RADIATION DETECTION

Of all the available sensors for detecting radiation, solid-state radiation detectors have always had the most aesthetic appeal. In principle, they provide the most sensitivity per unit volume, the most flexibility in packaging, and the most efficient conversion of ionizing radiation into electric signals suitable for measurement with modern instrumentation.

Traditionally, solid-state detectors were defined as sensors made from semiconductor materials in which the electronic charge produced by ionizing was collected with an electric field and amplified by external electronics for interpretation. More recently, this class of detectors has been expanded to include combinations of scintillator materials with solid-state photodetectors as contrasted with sensors relying on vacuum tube optical detectors such as photomultiplier tubes.

Until 25 years ago, the only solid-state detectors of importance were those made of germanium or silicon. Since that time, however, progress has been made in many other materials and the list now includes such materials as CdTe, CdZnTe, PbI_2, and HgI_2, as well as scintillation-based sensors combined with silicon *p–i–n* photodiodes, silicon avalanche photodiodes, HgI_2 photodiodes, PbI_2 photodiodes, and amorphous silicon photodiode arrays.

This article will review some of the mechanisms by which ionizing radiation interacts with matter, how these interactions are converted to electrical signals within the various types of solid-state sensors, the properties of many of the more common solid-state nuclear detectors, and a comparison of their properties as it relates to choosing among them for a particular application. More traditional radiation detectors, such as Geiger tubes and ion chambers, as well as important specialized detector systems, such as particle spectrometers, are addressed separately in other articles of this encyclopedia.

INTERACTIONS OF IONIZING RADIATION WITH MATTER

The major forms of ionizing radiation are X rays, gamma rays, charged particles, and neutrons. X rays and gamma rays are both electromagnetic radiation (photons) that differ only in their origination. X rays originate from transitions of electrons in the orbits of atoms, while gamma rays originate from transitions taking place within the nucleus. Charged particles include electrons or beta particles (electrons that originate from events in the nucleus), positrons, protons, alpha particles, fission fragments, and ions.

Ionizing radiation deposits energy in matter through several different sets of mechanisms of interaction, each of which is characteristic of the type of ionizing radiation involved. For the most common class of ionizing radiation, the high-energy photons (X rays and gamma rays), there are three primary mechanisms of interactions: photoelectric absorption, Compton scattering, and pair production. In each of these interactions, the photon loses all or part of its energy to a free or orbital electron, causing the electron to move through the material at high speed and transfer its newly found energy to other species in the solid. Each of these mechanisms is dominant over a different range of photon energy, the exact range being determined in part by the atomic number of the material. In general, the photoelectric effect is most probable at energies below about 100 keV, the Compton effect is dominant at energies between 100 keV and 2 MeV, and pair production is dominant for all higher energies.

In a photoelectric event, the photon loses all of its energy to an atomic electron (usually in the *K* shell) which is ejected from the atom. The energy of the ejected electron will be the energy of the incoming photon (E_{e^-}) minus the binding energy of the electron (E_b):

$$E_{e^-} = h\nu - E_b \tag{1}$$

The ion left behind is left with a vacancy in a low orbital that is quickly filled by capturing a free electron from the medium or by rearrangement of the atom's electrons. This process results in the emission of one or more of the characteristic X rays of the material. The X ray may be reabsorbed by another photoelectric event or may escape from the material. The probability of a photon undergoing a photoelectric event, φ, is a strong function of both energy and atomic number, Z, as follows:

$$\varphi \propto Z^n/E^3 \tag{2}$$

where n varies from 4 to 5 depending on the energy. This strong dependence on Z is the reason why high-Z materials are preferred for shielding and for use in detector materials.

In Compton scattering, the photon loses only a portion of its energy to the electron, resulting in the release of both an energetic electron and a photon of lower energy. The energy of the scattered photon, $h\nu'$, depends specifically on both the energy of the incident photon and the angle of the scattered photon (θ) as follows:

$$h\nu' = \frac{h\nu}{1 + (h\nu/m_0c^2)(1 + \cos\theta)} \tag{3}$$

where m_0c^2 is the rest mass of the electron (511 keV). The scattered photon may undergo a photoelectric event or a second scatter event or it may escape.

The third mechanism, pair production, can occur only at energies above 1.02 MeV, which equals twice the rest mass of an electron. If a photon at this energy is within a Coulomb field of a nucleus, it can transform into an electron and a positron, with both particles carrying off any energy excess to the amount needed to create them. In general, the electron will survive, but the positron, after slowing down as it moves through the material, will undergo an annihilation reaction with an electron and create two characteristic 511 keV photons that are emitted in opposite directions.

In contrast to photons, charged particles lose energy primarily through multiple Coulombic interactions with electrons in the medium. As the particle loses energy, it creates a wake of free electrons and characteristic X rays. The maximum distance that the charged particle goes before it loses all of its energy in a material (the range) is related to the

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

nature of the material (primarily its density) and is also related to the size, charge, and energy of the particle. For small particles such as electrons, the range can be substantial (mm to cm); while for larger particles involving nuclei, the range is typically very short (less than 1 μm) except at relativistic energies, with the typical ranges for protons being intermediate. For fission fragments, which often have significantly higher atomic weights, almost all of the ionization takes place within angstroms of the surface.

In general, the probability of a neutron interacting with matter is much less than that for charged particles. Neutrons interact with matter through several mechanisms, all of which are highly dependent on the energy of the neutron. For slow neutrons, those with energies below about 0.5 eV, the primary means of interaction are elastic scattering and nuclear reaction. Only a relatively small number of atomic species have nuclei with a high probability of absorbing neutrons. The most common of these elements include tritium, boron, lithium, and cadmium. In materials which do not contain such elements, the path of slow neutrons is quite long (centimeters) and the neutron essentially becomes a particle moving through the matter with the thermal energy dictated by the temperature (0.02 eV at 20°C). The energy imparted by low-energy neutron elastic scattering to the surrounding matter is too low to be directly measured, and therefore slow neutrons can only be detected if they produce reaction products after being absorbed by the nuclei of the medium. A number of such absorption interactions are possible including (n, γ) in which a gamma ray is emitted, (n, α) in which an alpha particle is emitted, (n, p) in which a proton is emitted, and $(n,$ fission) in which a fission fragment of the atom are emitted.

As the energy of the neutron increases, the probability of its undergoing a nuclear reaction decreases. Instead, the higher-energy neutrons can collide with and impart energy to the nuclei in the material through simple scattering. The nuclei to which energy has thus been imparted can then create secondary radiation as it now moves through the medium and interacts as an energetic charged particle. Eventually, the high-energy neutrons either escape from the material or lose enough energy to be absorbed and undergo a nuclear reaction.

MECHANISMS OF DETECTION

It should be evident from the discussion above that for all forms of ionizing radiation, the detection of radiation is primarily based on detecting the charge created by the electrons and their complementary positive ions or positive "holes" (depending on the detector type) that are generated by either the primary or secondary interactions. In spite of this, there are significant differences among the detectors used to detect different forms of ionizing radiation.

In most cases, it is the penetrating ability and the energy of the radiation that determines the specifications and requirements of the detector. For example, charged particles stop very quickly and thus a detector for such particles must have its active region very close to the surface facing the source. Neutrons, on the other hand, are very penetrating and neutron detectors must either be relatively large or rely on converter materials to convert the neutron energy into secondary radiation that is easier to stop. For X rays and gamma rays, the details of the detector structure is more dependent on the energy of the incoming photons. Low-energy photons are easy to stop, but require a very good signal-to-noise ratio in the detector such that the detector may have to be cooled or have internal gain (e.g., avalanche photodiodes). High-energy photons produce ample signals, but require detectors which are larger and made of high-Z materials in order to achieve useful sensitivity.

It is convenient to segregate the many types of detectors into two classes: (a) those that rely on the energy deposited by the ionizing radiation being converted into nonelectronic energy such as light energy or chemical energy and (b) those that rely on the energy being converted directly into detectable electronic charge. Useful detectors from both of these classes exist for virtually all types of ionizing radiation, and many of them involve semiconductor devices.

NONELECTRONIC MECHANISMS OF DETECTION

Scintillators

The most common nonelectronic methods for detecting ionizing radiation rely on the conversion of the ionizing radiation energy into visible light using a scintillating material. The resulting visible flux is then detected with photographic film, a photomultiplier tube, and a photodiode or some other optical detector. There are a variety of solid, liquid, and gaseous scintillating materials, and important characteristics in selecting such a scintillating material include the stopping power of the material for the ionizing radiation of interest (usually a function of atomic number and density), the energy conversion efficiency usually specified in terms of number of photons per unit of ionizing energy, and the speed of response, relating to the rise and fall times of optical pulses produced for each ionizing event.

The two major groups of scintillating materials are the organic and inorganic. For organic scintillators, the fluorescence process arises from molecular electronic transitions and thus the material can be a liquid, solid, or vapor. The characteristics of these molecular transitions are that they are typically fast (a few nanoseconds) and have wavelengths shorter than 500 nm. These materials often have low-energy conversion efficiencies because the processes which convert the ionizing radiation energy into light must compete with other, nonradiative electronic transitions. Many of these materials, being in the form of liquids or vapors, provide excellent flexibility in form, but at the cost of stopping power due to low density and low atomic number. Plastic scintillators made from solid scintillating polymers are also available in arbitrary shapes and sizes. These scintillators have relatively low light output, but are easy to form into complex shapes and are particularly useful for certain neutron applications.

The energy conversion mechanism of inorganic scintillators, typically crystalline solids, is significantly different. In these cases, the secondary electrons are promoted in energy to the valance band associated with the crystal lattice. Over a period of time (usually in the range of a few hundred nanoseconds to a few microseconds) the excited electrons in the valance band lose energy by one of several mechanisms resulting in heat and light generated in the scintillator. Light is generated when the excitation results in energy transfer to luminescent centers which are often associated with impuri-

Table 1. Properties of Scintillator Materials

Material	Atomic Number, Z	Density (g/cm^2)	Emision Wavelength (nm)	Output NaI = 100	Decay Time (μs)	Index of Refraction	Hygroscopic
NaI(Tl)	11, 53	3.67	415	100	0.23	1.85	Yes
CsI	55, 53	4.51	315	6	0.005	1.95 1.80	Slightly
CsI(Na)	55, 53	4.51	420	85	0.63	1.84	Slightly
CsI(Tl)	55, 53	4.51	550 565	110	1.0	1.79	Slightly
BGO	83, 32, 8	7.13	480	11	0.6	2.15	No
BaF_2	56, 9	4.88	220/310	2/15	0.00008/0.6	1.49	No
CaF_2(Eu)	20, 9	3.18	435	50	0.94	1.44	No
$CdWO_4$	48, 74, 8	7.90	480	38	1/10	2.25	No
LiF(W)	3, 9	2.64	430	4	40	1.4	No
LiI(Eu)	3, 53	4.08	470 485	35	1.4	1.96	Yes
LuAP	71, 13, 8	8.34	360	30	0.018		No
LSO	71, 14, 8	7.4	420	63	0.04	1.82	No
GSO	64, 14, 8	6.71	430	26	0.04/0.6	1.85	No
GOS	64, 16, 8	7.34	510	50	3		No
$PbSO_4$	82, 16, 8	6.20	350	10	0.1	1.88	No
CsF	55, 9	4.64	390	4	0.005	1.48	Yes
CeF_3	58, 9	6.16	300/340	11	0.005, .02	1.68	No
YAP	39, 13, 8	5.55		46	0.024		No
Anthracene	Organic	1.25	447	43	0.03	1.62	No
Plastic	Organic	0.9–1	385–580	10–25	0.001–0.02	1.4–1.5	No
Liquid	Organic	0.9–1	385–430	15–35	0.002–0.004	1.4–1.5	No

BGO = $Bi_4Ge_3O_{12}$; GOS = Gd_2O_2S; GSO = Gd_2SiO_5; LSO = Lu_2SiO_5, LuAP = $LuAlO_3$; YAP = $YAlO_3$.

ties in the scintillator material. The light emitted can then be detected by an external detector.

The efficiency of producing light is an important characteristic of a scintillator material. It can require from about 30 eV to hundreds of electronvolts to generate a single optical photon in such material. The pulse shape of the resulting optical pulses is also very material dependent and can range from nanoseconds to seconds. Many of these materials exhibit emissions with multiple time constants, so that it is not uncommon for 5% to 15% of the emitted light to have a time course which is hundreds of times longer than the primary light flash. The magnitude of this phenomenon, often referred to as afterglow, can often be a determining factor whether a scintillating material can be used for a particular application. Some of the more common scintillating materials are shown in Table 1.

When used as a spectrometer, the energy resolution that can be achieved with a scintillator depends on both the characteristics of the scintillator and the associated optical detector. Until recently, only photomultiplier tubes could provide the performance needed for most useful scintillation-based ionizing radiation detectors. These devices provide large diameters, high gain, and low noise with moderate power consumption. With these sensors, the limitations on the performance of the spectrometer as a whole are determined primarily by the properties of the scintillator. The variability in scintillator materials is such that “hand-picked” premium-grade samples can provide energy resolution twice as good as that of standard samples.

More recently, solid-state optical detectors have been used in place of photomultipliers for several applications. These devices are attractive because they are much more compact than photomultipliers, are insensitive to magnetic fields, have higher quantum efficiencies, and use much less power. However, they do have inherently more noise than photomultipliers as well as more stringent limitations on their maximum size. The most commonly used solid-state optical detectors in such applications are the low-noise silicon p–i–n diodes and the high-gain silicon avalanche diode, both of which have been successfully applied with diameters of up to 1 in. Of these two, the avalanche diode has internal gain and significantly better signal-to-noise ratio, but is more expensive and requires a much higher operating bias voltage.

As the cost of sophisticated electronics has come down, there has been a corresponding increase in the use of scintillation detectors in the form of multielement arrays. Previously, the only widely used configurations of scintillation detector to provide two-dimensional spatial resolution were either the Anger camera or the single-probe scanner. In the first configuration, an array of 20 to 100 photomultipliers are attached to the back of a large disc of scintillator material, and the sum and ratios of the light detected by the sensors are used to compute the total energy and position of the incident ionizing radiation (most frequently a gamma ray from a medical isotope).

The newer configurations of scintillators consist of two-dimensional arrays of segmented scintillators with opaque separations between the segments and are now being used for position-sensitive detectors and for imaging. The details of the solid scintillator surface preparation influences the performance of these sensors, and several varieties of techniques are in current use. For example, the surface of the scintillation material which is attached to the optical detector is often highly polished and has a coupling of index matching fluid to improve light collection. The other surfaces of the scintillator which are not in contact with the detector are frequently covered by white, reflective materials, including typist correcting fluid, teflon tape, and filter paper to improve the collection and transfer of optical photons to the photosensor.

Film Screens and Other Films of Scintillating Materials. The first scintillators used to detect X rays over 100 years ago were in the form of thin films. This practice continues with the widespread use of film screens for radiography. Films screens are prepared by depositing a layer of a ground-up scintillating material in a binder. Until recently, these films were used primarily in conjunction with photographic film.

There has been a dramatic increase in interest in using scintillators films coupled to electronic imaging detectors. This has led to research on producing large-area, thin films of scintillators with better spatial resolution than can be achieved with film screens, such as the production of CsI films made up of small columnar crystallites. These can be optically coupled to film charge coupled devices (CCDs) and amorphous silicon diode arrays and can achieve very high spatial resolution with higher X-ray detection efficiency than standard phosphor film screens.

Other Indirect Detection Techniques. Although the most common nonelectronic method of detecting ionizing radiation involves the conversion of the energy of the ionizing particles into light, there are other detection mechanisms that fall into this category. These methods involve the conversion of the energy of the electrons into heat or sound or involve the use of that energy to induce chemical reactions or phase changes. In some techniques the signals are read immediately, but in many others the energy is stored for later readout. For example, the energy can be stored by trapping the secondary electrons in stable elevated energy states for later excitation by heat (thermoluminescent devices) or by light (phosphor image plates) with a subsequent detection of the resulting emitted light detected using optical sensors.

In materials with sufficient electron mobility, the electrons can also be transported to the surface of the detection medium and then detected by one of several external means. In fluoroscopes, the electrons are emitted by thermionic emission from the inner surface of the medium (which can be similar to the CsI films described above) and accelerated in an electric field onto a secondary detection device that is sensitive to electrons such as a phosphor screen or a CCD or a microchannel plate coupled to a CCD. In an X-ray vidicon tube, an electron beam rasters the surface of the medium and detects the areas of the medium that have absorbed energy in exactly the same manner as does a traditional video vidicon. In xeroradiography, the charges generated by X-ray absorption are detected and imaged in the same way that photocopies are made.

A particularly sensitive method to detect ionizing radiation relies on the use of superconductors. The energy released upon interaction breaks the Cooper pairs in the superconductor and the free electrons created can be detected. Because of the small amount of energy required to break a Cooper pair, these detectors can have extremely good energy resolution, better than 30 eV; however, they must operate at temperatures near absolute zero.

ELECTRONIC MECHANISMS OF DETECTION

The primary detectors used for the direct detection of radiation are ionization chambers, proportional counters, Geiger–Mueller tubes, and a wide variety of semiconductor devices. This article emphasizes semiconductor detectors since the other direct detection devices are discussed elsewhere in this encyclopedia and in many texts such as Knoll (1) and Tsoulfanidis (2); thus only a brief description of the other detectors is provided to contrast their capabilities to those of solid-state devices.

Gas Ionization Detectors

An ionization chamber is a gaseous detector in which the ions and electrons generated by an ionizing event are collected in an electric field. When the applied electric field is sufficiently strong to prevent the recombination of the electron ion pair, the signal produced is proportional to the amount of energy deposited. Since the signals are quite small, ionization chambers are typically used in the direct current (dc) mode where the charges generated are integrated into a signal current that is proportional to the total energy deposition rate.

Proportional chambers are gas-filled detectors in which the charge pulse detected is proportional to the energy deposited by the ionizing event. However, they are operated under sufficient bias voltage that the electrons generated accelerate in the electric field to sufficient energy to ionize additional atoms, creating charges that undergo the same process until there is an avalanche of charges. Under the proper conditions, the gain is constant and the signal is still proportional to deposited energy. The charge gains that are achieved (10^2 to 10^4) are sufficient that the signals are relatively large, and proportional counters are usually used in pulse mode as spectrometers.

Geiger–Mueller counters (also called Geiger counters or G–M tubes) have been used since the late 1920s. They are also gas-filled tubes but with much higher applied fields than ionization chambers or proportional counters. As with proportional chambers, the electrons generated accelerate in the electric field and create avalanches. In parallel, the excited gas molecules can return to their ground state by emission of an ultraviolet (UV) photon that can be absorbed in another location in the tube setting off another avalanche process. This series of avalanches produces gains of 10^2 to 10^9 and results in a very large charge pulse. The pulses are not proportional to the amount of energy deposited by the ionizing radiation, so no energy information is available and thus Geiger–Mueller tubes can only be used as counters. They are rugged, inexpensive, and reliable and are commonly used on survey meters and dosimeters.

SEMICONDUCTOR DETECTORS

In principle, semiconductor radiation detectors are the most attractive means of detecting ionizing radiation. They can be very sensitive, compact, stable, and rugged, and they use low power, have low noise, are insensitive to magnetic fields, and provide exceptionally good quality information on the energy distribution of the incident radiation. However, practical limitations on their size, material uniformity, electrode structures, and cost have prevented them from replacing the more traditional sensors.

In a semiconductor detector, the energy of the ionizing radiation is transferred to the charge carriers of the crystal lattice, resulting in a cloud of free charge which can be externally measured in the form of an electronic pulse. The magnitude of the charge cloud is directly proportional to the energy absorbed from the ionizing radiation and the number of clouds equal to the number of absorbed ionizing particles. Thus, the magnitude of the charge pulse measured by the external electronics is truly proportional to the energy deposited. Thus, if the associated electronic noise from both the detector itself and the associated electronics is small, very high quality measurements can be made.

The key properties affecting the performance of a semiconductor detector include its stopping power, size, sensitivity, gain stability, noise, energy resolution, operational requirements, susceptibility to radiation damage, and, if required, its ability to provide position information. The stopping power of a semiconductor depends on the nature of the incident radiation, the atomic number of its constituents, and density. If the incoming radiation of interest consists of low-energy X rays or heavy ionizing particles, the energy transfer interactions all take place in the first few microns of the material and only the area of the detector is critical for determining its sensitivity. If, however, the incoming radiation is of a more penetrating type, then the thickness (and hence the volume) of the detector becomes more of a consideration.

Similarly, the atomic numbers of the constituents of the detector crystal and the density of the material help determine the size of crystal which must be used to achieve good detection efficiency. For penetrating radiation, the detection efficiency will increase approximately linearly with the density and as the atomic number to the 4.5 power.

The noise associated with a semiconductor detector arises from both the bulk material and the electrodes. The amount of this noise determines both (a) the lowest-energy ionizing particle that can be detected and (b) the precision with which the energy of such particles can be measured. The latter is referred to as the energy resolution and is a function of not only the noise, but also the magnitude and uniformity of the pulses produced throughout the volume of the detector.

Oftentimes, the operational requirements of a detector determine its suitability for a particular application. For example, some semiconductor detectors can operate only under cryogenic conditions while others operate well at room temperature, but both types of detector will permanently degrade when exposed to even slightly elevated temperatures. Similarly, some semiconductor detectors can operate with moderately low operating voltages, while others require several thousand volts.

The susceptibility of a detector to radiation damage depends on both the nature of the incident radiation and the material of the detector. In general, unless the flux levels are extremely high, X-ray and gamma-ray applications cause relatively little radiation damage, while high-energy particles cause substantially more. Applications involving neutrons are particularly challenging, because they are often associated with very high flux levels and can permanently damage many of the commonly used semiconductor materials.

Since the usefulness of different semiconductor detectors is so dependent on the application, it is useful to first become familiar with some of the details of the properties of semiconductor detectors before attempting to choose a detector for a specific requirement. Table 2 lists the relevant characteristics of materials used for fabricating radiation detectors. These characteristics form the basis for selecting a detector for specific application. The key properties to be considered include stopping power and detection efficiency, sensitivity, energy resolution, noise, operational requirements, radiation damage, and position resolution for imaging applications.

Stopping Power and Detection Efficiency

As discussed above, the stopping power is a function of atomic number and density. A number of factors influence the detec-

Table 2. Properties of Semiconductor Used for Radiation Detectors Materials at 25°C

Material	Atomic Number, Z	Density (g/cm^3)	Band gap (eV)	Melting point (°C)	E_{pair}(eV)	Resistivity (25°C) $\Omega \cdot$ cm	$\mu\tau(e)$ Product (cm^2/V)[a]	$\mu\tau(h)$ Product (cm^2/V)
Ge	32	5.33	0.67	958	2.96	50	>1	>1
Si	14	2.33	1.12	1412	3.62	up to 10^4	>1	≈1
CdTe	48, 52	6.2	1.44	1092	4.43	10^9	3.3×10^{-3}	2×10^{-4}
CdZnTe	48, 30, 52	≈6	1.5–2.2	1092–1295	≈5	$>10^{10}$	2×10^{-3}	1×10^{-5}
CdSe	48, 34	5.81	1.73	>1350	5.5[b]	10^8	7.2×10^{-4}	7.5×10^{-5}
HgI_2	80, 53	6.4	2.13	250 (127)[c]	4.2	10^{13}	10^{-4}	4×10^{-5}
GaAs	31, 33	5.32	1.43	1238	4.2	10^7	8×10^{-5}	4×10^{-6}
InI	49, 53	5.31	2.01	351		10^{11}	7×10^{-5}	
Diamond	6	3.51	5.4	4027	13.25		2×10^{-5}	$<1.6 \times 10^{-5}$
TlBr	81, 35	7.56	2.68	480	6.5	10^{12}	1.6×10^{-5}	1.5×10^{-6}
PbI_2	82, 53	6.2	2.32	402	4.9	10^{12}	8×10^{-6}	
InP	49, 15	4.78	1.35	1057	4.2	10^7	4.8×10^{-6}	$<1.5 \times 10^{-5}$
ZnTe	30, 52	5.72	2.26	1295	7.0[b]	10^{10}	1.4×10^{-6}	7×10^{-5}
a-Si	14	2.3	1.8		4	10^{12}	6.8×10^{-8}	2×10^{-8}
a-Se	34	4.3	2.3		7	10^{12}	5×10^{-9}	1.4×10^{-7}
CdS	48, 16	4.82	2.5	1477	7.8[b]			
SiC	14, 6	3.2	2.2		9.0[b]			

[a]Materials are listed in order of decreasing $\mu\tau(e)$ at room temperature.
[b]Estimated.
[c]Solid-solid phase transition.

tion efficiency in a detector. Not all of the radiation striking a detector is detected. As the atomic number or density increases, so does efficiency; and at higher energies where the photons can penetrate the detector, its efficiency increases with thickness. The ability to stop high-energy photons is proportional to the active area of the device and increases with thickness by the familiar attenuation equation:

$$I = I_0 \exp(-ut) \tag{4}$$

where I_0 is the initial intensity of the radiation, I is the intensity after attenuation by the medium (i.e., the detector), u is the linear attenuation coefficient in cm^{-1}, and t is the thickness in centimeters. The mass attenuation coefficient in square centimeters program is the linear coefficient divided by the density, u/ρ. The amount of radiation stopped in the detector is simply

$$I_0 - I \tag{5}$$

Tables of absorption coefficients are readily available for performing calculations of detector efficiency [such as in the *Health Physics Handbook* (3)], as is commercially available software. At low energies in real detectors, the measured count rate may be lower than calculated since some counts may be lost in the noise or absorbed in surface layers or protective packaging.

Charged particles can typically only penetrate a fraction of a micron, so that stopping power is usually not a factor; however, the ability of the particle to penetrate past inactive layers at the surface of the detector will limit the efficiency. All semiconductor materials have a "dead" layer at the surface. This dead layer results from damage that occurs during fabrication and from oxidation. In addition, the devices need some form of electrode and frequently protective coating, both of which absorb energy. Sometimes it is possible to combine the electrode and the protective coating, as is done in Schottky barrier alpha-particle detectors in which a thin layer of gold performs both functions.

Sensitivity

The sensitivity of a detector is the lower limit of detection in terms of energy and/or flux. Detector size affects sensitivity: As a detector gets larger, it will obviously interact with more radiation; however, as a general rule, noise and background effects increase with size. As the area of a detector gets larger, both the capacitance and the leakage current increase. Both of these factors result in a decrease in signal-to-noise ratio. As a detector gets thicker, it stops more penetrating radiation and the capacitance decreases. However, charge collection effects such as ballistic deficit (where the amplifier integration time is not sufficiently long to integrate the entire pulse) and trapping increase, as does the associated noise due to semiconductor generation/recombination effects (g–r noise). These conflicting parameters usually result in the user making a trade-off between various parameters to optimize the performance for a specific application.

Energy Resolution

In many applications, energy resolution is an important property. The ability to resolve energy allows the user to identify a source and also to separate the signal generated by the source or the energy range of interest from background or other unwanted radiation signals. The energy resolution of a detector is affected by noise, charge carrier properties, and detector uniformity. In an ideal detector, every signal pulse would be exactly proportional to the absorbed energy, and all photon of the same energy would generate identical signal pulses, within the statistics of charge generation. In a real detector, a number of factors influence the energy resolution that is attainable. The statistics of charge generation process itself causes a broadening of energy, electronic noise adds a Gaussian distribution to the photopeak, and charge collection effects and material nonuniformity also add to this broadening in nonstatistical ways. Energy resolution is commonly expressed as the full width at half-maximum (FWHM) of a photopeak at an energy or as a percent of the energy. The detector type of choice greatly affects the energy resolution attainable, with Ge detectors having better than 1% resolution (below 0.1% under favorable conditions) and other materials ranging from 2% to 10% depending on the energy.

Factors Affecting Device Performance of Semiconductor Detectors

Charge Carrier Properties. Sensitivity and energy resolution depend on the characteristics of the electronic signal generated in a detector and on electronic noise. The signal comes from electronic charge generated by an ionizing event. In crystalline semiconductor materials, charges (electron–hole pairs) generated by ionizing interactions are promoted into the conduction band. The charges can be collected at electrodes on the surfaces of the device by applying an electric field across the device. Two of the most important characteristics of the electronic charge generated in a material are the charge carrier mobility (μ), in square centimeters per volt-second, and charge carrier lifetime (τ), in seconds. The product of the mobility and the lifetime, the "$\mu\tau$ product," is an important figure of merit for detector materials. A larger value of the $\mu\tau$-product results in lower losses from charge trapping which in general permits the fabrication of larger detectors since charges can be collected over greater distances. If either the electrons or the holes are not completely collected (as is the case in many compound semiconductor detectors) a larger $\mu\tau$-product results in a larger signal.

Resistivity and Noise. The other important electronic property is the resistivity of the material. Noise generated in the detector comes from the collection of electronic charge generated by means other than an ionizing event. A major component of this noise is the leakage current that flows through a semiconductor when it is under bias. Lower resistivity results in higher leakage current and more noise. The leakage current is proportional to the number of charge carriers present in the conduction band. The resistivity (Ω) of a semiconductor is given by the equation

$$\rho = 1/ne\mu \tag{6}$$

where n is the density of charge carriers and e is the charge on the electron. The number of charge pairs is a function of temperature and bandgap. The probability (p) of thermally generating an electron–hole pair is given by:

$$p(T) \propto T^{2/3} \exp(-E_g/2kT) \tag{7}$$

where T is temperature in Kelvin, E_g is the semiconductor bandgap, and k is Boltzmann's constant.

Theoretically, the inherent resistivity increases with increasing bandgap and decreasing temperature. This dependence on temperature results in two broad classes of semiconductor detectors: room temperature detectors and cooled detectors. Cooling a detector improves performance by decreasing the number of electrons in the conduction band, increasing the resistivity, and reducing the noise. In general, room-temperature detectors have bandgaps larger than 1 eV.

Factors Affecting Device Performance of Semiconductor Detectors

Statistics of Charge Generation. The statistical spread of charge generation may be described by a Poisson process and because the average number of charges (N) is relatively large it can be described by a Gaussian function $G(H)$:

$$G(H) = (A/\sigma(2\pi)^{1/2}) \exp[-(H-H_0)^2/(2\sigma^2)] \tag{8}$$

where H_0 is the centroid of the Gaussian (i.e., the average pulse height) and is proportional to N; K is a proportionality constant; A is the area of the peak; σ^2 is the variance; σ is the standard deviation. For a Gaussian distribution, FWHM = 2.35 σ. The resolution R due to the statistics of the charge generation is:

$$R = \mathrm{FWHM}/H_0 - 2.35K(N)^{1/2}/KN = 2.35/(N)^{1/2} \tag{9}$$

In real detectors, the broadening due to this statistical spread can actually be lower than predicted, indicating that the processes by which charge carriers are produced are not independent events. This phenomenon is described by the Fano factor, F. F is an empirical scalar that accounts for the difference between the observed and the Poisson-predicted variance. It is always less than unity. Applying the Fano factor to Eq. (9) gives the resolution as $2.35(F/N)^{1/2}$.

Noise. All detectors and detector electronics have noise associated with them. There are three main sources of noise which originate in the detector and the amplifier used with the detector: shot noise due to fluctuations in the leakage current, thermally generated noise in the input amplifier, and $1/f$ noise generated by the detector itself and/or the amplifier.

Shot noise (or parallel thermal noise) is given by:

$$\mathrm{ENC_p} = e/2(\tau I_d/q)^{1/2} \tag{10}$$

where ENC is the equivalent electronic noise charge in electrons rms, e = 2.718 . . ., I_d is the detector leakage current, q is the electronic charge, and τ is the integration time of the amplifier which incorporates CR–RC (capacitance–resistance) filtering circuitry, which is common in radiation spectroscopy (4).

The thermal series noise from the input FET (field-effect transistor) of the preamplifier is given by

$$\mathrm{ENC_s} = (e/q)C_i((\mathrm{kT}/2\tau)(0.7/g_m))^{1/2} \tag{11}$$

where C_i is the input capacitance of the preamplifier, which is the sum of the detector, gate, and stray capacitance, k is Boltzmann's constant, and g_m is the transconductance where the input device is an FET.

The $1/f$ noise of the detector is given by

$$\mathrm{ENC}_t = (e/q)[C_i(A_f))^{1/2} \tag{12}$$

where A_f is the $1/f$ spectral noise density. These noise terms add in quadrature. Figure 1 shows how these sources combine in a detector. The noise contributions add to the other statistical contributions in quadrature. Extensive discussions of noise in preamplifiers used with semiconductor detectors are available in the literature (e.g., see Refs. 4 and 5).

Charge Collection and Hole Tailing. Clearly, after the charges are generated by an ionizing event, they need to be detected. In direct detection detectors, this is achieved by applying an electric bias voltage across the device. During collection, charges can be lost due to trapping and recombination. Some of these effects are random, and some are dependent on the position of the interaction in the device. These effects decrease the total quantity of charges collected and are not Gaussian and give rise to a "tail" of counts on the energy side of the energy spectrum obtained.

Nonuniformity. All materials exhibit some degree of nonuniformity. In semiconductors, for example, there are distributions of defect type and concentration as well as in dopant concentration. For compound semiconductors variations in composition are difficult to avoid. These variations can and do affect charge collection in the material.

Pulse Shape and Speed of Response

The collection of charges results in a signal pulse whose rise time, shape, and duration depend on the detector used. Pulses from detectors used in pulse mode can be characterized by their rise time and fall time. Typically, the rise time is a function of the detector type and design, while the fall time is determined by the characteristics of the detector and the readout circuitry. The speed of response is a measure of the

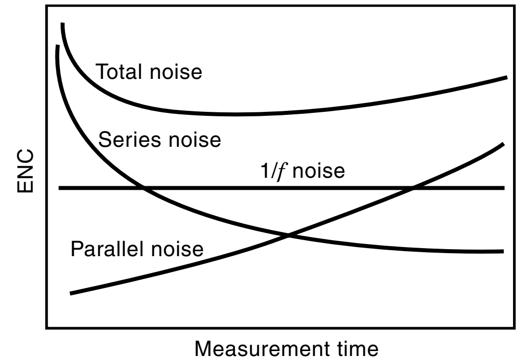


Figure 1. Contribution of various noise sources as a function of the measurement time (integration time) of the amplifier. At very short times (e.g., less than 0.1 μs for most semiconductors) the series noise dominates. As more of the signal is integrated (times over 5 μs for most semiconductors), the parallel noise dominates. These parameters differ for each semiconductor and at different temperatures, so the optimum operating point is usually determined experimentally by varying the integration time of the amplifier.

rise time of the detector, and the timing resolution is a measure of the ability to separate two sequential pulses in time. Time resolution is typically measured in FWHM and full width at tenth maximum (FWTM). The speed of response is a function of the capacitance of the device and the readout circuitry, the applied bias, and the mobility of the charge carriers. The ability to separate pulses determines the maximum count rate at which a detector can be used.

Radiation Damage

Another important requirement for detectors in many important applications in research, medicine, and industry is the susceptibility of the detector to radiation damage. Radiation damage causes the size of the signal to change with exposure. Most materials can tolerate a large exposure before noticeable changes occur. The detrimental effects of radiation damage are due to defects created in the material. In both semiconductors and scintillators these defects trap charge and reduce the size of the resulting signal (6,7). The radiation dose at which such effects become significant varies with material and radiation type. Typically, exposures of 10^{11} cm^{-2} to 10^{14} cm^{-2} cause signal reduction. In semiconductors, the effect of damage becomes important when the concentration of defect sites in the bandgap caused by the radiation approaches the same order of magnitude as the level of dopant added to the material or of other impurities and native defects. Typically, compound semiconductors are more radiation-resistant than elemental semiconductors because they normally contain higher concentrations of defects.

Fundamentals of Semiconductor Device Fabrication

Solid-state detectors are usually fabricated from ultrapure single crystals of the semiconductor material. A variety of methods are used to grow semiconductor materials for nuclear sensor applications (8). Si, Ge, GaAs, and InP are typically grown by the Czochralski method, although the float zone technique is also popular for Si growth (9). In the Czochralski method, single crystals of the material are slowly pulled up out of the melt by touching the surface of the liquid with a seed crystal and raising it; as the material rises out of the pool of liquid, it cools and crystallizes. In float zone growth, a short zone of molten material is passed through a vertical ingot of material by moving a heater along the length of the material. Surface tension keeps the liquid in place, and the material melts and crystallizes as the heater passes. The Bridgman crystal growth method is also used, especially in the early stages of development in a new material because it is a relatively straightforward technique which can be implemented without a large capital investment. In this method, material is melted in a sealed ampoule in a furnace and slowly dropped out of the furnace. Vertical zone and horizontal zone melt growth techniques are used on a variety of materials including cadmium telluride (CdTe) and lead iodide (PbI_2). Solution growth techniques can also yield good results; the best CdTe available at the time of this article is grown by a vertical solution zone technique, the traveling heater method (THM) (10,11), which has also been used for other II–VI materials. The ternary material cadmium zinc telluride (CZT) is grown at high pressures by a process called high-pressure Bridgman (HPB) crystal growth (12).

Vapor growth of single crystals for some semiconductor materials used as radiation detectors has been investigated, but only mercury iodide (HgI_2) crystals are regularly grown from the vapor phase (13–15). HgI_2 must be grown by vapor phase growth because of a solid–solid phase transition at 127°C that destroys the quality of any crystals grown from the melt. In general, when possible, growth from the melt or from solution is preferred because vapor growth processes are generally much slower than liquid techniques.

Thin films, however, are readily grown epitaxially on selected substrates from the vapor phase or the liquid phase. Most thin films of the materials of interest for nuclear detectors are presently grown by physical vapor deposition or one of several modifications of the chemical vapor deposition (CVD) technique. Since the films are thin, the relatively slow growth rates from the vapor are not a detrimental factor and CVD processes allow tight control over growth parameters and film stoichiometry.

A major part of any development effort on new materials is research to identify appropriate device fabrication procedures such as finding etching procedures and workable electrode structures. In general, two generic types of devices are fabricated on the crystalline materials during the early stages of developing new materials: photoconductors and photodiodes. These devices have a relatively simple configuration: Parallel planar electrodes are vacuum evaporated, plated, or painted onto both surfaces of cut or cleaved wafers that have been cleaned, polished, and etched. The electrodes are selected from materials that form ohmic contacts for photoconductors and Schottky barrier contacts for diodes. As a material matures and its properties are better understood, more sophisticated electrode structures, diffused junctions and specialized surface treatments are often used to modify and improve the performance. Thin semiconductor films can also be tested by fabricating simple ohmic and diode structures; but for imaging sensors, device fabrication makes use of existing photolithographic technology to build arrays of sophisticated multilayer diodes, photodiodes, and transistors.

Materials Used in Semiconductor Detectors

Of the many semiconductor materials available, only three have been regularly used for commercial radiation detectors: Si, Ge, and CdTe (and its ternary alloy with zinc, $Cd_{1-x}Zn_xTe$, or CZT), and only Si, CdTe, and CZT are used at room temperature. Germanium detectors must always be cooled; and to obtain the best performance from silicon detectors, some cooling is also needed.

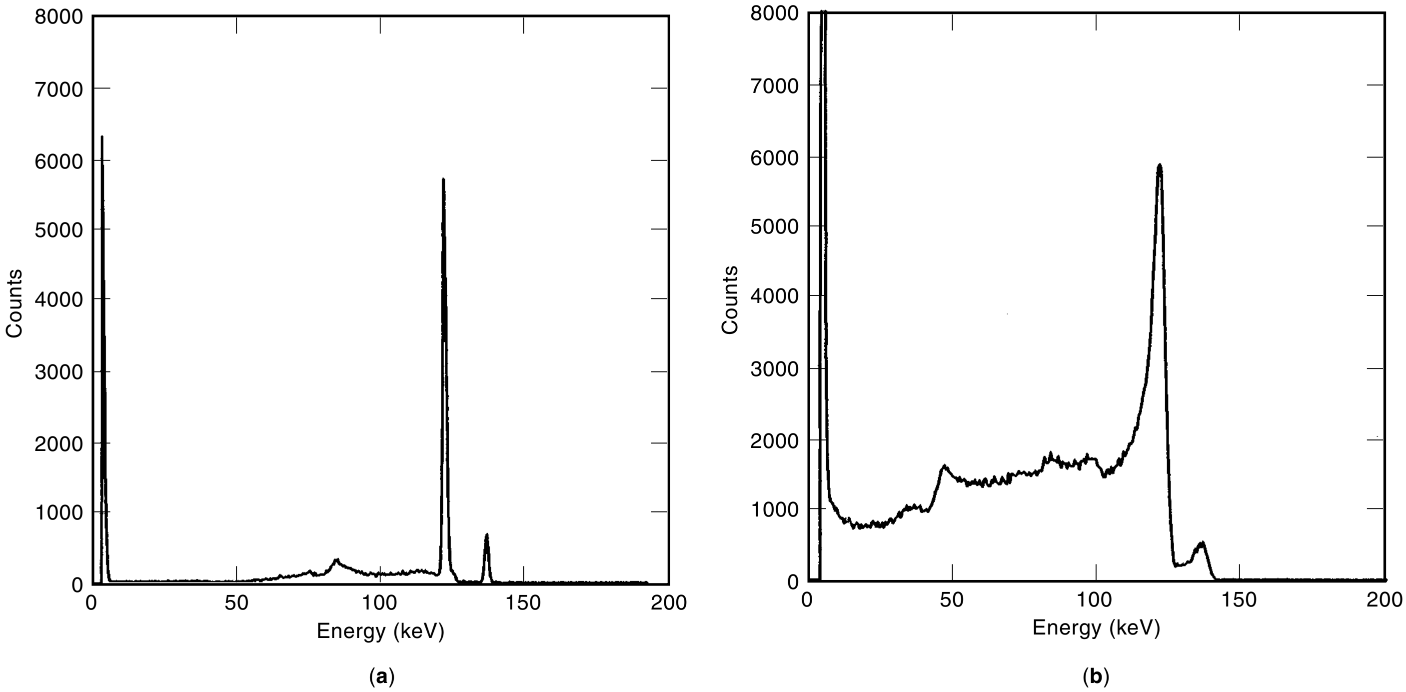
Cooled Detectors. Whenever energy resolution is the highest priority, either Si or Ge is used at reduced temperature. They are attractive detector materials because of the very high values of the $\mu\tau$ product of electrons and holes. However, because of the relatively small bandgaps, thermally generated charges are a problem. The easiest method for solving this problem is cooling the detector.

Because Ge has a higher atomic number, Z, than Si (32 versus 14), has excellent charge carrier properties, and is available in large sizes, high-purity germanium (HPGe) is usually the preferred detector for high-resolution gamma-ray spectroscopy. HPGe detectors must be cooled to cryogenic temperatures to obtain good energy resolution and to avoid damaging the crystal during operation. Thus an HPGe detector must be attached to a liquid nitrogen cryostat or else connected to multistage thermoelectric coolers. This adds considerably to system complexity and expense. Figure 2(a) shows the performance that can be obtained from an HPGe detector in comparison with that obtained using other detector technologies in Figs. 2(b) and 2(c).

Cooled silicon detectors provide excellent performance for low-energy X-ray spectrometry. Cryogenically cooled and thermoelectrically cooled Si detectors can have energy resolutions better than 150 eV at 1 keV to 10 keV. Such detectors are commonly used in energy dispersive X-ray analysis systems.

Germanium Detectors. Germanium detectors have been the most widely used detectors for high-resolution X-ray and γ-ray spectroscopy for over 30 years. HPGe detectors are currently used in diverse applications such as nuclear physics research, environmental monitoring, high-energy physics, material science studies, geophysical exploration, health physics, and γ-ray astronomy.

Early germanium detectors were fabricated by compensating p-type material (with impurity concentration of about 10^{13} cm^{-3} to 10^{14} cm^{-3}) using an interstitial donor (lithium) in order to produce material with lower carrier concentration (16). These were referred to as *lithium-drifted germanium*



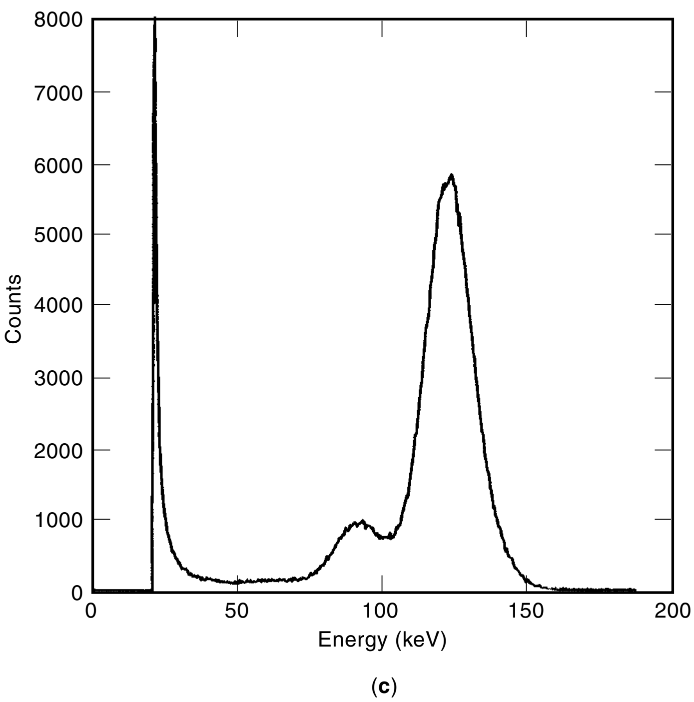


Figure 2. Spectrum of the 122 keV and 136 keV gamma rays of ^{57}Co. Spectrum (a) shows the results obtained using a cryogenically cooled Ge detector. The FWHM is about 1%. Spectrum (b) shows the results obtained using CdTe at room temperature. The FMHM is about 3%, but the effect of hole tailing is evident. The 136 keV photopeak is still well separated from the peak at 122 keV. Spectrum (c) was obtained using an APD coupled to a CsI scintillation crystal at room temperature. The resolution is dominated by the properties of the scintillator, and the FWHM is about 13%. The 136 keV photopeak cannot be resolved.

and Ge(Li) "jelly" detectors. In the early 1970s, inherently pure single crystals of germanium became available (17). Such HPGe crystals achieved carrier concentrations as low as 10^{10} cm^{-3} (at 77 K) and resulted in switch from Ge(Li) to HPGe for almost all germanium detector fabrication efforts. This was primarily due to the fact that while Ge(Li) detectors had to be kept cool (77 K) at all times, even when not in operation (in order to prevent decompensation), HPGe detectors need to be cooled only during actual operation. As a result, almost all commercial suppliers of germanium detectors use HPGe material at present.

Significant advances have been made during the last decade in high-purity germanium crystal growth; and as a result, large-volume crystals (both p-type and n-type) are routinely produced. A variety of germanium detectors are fabricated using such crystals, and the two popular geometries for HPGe detectors are the coaxial detectors and the planar detectors. The coaxial detectors are generally used for detection of X rays and γ rays with energies from a few kiloelectronvolts to about 10 MeV, with high efficiency, while the planar detectors are used for high-resolution detection of lower-energy photons (few kiloelectronvolts to about 200 keV). All HPGe detectors have a p^+–i–n^+ structure, where the intrinsic (i) region is the sensitive detection volume. In planar detectors, both the parallel-plate and wrap-around contact designs are used, as shown in Fig. 3. The wrap-around contact or LEGe design has the advantage of lower capacitance for a fixed detector area and thickness (as compared to parallel electrode design). In coaxial detectors, a closed coaxial structure is used as shown in the figure (as opposed to an open coaxial structure, where the core is drilled through the entire detector thickness), because in closed coaxial detectors, there is only one face with junction, where the exposed germanium needs to be passivated.

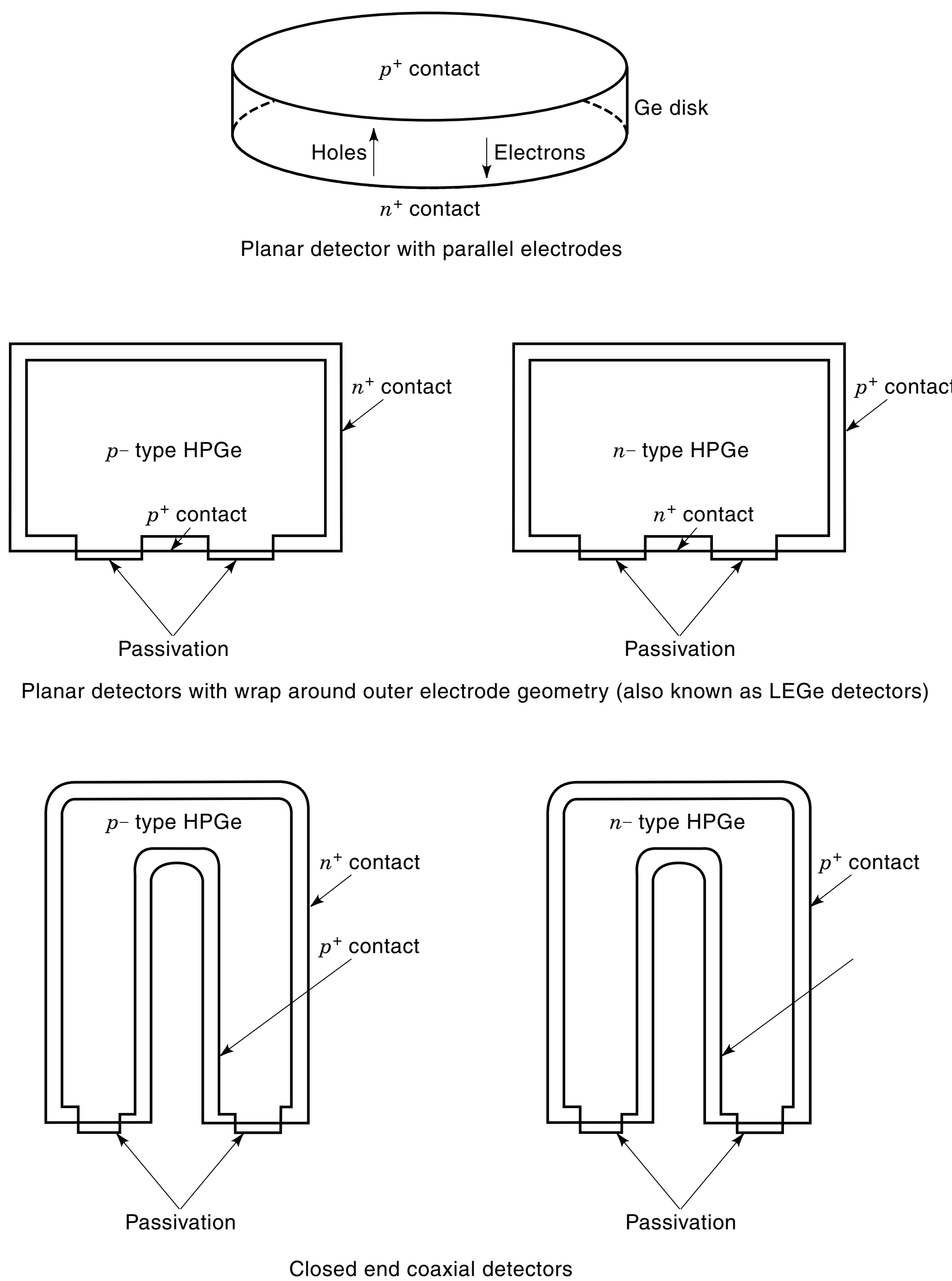


Figure 3. Schematic representation of various germanium detectors. The top figure shows a planar detector. The middle figures show modified planar or LEGe detectors with wrap-around outer junction contacts with reduced capacitance. The bottom figures show coaxial detectors which are mainly used for detection of high-energy γ-rays.

Materials Used for Room-Temperature Semiconductor Detectors

Operating at room temperature dramatically increases the convenience and decreases the cost of operating a detector. Silicon is the semiconductor material most often used for ionizing particles; but for X rays and gamma rays where room-temperature operation, small size, and high sensitivity is required, CdTe or CZT is often used. Other materials such as HgI_2 and GaAs have been extensively studied for many years.

Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CZT) Detectors. CdTe is a very-high-atomic-number semiconductor and as such is very efficient at stopping X rays. For instance, at 60 keV (the average photon energy from a typical X-ray tube), 90% of X-ray photons stop in a 500 μm thickness of CdTe as opposed to 3 mm of silicon.

The more common application of CdTe detectors is for single-photon gamma-ray spectrometers. Single-photon CdTe spectrometers are constructed of very-high-resistivity CdTe with two nearly ohmic platinum electrodes applied to the faces of the CdTe crystal. These detectors are typically 2 mm to 4 mm thick and are operated at a bias of approximately 100 V. The resistivity of the CdTe crystals is made high by doping the CdTe crystal with a deep level acceptor. The resistivity can be raised higher by adding zinc to form the ternary CZT alloy.

Electronic Properties of CdTe and CZT. CdTe is a compound semiconductor with a bandgap of 1.44 eV. It has many attractive properties for use as a nuclear detector material. THM-grown material is usually doped with chlorine, which compensates the cadmium vacancies that are characteristic of CdTe grown at low pressure. Compensated material has a resistivity on the order of 10^9 Ω-cm. The values of the $\mu\tau$ products for CdTe that are typically obtained are 3.5×10^{-3} cm^2/V for electrons and 2×10^{-4} cm^2/V for holes. Because the $\mu\tau$ product for holes is lower than for electrons, it tends to have a more significant effect on the energy resolution. The electronic properties of CZT depend on the fraction of Zn used. In the range of 5% to 20% zinc, the resistivity ranges from 10^{10} Ω-cm to 10^{12} Ω-cm. As the amount of Zn increases, however, the mobility of the holes decreases. For CZT with 5% Zn the $\mu\tau$ product for electrons and holes are 2×10^{-3} cm^2/V and 5×10^{-5} cm^2/V, respectively.

Energy Resolution, Charge Trapping, and Hole Tailing. The effects of electronic noise and broadening due to charge collection interact and the relative importance of the effects depends on the energy of the radiation. The use of *RC* filtering to optimize the signal-to-noise ratio can result in optimum filtering parameters that do not permit all of the charges generated by an event to be collected during the amplifier integration time. At low energy (below about 100 keV) the photons stop near the surface of the detector where the charges are collected uniformly since all of the electrons travel about the same distance toward the positive electrode and the holes travel about the same distance to the negative electrode. Because of this, the width of the photopeak is dominated by electronic noise and it is almost symmetrical. At higher energies the noise due to leakage current becomes less important because the signal is larger but the effects of charge collection become more prominent. Charge collection problems are seen as an asymmetric broadening on the low energy side of the photopeak. This is primarily due to the fact that the $\mu\tau$-products of holes and electrons differ significantly and all of the charge may not be fully collected during the measurement time of the amplifier. Typically, the $\mu\tau$-product of holes is significantly less than that for electrons. For compound semiconductors, charge collection effects at energies above a few hundred keV dominate the resolution, and photopeaks can be quite broad and asymmetric. Figure 2(b) shows a spectrum obtained using CdTe. This low-energy broadening and low-energy plateau caused by poor charge collection is called "hole tailing." When a gamma ray deposits energy in a semiconductor, it generates electron–hole pairs, with both the electrons and holes participating in the charge collection. Since the mobility–lifetime product of the electrons is much higher than the mobility–lifetime product of the holes, and since the distance they must traverse varies with depth of interaction, the collection time and thus the rise time depend upon the depth of interaction. In interactions which occur near the negatively biased front surface of the detector, the charge is mainly collected by electrons, with a very short collection time and high charge collection efficiency. In interactions occurring deeper in the crystal, the hole collection is more important, leading to slower rise times and lower charge collection efficiency. This leads to degradation in both energy resolution and efficiency since many of the events do not show up in the photopeak, but are in the low-energy tail as can be seen in the spectrum in Fig. 2(b).

Room-Temperature Silicon Detectors

Silicon Diodes. Silicon is technologically the most mature semiconductor, and it is readily available in high purity and relatively inexpensive. Figure 4 shows a variety of silicon diode configurations. Numerous preparation and fabrication technologies exist to fabricate devices. These features make it an attractive material for use in making detectors. The limitations of using silicon are its low atomic number and relatively low resistivity at room temperature. There are applications where these factors do not preclude the use of silicon. For example, large-area silicon diodes are used as alpha particle detectors because alpha-particles do not penetrate far and generally have high energies. A variety of diodes structures are used on silicon. The formation of a good semiconductor barrier is important to reduce the leakage current. The most common diode structures are surface barrier diodes and *p–i–n* diodes. The *p–i–n* structure uses a relatively thick silicon active region (100 μm to 500 μm) of very high resistivity silicon (1000 Ω-cm to 10,000 Ω-cm). This provides two significant advantages, the first of which is improved X-ray stopping power. More importantly, the thicker device has significantly lower capacitance than the surface barrier detector; and as seen in Eq. (11) above, the noise increases with increasing capacitance. Such devices are also attractive because of their very low cost (10 to 100 dollars).

Avalanche Photodiodes. At room temperature, low energy performance is often limited by noise in the preamplifier. One method to overcome this problem is to design a device with internal gain. The avalanche photodiode (APD) is such a device. The avalanche photodiode is unique among solid-state radiation detectors in that it has internal gain. In its simplest form, an APD is a *p–n* junction formed in a silicon wafer, structured so that it may be operated near breakdown voltage under reverse bias. Compared to conventional solid-state sensors, relatively large output pulses are produced, along with an improved signal-to-noise ratio (18). APDs can be used directly to detect low energy X rays and particles or used cou-

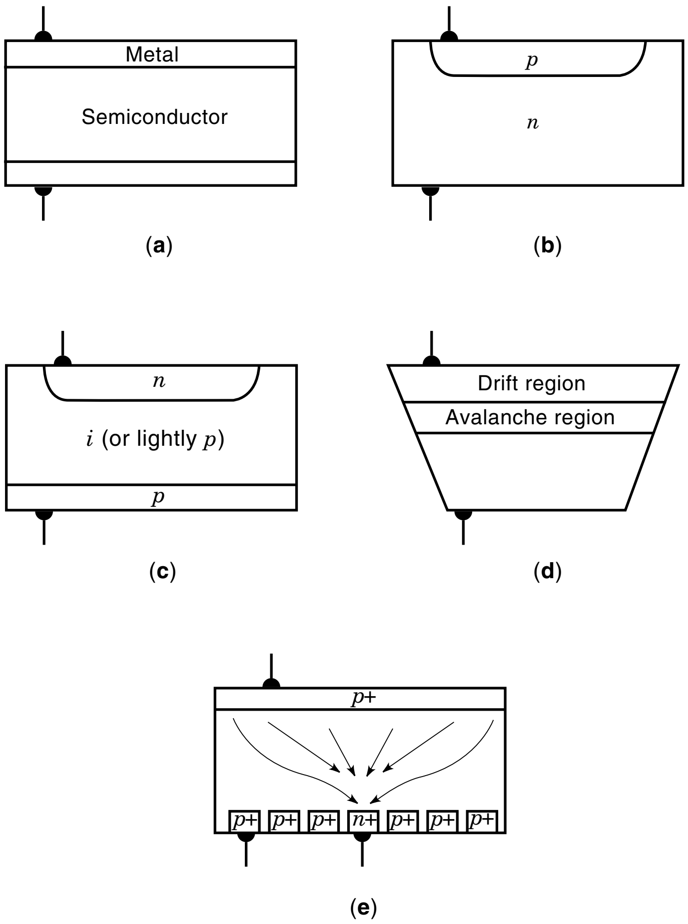


Figure 4. Various detector configurations used in silicon detector technology. (a) Simple planar structure used in Schottky diodes and photoconductors. (b) Simple *pn* diode. (c) A *p–i–n* which provides a larger active volume and lower capacitance. (d) Avalanche photodiode (APD). (e) Silicon drift diode (SDD).

pled to a scintillator for higher energy. Figure 2(c) shows a γ-ray spectrum taken using an APD coupled to a CsI scintillator.

Very small APDs have been in routine use in the telecommunications industry for some years and have also been used in a variety of other applications such as optical decay measurement, time-domain reflectometry, and laser ranging. They are most often used for the detection of optical radiation, which was their original purpose. In recent years, research has led to an improved device, allowing application to a wide variety of nuclear spectroscopy applications (19,20). In comparison to photomultiplier tubes, which are one of the most commonly used low-light-level sensors, APDs are smaller, more rugged, and more stable, have higher quantum efficiency, and use much less power. They are far more sensitive and have inherently better signal-to-noise ratios than other semiconductor photosensors. In addition, they may be operated without cooling and are insensitive to magnetic fields and vibration. These detectors may be fabricated to directly sense both high- and low-energy beta particles with high efficiency, and thus they provide a very attractive sensor for the proposed instrument.

Figure 4(d) presents a schematic diagram of the cross section of an APD. It consists of several regions, including the "drift" region and the active junction, which contains the multiplication region. The "drift" region is typically 20 μm thick, the active region of the device is approximately 120 μm thick, and the multiplication region is less than 10 μm thick. Ionizing radiation or light with an energy greater than the bandgap that strikes the drift region will cause the generation of free charge carriers which then drift to the active region. No external field is present here, but a gentle gradient in dopant concentration causes a weak electric field, imparting a net drift of electrons toward the multiplication region. Since the dopant concentration in this region is relatively light, the carrier lifetimes are quite large and efficient transport is easily attained with the high-quality silicon now available.

Within the multiplication region, the number of charge carriers is amplified in accordance with the gain of the device. Electrons entering this region quickly attain velocities large enough to cause knock-on collisions with bound electrons in the lattice. This process frees additional electrons, which undergo new collisions. The multiplication process occurs many times, with the result that a single electron generates hundreds or thousands of free electrons, thus producing a significant net gain in the current. APD gains of up to 10,000 at room temperature are possible, and the signal is proportional to the gain. The noise has a more complicated dependence. For low values of gain, the noise is almost constant; but at high values, it increases rapidly. There is some optimum value where the maximum signal-to-noise ratio is obtained. This optimum value is much higher than is achievable in detectors without internal gain. The higher signal size also relaxes the requirements on subsequent electronics.

APDs as Particle Detectors. Although avalanche diodes were initially investigated for use as large-area optical sensors, they are also sensitive to directly incident ionizing radiation, including X rays, alpha particles, and beta particles. The high signal-to-noise ratio due to the internal gain makes them particularly useful for detecting low-energy radiation. The higher-energy beta particles, including those from ^{90}Sr, ^{35}S, and ^{32}P, are detected with very high efficiency. APDs can be used to detect the low-energy beta particles from ^{3}H with about 50% efficiency.

APDs can also be used to detect low-energy X rays, such as the 5.9 keV X rays from ^{55}Fe. At 5.9 keV, an energy resolution of 550 eV is achievable. The noise level in APDs can be as low as about 200 eV, so that noise does not limit sensitivity. APDs are sensitive to X rays over the range of about 1 keV to about 20 keV. Below 1 keV, most of the X rays are stopped in the front surface dead layer; above 20 keV, the radiation begins to be too penetrating for high efficiency.

Silicon Strip Detectors. Silicon strip detectors and microstrip detectors are silicon devices which are fabricated using planar processing techniques and which can be made relatively large and have position sensitivity. They are used in high-energy physics experiments to determine the energy and position (track) of ionizing particles. One face of the device is fabricated with thin parallel strips which provide one-dimensional position resolution on the order a few micrometers.

Silicon Drift Detectors. Figure 4(e) shows the cross section of a silicon drift diode (SDD). As discussed above, lowering the capacitance of the device improves performance. It is possible to significantly decrease the capacitance further using silicon drift diodes. This device uses a similar strip electrode structure to the microstrip detector, but strip electrodes are fabricated on both sides of the device. An electric field is created that forces the charges to drift laterally in the silicon. There appears to be great promise in this relatively new Si device structure, the silicon drift diode (21–23). The low capacitance of drift diodes results from the use of a very small anode and in conjunction with a series of cathode strips held at varying bias voltages. The charges generated by an ionizing event drift laterally in the device until close to the anode where they are collected. The high mobility and long lifetimes in silicon make it possible to collect these charges over devices many millimeters across. The capacitance is reduced to the point that performance is limited by the stray capacitance in the system. To address this limitation, device structures have been made with the first-stage FET fabricated on the silicon as part of the device structure.

New Detector Materials

Although no other materials have been studied as extensively as Si, Ge, CdTe, and HgI_2, a considerable level of interest has recently developed in three materials: GaAs, TlBr, and PbI_2 (24). GaAs has seemed like an ideal candidate for many years because it has a bandgap similar to CdTe but has much higher electron mobility (8000 cm^2/V). However, the very short lifetimes limit the $\mu\tau$ product to below 10^{-4} cm^2/V-s. GaAs has been considered for uses where very fast measurement times or very high intensities are encountered. TlBr and PbI_2 are two of several materials that, like HgI_2, have wider bandgaps than Si or CdTe. Neither material is as advanced as HgI_2, but both can be grown from the melt and have high environmental and chemical stability. Some of the other materials that have been investigated are listed in Table 2.

In addition to single-crystal detectors, several materials have been examined for use in radiographic imaging in polycrystalline or amorphous thin film form. For example, Se and CdS have been used in the photoconductive mode as xeroradiographic films, and thin films of a number of materials including CdS, CdSe, and GaAs have been used to fabricate arrays of diodes or transistors for digital imaging.

Amorphous silicon (a-Si) device technology offers the promise of very-large-area imaging detectors for medical radiography. By itself, the stopping power is quite low, but can be improved by adding an X-ray conversion layer to it. There is presently a great deal of interest in a-Se and PbI_2 films for use on hybrid devices in which a layer of high-Z conversion material is bonded to a readout device such as a CCD or an a-Si imaging device.

SUMMARY

Solid-state radiation detectors provide unique and diverse capabilities in many technological areas. Two factors have made this the fastest-growing segment of radiation detection technology. These are (i) the desire for digital radiography and (ii) the availability of low-cost, high-performance computers to handle the large amounts of data generated using a large number of solid-state detector elements. The limitations of existing technologies have made the search for new device structures (such as the drift diode) and new materials (such as PbI_2 semiconductor films and LSO scintillators) very active areas of research and development which promise to advance the field at an unprecedented rate over the next decade.

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