15

Radiation Detectors

Figure 3.41 of Chapter 3 shows a spectrum of the electromagnetic waves. On its left-hand side, there is a region of the γ-radiation. However, this is not the shortest possible length of the electromagnetic waves. In addition, a spontaneous radiation from the matter is not necessarily electromagnetic: There is the so-called nuclear radiation which is the emission of particles from the atomic nuclei. It can be of two types: the charged particles (α and β particles and protons) and uncharged particles, which are the neutrons. Some particles are complex like the α-particles, which are nuclei of helium atoms consisting of two neutrons; other particles are generally simpler, like the β-particles, which are either electrons or positrons. The γ- and X-rays belong to the nuclear type of electromagnetic radiation. In turn, X-rays depending on the wavelengths are divided into hard, soft, and ultrasoft rays. Ionizing radiations are given that name because as they pass through various media which absorb their energy, additional ions, photons, or free radicals are created.

Certain naturally occurring elements are not stable but slowly decompose by throwing away a portion of their nucleus. This is called *radioactivity*. It was discovered in 1896 by Henry Becquerel when he found that uranium atoms ($Z = 92$)[1] give off radiation which fogs photographic plates. In addition to the naturally occurring radioactivity, there are many man-made nuclei which are radioactive. These nuclei are produced in nuclear reactors, which may yield highly unstable elements. Regardless of the sources or ages of radioactive substances, they decay in accordance with the same mathematical law. The law is stated in terms of the number N of nuclei still undecayed and dN, the number of nuclei which decay in a small interval dt. It was proven experimentally that

$$dN = -\lambda N\, dt, \tag{15.1}$$

where λ is a decay constant specific for a given substance. From Eq. (15.1), it can be defined as the fraction of nuclei which decays in unit time:

$$\lambda = -\frac{1}{N}\frac{dN}{dt}. \tag{15.2}$$

[1] Z is the atomic number.

The SI unit of radioactivity is the *becquerel* (Bq) which is equal to the activity of a radionuclide decaying at the rate of one spontaneous transition per second. Thus, the becquerel is expressed in a unit of time: $\text{Bq} = \text{s}^{-1}$. To convert to the old historical unit, the *curie*, the becquerel should be multiplied by 3.7×10^{10} (Table A.4). The absorbed dose is measured in *grays* (Gy). A gray is the absorbed dose when the energy per unit mass imparted to matter by ionizing radiation is 1 joule per kilograms; that is, Gy = J/kg. When it is required to measure exposure to X- and γ-rays, the dose of ionizing radiation is expressed in coulombs per kilogram, which is an exposure resulting in the production of 1 C of electric charge per 1 kg of dry air. In SI, the unit C/kg replaces the older unit *roentgen*.

The function of any radiation detector depends on the manner in which the radiation interacts with the material of the detector itself. There are many excellent texts available on the subject of detecting radioactivity—for instance, Refs. [1] and [2].

There are three general types of radiation detector: the scintillation detector, the gaseous detector, and the semiconductor detector. Further, all detectors can be divided into two groups according to their functionality: the collision detector and the energy detector. The former merely detect the presence of a radioactive particle, whereas the latter can measure the radiative energy; that is, all detectors can be either quantitative or qualitative.

15.1 Scintillating Detectors

The operating principle of these detectors is based on the ability of certain materials to convert nuclear radiation into light. Thus, an optical photon detector in combination with a scintillating material can form a radiation detector. It should be noted, however, that despite the high efficiency of the conversion, the light intensity resulting from the radiation is extremely small. This demands photomultipliers to magnify signals to a detectable level.

The ideal scintillation material should possess the following properties:

1. It should convert the kinetic energy of charged particles into detectable light with a high efficiency.
2. The conversion should be linear; that is, the light produced should be proportional to the input energy over a wide dynamic range.
3. The postluminescence (the light decay time) should be short to allow fast detection.
4. The index of refraction of the material should be near that of glass to allow efficient optical coupling of the light to the photomultiplier tube.

The most widely used scintillators include the inorganic alkali halide crystals (of which sodium iodine is the favorite) and organic-based liquids and plastics. The inorganics are more sensitive, but generally slow, whereas organics are faster, but yield less light.

One of the major limitations of scintillation counters is their relatively poor energy resolution. The sequence of events which leads to the detection involves many

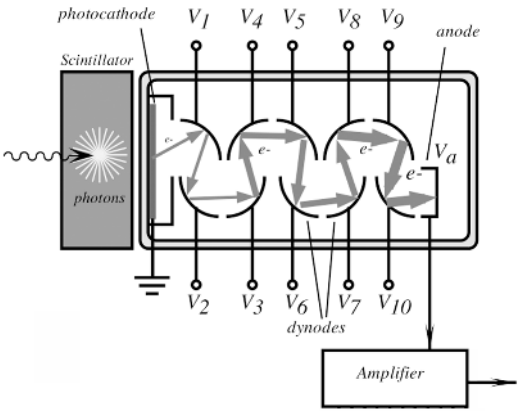

Fig. 15.1. Scintillation detector with a photomultiplier.

inefficient steps. Therefore, the energy required to produce one information carrier (a photoelectron) is on the order of 1000 eV or more, and the number of carriers created in a typical radiation interaction is usually no more than a few thousand. For example, the energy resolution for sodium iodine scintillators is limited to about 6% when detecting 0.662-MeV γ-rays and is largely determined by the photoelectron statistical fluctuations. The only way to reduce the statistical limit on energy resolution is to increase the number of information carriers per pulse. This can be accomplished by the use of semiconductor detectors, which are described in Section 15.2.4.

A general simplified arrangement of a scintillating sensor is shown in Fig. 15.1 in conjunction with a photomultiplier. The scintillator is attached to the front end of the photomultiplier (PM). The front end contains a photocathode which is maintained at a ground potential. There is a large number of special plates called *dynodes* positioned inside the PM tube in an alternating pattern, reminding one of the shape of a "venetian blind." Each dynode is attached to a positive voltage source in a manner that the farther the dynode from the photocathode, the higher is its positive potential. The last component in the tube is an anode, which has the highest positive potential, sometimes on the order of several thousand volts. All components of the PM are enveloped into a glass vacuum tube, which may contain some additional elements, like focusing electrodes, shields, and so forth.

Although the PM is called a photomultiplier, in reality it is an electron multiplier, as there are no photons, only electrons inside the PM tube during its operation. For the illustration, let us assume that a γ-ray particle has a kinetic energy of 0.5 MeV (megaelectron volt). It is deposited on the scintillating crystal resulting in a number of liberated photons. In thallium-activated sodium iodine, the scintillating efficiency is about 13%, therefore, a total of $0.5 \times 0.13 = 0.065$ MeV, or 65 keV, of energy is converted into visible light with an average energy of 4 eV. Therefore, about 15,000 scintillating photons are produced per gamma pulse. This number is too small to be detected by an ordinary photodetector; hence, a multiplication effect is required before the actual detection takes place. Of the 15,000 photons, probably about 10,000 reach the photocathode, whose quantum efficiency is about 20%. The photocathode serves to

convert incident light photons into low-energy electrons. Therefore, the photocathode produces about 2000 electrons per pulse. The PM tube is a linear device; that is, its gain is almost independent of the number of multiplied electrons.

Because all dynodes are at positive potentials (V_1 to V_{10}), an electron released from the photocathode is attracted to the first dynode, liberating several very low energy electrons at impact with its surface. Thus, a multiplication effect takes place at the dynode. These electrons will be easily guided by the electrostatic field from the first to the second dynode. They strike the second dynode and produce more electrons which travel to the third dynode, and so on. The process results in an increasing number of available electrons (avalanche effect). An overall multiplication ability of a PM tube is in the order of 10^6. As a result, about 2×10^9 electrons will be available at a high voltage anode (V_a) for the production of electric current. This is a very strong electric current which can be easily processed by an electronic circuit. A gain of a PM tube is defined as

$$G = \alpha \delta^N, \tag{15.3}$$

where N is the number of dynodes, α is the fraction of electrons collected by the PM tube, and δ is the efficiency of the dynode material (i.e., the number of electrons liberated at impact). Its value ranges from 5 to 55 for a high yield dynode. The gain is sensitive to the applied high voltage, because δ is almost a linear function of the interdynode voltage.

A new design of a photomultiplier is called the channel photomultiplier or CPM for short. It is the evolution of the classical photomultiplier tube. The modern CPM technology preserves the advantages of the classical PM while avoiding its disadvantages. Figure 15.2A shows the face plate with a photocathode, the bent channel amplification structure, and the anode. As in the PM of Fig. 15.1, photons in the CPM are converted inside the photocathode into photoelectrons and accelerated in a vacuum toward the anode by an electrical field. Instead of the complicated dynode structure, there is a bent, thin semiconductive channel which the electrons have to pass. Each time the electrons hit the wall of the channel, secondary electrons are

Fig. 15.2. Channel photomultiplier: cross-sectional view (A) and external view with potted encapsulation at left and without encapsulation at right (B). (Courtesy of Perkin-Elmer, Inc.)

emitted from the surface. At each collision, there is a multiplication of the secondary electrons resulting in an avalanche effect. Ultimately, an electron multiplication of 10^9 and more can be obtained. The resulting current can be read out at the anode. The CPM detector is potted with encapsulation material and is quite rugged compared to the fragile PM. Magnetic field disturbance is negligibly small. Figure 15.2B illustrates the CPM: on the left is a potted structure and on the right is the unpotted structure. An important advantage of the CPM technology is its very low background noise. The term "background noise" refers to the measured output signal in the absence of any incident light. With classical PMs, the background noise originating from the dynode structure is generally a non-negligible part of the total background. As a result the only effective source of background for the CPM is generated from the thermal emission of the photocathode. Because the CPM is manufactured in a monolithic semiconductive channel structure, no charge-up effects might occur as known from classical PMs with isolating glass bulbs. As a result, extremely stable background conditions are observed. No sudden bursts occur. Also, due to the absence of dynode noise, a very clean separation between an event created from a photoelectron and electronic noise can be performed. This leads into a high stability of the signal over time.

15.2 Ionization Detectors

These detectors rely on the ability of some gaseous and solid materials to produce ion pairs in response to the ionization radiation. Then, positive and negative ions can be separated in an electrostatic field and measured.

Ionization happens because upon passing at a high velocity through an atom, charged particles can produce sufficient electromagnetic forces, resulting in the separation of electrons, thus creating ions. Remarkably, the same particle can produce multiple ion pairs before its energy is expended. Uncharged particles (like neutrons) can produce ion pairs at collision with the nuclei.

15.2.1 Ionization Chambers

These radiation detectors are the oldest and most widely used. The ionizing particle causes ionization and excitation of gas molecules along its passing track. As a minimum, the particle must transfer an amount of energy equal to the ionization energy of the gas molecule to permit the ionization process to occur. In most gasses of interest for radiation detection, the ionization energy for the least tightly bound electron shells is between 10 and 20 eV [2]. However, there are other mechanisms by which the incident particle may lose energy within gas that do not create ions (e.g., moving gas electrons to a higher energy level without removing it). Therefore, the average energy lost by a particle per ion pair formed (called the *W value*) is always greater than the ionizing energy. The W value depends on the gas (Table 15.1), the type of radiation, and its energy.

In the presence of an electric field, the drift of the positive and negative charges represented by the ions end electrons constitutes an electric current. In a given volume

Table 15.1. W Values for Different Gases

	W Value (in eV/Ion Pair)	
Gas	Fast electrons	Alphas
A	27.0	25.9
He	32.5	31.7
N_2	35.8	36.0
Air	35.0	35.2
CH_4	30.2	29.0

Source: Ref. [2].

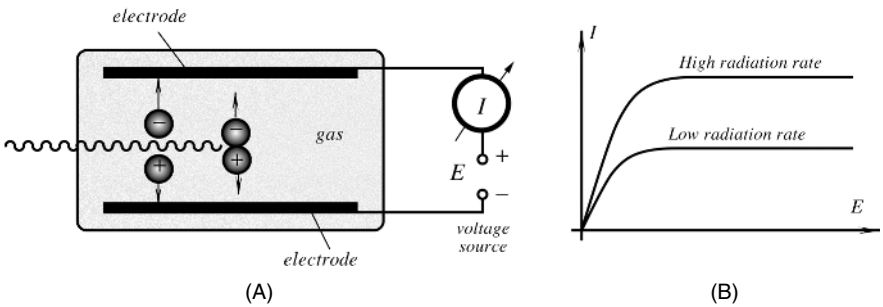

Fig. 15.3. Simplified schematic of an ionization chamber (A) and a current versus voltage characteristic (B).

of gas, the rate of the formation of the ion pair is constant. For any small volume of gas, the rate of formation will be exactly balanced by the rate at which ion pairs are lost from the volume, either through recombination or by diffusion or migration from the volume. If recombination is negligible and all charges are effectively collected, the steady-state current produced is an accurate measure of the rate of ion-pair formation. Figure 15.3 illustrates a basic structure of an ionizing chamber and the current versus voltage characteristic. A volume of gas is enclosed between the electrodes which produce an electric field. An electric current meter is attached in series with the voltage source E and the electrodes. There is no electrical conduction and no current under the no-ionization conditions. Incoming radiation produces, in the gas, positive and negative ions which are pulled by the electric field toward the corresponding electrodes, forming an electric current. The current versus voltage characteristic of the chamber is shown in Fig. 15.3B. At relatively low voltages, the ion recombination rate is strong and the output current is proportional to the applied voltage, because the higher voltage reduces the number of recombined ions. A sufficiently strong voltage completely suppress all recombinations by pulling all available ions toward the electrodes and the current becomes voltage independent. However, it still depends on the intensity of irradiation. This is the region called *saturation* and where the ionization chamber normally operates.

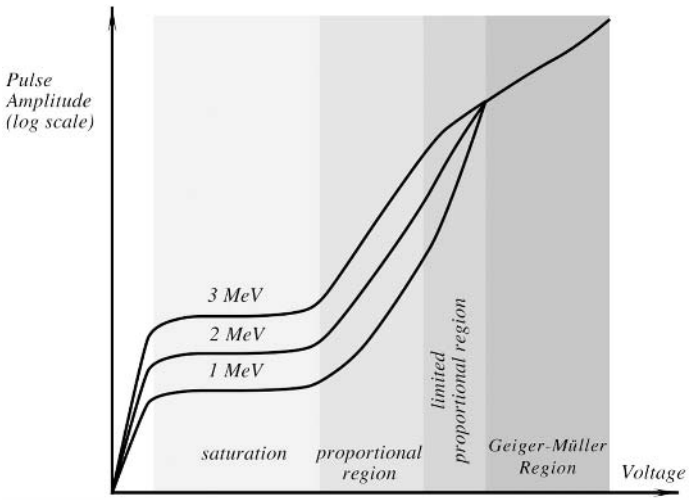

Fig. 15.4. Various operating voltages for gas-filled detectors. (Adapted from Ref. [2].)

15.2.2 Proportional Chambers

The proportional chamber is a type of a gas-filled detector which almost always operates in a pulse mode and relies on the phenomenon of gas multiplication. This is why these chambers are called the proportional counters. Due to gas multiplication, the output pulses are much stronger than in conventional ion chambers. These counters are generally employed in the detection and spectroscopy of low-energy X-radiation and for the detection of neutrons. Contrary to the ionization chambers, the proportional counters operate at higher electric fields which can greatly accelerate electrons liberated during the collision. If these electrons gain sufficient energy, they may ionize a neutral gas molecule, thus creating an additional ion pair. Hence, the process is of an avalanche type, resulting in a substantial increase in the electrode current. The name for this process is the Townsend avalanche. In the proportional counter, the avalanche process ends when the electron collides with the anode. Because in the proportional counter, the electron must reach the gas ionization level, there is a threshold voltage after which the avalanche process occurs. In typical gases at atmospheric pressure, the threshold field level is on the order of 10^6 V/m.

Differences between various gas counters are illustrated in Fig. 15.4. At very low voltages, the field is insufficient to prevent the recombination of ion pairs. In the saturation level, all ions drift to the electrodes. A further increase in voltage results in gas multiplication. Over some region of the electric field, the gas multiplication will be linear, and the collected charge will be proportional to the number of original ion pairs created during the ionization collision. An even further increase in the applied voltage can introduce nonlinear effects, which are related to the positive ions, due to their slow velocity.

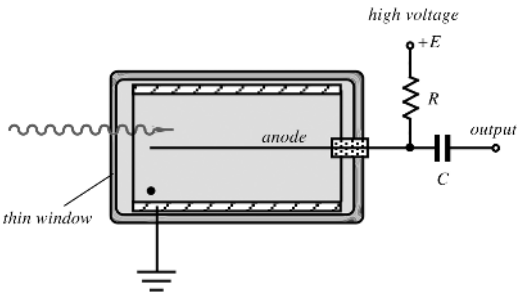

Fig. 15.5. Circuit of a Geiger–Müller counter. The symbol • indicates gas.

15.2.3 Geiger–Müller Counters

The Geiger–Müller(G-M) counter was invented in 1928 and is still in use because of its simplicity, low cost, and ease of operation. The G-M counter is different from other ion chambers by its much higher applied voltage (Fig. 15.4). In the region of the G-M operation, the output pulse amplitude does not depend on the energy of ionizing radiation and is strictly a function of the applied voltage. A G-M counter is usually fabricated in the form of a tube with an anode wire in the center (Fig. 15.5). The tube is filled with a noble gas, such as helium or argon. A secondary component is usually added to the gas for the purpose of *quenching*, which prevents the retriggering of the counter after the detection. The retriggering may cause multiple pulses instead of the desired one. The quenching can be accomplished by several methods, among which are a short-time reduction of the high voltage applied to the tube, use of high-impedance resistors in series with the anode, and the addition of the quench gas at concentrations of 5–10%. Many organic molecules possess the proper characteristics to serve as a quench gas. Of these, ethyl alcohol and ethyl formate have proven to be the most popular.

In a typical avalanche created by a single original electron, secondary ions are created. In addition to them, many excited gas molecules are formed. Within a few nanoseconds, these excited molecules return to their original state through the emission of energy in the form of ultraviolet (UV) photons. These photons play an important role in the chain reaction occurring in the G-M counter. When one of the UV photons interacts by photoelectric absorption in some other region of the gas, or at the cathode surface, a new electron is liberated which can subsequently migrate toward the anode and will trigger another avalanche. In a Geiger discharge, the rapid propagation of the chain reaction leads to many avalanches which initiate, at random, radial and axial positions throughout the tube. Secondary ions are therefore formed throughout the cylindrical multiplying region which surrounds the anode wire. Hence, the discharge grows to envelop the entire anode wire, regardless of the position at which the primary initiating event occurred.

Once the Geiger discharge reaches a certain level, however, collective effects of all individual avalanches come into play and ultimately terminate the chain reaction. This point depends on the number of avalanches and not on the energy of the initiating

particle. Thus, the G-M current pulse is always of the same amplitude, which makes the G-M counter just an indicator of irradiation, because all information on the ionizing energy is lost.

In the G-M counter, a single particle of a sufficient energy can create about 10^9–10^{10} ion pairs. Because a single ion pair formed within the gas of the G-M counter can trigger a full Geiger discharge, the counting efficiency for any charged particle that enters the tube is essentially 100%. However, the G-M counters are seldom used for counting neutrons because of a very low efficiency of counting. The efficiency of G-M counters for γ-rays is higher for those tubes constructed with a cathode wall of high-Z material. For instance, bismuth ($Z = 83$) cathodes have been widely used for the γ-detection in conjunction with gases of high atomic numbers, such as xenon and krypton, which yield a counting efficiency up to 100% for photon energies below about 10 keV.

15.2.4 Semiconductor Detectors

The best energy resolution in modern radiation detectors can be achieved in semiconductor materials, where a comparatively large number of carriers for a given incident radiation event occurs. In these materials, the basic information carriers are *electron–hole pairs* created along the path taken by the charged particle through the detector. The charged particle can be either primary radiation or a secondary particle. The electron–hole pairs in some respects are analogous to the ion pairs produced in the gas-filled detectors. When an external electric field is applied to the semiconductive material, the created carriers form a measurable electric current. The detectors operating on this principle are called a solid-state or semiconductor diode detectors. The operating principle of these radiation detectors is the same as that of the semiconductor light detectors. It is based on the transition of electrons from one energy level to another when they gain or lose energy. For the introduction to the energy-band structure in solids the reader should refer to Section 14.1 of Chapter 14.

When a charged particle passes through a semiconductor with the band structure shown in Fig. 14.1 of Chapter 14, the overall significant effect is the production of many electron–hole pairs along the track of the particle. The production process may be either direct or indirect, in that the particle produces high-energy electrons (or Δ rays) which subsequently lose their energy in production more electron–hole pairs. Regardless of the actual mechanism involved, what is of interest to our subject is that the average energy expended by the primary charged particle produces one electron–hole pair. This quantity is often called the "ionization energy." The major advantage of semiconductor detectors lies in the smallness of the ionization energy. Its value for silicon or germanium is about 3 eV, compared with 30 eV required to create an ion pair in typical gas-filled detectors. Thus, the number of charge carriers is about 10 times greater for the solid-state detectors for a given energy of a measured radiation.

To fabricate a solid-state detector, at least two contacts must be formed across a semiconductor material. For detection, the contacts are connected to the voltage source, which enables carrier movement. The use of a homogeneous Ge or Si, however, would be totally impractical. The reason for that is in an excessively high leakage

current caused by the material's relatively low resistivity (50 kΩ cm for silicon). When applied to the terminals of such a detector, the external voltage may cause a current which is three to five orders of magnitude greater than a minute radiation-induced electric current. Thus, the detectors are fabricated with the blocking junctions, which are reverse biased to dramatically reduce leakage current. In effect, the detector is a semiconductor diode which readily conducts (has low resistivity) when its anode (p side of a junction) is connected to a positive terminal of a voltage source and the cathode (an n side of the junction) to the negative. The diode conducts very little (it has very high resistivity) when the connection is reversed; thus, the name reverse biasing is implied. If the reverse bias is made very large (in excess of the manufacturer specified limit), the reverse leakage current abruptly increases (the breakdown effect), which often may lead to a catastrophic deterioration of detecting properties or to the device destruction.

Several configurations of silicon diodes are currently produced; among them are diffused junction diodes, surface-barrier diodes, ion-implanted detectors, epitaxial layer detectors, and others. The diffused junction and surface-barrier detectors find widespread applications for the detection of α-particles and other short-range radiation. A good solid-state radiation detector should possess the following properties:

1. Excellent charge transport
2. Linearity between the energy of the incident radiation and the number of electron–hole pairs
3. Absence of free charges (low leakage current)
4. Production of a maximum number of electron–hole pairs per unit of radiation
5. High detection efficiency
6. Fast response speed
7. Large collection area
8. Low cost

When using semiconductor detectors, several factors should be seriously considered. Among them are the dead-band layer of the detector and the possible radiation damage. If heavy charged particles or other weakly penetrating radiations enter the detector, there may be a significant energy loss before the particle reaches the active volume of the semiconductor. The energy can be lost in the metallic electrode and in a relatively thick silicon body immediately beneath the electrode. This thickness must be measured directly by the user if an accurate compensation is desirable. The simplest and most frequently used technique is to vary the angle of incidence of a monoenergetic charged particle radiation [2]. When the angle of incidence is zero (i.e., perpendicular to the detector's surface), the energy loss in the dead layer is given by

$$\Delta E_0 = \frac{dE_0}{dx} t, \tag{15.4}$$

where t is the thickness of the dead layer. The energy loss for an angle of incidence of Θ is

$$\Delta E(\theta) = \frac{\Delta E_0}{\cos\theta}. \tag{15.5}$$

Therefore, the difference between the measured pulse height for angles of incidence of zero and Θ is given by

$$E' = [E_0 - \Delta E_0] - [E_0 - \Delta E(\theta)] = \Delta E_0 \left(\frac{1}{\cos\theta} - 1 \right). \tag{15.6}$$

If a series of measurements is made as the angle of incidence is varied, a plot of E' as a function of $(1/\cos\Theta) - 1$ should be a straight line whose slope is equal to ΔE_0. Using tabular data for dE_0/dx for the incident radiation, the dead-layer thickness can be calculated from Eq. (15.4).

Any excessive use of the detectors may lead to some damage to the lattice of the crystalline structure, due to disruptive effects of the radiation being measured as it passes through the crystal. These effects tend to be relatively minor for lightly ionizing radiation (β-particles or γ-rays), but they can become quite significant under typical conditions of use for heavy particles. For example, prolonged exposure of silicon surface-barrier detectors to fusion fragments will lead to a measurable increase in leakage current and a significant loss in energy resolution of the detector. With extreme radiation damage, multiple peaks may appear in the pulse height spectrum recorded for monoenergetic particles.

As mentioned earlier, diffused junction diodes and surface-barrier diodes are not quite suitable for the detection of penetrating radiation. The major limitation is in the shallow active volume of these sensors, which rarely can exceed 2–3 mm. This is not nearly enough, for instance, for γ-ray spectroscopy. A practical method to make detectors for a more penetrating radiation is the so-called ion-drifting process. The approach consists of creating a thick region with a balanced number of donor impurities, which add either p or n properties to the material. Under ideal conditions, when the balance is perfect, the bulk material would resemble the pure (intrinsic) semiconductor without either properties. However, in reality, the perfect pn balance never can be achieved. In Si or Ge, the pure material with the highest possible purity tends to be of p type. To accomplish the desired compensation, the donor atoms must be added. The most practical compensation donor is lithium. The fabrication process involves a diffusing of lithium though the p crystal so that the lithium donors greatly outnumber the original acceptors, creating an n-type region near the exposed surface. Then, temperature is elevated and the junction is reverse biased. This results in a slow drifting of lithium donors into the p type for the near-perfect compensation of the original impurity. The process may take as long as several weeks. To preserve the achieved balance, the detector must be maintained at low temperature: 77K for the germanium detectors. Silicon has very low ion mobility; thus, the detector can be stored and operated at room temperature. However, the lower atomic number for silicon ($Z = 14$) as compared with germanium ($Z = 32$) means that the efficiency of silicon for the detection of γ-rays is very low and it is not widely used in general γ-ray spectroscopy.

A simplified schematic of a lithium-drifted detector is shown in Fig. 15.6A. It consists of three regions; the "intrinsic" crystal is in the middle. In order to create detectors of a larger active volume, the shape can be formed as a cylinder (Fig. 15.6B),

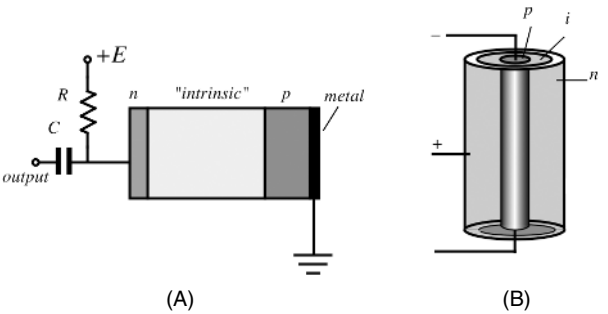

Fig. 15.6. Lithium-drifted PIN junction detector: (A) structure of the detector; (B) coaxial configuration of the detector.

Table 15.2. Detecting Properties of Some Semiconductive Materials

Material (Operating Temperature in K)	Z	Band Gap (eV)	Energy per Electron–Hole Pair, (eV)
Si (300)	14	1.12	3.61
Ge (77)	32	0.74	2.98
CdTe (300)	48–52	1.47	4.43
HgI_2 (300)	80–53	2.13	6.5
GaAs (300)	31–33	1.43	4.2

Source: Ref. [2].

where the active volumes of Ge up to 150 cm^3 can be realized. The germanium lithium-drifted detectors are designated Ge(Li).

Regardless of the widespread popularity of the silicon and germanium detectors, they are not the ideal from certain standpoints. For instance, germanium must always be operated at cryogenic temperatures to reduce thermally generated leakage current, and silicon is not efficient for the detection of γ-rays. There are some other semiconductors that are quite useful for detection of radiation at room temperatures. Among them are cadmium telluride (CdTe), mercuric iodine (HgI_2), gallium arsenide (GaAs), bismuth trisulfide (Bi_2S_3), and gallium selenide (GaSe). Useful radiation detector properties of some semiconductive materials are given in Table 15.2.

Probably the most popular at the time of this writing is cadmium telluride, which combines a relatively high Z-value (48 and 52) with a large enough band-gap energy (1.47 eV) to permit room-temperature operation. Crystals of high purity can be grown from CdTe to fabricate the intrinsic detector. Alternatively, chlorine doping is occasionally used to compensate for the excess of acceptors and to make the material a near-intrinsic type. Commercially available CdTe detectors range in size from 1 to 50 mm in diameter and can be routinely operated at temperatures up to 50°C without an excessive increase in noise. Thus, there are two types of CdTe detector available:

the pure intrinsic type and the doped type. The former has a high-volume resistivity up to $10^{10}\Omega$ cm, however, its energy resolution is not that high. The doped type has significantly better energy resolution; however, its lower resistivity ($10^{8}\Omega$ cm) leads to a higher leakage current. In addition, these detectors are prone to polarization, which may significantly degrade their performance.

In the solid-state detectors, it is also possible to achieve a multiplication effect as in the gas-filled detectors. An analog of a proportional detector is called an *avalanche detector*, which is useful for the monitoring of low-energy radiation. The gain of such a detector is usually in the range of several hundreds. It is achieved by creating high-level electric fields within a semiconductor. Also, the radiation PSDs are available whose operating principle is analogous to similar sensors functioning in the near-infrared region (see Section 7.5.6 of Chapter 7).

References

1. Evans, R.D. *The Atomic Nucleus*. McGraw-Hill, New York, 1955.
2. Knoll, G.F. *Radiation Detection and Measurement*. 3rd ed., John Wiley & Sons, New York, 1999.