Detection and Measurement of Radiation

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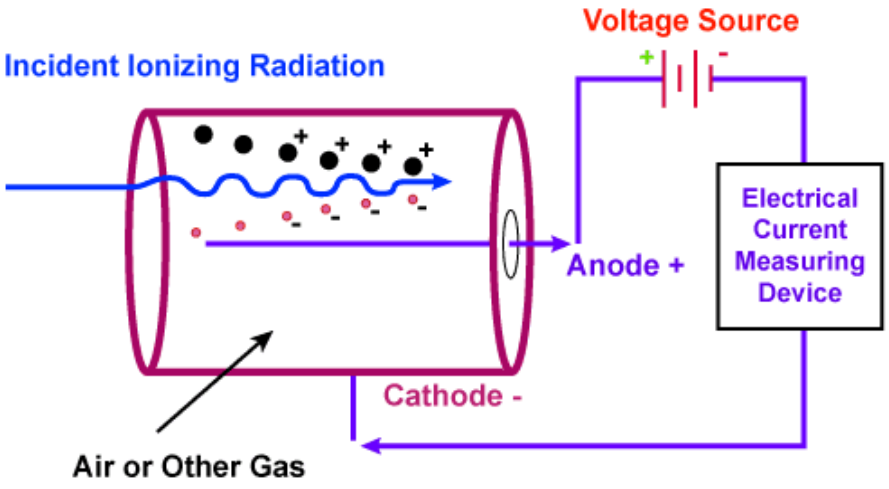
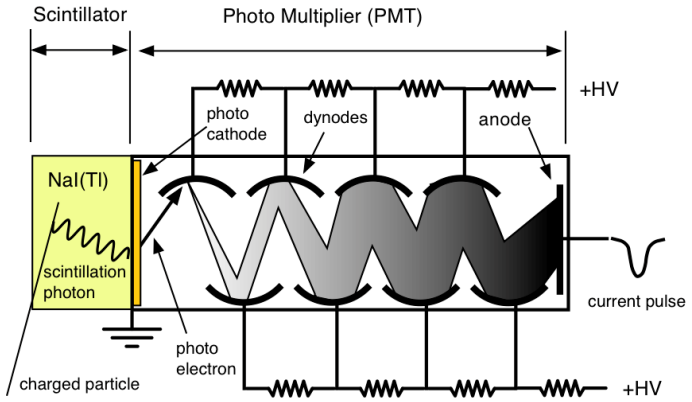
Introduction

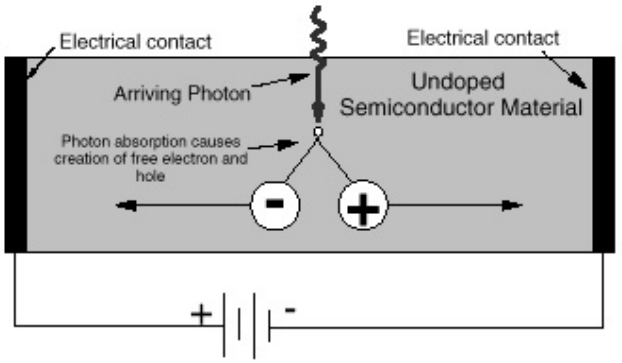
- Radiation detectors of a wide variety are used for detecting, measuring, characterizing, and classifying radiation emissions.
- The three main functions that characterize a radiation detector are (1) a radiation absorber, (2) an observable phenomenon from the interaction, and (3) a method to measure the observable.
- Commonly used detectors



Gas-filled detector



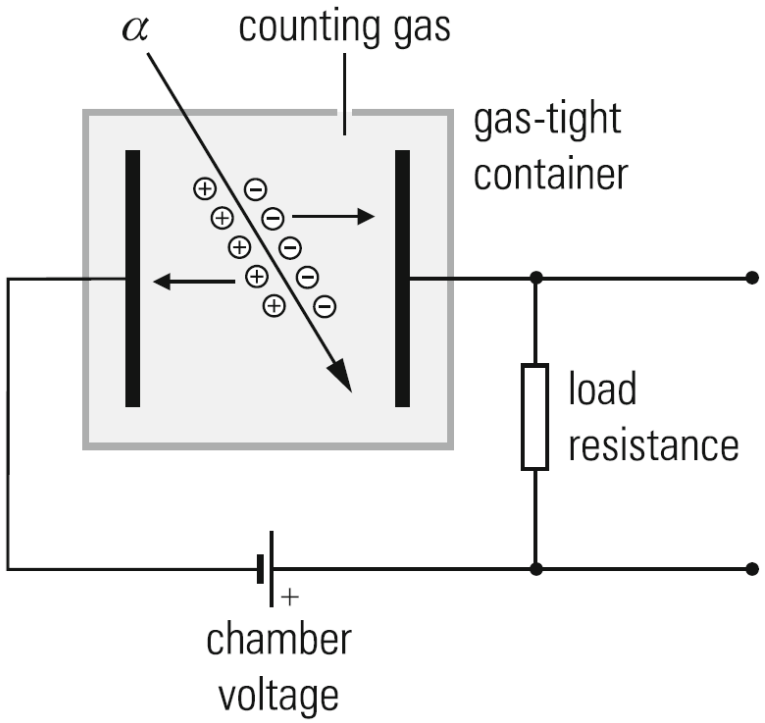
Scintillation detector

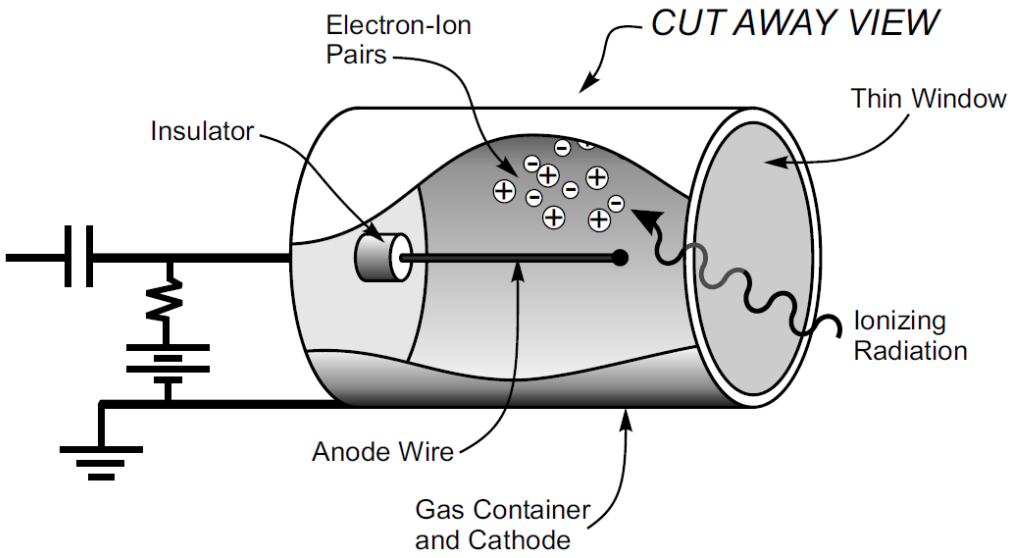


Semiconductor detector

Gas-filled detectors

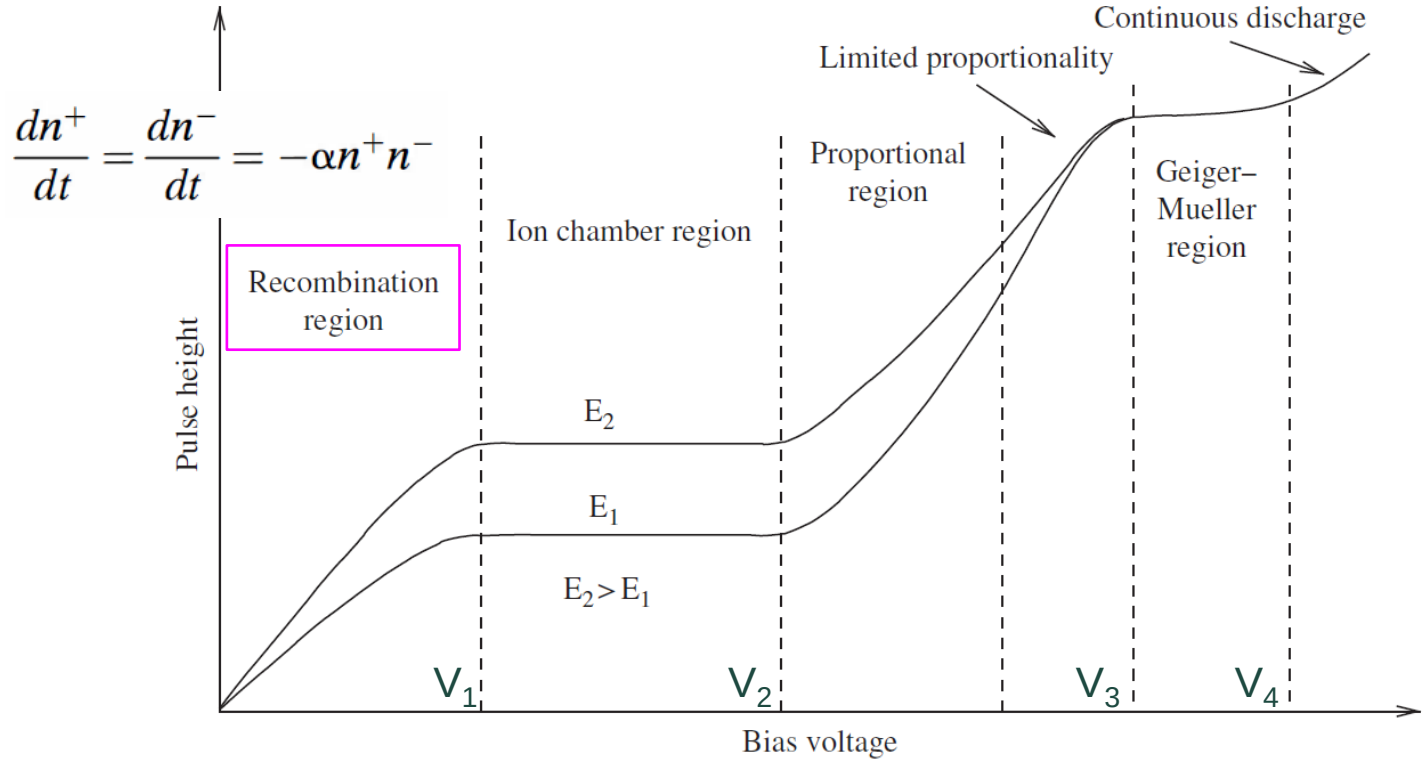
- Radiation passing through a gas can ionize the gas molecules, provided the energy it delivers is higher than the ionization potential of the gas. The charge pairs produced can be made to move in opposite directions by the application of an external electric field, resulting in a measureable electrical pulse. This process has been used to construct the so-called gas-filled detectors.





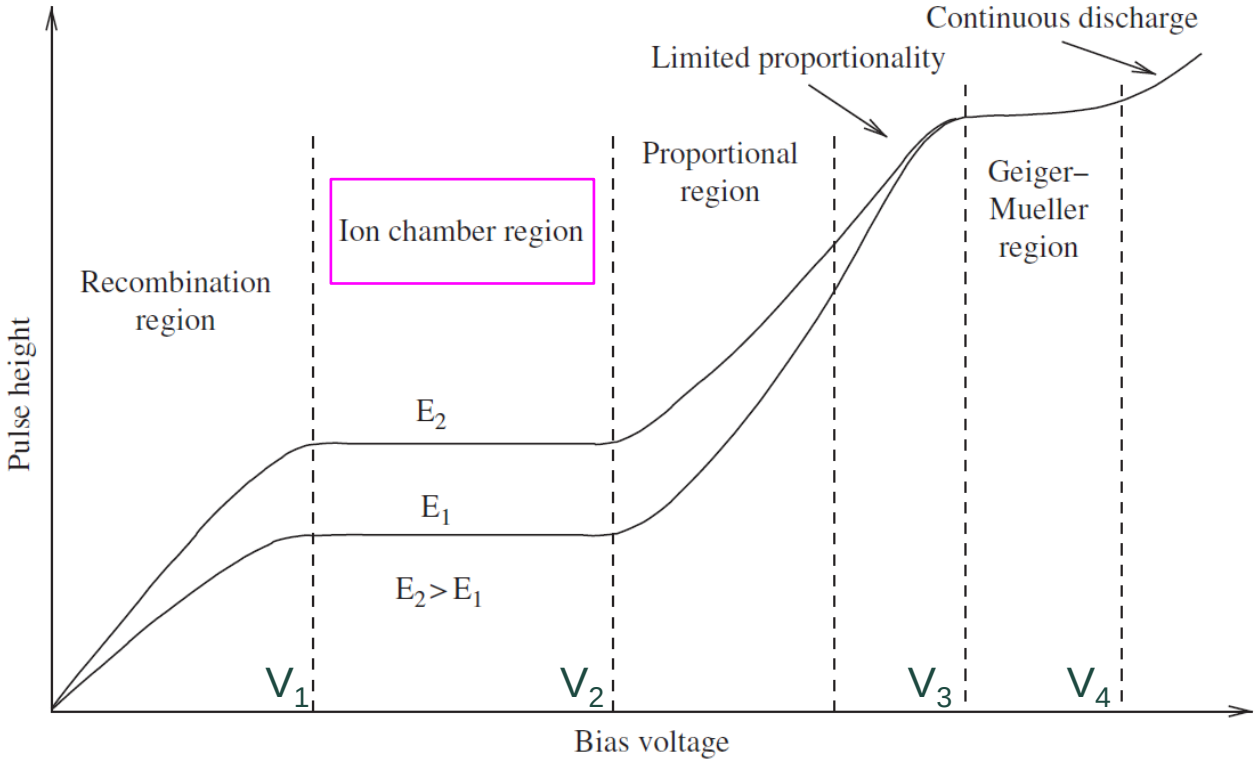
Operation regions of gas-filled detectors

- Recombination region: When the voltage is very low, the electric field in the detector is not strong, electrons and ions move with relatively slow speeds, and their recombination rate is considerable. As V increases, the field becomes stronger, the carriers move faster, and their recombination rate decreases up to the point where it becomes zero. Then, all the charge created by the ionizing radiation is being collected ($V = V_1$).

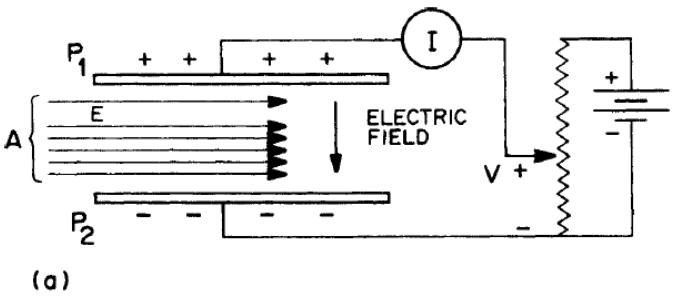


Operation regions of gas-filled detectors

- Ion chamber region: In this region further increasing the high voltage does not affect the measured current since all the charges being produced are collected efficiently by the electrodes. The current measured by the associated electronics in this region is called the saturation current and is proportional to the energy deposited by the incident radiation. The detectors designed to work in this region are called ionization chambers.



Saturation current by radiation



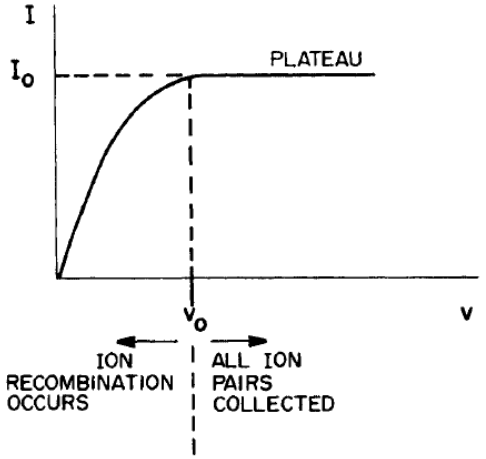


Fig. 10.1 (a) Monoenergetic beam of particles stopping in parallel-plate ionization chamber with variable potential difference V applied across plates P_1 and P_2 (seen edge on). (b) Plot of current I vs. V.

Since it is readily measurable, it is important to see what information the saturation current gives about the radiation. If the fluence rate is $\dot{\Phi}$ cm^{-2} s^{-1}, then the intensity $\dot{\Psi}$ of the radiation (Section 8.8) entering the chamber is given by $\dot{\Psi} = \dot{\Phi}E$. If W denotes the average energy needed to produce an ion pair when a particle of initial energy E stops in the chamber, then the average number N of ion pairs produced by an incident particle and its secondary electrons is $N = E/W$. The average charge (either + or –) produced per particle is Ne, where e is the magnitude of the electronic charge. The saturation current I_0 in the circuit is equal to the product of Ne and $\dot{\Phi}A$, the total number of particles that enter the chamber per unit time. Therefore, we have

$$I_0 = Ne\dot{\Phi}A = \frac{e\dot{\Phi}AE}{W}. \tag{10.1}$$

It follows that

$$\dot{\Psi} = \dot{\Phi}E = \frac{I_0 W}{eA}, \tag{10.2}$$

showing that the beam intensity is proportional to the saturation current.

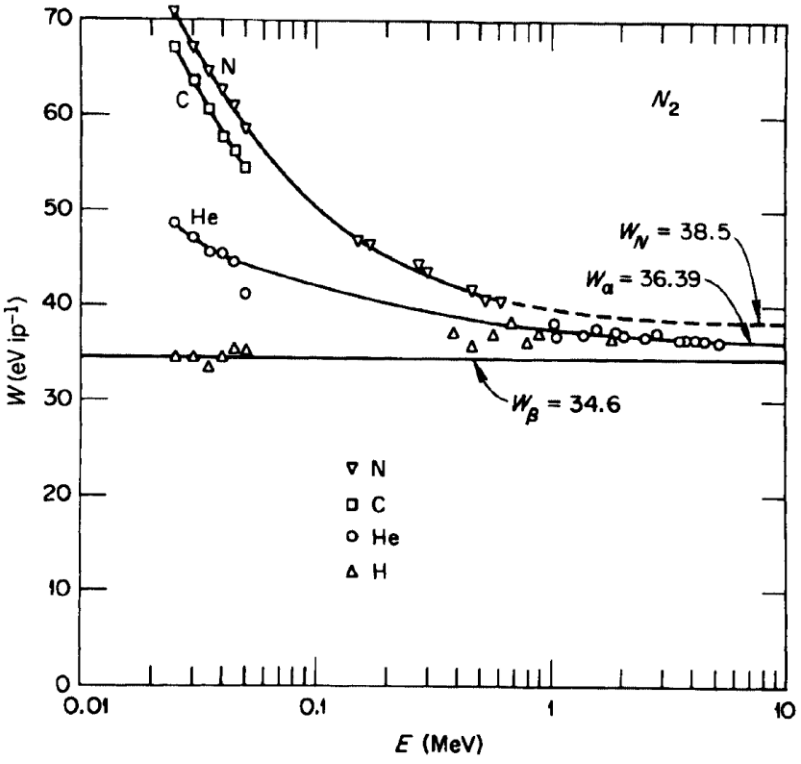
The important relationship (10.2) is of limited use, because it applies to a uniform, parallel beam of radiation. However, since the rate of total energy absorption in the chamber gas, $\dot{E}_{abs}$, is given by $\dot{E}_{abs} = \dot{\Psi}A$, we can write in place of Eq. (10.2)

$$\dot{E}_{abs} = \frac{I_0 W}{e}. \tag{10.3}$$

→ The saturation current gives a direct measure of the rate of energy absorption in the gas, or similarly in a biological system.

W-value and total number of electron-ion pairs

- W-value: the average energy expended per ion pair when a particle of initial energy E and all of the secondary electrons it produces stop in the gas. It significantly higher than the first ionization potential for gases, implying that not all the energy goes into creating electron-ion pairs.



$$\text{eV ip}^{-1} = \text{J C}^{-1}$$

Table 10.1 W Values, W_α and W_β, for Alpha and Beta Particles in Several Gases

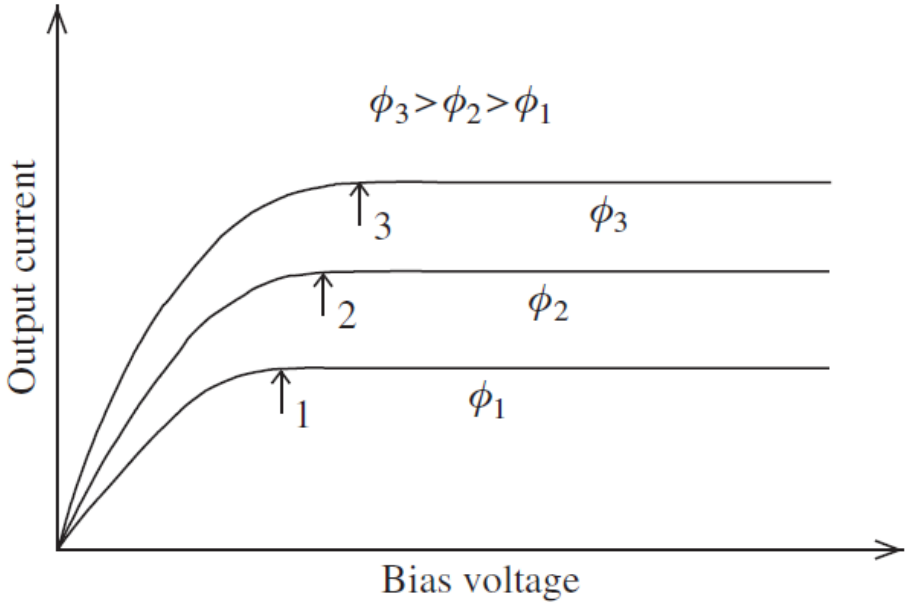
Gas	W_α (eV ip^{-1})	W_β (eV ip^{-1})	W_α / W_β
He	43	42	1.02
H_2	36	36	1.00
O_2	33	31	1.06
CO_2	36	33	1.09
CH_4	29	27	1.07
C_2H_4	28	26	1.08
Air	36	34	1.06

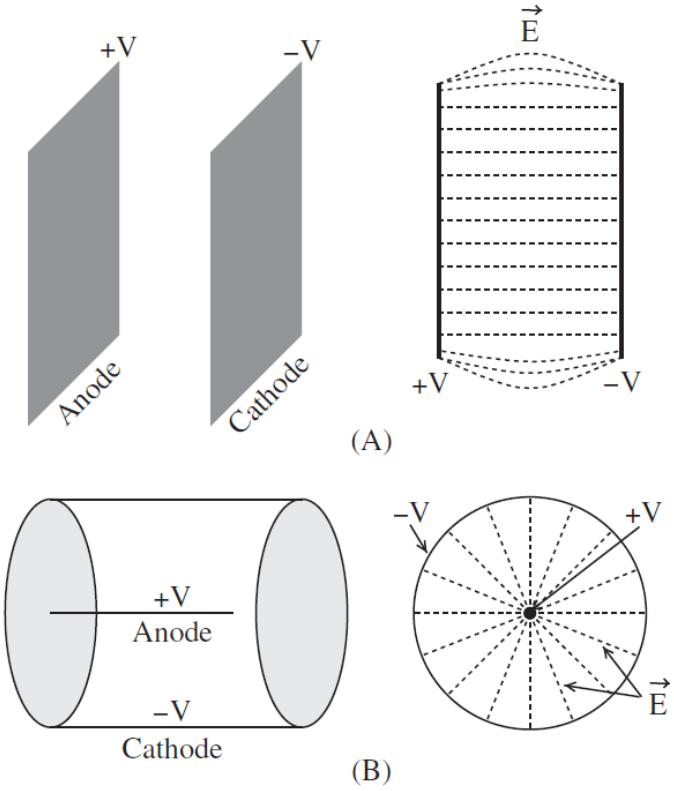
If a 3-MeV particle deposits all its energy in the detector, it will produce, on the average,

$$N = \frac{\Delta E}{W} \approx \frac{3 \times 10^6}{30} \approx 10^5 \text{ electron} - \text{ion pairs}$$

Ionization chambers

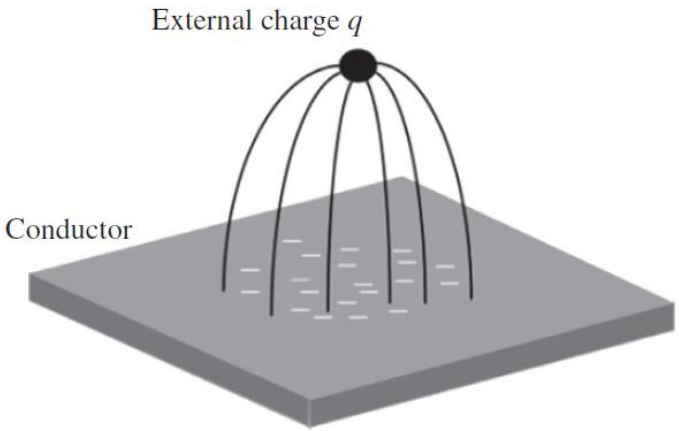
- No charge multiplication takes place. The output signal is proportional to the particle energy dissipated in the detector; therefore, measurement of particle energy is possible. Since the signal from an ionization chamber is not large, only strongly ionizing particles such as alphas, protons, fission fragments, and other heavy ions are detected by such detectors. The voltage applied is less than 1000 V.

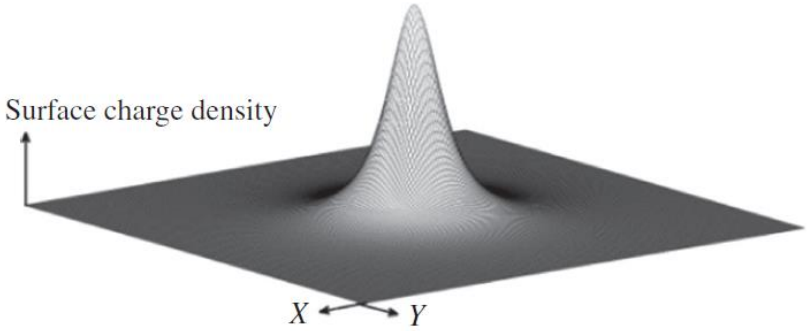




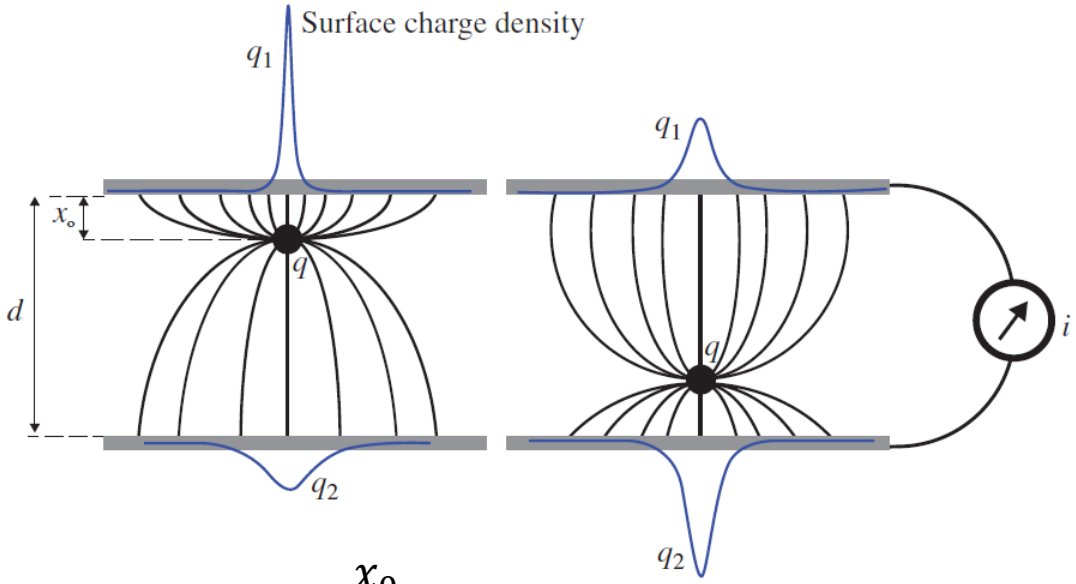
Signal induction mechanism

- Induced charge and induced current





$$q_1 = -q\left(1 - \frac{x_0}{d}\right)$$



$$q_2 = -q\frac{x_0}{d}$$

$$q_1 + q_2 = -q$$

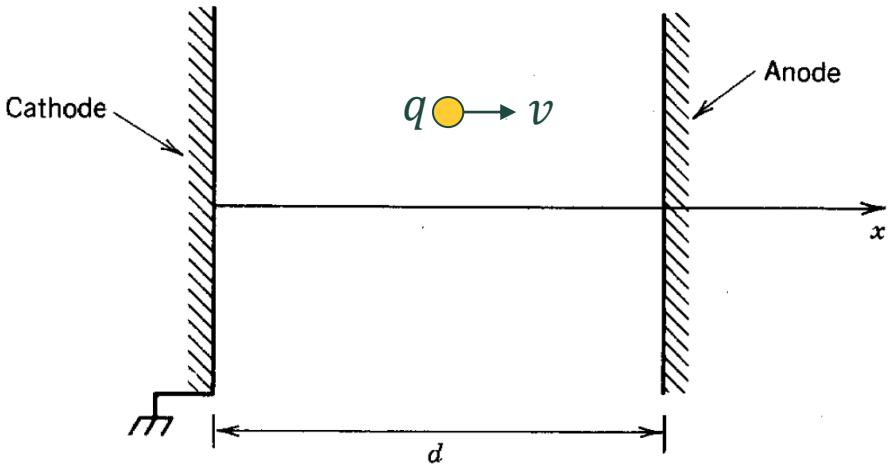
Shockley-Ramo theorem

- Shockley (1938), Ramo (1939): The induced current i between two electrodes separated by d by a moving point charge q with a velocity v is given by:

$$i = \frac{qv}{d}$$

Energy conservation

$$qE \cdot dx = Vi \cdot dt \quad \Rightarrow \quad i = \frac{qEdx}{Vdt} = \frac{qv}{d}$$



Currents Induced by Electron Motion*

SIMON RAMO†, ASSOCIATE MEMBER, I.R.E.

Summary—*A method is given for computing the instantaneous current induced in neighboring conductors by a given specified motion of electrons. The method is based on the repeated use of a simple equation giving the current due to a single electron's movement and is believed to be simpler than methods previously described.*

Introduction

IN designing vacuum tubes in which electron transit-time is relatively long, it becomes necessary to discard the low-frequency concept that the instantaneous current taken by any electrode is proportional to the number of electrons received by

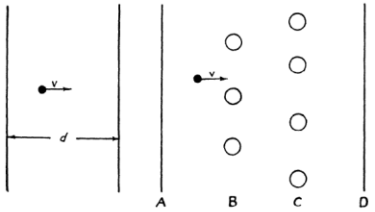


Fig. 1 Fig. 2

it per second. Negative grids, it is known, may carry current even though they collect no electrons and current may be noted in the circuit of a collector during the time the electron is still approaching the collector. A proper concept of current to an electrode must consider the instantaneous change of electrostatic flux lines which end on the electrode and the methods given in the literature for computing induced current due to electron flow are based on this concept.

A method of computing the induced current for a specified electron motion is here explained which is believed to be more direct and simpler than methods previously described. In the more difficult cases, in which flux plots or other tedious field-determination methods must be used, only one field plot is needed by the present method while the usual methods require a large number.

* Decimal classification: R138. Original manuscript received by the Institute, September 16, 1938.
† General Engineering Laboratory, General Electric Company, Schenectady, N. Y.

Method of Computation

The method is based on the following equation, whose derivation is given later:

$$i = E_v ev \qquad (1)$$

where i is the instantaneous current received by the given electrode due to a single electron's motion, e is the charge on the electron, v is its instantaneous velocity, and E_v is the component in the direction v of that electric field which would exist at the electron's instantaneous position under the following circumstances: electron removed, given electrode raised to unit potential, all other conductors grounded. The equation involves the usual assumptions that induced currents due to magnetic effects are negligible and that the electrostatic field propagates instantaneously.

Simple Example

A simple example is offered in the computation of the instantaneous current due to an electron's motion between two infinite plates (Fig. 1). (The result is a starting point for the analysis of a diode, for example, when the transit-time is long.)

From (1) we obtain immediately

$$i = evE_v = \frac{ev}{d}.$$

In the literature[1] it is stated that this same result is deduced from image theory. This involves the setting up of an infinite series of image charges on each side of the plates for a given position of the electron and a consideration of the total flux crossing one of the planes due to the series of charges, a method which is lengthy and requires no little familiarity with methods of handling infinite series.

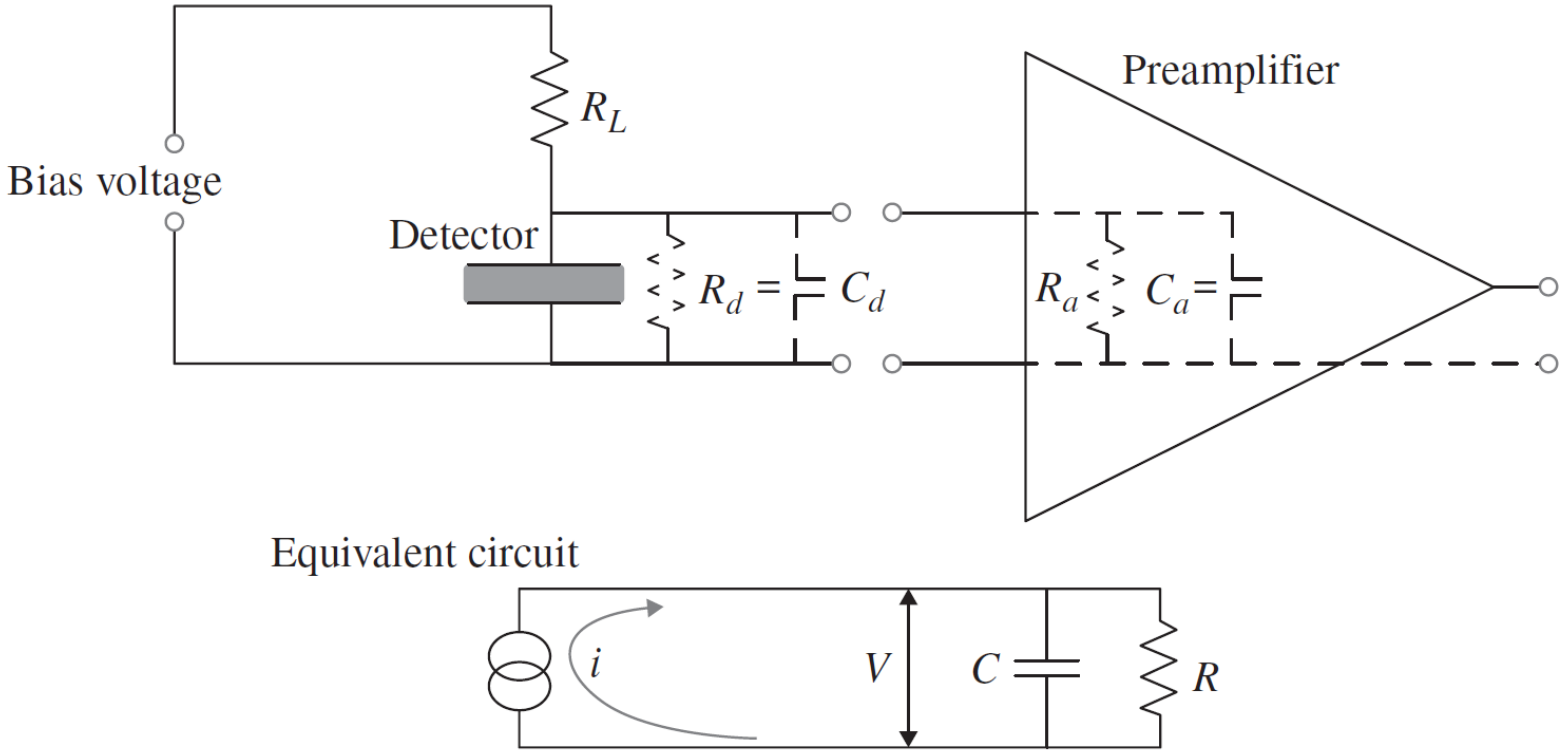
The General Case

Consider a number of electrodes, A, B, C, D, in the presence of a moving electron (Fig. 2) whose path and instantaneous velocity are known. A tedious way to find the current induced in, say, electrode

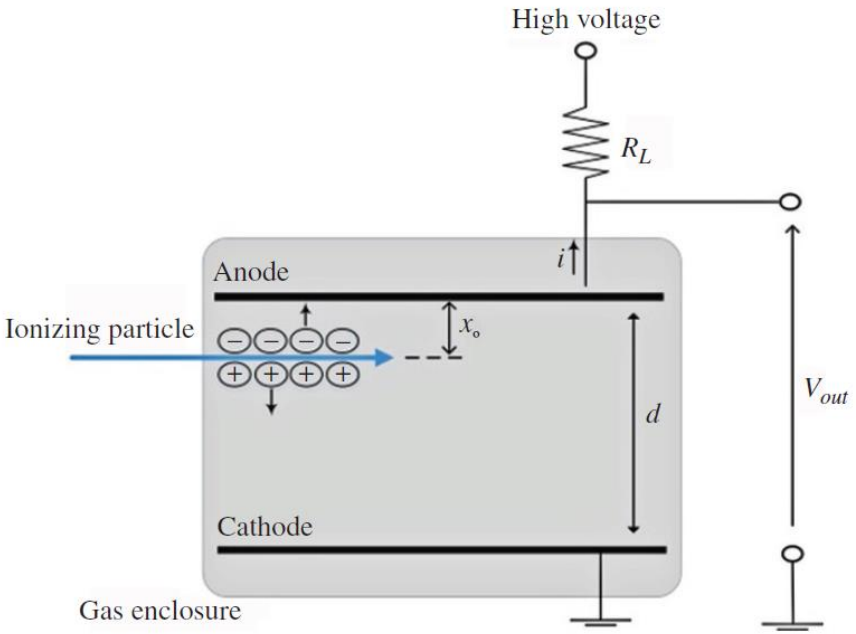
[1] D. O. North, "Analysis of the effects of space charge on grid impedance," Proc. I.R.E., vol. 24, pp. 108–158; February, (1936).

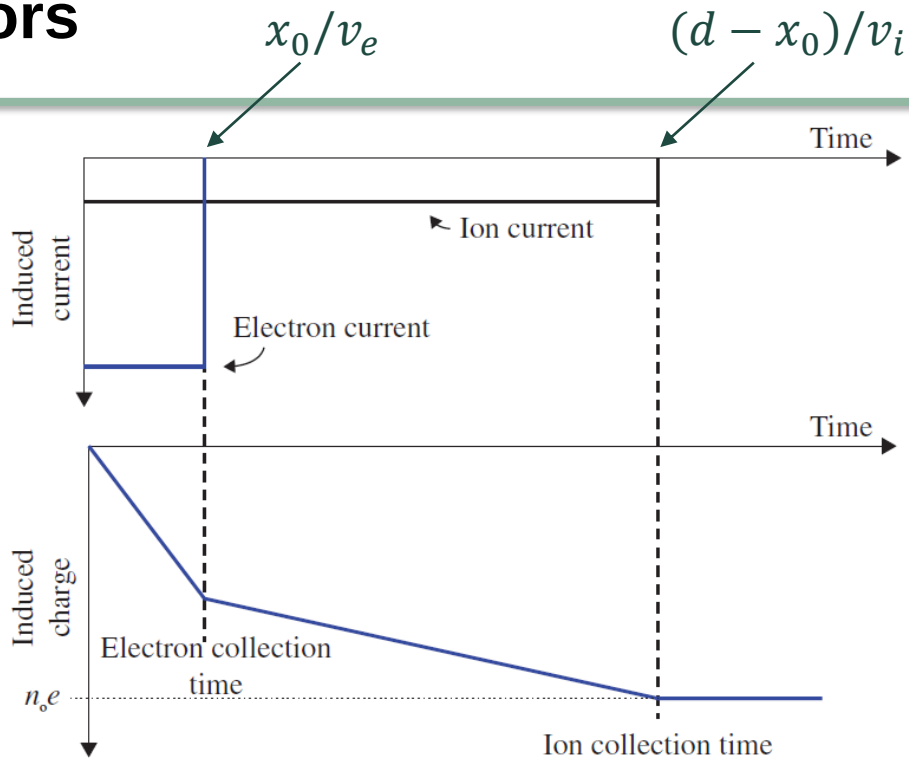
Detectors as a signal generator

- Ionization detectors produce a current pulse in response to an interaction with the detector. Therefore, detectors can be considered as a current source in the circuit.
- The current pulse induced by the moving charge carriers on the detector's electrodes appears as a voltage pulse at the input of the readout electronics.



Pulses from ionization detectors





$$i(t) = i_e(t) + i_i(t) = \frac{n_0 e v_e}{d} + \frac{n_0 e v_i}{d}$$

$$v_e = \mu_e E = \frac{e}{m_e \nu_m} E \sim 10^4 \text{ m/s}$$

$$v_i \ll v_e$$

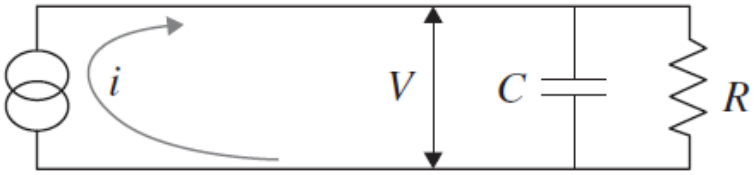
$$Q(t) = \int (i_e + i_i)dt = \frac{n_0 e}{d}(v_e + v_i)t \quad \text{for} \quad 0 \le t \le x_0/v_e$$

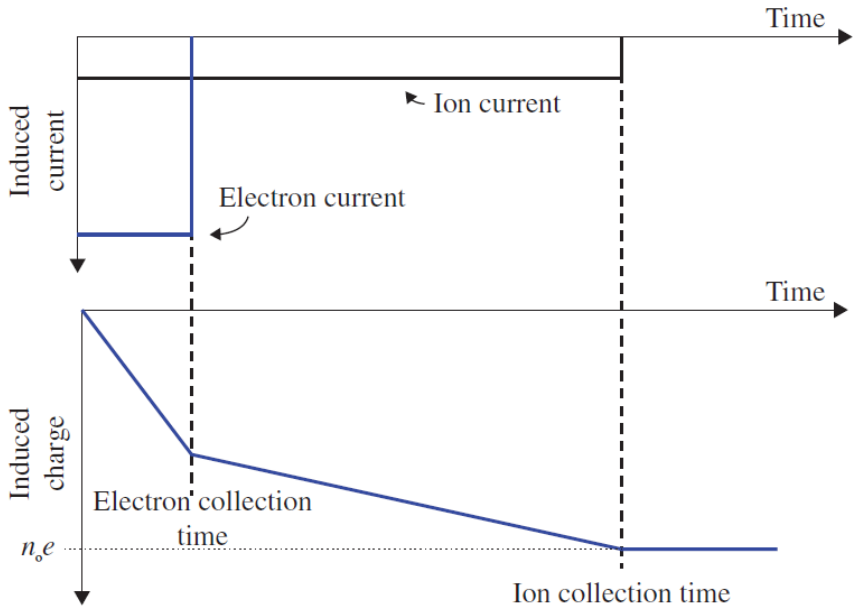
$$Q(t) = \frac{n_0 e}{d} x_0 + \frac{n_0 e}{d} v_i t \quad \text{for} \quad x_0/v_e \le t \le (d - x_0)/v_i$$

Output voltage pulse amplitude

- The maximum pulse amplitude to be expected from the creation of n_0 ion pairs in ion chamber is given by

$$V_{\max} = \frac{n_0 e}{C}$$





If a 1 MeV charged particle loses all its energy within the chamber, n_0 can be estimated as

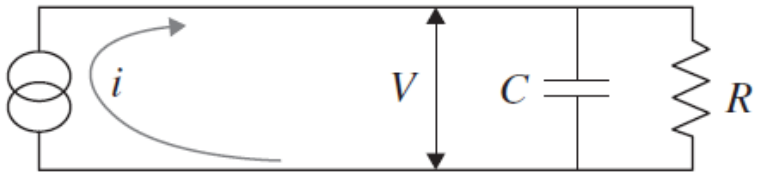
$$n_0 = \frac{E_0}{W} \cong \frac{10^6 \text{eV}}{35\ \text{eV/ion pair}} = 2.86 \times 10^4$$

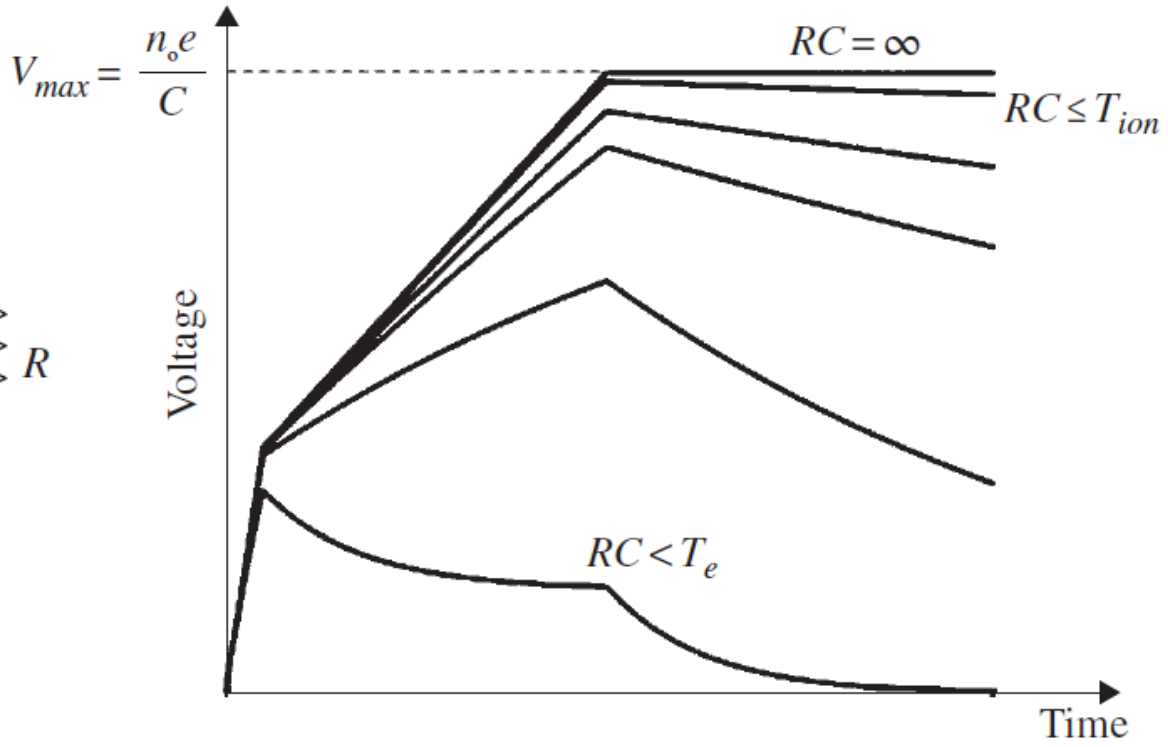
For typical ion chambers and associated wiring, the capacitance C will be of the order of 10^{-10} farads. We then calculate a pulse amplitude of

$$V_{\max} = \frac{(2.86 \times 10^4)(1.60 \times 10^{-19}\text{C})}{10^{-10}\text{F}} = 4.58 \times 10^{-5}\text{V}$$

Output voltage pulse for different circuit time constants

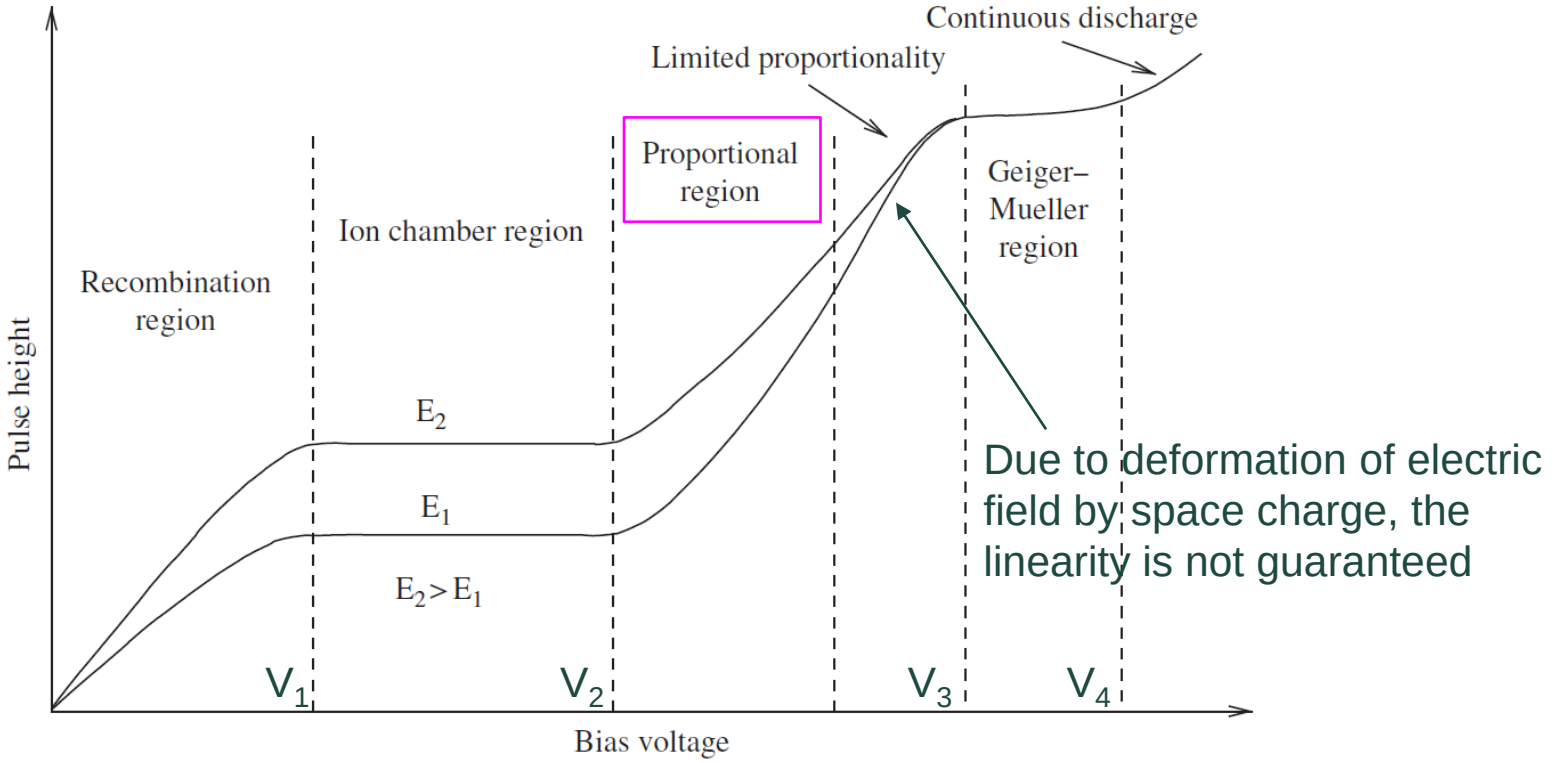
- When the detector is connected to the measuring circuit, the equivalent input resistance, R, and capacitance, C, are obtained by combining all the resistances and capacitances at the input of the measuring circuit.
- The shape of a voltage pulse is a function of the time constant of the detector circuits.





Operation regions of gas-filled detectors

- Proportional region: The collected charge starts increasing because the electrons produce secondary ionization that results in charge multiplication. The charge multiplication factor—the ratio of the total ionization produced divided by the primary ionization—is, for a given voltage, is independent of the primary ionization. Thus, the total number of charges produced after multiplication is proportional to the initial number of charges.



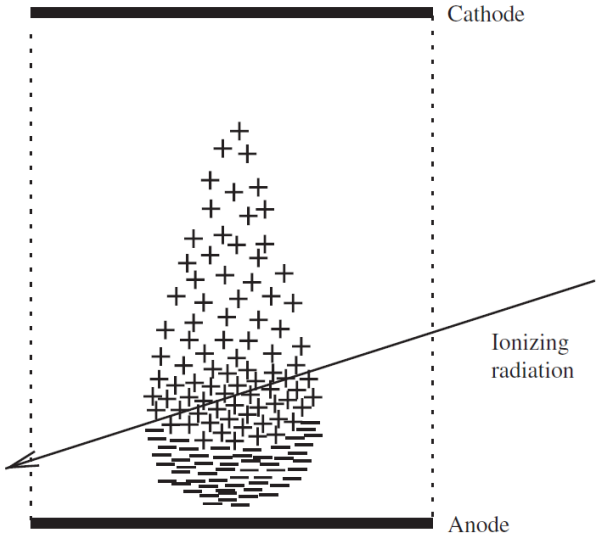
Avalanche multiplication

- Avalanche multiplication: Due to the high electric field between the electrodes, the charges quickly gain energy between collisions. If the total energy of an electron or an ion becomes higher than the ionization potential of the gas atoms, it can ionize an atom, thus creating another charge pair.
- In uniform electric field, the change in the number of charge pairs per unit path length is simply proportional to the total number of charge pairs:

$$\frac{dn}{dx} = \alpha n \qquad \alpha = \frac{1}{\lambda_{iz}} : \text{Townsend 1}^{\text{st}} \text{ ionization coefficient}$$

- Multiplication factor: $M = \frac{n}{n_0} = e^{\alpha x}$
- For non-uniform field, $M = \exp\left[\int_{r1}^{r2} \alpha(x)dx\right]$
- The first Townsend coefficient is given by

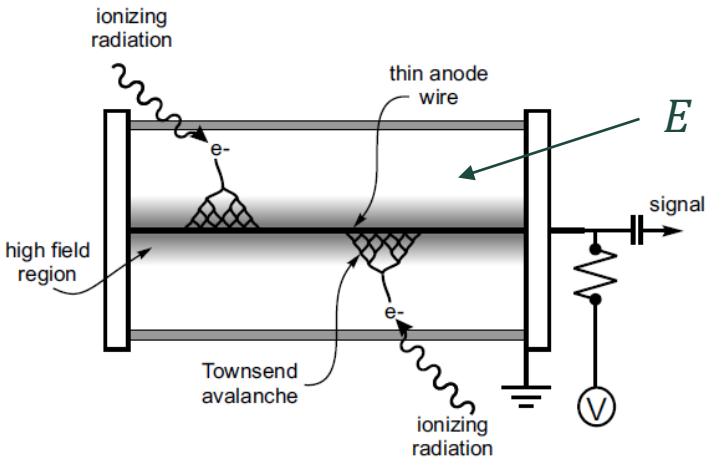
$$\frac{\alpha}{p} = f\left(\frac{E}{p}\right) = A \exp\left[-\frac{Bp}{E}\right]$$



Proportional counters

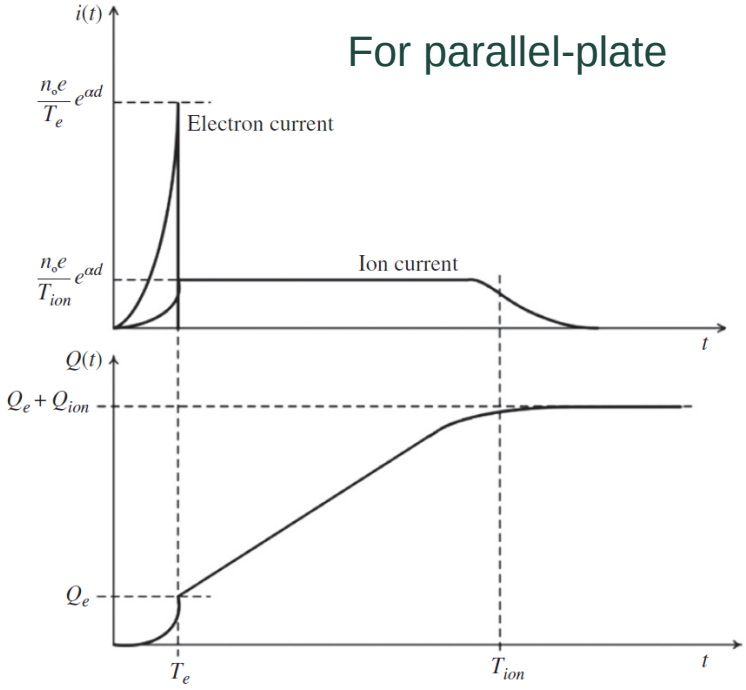
- Charge multiplication takes place, but the output signal is still proportional to the energy deposited in the counter. Measurement of particle energy is possible. Proportional counters may be used for the detection of any charged particle. Identification of the type of particle is possible with both ionization and proportional counters. An alpha particle and an electron having the same energy and entering either of the detectors will give a different signal. The alpha particle signal will be bigger than the electron signal. The voltage applied to proportional counters ranges between 800 and 2000 V.

$$i_e(t) = \frac{n_0 e v_e}{d} e^{\alpha x} = \frac{n_0 e v_e}{d} e^{\alpha v_e t}$$



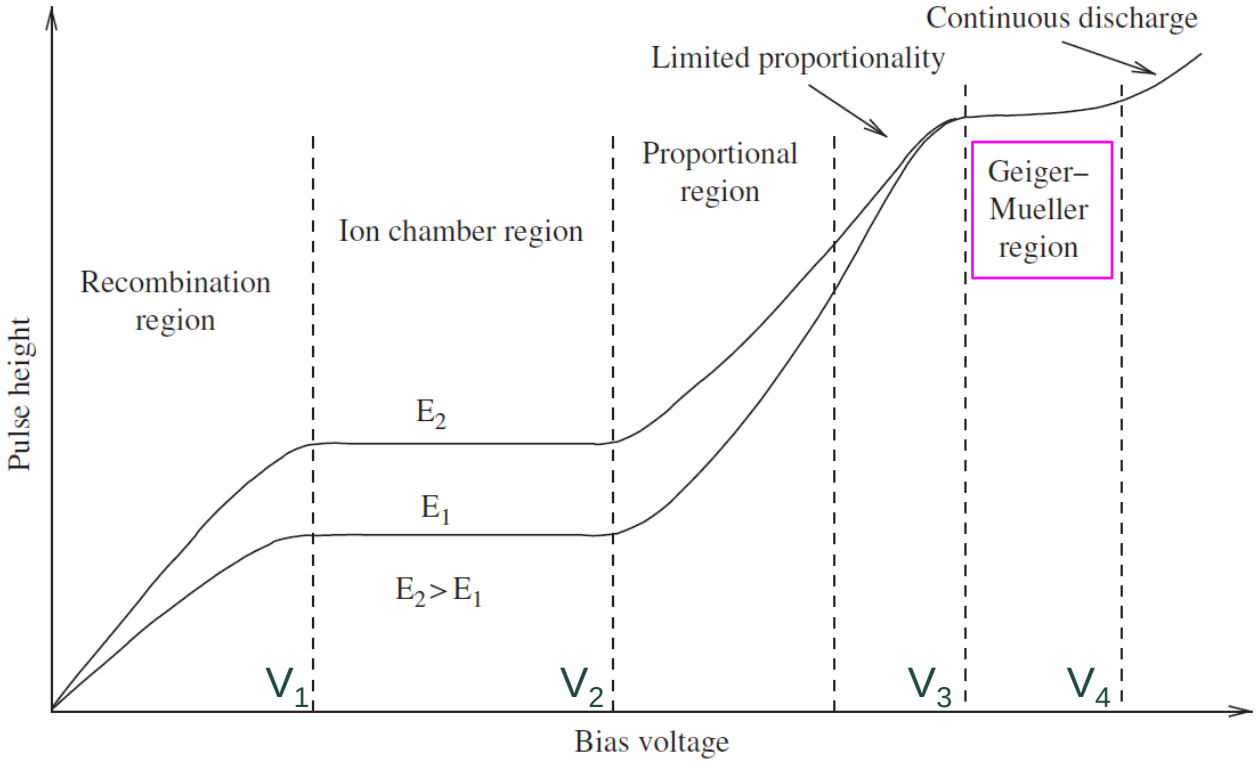
$$E = \frac{V}{r \ln(b/a)}$$

For parallel-plate



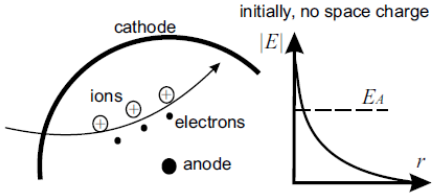
Operation regions of gas-filled detectors

- Geiger-Muller region: In this region, the electric field inside the detector is so strong that a single electron–ion pair generated in the chamber is enough to initiate an avalanche of electron–ion pairs. This avalanche will produce a strong signal with shape and height independent of the primary ionization and the type of particle, a signal that depends only on the electronics of the detector. Thus, the detectors operated in this region are not appropriate for spectroscopy.

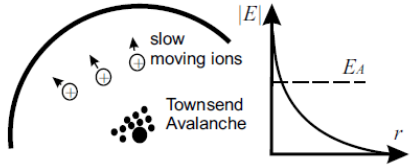


GM counters

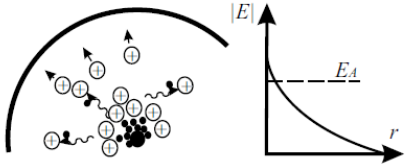
- Simple and provides a very strong signal. They can be used with any kind of ionizing radiation. The disadvantage of GM counters is that their signal is independent of the particle type and its energy. Therefore, a GM counter provides information only about the number of particles. The voltage ranges are 500 ~ 2000 V.



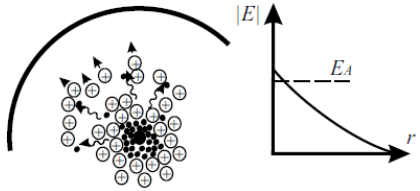
1. Primary event creates ion pairs.



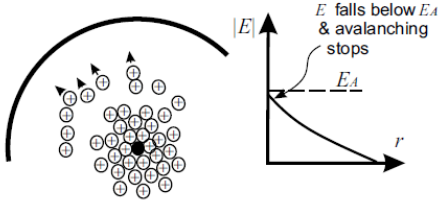
2. Electrons rapidly drift to the anode and cause a Townsend avalanche - which creates a tremendous number of ion pairs.



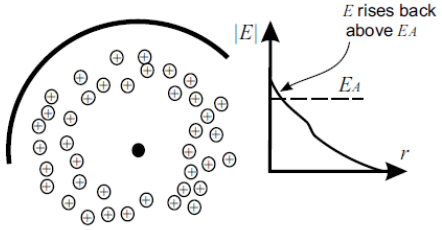
3. UV light from excited atoms in the avalanche excite more ion pairs.



4. Waves of avalanches occur from the ion pairs excited by released UV light. Positive space charge begins to build up around the anode.

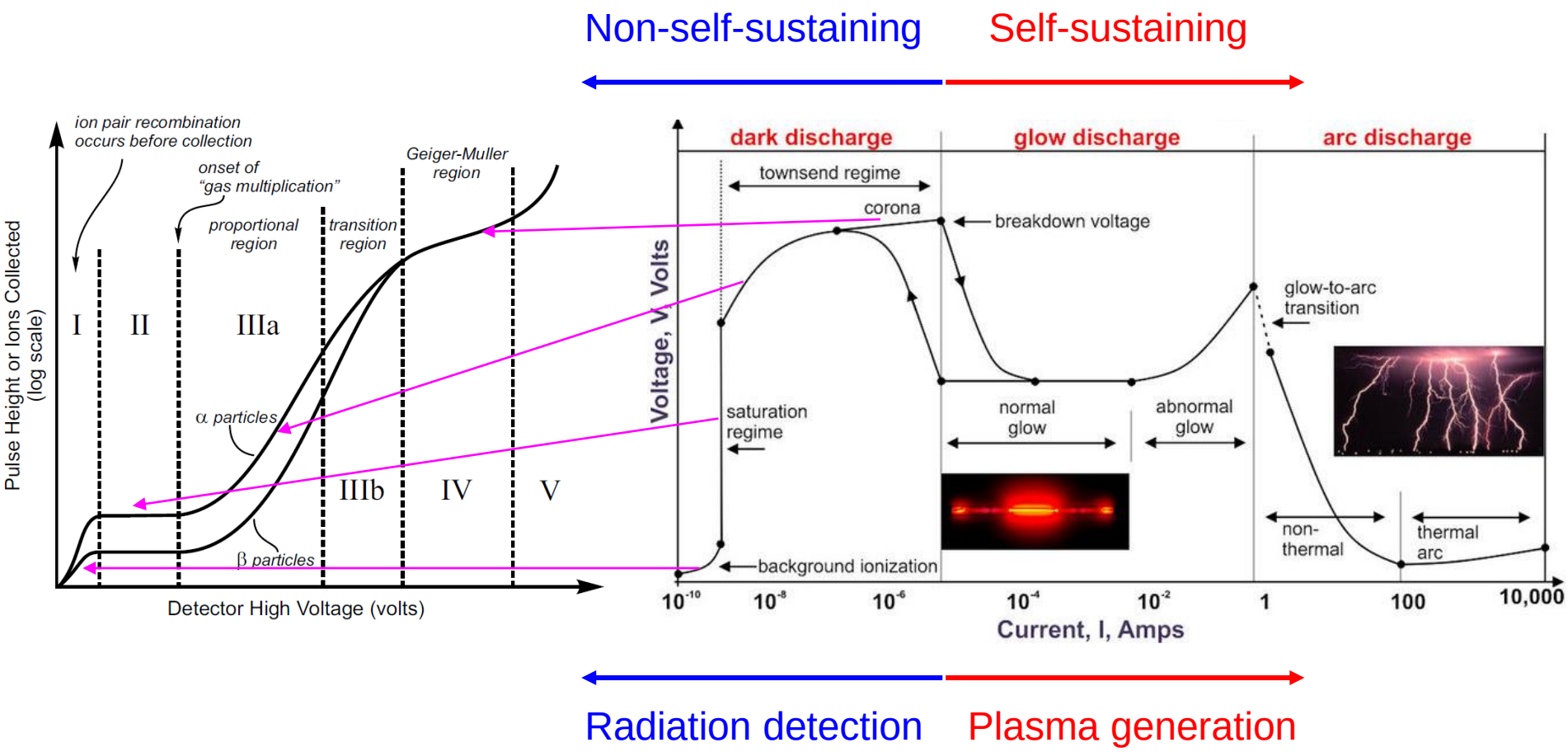


5. Positive space charge builds up around the anode to the point that the electric field is reduced below the critical value for avalanching. The avalanching ceases.



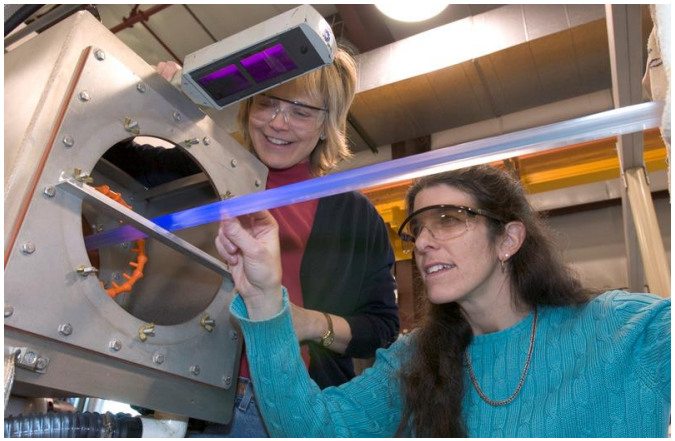
6. The space charge drifts away from the anode towards the cathode (wall). The electric field recovers such that another Geiger discharge can occur.

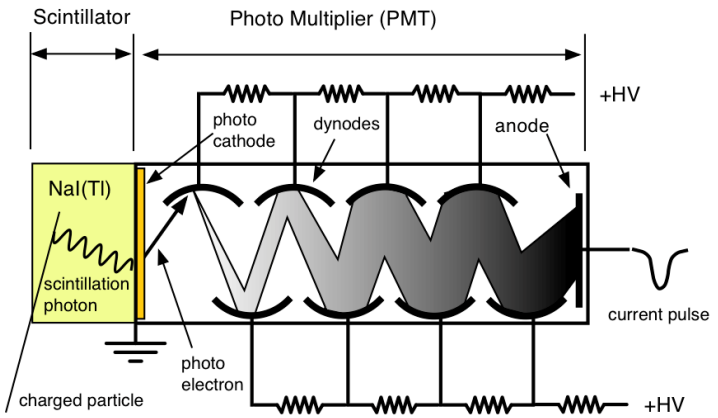
Operating regimes of gas-filled detectors in a typical characteristic curve for gas discharges



Scintillation detectors

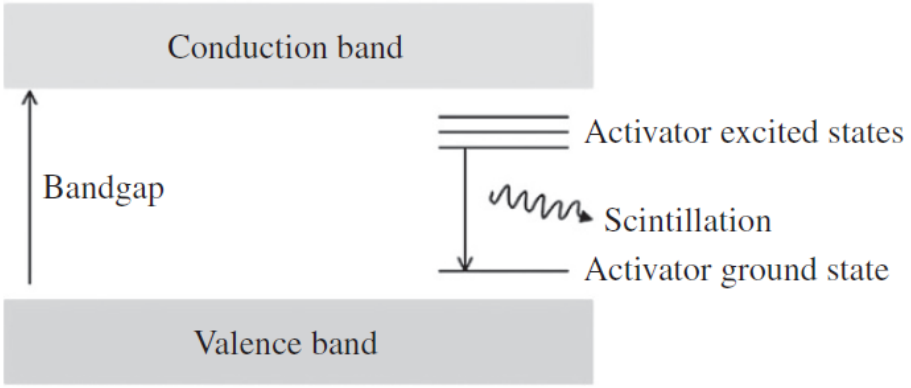
- Radiation detection is accomplished by the use of a scintillator material: a substance that emits light when struck by an ionizing particle. The scintillations emitted from the scintillator are then converted to an electrical signal by means of a photodetector.
- They can be broadly categorized into organic and inorganic scintillators.
  - Organic scintillators are composed of low atomic number elements and, therefore, are more suitable for neutron and charged particle detection.
  - Inorganic scintillators normally contain a large fraction of atoms with a high atomic number and, therefore, are suitable for gamma-ray detections.





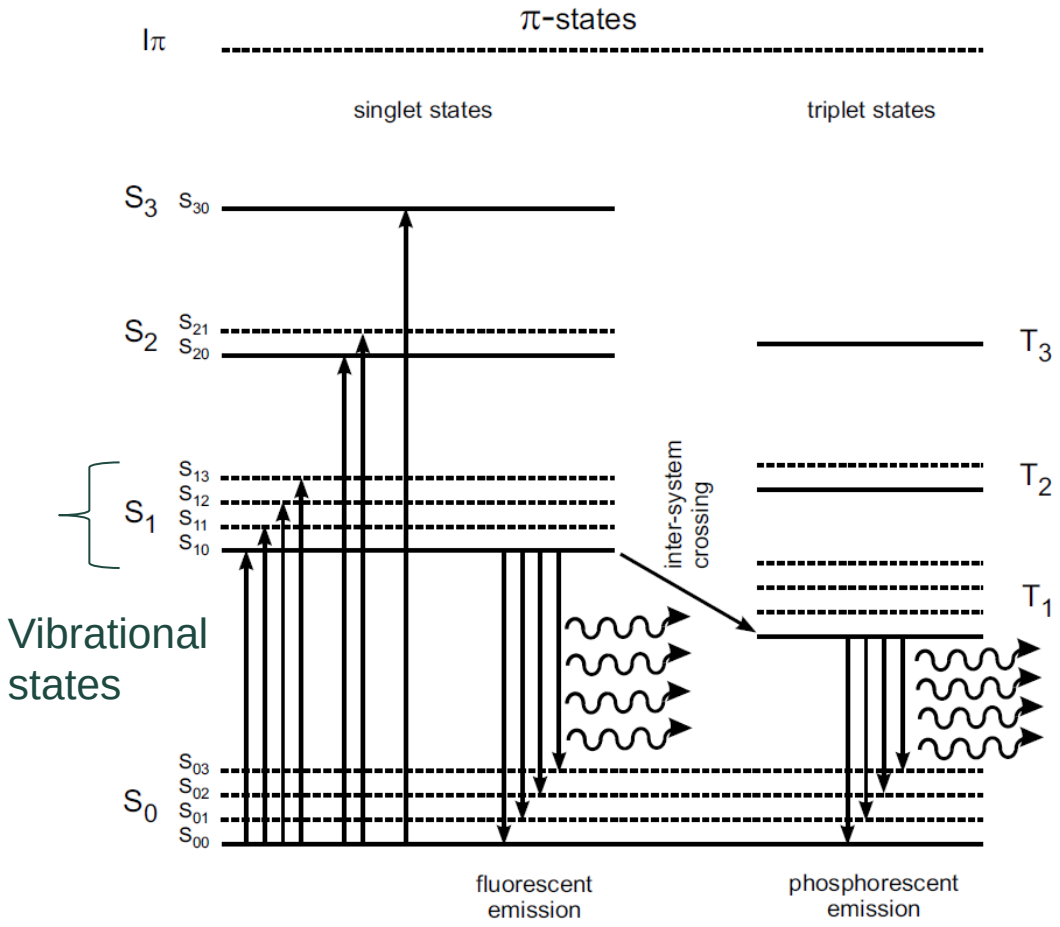
Inorganic scintillators

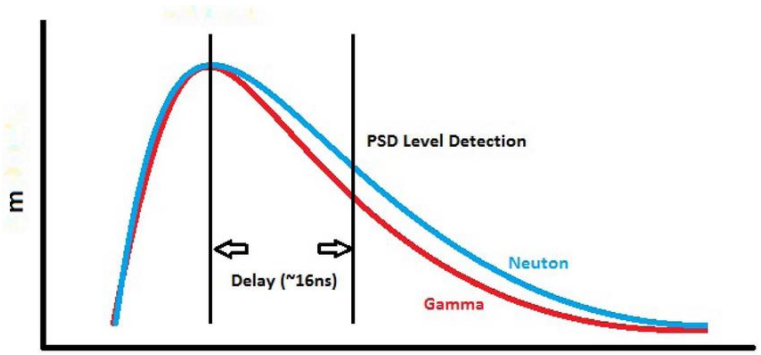
- Inorganic scintillators depend primarily on the crystalline energy band structure of the material for the scintillation mechanism.
- The absorption of energy can elevate electrons from the valence band to the conduction band, leaving a hole in the valence band. The return of an electron to the valence band leads to the emission of a de-excitation photon.
- The efficiency of light emission can be significantly increased by adding a small amount of impurities, called activators, to the crystal.
- The main properties are scintillation efficiency (the ratio of the energy of the emitted photons to the total absorbed energy), light output (the number of photons per MeV of energy absorbed in the detector), emission spectrum, and decay time of scintillation light.
- NaI(Tl): thallium-doped sodium iodide
  - Light output: ~38000 photons/MeV
  - Most probable wavelength: ~415 nm
  - Decay time: ~230 ns
- Others: CsI(Na), CsI(Tl), BGO (bismuth germanate), $LaBr_3$,…

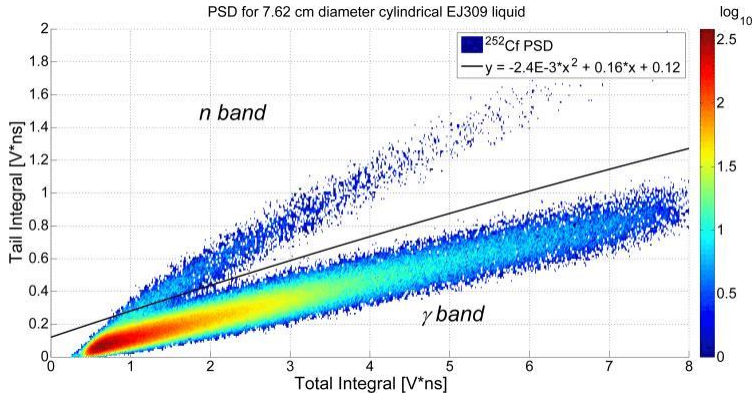


Organic scintillators

- The scintillation mechanism in organic materials arises from transitions in the energy levels of a single molecule, and therefore organic scintillators can be found independently of the physical state (very fast: a few ns).

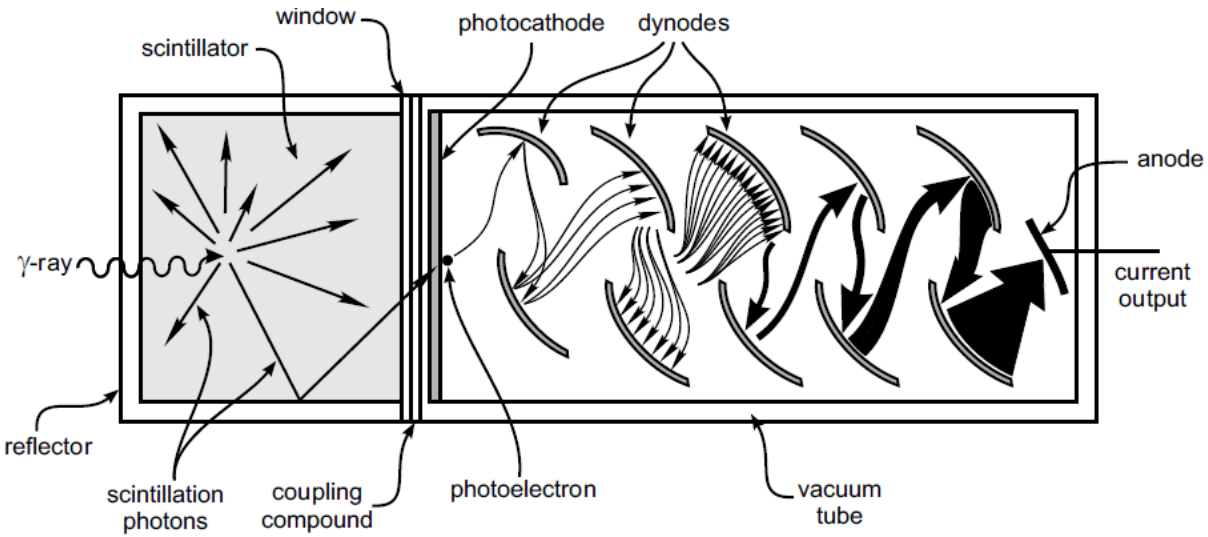






Light collection

- Photomultiplier tube (PMT)

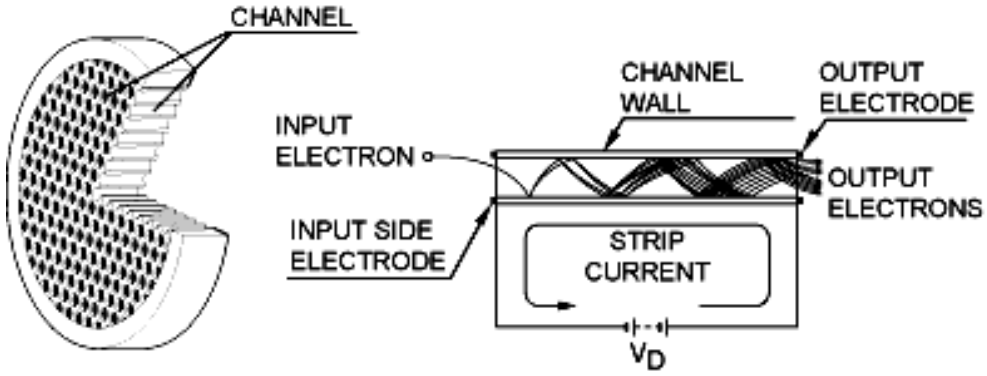


# of dynodes

$$Q = qN_0G^n$$

Gain (γ_e)

- Microchannel plate (MCP)



Current signal example

A numerical example is instructive at this point. Assume we start with a scintillation event that liberates 1000 photoelectrons from the photocathode of the PM tube. Further assume that the PM tube provides an overall gain of 10^6, so that 10^9 electrons per pulse leave the last dynode and are collected by the anode. If these scintillation pulses are occurring at a rate of 10^5 per second, then the average dc anode current can easily be calculated as

$$\begin{aligned} I_{\text{avg}} &= 10^9 \frac{\text{electrons}}{\text{pulse}} \times 1.6 \times 10^{-19} \frac{\text{coulomb}}{\text{electron}} \times 10^5 \frac{\text{pulses}}{\text{second}} \\ &= 1.6 \times 10^{-5}\ \text{A} = 0.016\ \text{mA} \end{aligned}$$

Because this current appears in discrete pulses, however, the peak current during a pulse is substantially higher. As an extreme case, assume we have a very fast organic scintillator whose decay time combined with the transit time spread in the PM tube produces a narrow electron pulse of 5-ns width. The peak pulse current is then approximately

$$\begin{aligned} I_{\text{peak}} &= 10^9 \text{electrons} \times 1.6 \times 10^{-19} \frac{\text{coulomb}}{\text{electron}} \times \frac{1}{5 \times 10^{-9}\ \text{s}} \\ &= 0.032\ \text{A} = 32\ \text{mA} \end{aligned}$$

Band structure of solids

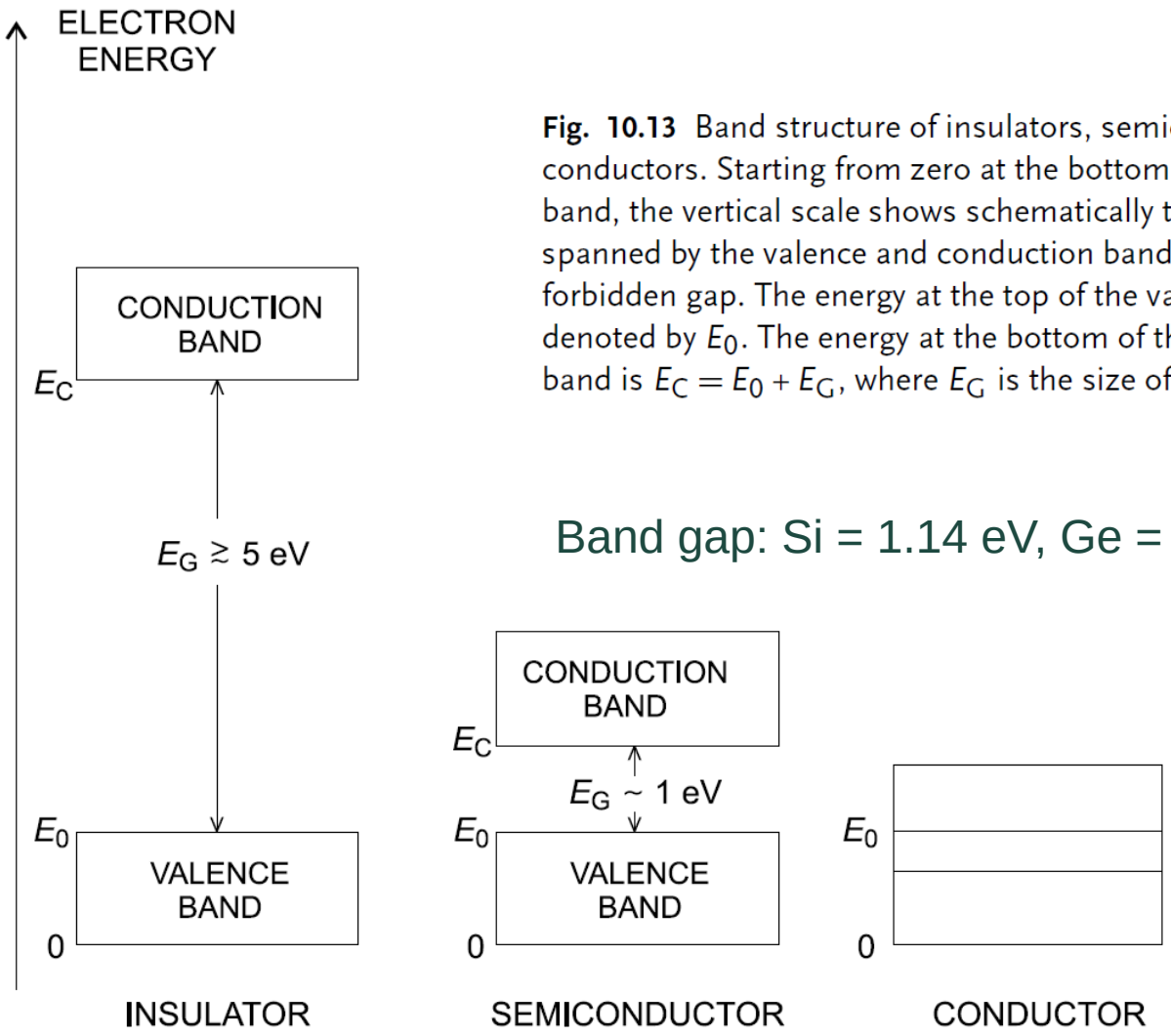
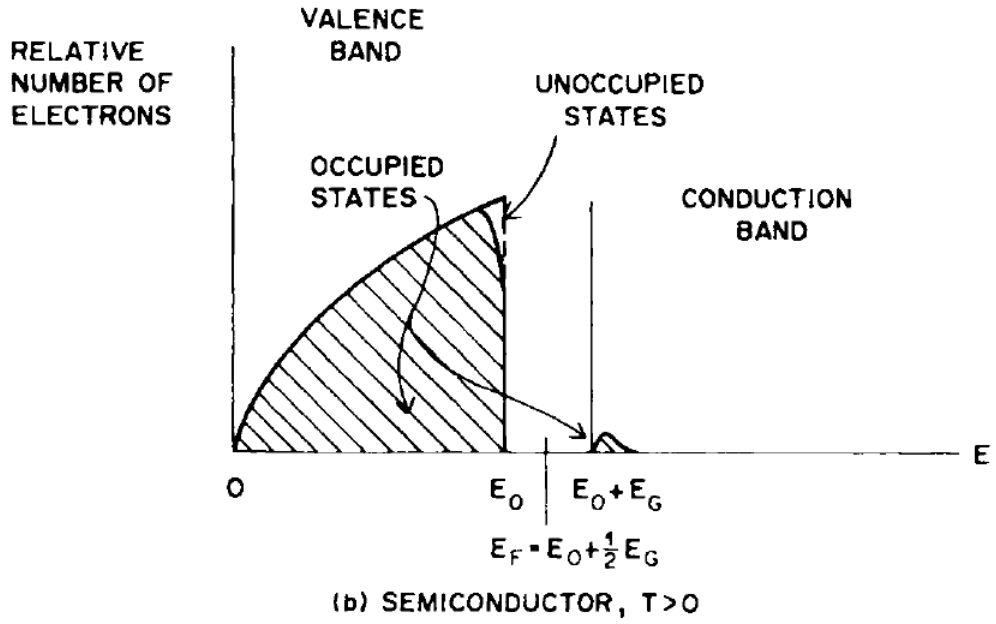


Fig. 10.13 Band structure of insulators, semiconductors, and conductors. Starting from zero at the bottom of the valence band, the vertical scale shows schematically the energies spanned by the valence and conduction bands and the forbidden gap. The energy at the top of the valence band is denoted by E_0. The energy at the bottom of the conduction band is $E_C = E_0 + E_G$, where E_G is the size of the band gap.

Band gap: Si = 1.14 eV, Ge = 0.67 eV

Semiconductor

- The motions of both the conduction-band electrons and the valence-band holes contribute to the observed conductivity.
- Its inherent conductivity at room temperature is restricted by the small number of electron–hole pairs, which, in turn, is limited by the size of the gap compared with kT.



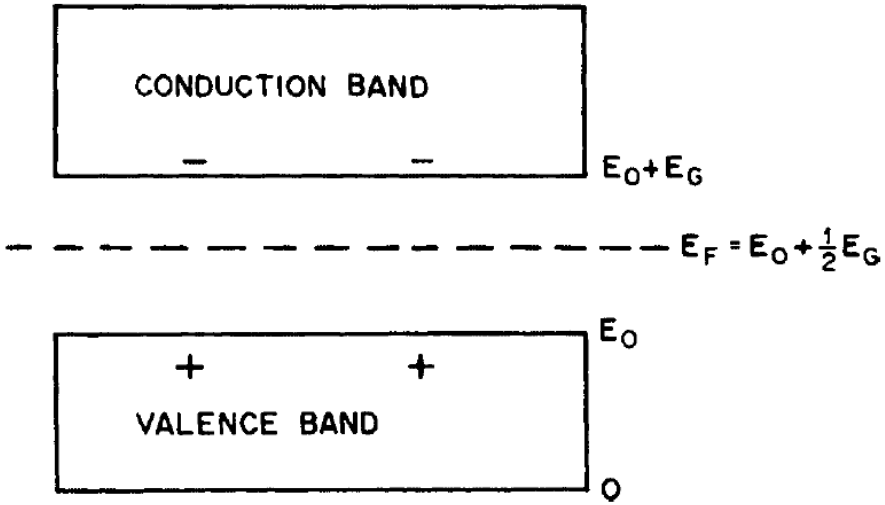


Fig. 10.16 Occupation of energy states in an intrinsic semiconductor at room temperature. A relatively small number of electrons (–) are thermally excited into the conduction band, leaving an equal number of holes (+) in the valence band. The Fermi energy E_F lies at the middle of the forbidden gap.

Semiconductor

- The conductivity of a semiconductor can be greatly enhanced by doping the crystal with atoms from a neighboring group in the periodic system.
- There is no state for the extra electron to occupy in the filled valence band.

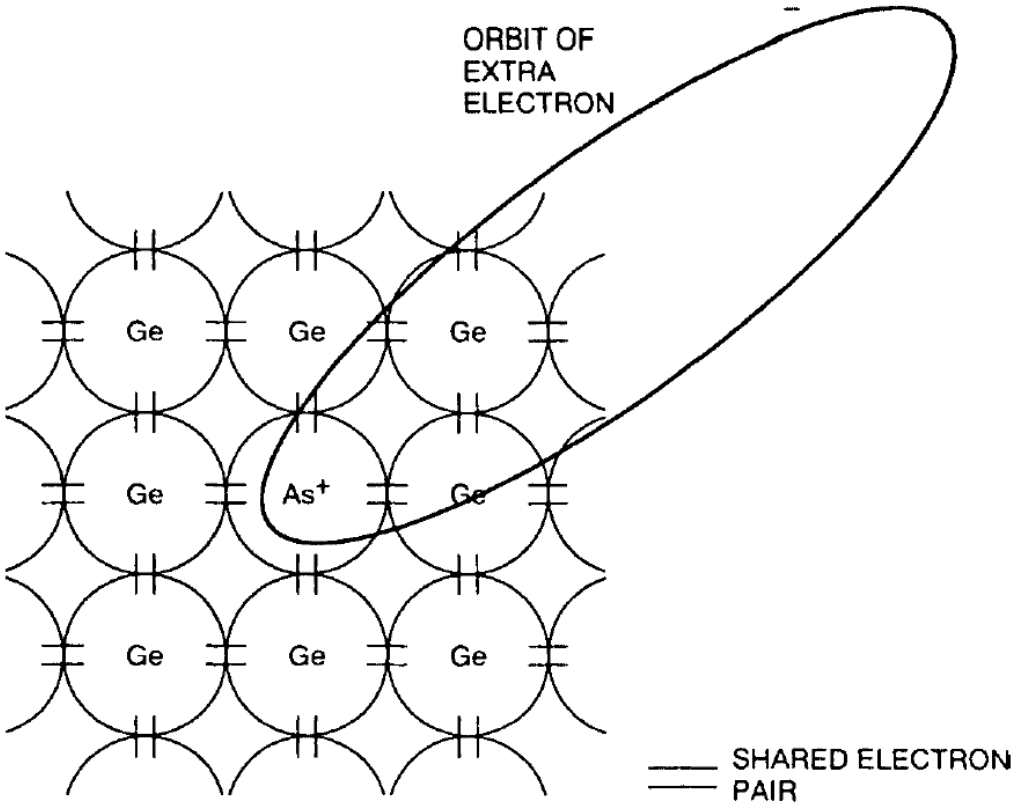


Fig. 10.17 Addition of a small quantity of pentavalent As to Ge crystal lattice provides very loosely bound "extra" electrons that have a high probability of being thermally excited into the conduction band at room temperatures. Arsenic is called a donor impurity and the resulting semiconductor, n-type.

Semiconductor

- Since the extra electron is only very loosely bound to the As^+ ion (its orbit can extend over several tens of atomic diameters), this electron has a high probability of being thermally excited into the conduction band at room temperature. The conductivity of the doped semiconductor is thus greatly increased over its value as an intrinsic semiconductor.

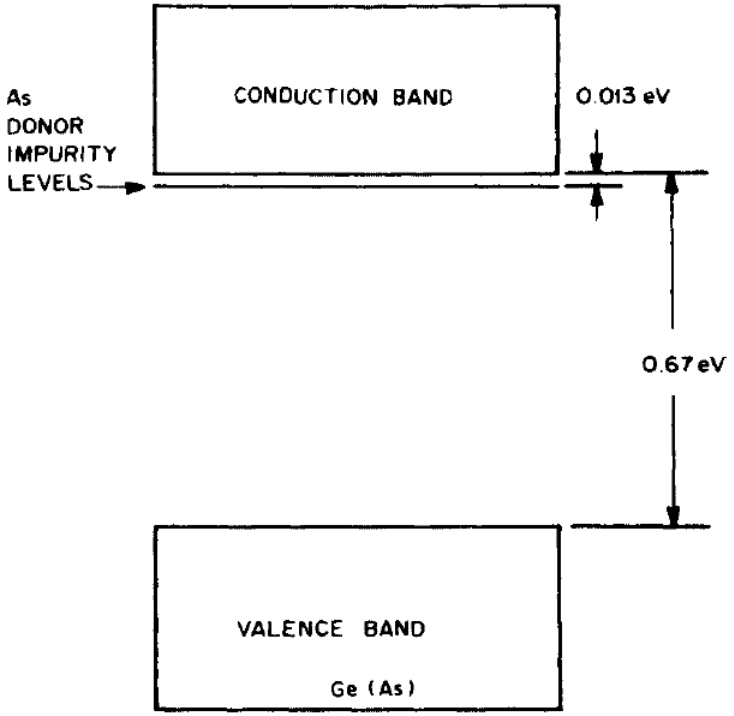


Fig. 10.18 Energy-level diagram for Ge crystal containing As donor atoms (n-type semiconductor).

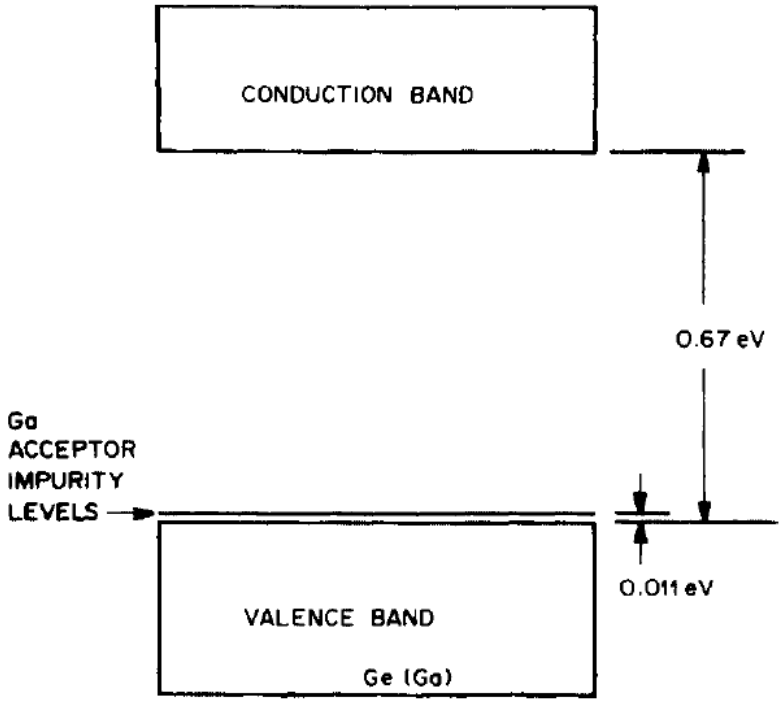


Fig. 10.19 Energy-level diagram for Ge crystal containing Ga acceptor atoms (p-type semiconductor).

Properties of common semiconductor materials

Table 11.1 Properties of Intrinsic Silicon and Germanium

	Si	Ge
Atomic number	14	32
Atomic weight	28.09	72.60
Stable isotope mass numbers	28-29-30	70-72-73-74-76
Density (300 K); g/cm^3	2.33	5.32
Atoms/cm^3	4.96×10^{22}	4.41×10^{22}
Dielectric constant (relative to vacuum)	12	16
Forbidden energy gap (300 K); eV	1.115	0.665
Forbidden energy gap (0 K); eV	1.165	0.746
Intrinsic carrier density (300 K); cm^{-3}	1.5×10^{10}	2.4×10^{13}
Intrinsic resistivity (300 K); $\Omega \cdot cm$	2.3×10^{5}	47
Electron mobility (300 K); $cm^2/V \cdot s$	1350	3900
Hole mobility (300 K); $cm^2/V \cdot s$	480	1900
Electron mobility (77 K); $cm^2/V \cdot s$	2.1×10^{4}	3.6×10^{4}
Hole mobility (77 K); $cm^2/V \cdot s$	1.1×10^{4}	4.2×10^{4}
Energy per electron–hole pair (300 K); eV	3.62	
Energy per electron–hole pair (77 K); eV	3.76	2.96

Pulse formation

- When a particle deposits energy in a semiconductor detector, equal numbers of conduction electrons and holes are formed within a few picoseconds along the particle track. The detector configurations ensure that an electric field is present throughout the active volume, so that both charge carriers feel electrostatic forces that cause them to drift in opposite directions.
- The motion of either the electrons or holes constitutes a current that will persist until those carriers are collected at the boundaries of the active volume.

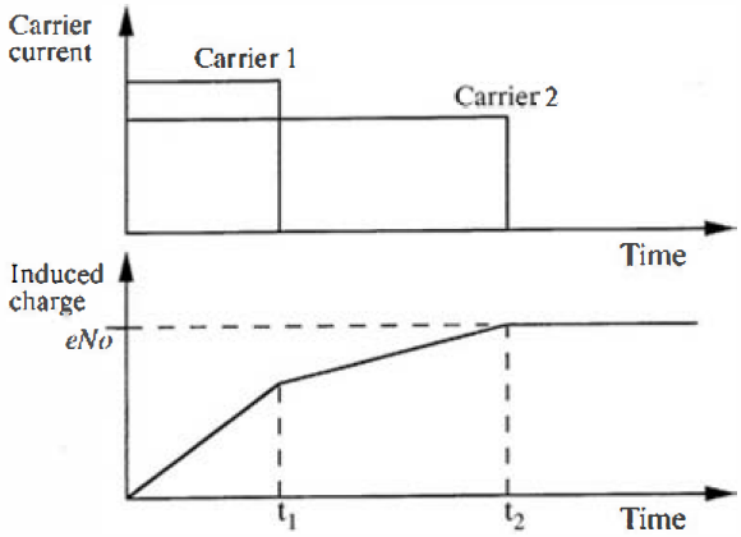


Figure 11.7 The upper plot shows an idealized representation of the electron and hole currents flowing in a semiconductor following the creation of N_0 electron–hole pairs. In the lower plot, t_1 represents the collection time for the carrier type (either electrons or holes) that is collected first, and t_2 is the collection time for the other carrier. If both are fully collected, a charge of eN_0 is induced to form the signal, where e is the electronic charge.

Semiconductor junction

- The junction region over which the charge imbalance occurs is also called the depletion region, because any mobile charges initially there moved out when the two sides were joined.
- The depletion region acts, therefore, like a high-resistivity parallel-plate ionization chamber, making it feasible to use it for radiation detection.

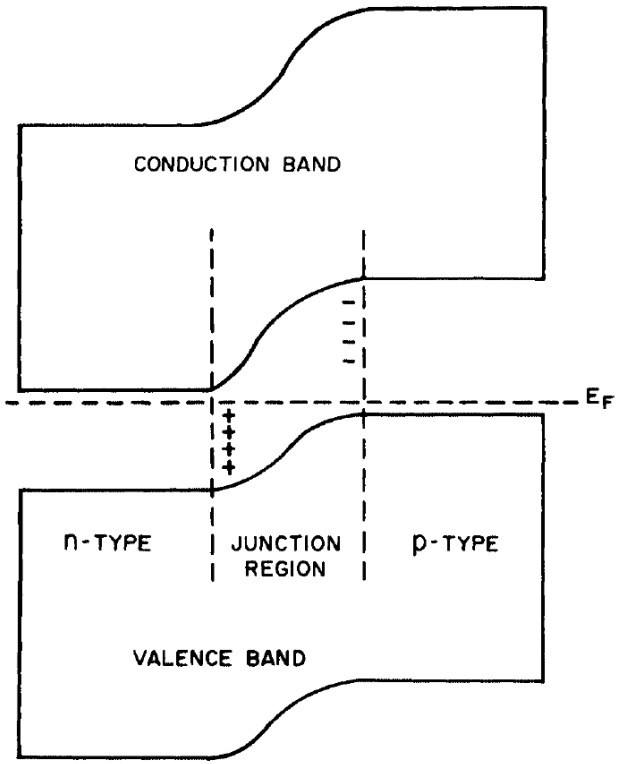
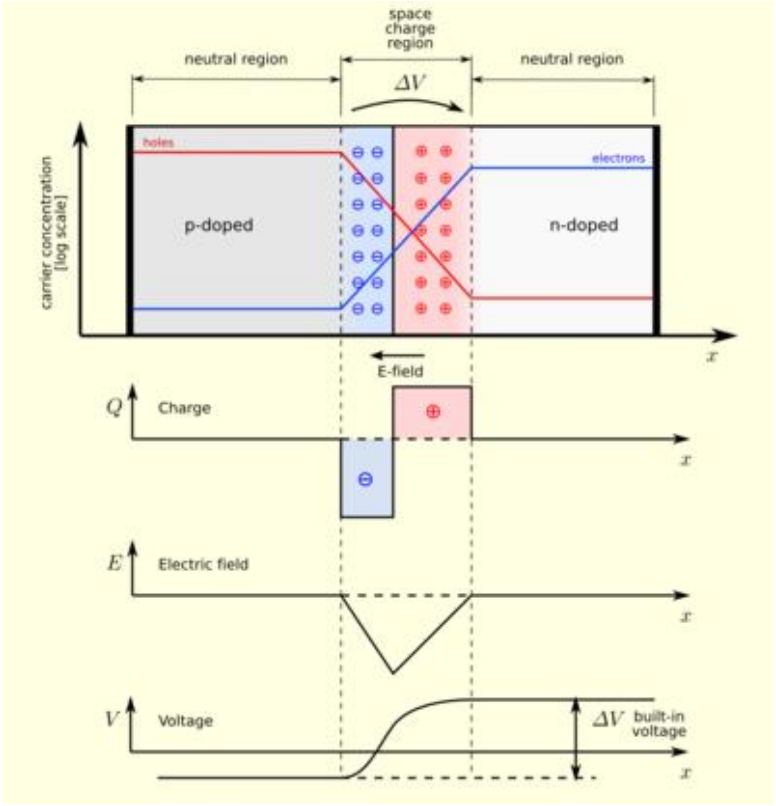


Fig. 10.20 Energy-level diagram for n–p junction.



Semiconductor radiation detector

- The reverse-biased n–p junction constitutes an attractive radiation detector.

- The depletion region, which is the active volume, has high resistivity, and ions produced there by radiation can be collected swiftly and efficiently. It can serve as a rate meter or to analyze pulses.
- The number of electron–hole pairs produced in a pulse is proportional to the energy absorbed in the active volume, and so the junction can be used as a spectrometer.
- The “W values” for Si and Ge are, respectively, 3.6 eV and 3.0 eV per electron–hole pair, as compared with the corresponding figure of ~30 eV per ion pair in gases. → Better energy resolution than other detectors.

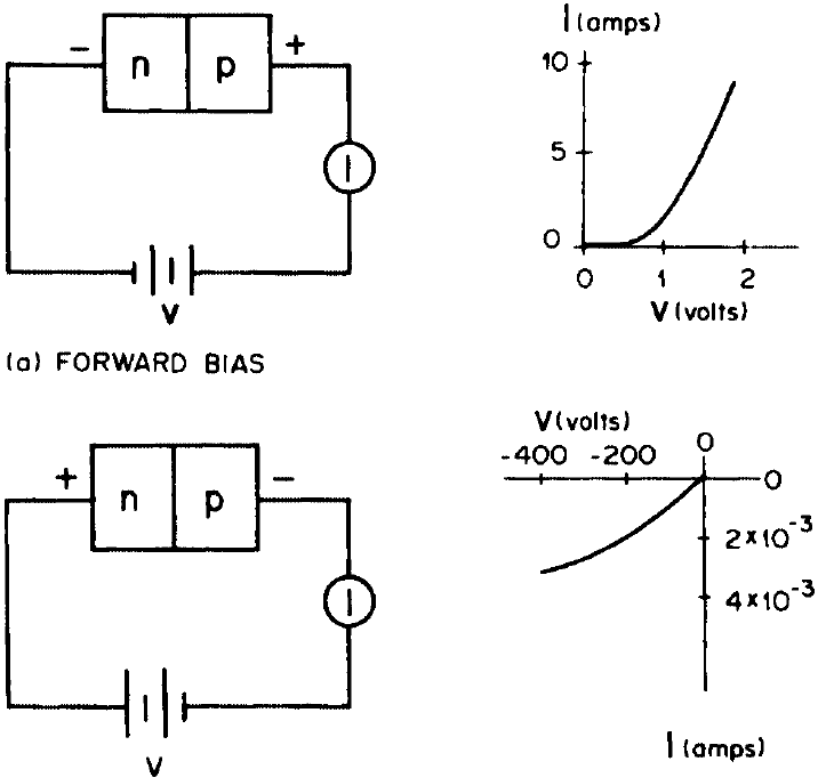
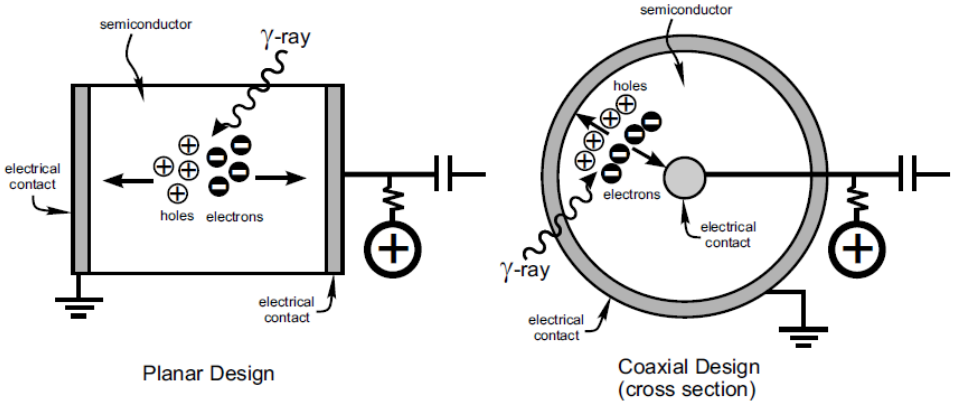
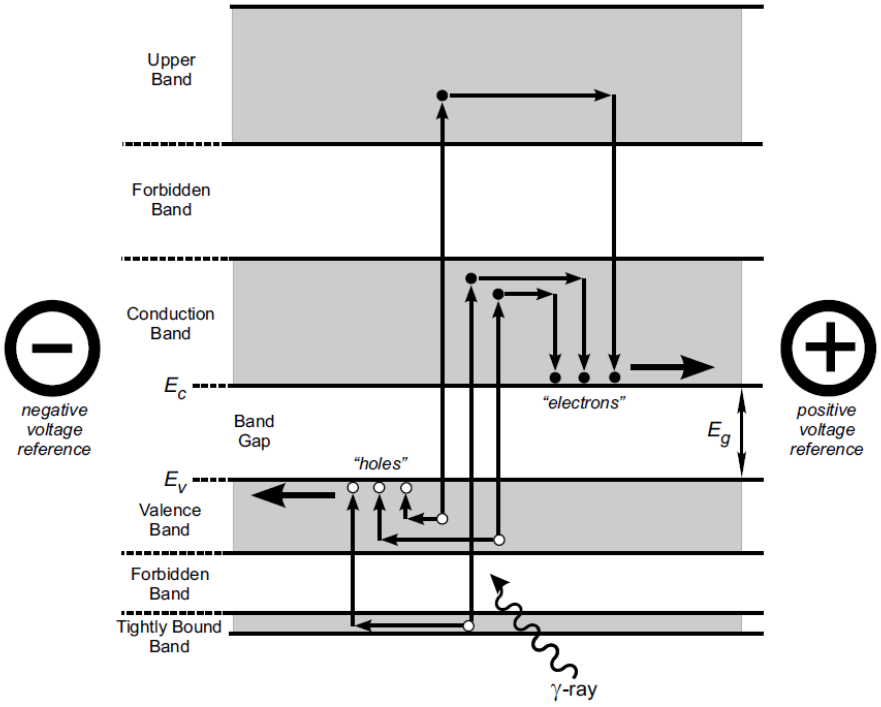


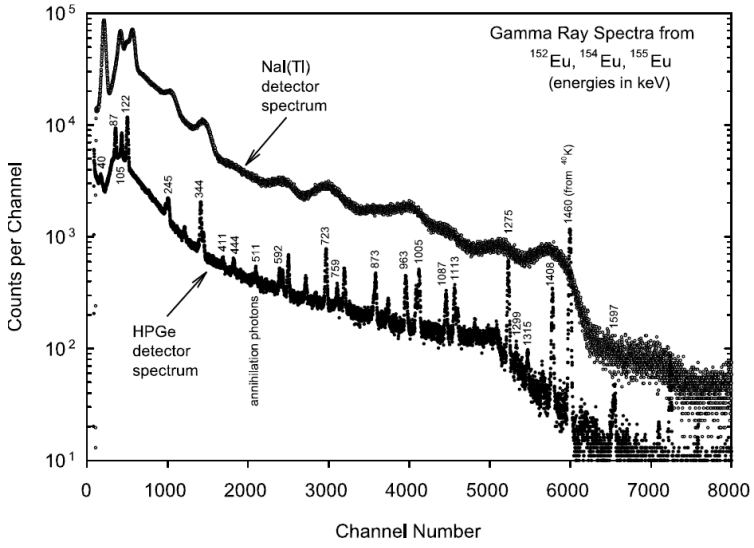
Fig. 10.21 (a) Forward- and (b) reverse-biased n–p junctions and typical curves of current vs. voltage. Note the very different scales used for the two curves. Such an n–p junction is a good rectifier.

Semiconductor detectors

- The operation of a semiconductor detector combines the concepts of the charge excitation method in a crystalline inorganic scintillator and the charge collection method of a gas-filled ion chamber.
- High energy resolution
- High electron-hole pairs ($W_i = 3{\sim}5\ eV$)
- High mobility

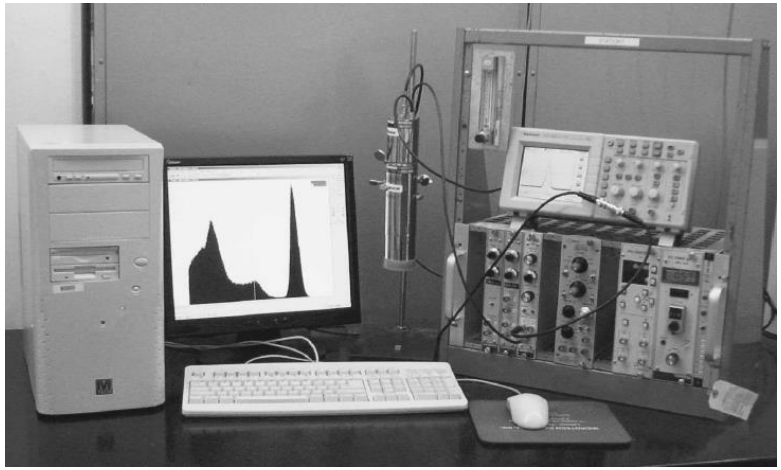


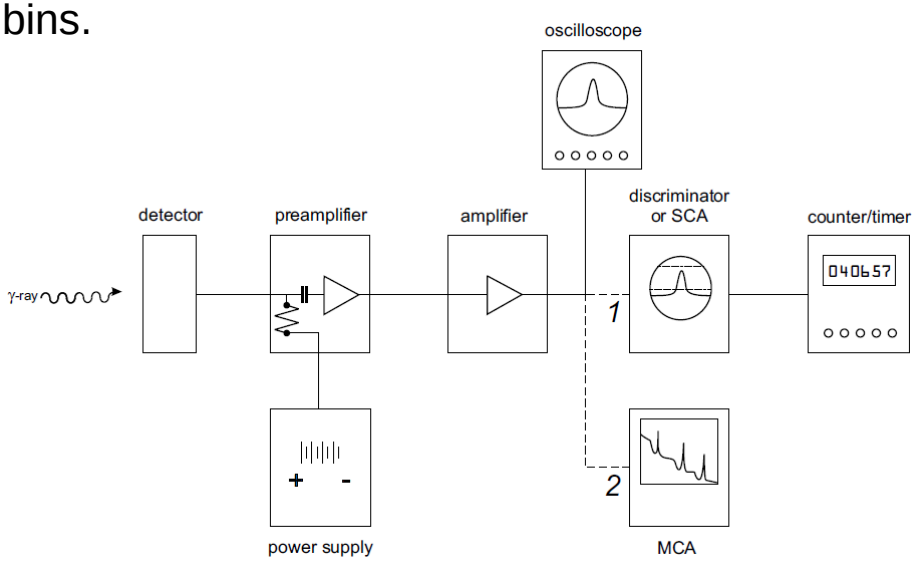




Detection equipment

- Instrumentation for the nuclear industry was standardized in 1969 according to the U.S. Atomic Energy Commission (now the Department of Energy) to what are referred to as Nuclear Instrument Modules (NIM).
- Important components
  - Preamplifier: (1) to provide low noise coupling of the detector to the string of amplifier and readout electronics, and (2) to produce a first stage of signal amplification.
  - Amplifier: (1) pulse shaping and (2) amplification.
  - Discriminator/SCA: passing only pulses of certain voltages that are of interest.
  - Multichannel analyzer (MCA): separates by amplitude (energy) the voltage pulses exiting the amplifier unit into numerous bins.





Homework

- J. Turner, Atoms, Radiation, and Radiation Protection, Wiley (2007), chapter 10

  Problems: 4, 11

- The whole energy of an alpha particle of 6 MeV is absorbed at the center of a parallel-plate gas-filled detector with gap distance of 2 cm and W-value of 30 eV. The mobilities of electrons and ions are $\mu_e = 2\ \mathrm{m^2V^{-1}s^{-1}}$ and $\mu_i = 0.2\ \mathrm{m^2V^{-1}s^{-1}}$, respectively.
  1. Plot the waveforms for current ($i_e(t)$ and $i_i(t)$) and induced charge (indicate the values in the figure) when the applied voltage is 200 V operating in the ion chamber region.
  2. Find the maximum electron current induced in the circuit when the voltage is increased to 1000 V so as to operate in the proportional region with $\alpha = 20\ \mathrm{cm^{-1}}$.