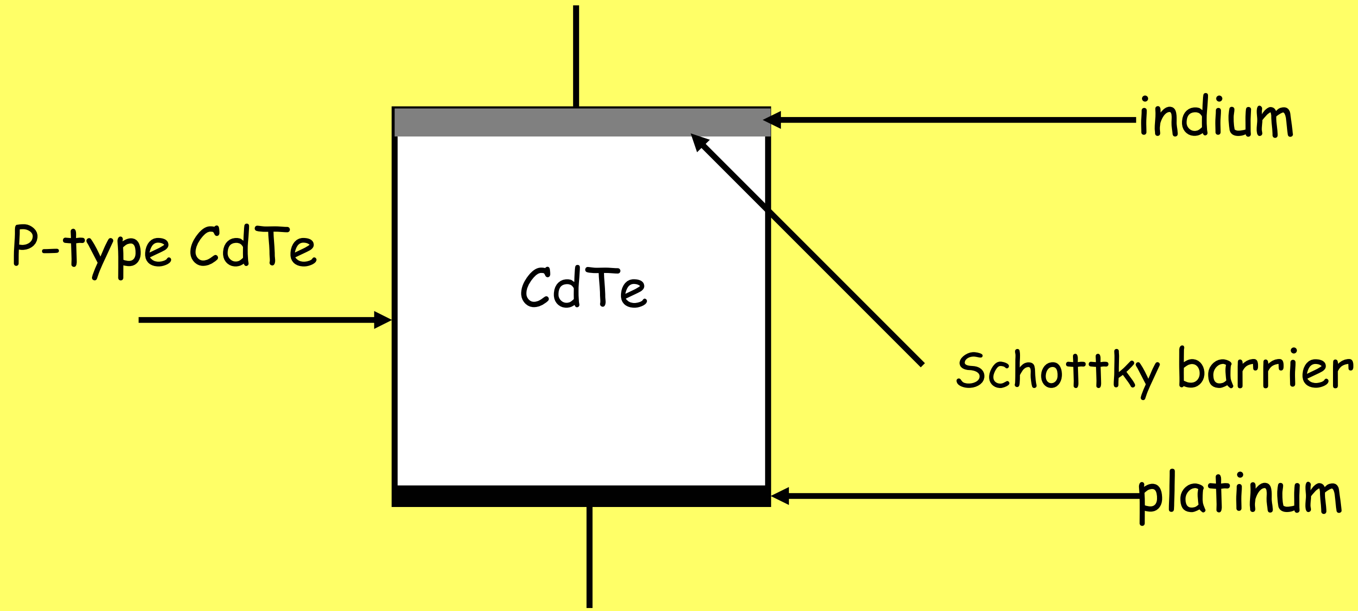
It is a material of a high atomic number and as such can be utilized for gamma-ray detection. Besides, its comparatively large E_G allows the operation at room temperature or at a moderate cooling. Its limitations are:

• Low mobility of both carriers, in particular of the holes.

• Limited purity level of the material, therefore presence of traps

• Non negligible leakage current, particularly in CdTe.

Example of a CdTe detector where the junction is based on a Schottky barrier .



DIAMOND DETECTORS

Parameters and characteristics of diamond as a detector material

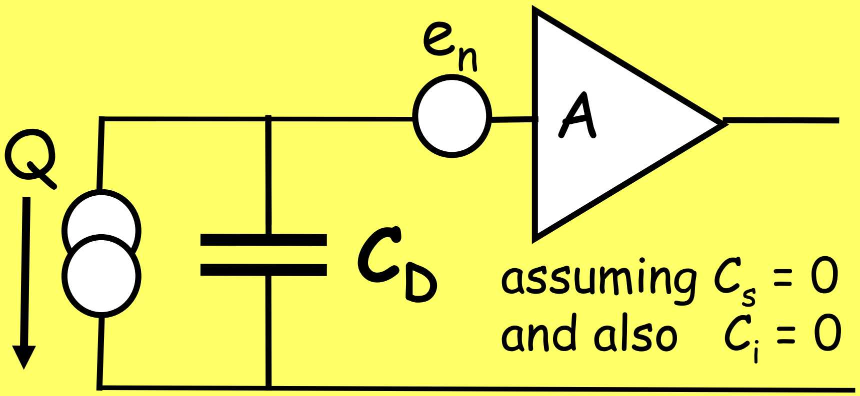
E_G = 5.7 eV ε = 13.2 eV

- Extremely small leakage current
- High carrier mobility, thus short collection times, a few nanoseconds in a thin detector
- High radiation resistance
- Suitable for operation at high temperatures. It has been proven suitable for spectrometric applications up to 250 °C
- It has been shown that diamond detectors provide a suitable solution in β spectrometry at energies in the 100 KeV region keV and in dE/dx measurements on minimum ionizing particles.

An R&D program was established at CERN to study the feasibility of diamond-based tracking detectors for LHC experiments. Diamond was considered appealing by virtue of its radiation hardness features.

IMPORTANT REMARK ABOUT DIAMOND vs SILICON

It will be taken advantage of the parameters of silicon and diamond to introduce an important consideration about the comparison between detectors made of different materials. Consider, for instance silicon and diamond. In **Silicon** $\varepsilon = $ **3.67 eV in Diamond** $\varepsilon = $ **13.2 eV.** It can be concluded that for the same energy released in the two detectors, the charge made available in silicon is about 3.5 times larger than in diamond. However, the quality factor of a detector for spectrometry applications is not only ε. It must be pointed out, indeed, that in both cases the energy resolution is limited, to a large extent, by the noise in the amplification process. The comparison between detectors of different materials must be done on the basis of the following schematics, where the voltage signal Q/C_D is compared to the noise v_n of the amplifier. It is understood, then, that it makes more sense to assume as a quality factor the ratio ε / dielectric constant. On this basis, diamond, which has a smaller dielectric constant, appears less unfavorable in its comparison with silicon.



MORE SOLID STATE DETECTORS – There are more solid materials that can be employed to detect radiation. Among them it is worth quoting:

Mercury Iodide, ***HgI_2***, suitable for X-ray spectrometry at room temperature. Mercury Iodide detectors are realized as solid state ionization chambers.

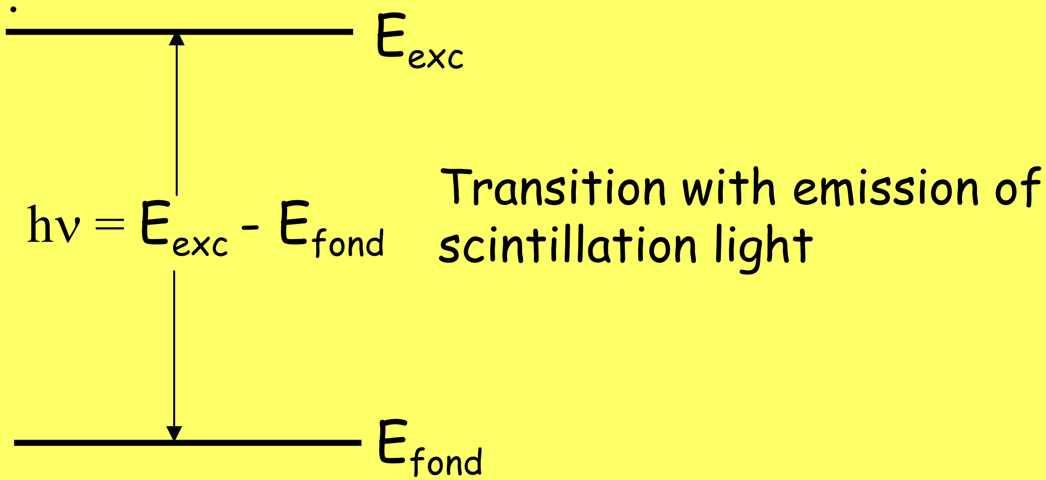
Gallium Arsenide, ***GaAs***, featuring a very high electron mobility. Gallium arsenide detectors are realized as Schottky barrier junctions. They are suitable for the detection od charged particles as well as for gamma ray spectrometry at room temperature.

Silicon Carbide, SiC_4, suitable for charged particle spectrometry at room temperature.

scintillation detectors

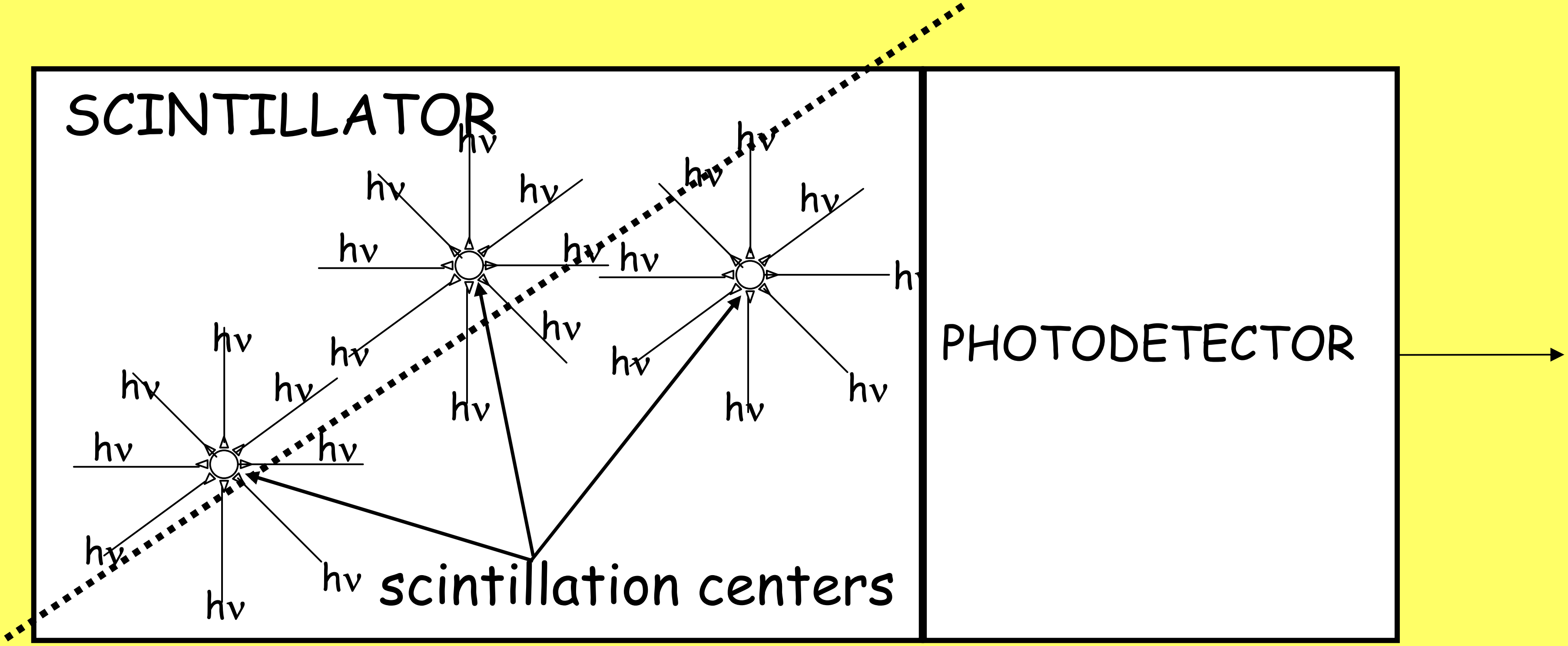
SCINTILLATION DETECTORS

The scintillation detector consists in un a sensor, the scintillator, where a fraction of the energy released by the radiation induces the transition of molecules of the medium to excited energy levels. The return of the molecules to their fundamental level is accompanied by the emission of a short flash of light.



The scintillator, which obviously must be transparent to the light it emits, is coupled to a photodetector, which provides an electrical signal in response to the light pulse from the scintillator.

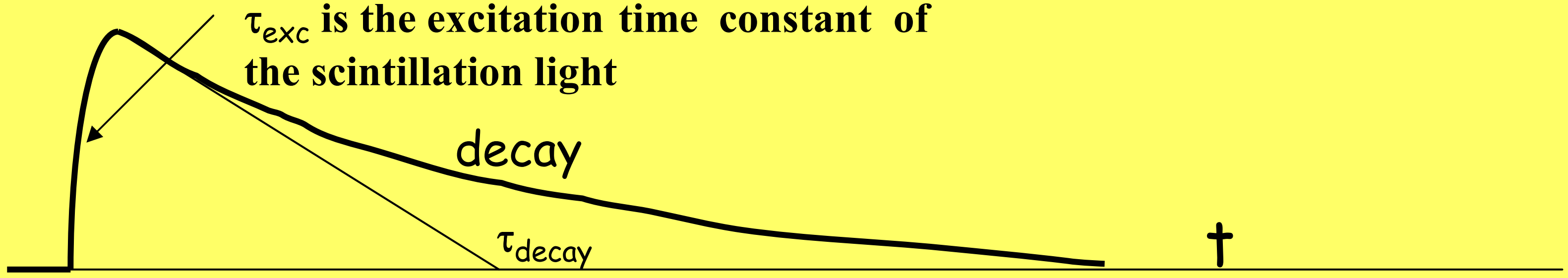
SCINTILLATION DETECTOR



The scintillation light can be described by the following time dependence:

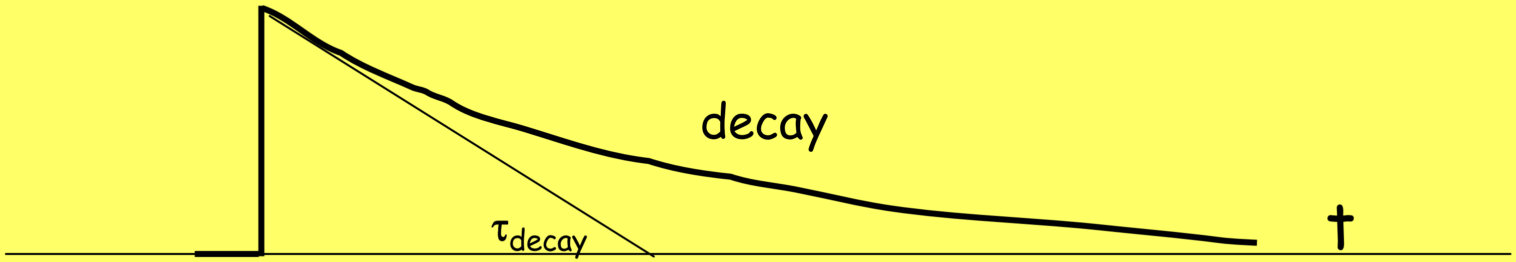
$$I(t) = I_o[\exp(-t/\tau_{decay}) - \exp(-t/\tau_{exc})]$$

where I(t) is the intensity at time t, τ_{exc} the excitation time constant and τ_{decay} the decay time constant.



Generally, $\tau_{decad} \gg \tau_{exc}$ so that the scintillation light is represented as:

$$I(t) = I_o\exp(-t/\tau_{decad})$$



CHARACTERISTICS OF SOME SCINTILLATORS

Scintillator type	decay time constant (ns)	efficiency (photons/MeV)
NaI(Tl)	230	38000
CsI(Tl)	1000	52000
BGO	300	11000
NE 102A (plastic)	2	10000
ANTRACENE	28	
P-TERFENILE	4.5	
STILBENE	<3	

Before the advent of semiconductor detectors, NaI(Tl) e CsI(Tl) represented the most suitable solution for the detection of gamma rays and their spectrometry. They are still used in those applications when large detection volumes, that would be extremely expensive if realized withy solid state detectors, are required.

An interesting material which, as already, pointed out, can be used both as an ionization medium, and as a scintillator is liquid Xenon (cryogenic).

As an ionization medium it features:

$\varepsilon = 19.5$ eV for α particles

$\varepsilon = 25$ eV for electrons

The features of liquid Xenon as a scintillator are:

Decay time constants (ns) 4, 22 for α particles

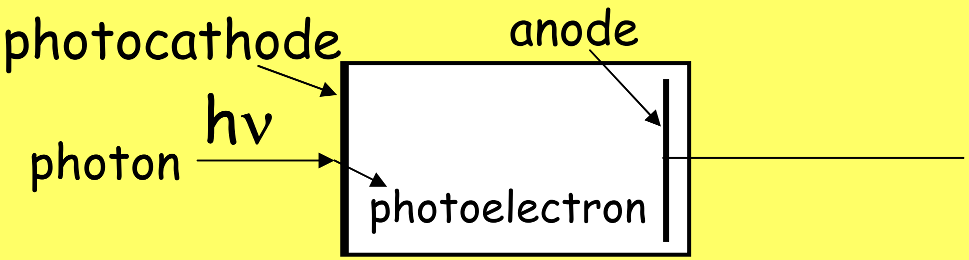
45 for electrons

Efficiency (photons/MeV) approx 40.000

Wavelength λ of scintillation light 1780 Angstrom

PHOTODETECTORS- Are basically ***of*** three types:

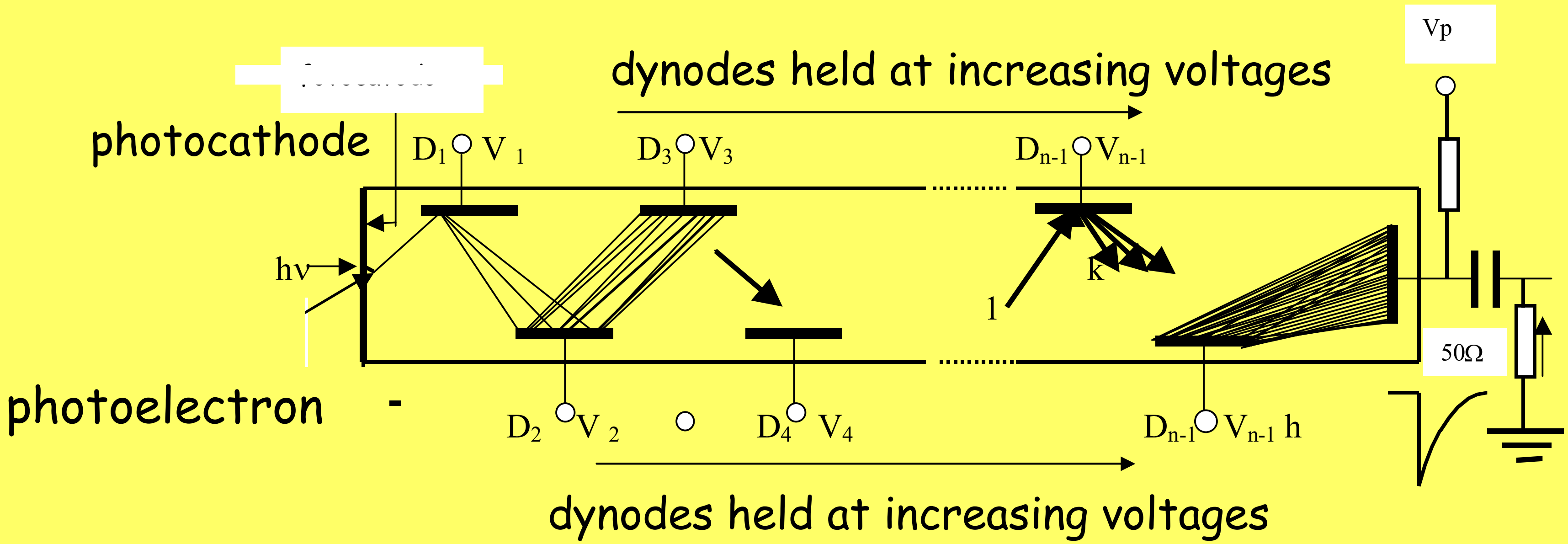
- Solid state photodiodes. usually P-I-N structures to reduce their capacitance
- Vacuum photodiodes, whose structure is shown in the figure



- Multiplier phototubes, where successive secondary emission steps allow values of the charge multiplication of up to 10^8

There are photodetector structures that are intermediate between the photodiode (absence of multiplication) and the multiplier phototube, like, for instance, the vacuum phototriode.

BASIC STRUCTURE OF MULTIPLIER PHOTOTUBE.

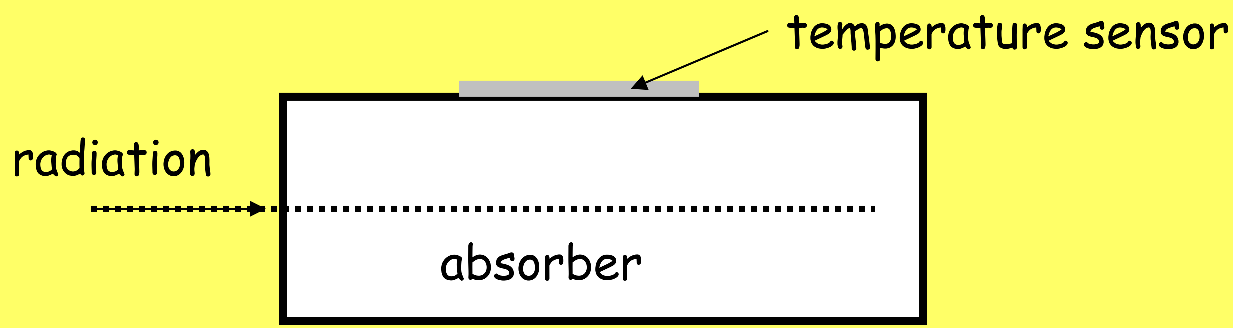


The charge gain of a phototube is usually so large that a further signal amplification is unnecessary and the signal is directly extracted on a resistive load on the photomultiplier anode.

bolometric detectors

To introduce the idea why a bolometric detector is appealing, refer, for instance, to the case of a scintillator, where only a fraction of the energy deposited by the radiation goes into the excitation of the active molecules. The remaining portion is converted into heat, which however remains undetected.

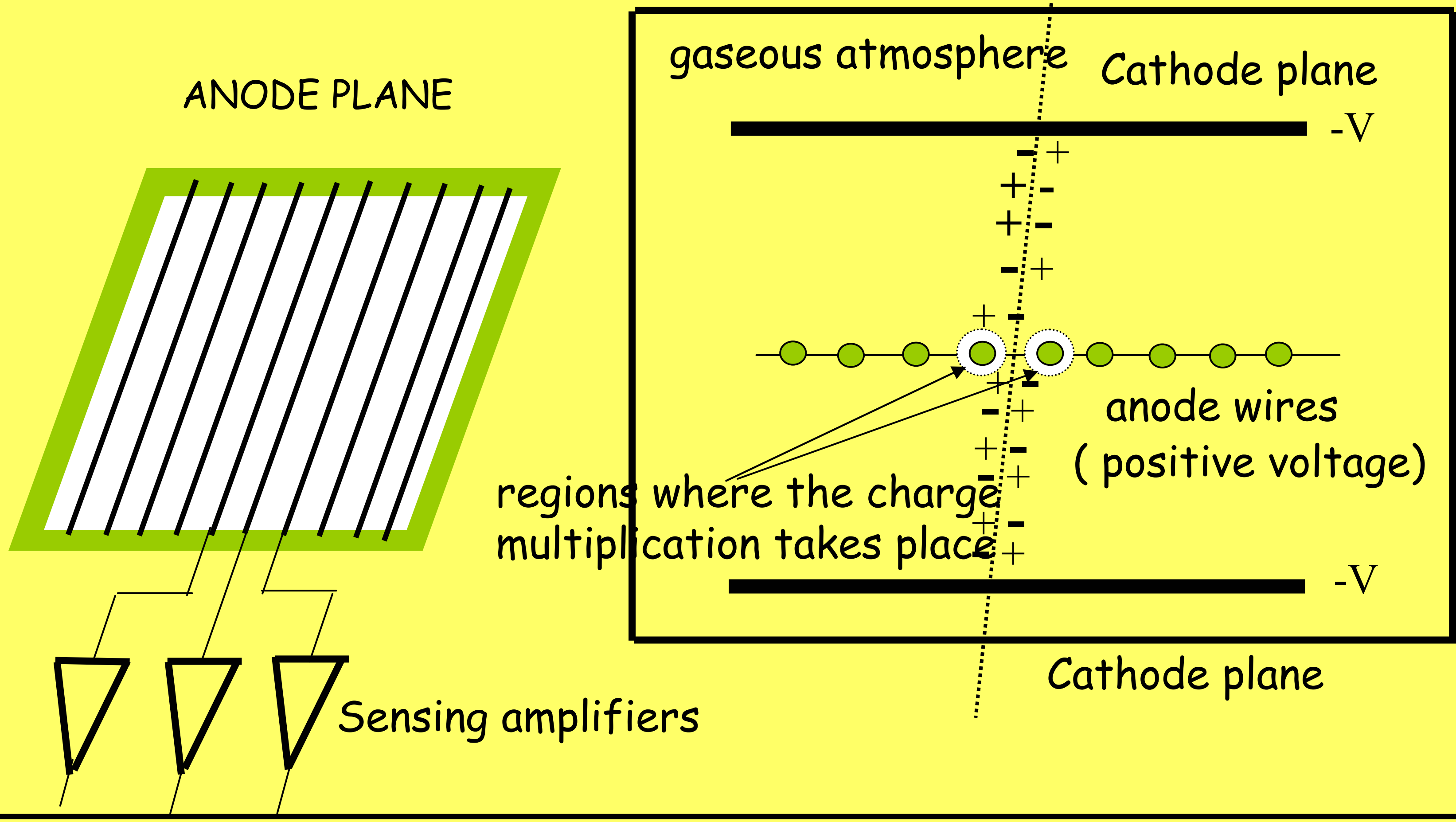
The bolometric detectors are based upon the idea of detecting the warming-up undergone by an absorber which represents the sensitive volume. In this way, if the incoming radiation interacts in the sensitive volume with several competing processes, no energy transfer due to a particular process would be undetected.



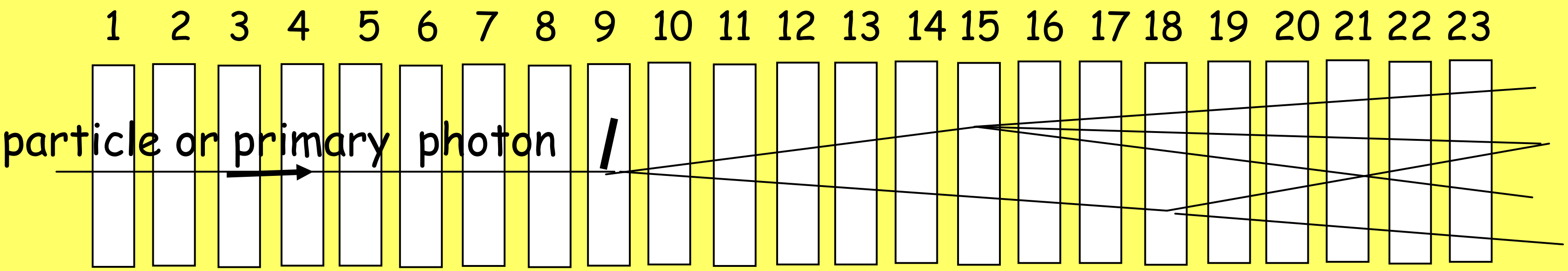
The absorber is usually made of a dielectric, diamagnetic material and operates at cryogenic temperatures, down to the mK region, to reach the highest possible temperature sensitivity by keeping the thermal capacitance as small as possible. Provided that these conditions are met, a high degree of freedom exists in the choice of the absorber material.

Segmented detectors for position sensing

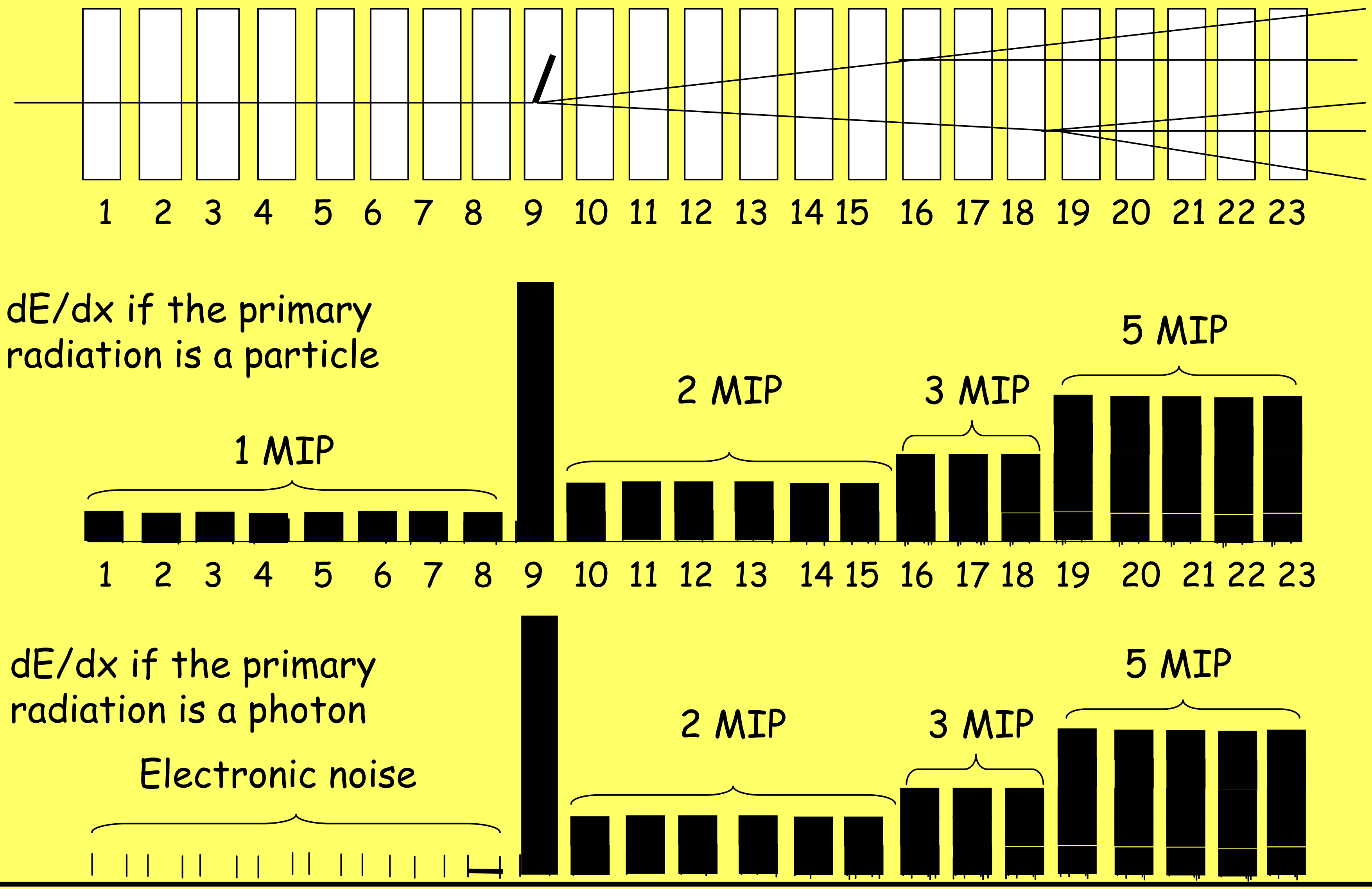
Historically the Multiwire Proportional Chamber (MWPC) was the first position-sensing detector of a high spatial resolution. It is based on the charge multiplication in a gas discussed with reference to the proportional counter.



Nowadays semiconductor position-sensitive detectors like highly segmented microstrip or pixel structures and vertex detectors based upon them have become essential parts of every experiment in physics and in several other fundamental sciences and applications. Before moving to them, it is worth describing a particular class of position-sensing detectors, the so called active targets that have been employed in some fixed-target experiments about two-to three decades ago. An active target is shown below.

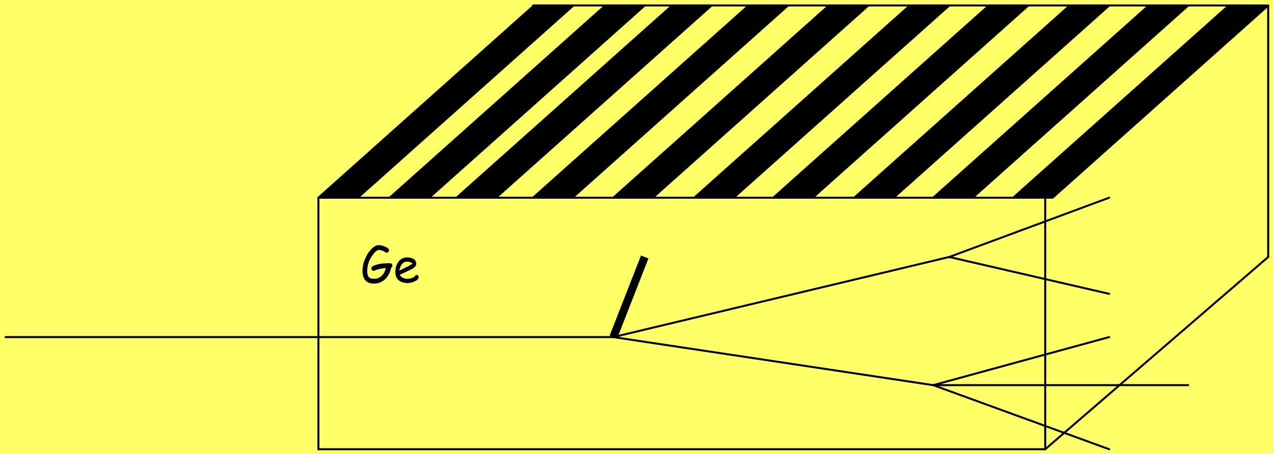


In its first implementation the active target was a telescope of silicon detectors which implemented a twofold function. Besides providing the target material it sampled the specific energy loss dE/dx in the beam direction. In its first version the active target of FRAMM experiment at CERN employed 40 silicon layers.



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
dE/dx if the primary radiation is a particle
1 MIP
2 MIP
3 MIP
5 MIP
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
dE/dx if the primary radiation is a photon
Electronic noise
2 MIP
3 MIP
5 MIP

The telescope configuration of the active was limited by the presence of the electronic noise in the readout preamplifiers. The detectors were required to be sufficiently thin, a few hundred microns and to have a large active area, some square centimeters. The resulting capacitance was large, hundreds of pF and the noise in the front-end amplifiers was a real problem. An active target which avoids this problem is the Ge microstrip detector, employed to complete the FRAMM active target (1980-1983). The strips detect the ionization density underneath.



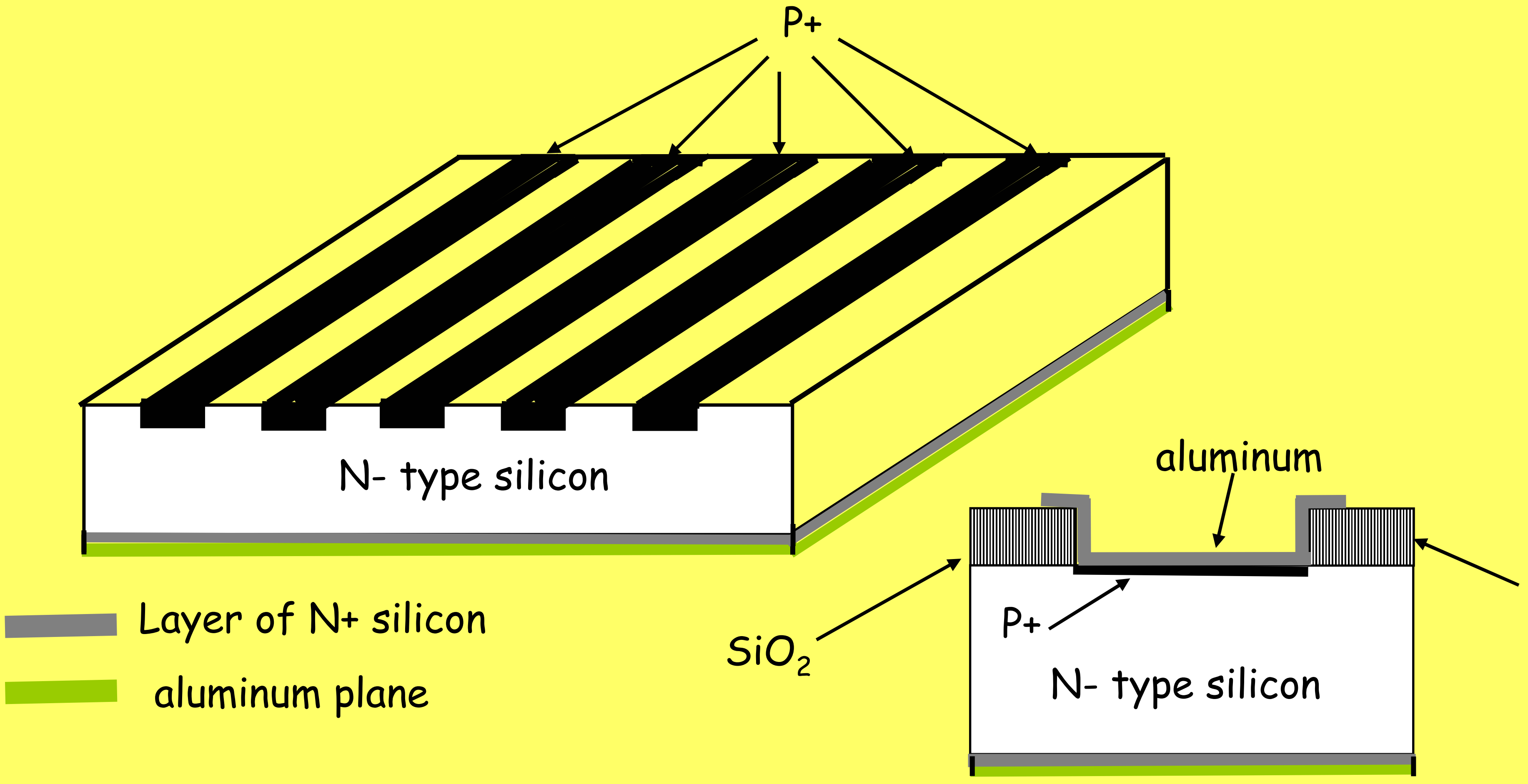
The first microstrip vertex detector was installed in the E687 fixed-target experiment at FERMILAB in 1985.

At about the same time vertex detectors were installed in Delphi and Aleph collider experiments at LEP.

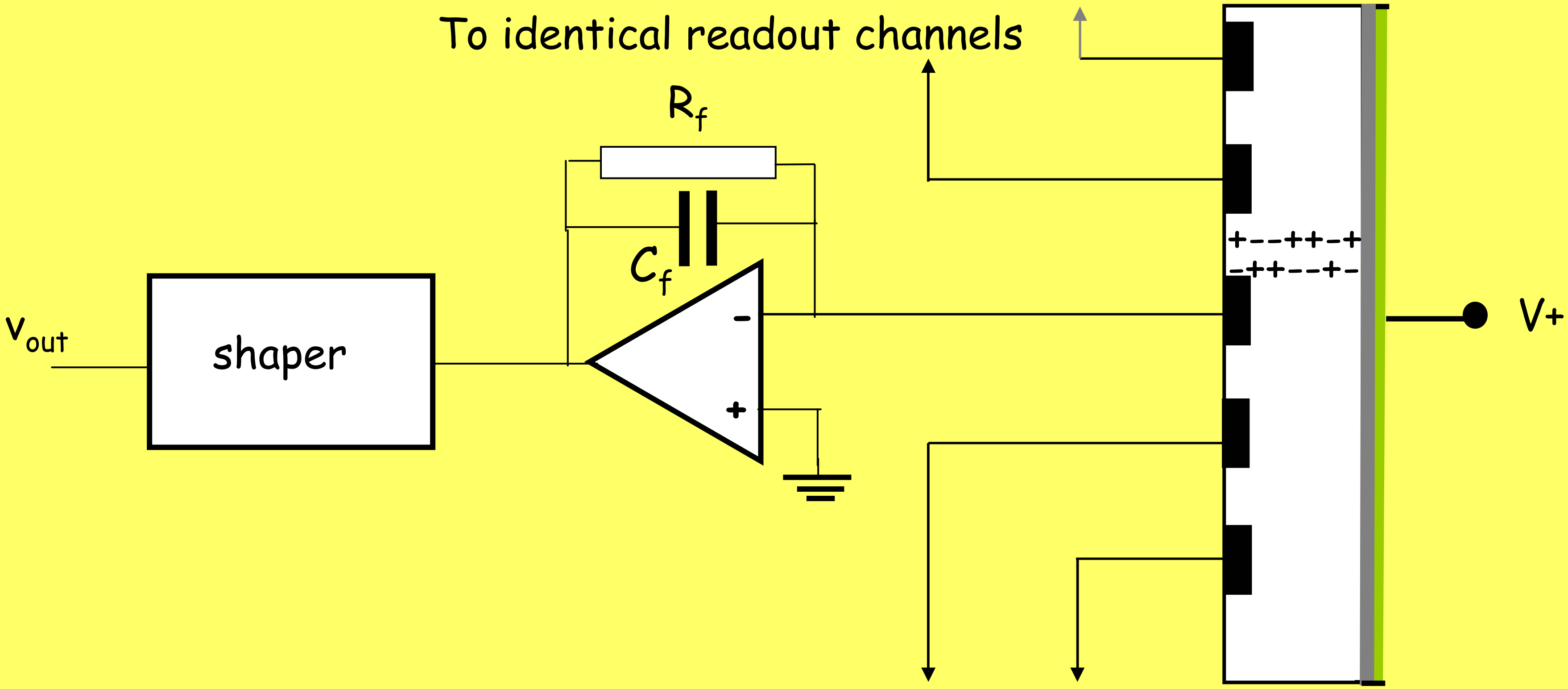
Since then, many more microstrip vertex detectors have been introduced in particle physics (CLEO, CDF, D0, BaBar). Much more complex vertex detectors employing both microstrip and pixel structures have been developed for the forthcoming experiments at LHC.

Just one example to point out the importance of vertex detectors: at CDF the vertex detector, which was introduced when the experiment was already advanced, was instrumental in the detection of the TOP QUARK

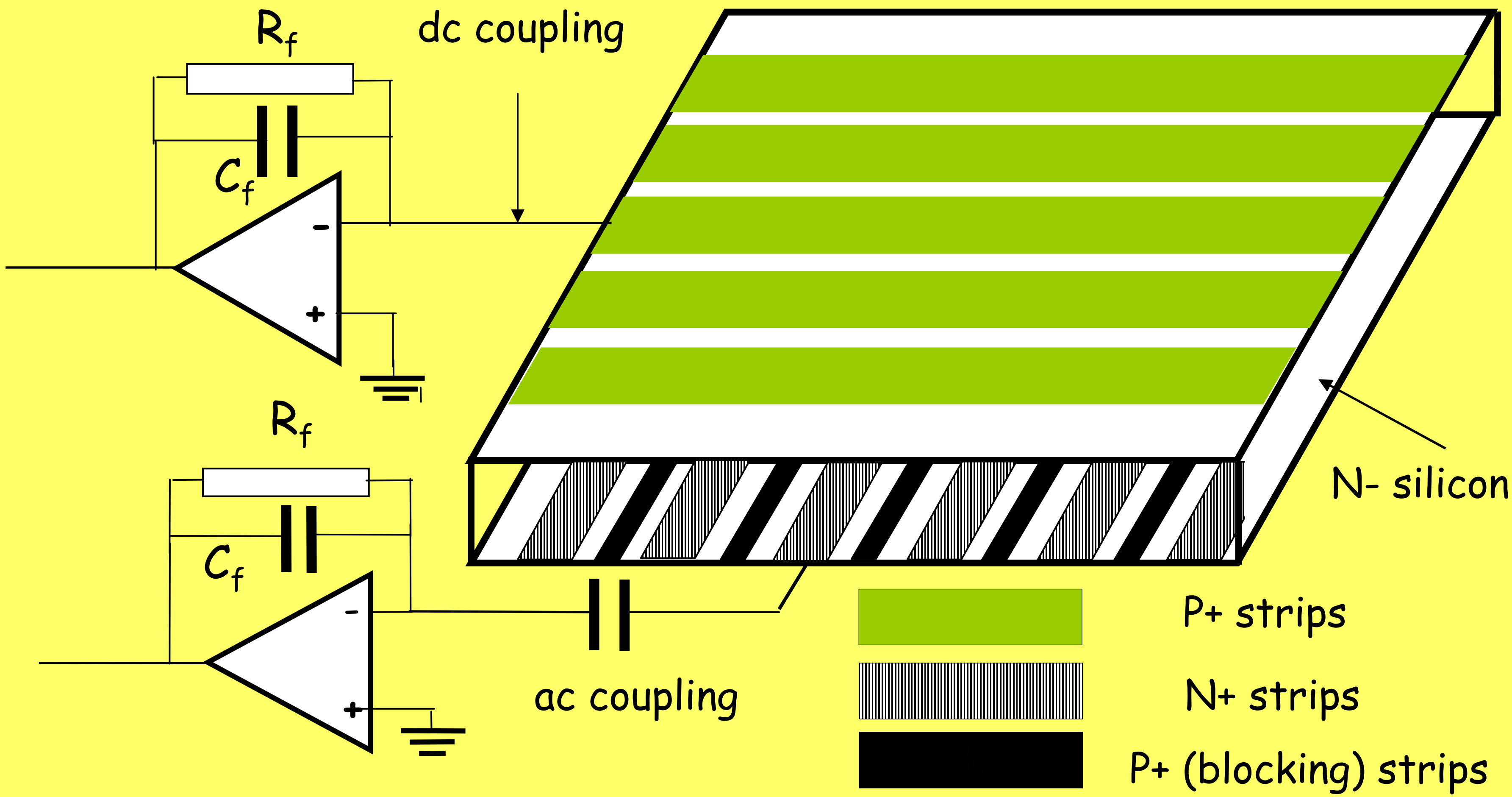
A SINGLE-SIDED MICROSTRIP DETECTOR



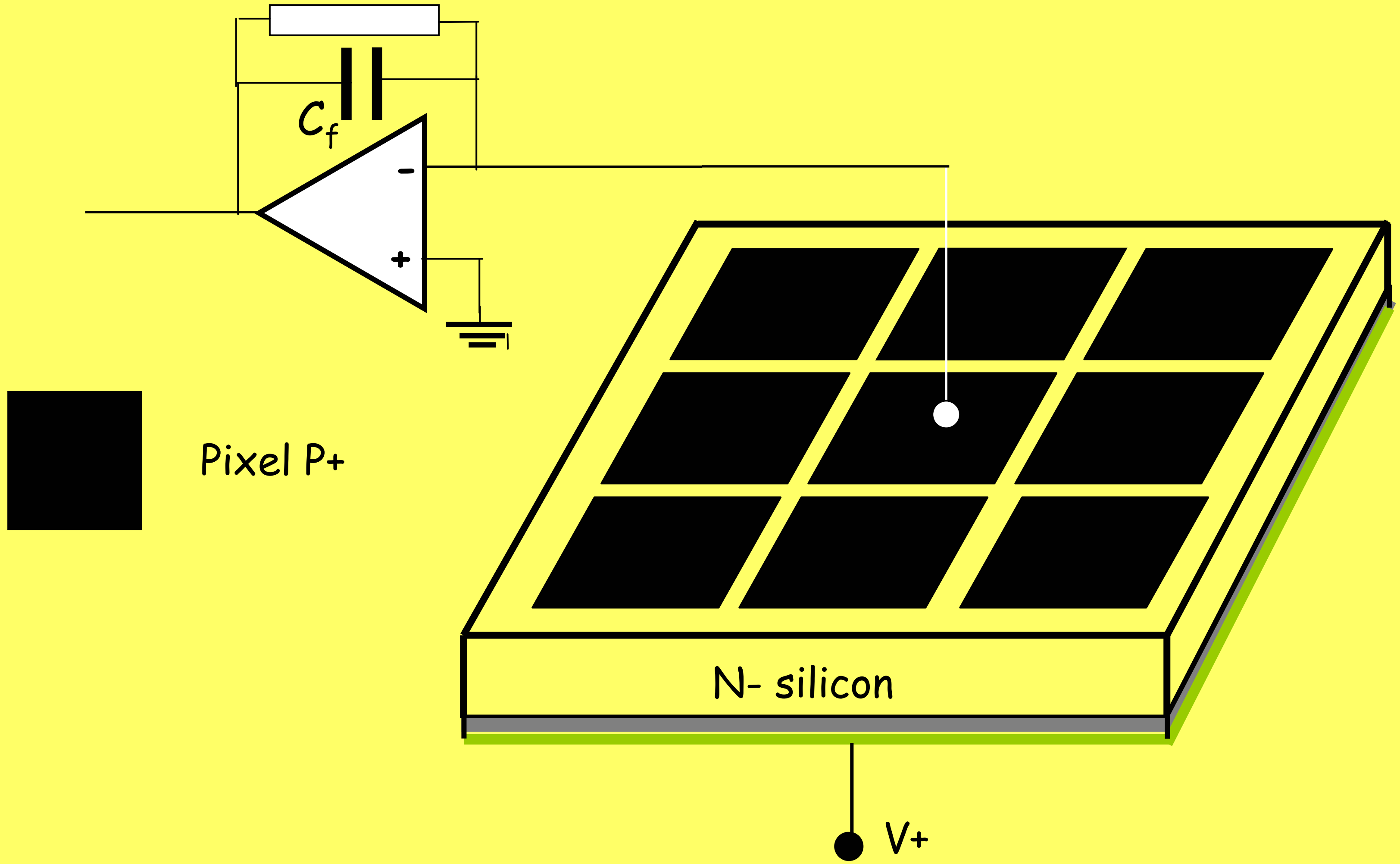
JUNCTION-SIDE (P+STRIPS)READOUT OF A SINGLE-SIDED MICROSTRIP DETECTOR



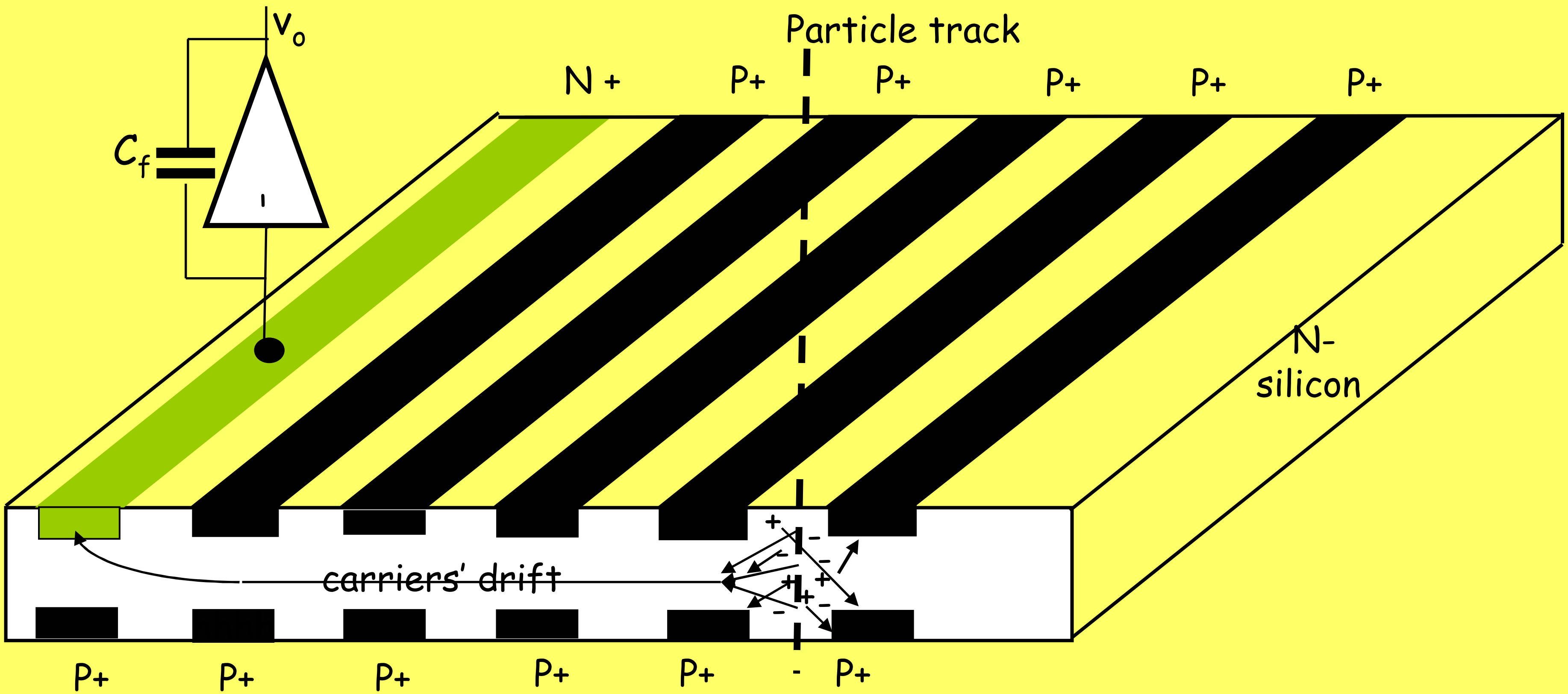
Double-sided microstrip detector. The readout preamplifiers are dc coupled on the junction side and ac coupled on the ohmic side.



A PIXEL DETECTOR



THE DRIFT CHAMBER – The drift chamber invented by E. Gatti and P. Rehak employs an original charge transport method. The capacitance presented to the readout preamplifier by the collecting electrode is largely independent of the sensitive area. This feature reduces the effect of preamplifier noise to a remarkable extent.



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