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NUCLEAR RADIATION DETECTORS
E. E. Haller and F. S. Goulding

Introduction

This volume of the handbook of semiconductors contains many examples of semiconductor devices. The theory of junctions which forms the basis for many of these devices is considered in Chapter 1. The unique feature of semiconductor detectors for various types of energetic electromagnetic radiation or charged particles is the need for thick sensitive regions, since these radiations are generally very penetrating. This is in contrast, for example, to visible light photodiodes where the incident radiation is absorbed very close (<1 µm) to the surface of a semiconductor. Therefore, emphasis in semiconductor high-energy radiation detectors is on reversed-biased junctions made from relatively high-resistivity semiconductors, so that the depletion layers, which form the sensitive regions of such detectors, are quite thick (up to a few centimeters in some cases) and are well matched to the absorption length of the radiation to be detected (and measured).

The demanding requirements on semiconductor materials to be used for these detectors are illustrated by the observation that the volume of radiation detectors is commonly as much as 10^8 times that of a transistor. Furthermore, almost perfect carrier transport (~99.9% or more) must be achieved over distances ranging up to one or more centimeters. These requirements mean that very pure materials with extremely small concentrations of trapping centers must be used. These properties must apply throughout large volumes--sometimes as much as 100 cm^3.
Added to these requirements is a frequent need to operate detectors at low temperatures (usually 77°K) to reduce leakage current and its attendant noise. In the case of germanium detectors, such operation is obligatory due to the small bandgap of this semiconductor. Silicon and some other detector materials (CdTe, HgI₂) can be used at or above room temperature in some applications but even in the case of silicon low temperature operation is frequently beneficial.

Another distinctive feature of semiconductor detectors is their large sensitive surfaces which do not lend themselves to the passivation procedures used in many semiconductor devices.

Radiation detectors are generally used not only to detect radiation but to measure the energy of individual, randomly-occurring photons or particles and thereby construct a spectral (i.e. energy) distribution curve. Much of nuclear spectroscopy is carried out using such detectors and most of the information on nuclear structure has come from this source. The range of energies measured by semiconductor radiation detectors is extremely broad spanning from ~100 eV to many GeV.

In order to measure the energies accurately, severe conditions must be imposed on such factors as electronic noise, charge trapping in the detector material, etc. These will be discussed in the course of this section. For an indepth study of nuclear radiation detection with semiconductors we refer to the books by Dearnaley and Northrop (1966)\(^{(1)}\) and Bertolini and Coche (1968)\(^{(2)}\) and to a more recent article by Goulding and Pehl (1974)\(^{(3)}\).
2. Absorption of Radiation

2.1 Electrons

Semiconductor detectors are used to measure electron energy spectra at energies ranging up to 1 MeV or more. The pulse amplitude spectrum obtained when a detector is irradiated with monoenergetic electrons consists of a narrow peak corresponding to the incident electron's full energy and a relatively flat background (~10% of the total events) ranging from zero to the full amplitude. This background results from the escape of electrons from the entry surface of the detector which causes some loss in the charge which is produced by total absorption of the incident electron's energy in the detector.

The low mass of electrons causes them to be easily deflected from their original direction, and although most interactions are long-range Coulomb exchanges, occasional close collisions with electrons and atoms in the detector material cause severe changes in the electron's direction. Consequently, high-energy electrons are not characterized by a well-defined range, as in the case of heavier particles, but an extrapolated range can be determined which corresponds to the maximum path length of electrons of a given energy. Ideally, a detector designed to measure the energy of electrons by total absorption should be thicker than the extrapolated range shown in Fig. 1 (Berger and Seltzer, 1964). However, a full-energy peak of somewhat reduced intensity is observed.
when detectors thinner than the extrapolated range are used; this peak is produced by electrons whose tortuous path stays within the detector.

While detectors are typically used to measure the energy of electrons, it is sometimes of interest to determine their rate of energy loss. In this case, thin detectors, which sample only a small fraction of an electron's range, can be used to measure dE/dx. Figure 2 shows the average energy loss per micron in silicon and germanium as a function of electron energy. The high probability of large energy exchanges occurring in an electron's path (due to the low mass of the electron) makes such dE/dx measurements subject to large signal amplitude fluctuations. Figure 2 is also very useful in determining the expected energy loss resulting from an absorbing layer which might be present on the entry surface of the detector.

Along the track of each primary electron and its high-energy secondaries showers of electrons and holes are produced. The relatively high-energy electrons and holes (i.e., "hot" in semiconductor parlance) produce secondary holes and electrons which, in turn, produce more secondaries until the final products have insufficient energy to produce further ionization. Competing with the ionization process are energy losses by phonon emission (i.e., excitation of lattice vibrational modes) which do not produce a useful charge signal in the detector. The statistical nature of sharing of energy losses
between phonon emission and ionization provides a basic fluctuation in the signals produced by monoenergetic electrons. Since all other types of radiation are, in the final analysis, determined by measuring the sum of secondary electrons and holes produced in the detector, this charge fluctuation is a significant factor in the energy resolution that can be achieved in all radiation spectrometry using semiconductor detectors.

2.2 Heavy Charged Particles

Heavy-charged particles, such as protons, α-particles and heavier ions, are not substantially deflected from their path by interactions along the track. Therefore, in contrast to electrons, they follow a straight path and have a well-defined range. They leave behind a track consisting of a plasma of electrons and holes released by the (Coulomb) ionization process. The density of ionization increases drastically as the particle slows down near the end of its track ("Bragg peak").

The range \( R \) of a heavy particle is found empirically to obey a power law:

\[
R = A E^B
\]

where \( E \) is the particle energy, \( A \) is a function of the type of particle and absorber and \( B \) is very nearly constant. Its value is approximately 1.73 for normal energies of light particles such as protons and α-particles, but it varies slowly (to lower values) for heavy ions and slow particles.
Range-energy curves\(^{(5)}\) for several types of particles in silicon and germanium are shown in Fig. 3.

The energy loss of charged particles in crystalline materials can be influenced by channeling caused by the low average electron density along preferred crystal axes between the atomic "rows." This results in charged particles exhibiting abnormally long ranges in these preferred crystal directions. This effect can be very serious in \(\Delta E\) detectors where only a small amount of a particle's energy is deposited in a thin detector. Such detectors should always be arranged so that incident particles touch off major crystal axes. The energy loss is then well defined. Figure 4 shows the variation of \(dE/dx\) for a number of ions in silicon as a function of energy.\(^{(5)}\)

2.3 **Photons**

Semiconductor detectors are often used in \(\gamma\)-ray and X-ray spectroscopy. Unlike charged particles, photons do not directly produce ionization; instead the photon must interact in the detector material to produce one or more electrons (or an electron-positron pair) which then produce ionization and a measurable signal. For the signal to be a good representation of the energy of the incident photon it is desirable that the photon energy is completely converted into kinetic energy of electrons in the material and that no energy escapes from the volume of the detector in the
form of low-energy photons, back scattered or secondary electrons.

Three basic interaction processes are dominant in converting the incident photon energy into electrons in a detector:

(i) **Photoelectric Effect**

This process results in the total absorption of a photon and release of an electron from an atom of the detector material. The photoelectron energy is equal to the incident photon energy minus the binding energy of the electron in its parent atom. The X-rays subsequently emitted by vacancy filling the shells of the parent atom are generally absorbed in a very short distance in the detector, so the total signal corresponds to total conversion of the original photon energy into kinetic energy of electrons.

The presence of a large mass is required to conserve momentum in the photoelectric process. Consequently, the innermost or K-shell electrons participate most in this process and the probability of an interaction is a strong function of the atomic number of the absorbing material.

Theory predicts the relationship:

\[ P_{\alpha} = \frac{Z^5}{E^{3.5}} \]  

where \( P \) is the probability of a photon of energy \( E \) interacting with an electron in a material of atomic
number Z. The low Z of silicon prohibits its use for photoelectric detection of photons of energy greater than 30 keV and higher-Z materials (e.g., germanium, CdTe and HgI₂) must be used for most γ-ray applications.

(ii) Compton Effect

This is the classical "billiard ball" collision process whereby the photon strikes an electron resulting in the electron acquiring some of the photon's original energy and leaving a lower energy photon with the remaining energy. The maximum energy $E_{\text{max}}$ given to the electron (in a head-on collision) is:

$$E_{\text{max}} = E/(1-2m_0c^2/E)$$

where $E$ is the photon energy in keV, $m_0$ is the rest mass of an electron and $c$ is the velocity of light ($m_0c^2 = 511$ keV). In a spectrum the Compton effect produces a generally flat pulse height distribution up to the energy given by Eq. (3) which is known as the "Compton edge" while the photoelectric effect produces a narrow peak at an amplitude equivalent to the energy $E$. At high incident photon energies, the photoelectric effect becomes quite improbable (see Eq. 2) but the Compton process remains relatively effective since its probability is given by:

$$P \propto E^{-2}$$

This is fortunate because the Compton-scattered photons stand a good chance of producing photoelectrons; in
this case the summed energies of the Compton-produced electron and the photoelectron is equal to \( E \), and the double event appears as one count in the full amplitude peak. Over much of the gamma-ray energy range (i.e., \( \sim 200 \) keV to 2 MeV) this double (or multiple) process contributes most of the counts in the full-energy peak.

(iii) **Pair Production**

This process can only take place when the incident photon energy exceeds the 1.02 MeV required to create an electron-positron pair. The excess energy (over the 1.02 MeV) appears as kinetic energy of the electron and positron which then produce ionization along their tracks. When the positron comes to rest, it annihilates to produce two 511 keV photons which travel in opposite directions.

The spectrum produced by this process always contains features whose relative intensities depend on the particular geometry of the detector. A full energy peak is produced when both 511 keV annihilation photons are absorbed in the detector, a peak 511 keV below the full energy corresponds to the escape of one 511 keV photon (single escape) while a third peak of 1.02 MeV below the full energy corresponds to escape of both 511 keV photons (double escape).

Generally, a gamma ray or X-ray spectrum produced by a detector consists of the appropriate mix of the results of these processes. Since all are statistical in nature, the differential decrease of a flux \( I \) of
photons in passing through a slice of absorber $dx$ in thickness is given by:

$$dI = -I_0 \alpha dx$$

(5)

where $\alpha$ is the absorption coefficient for the radiation. This equation may be applied to a single process, in which case $\alpha$ is the absorption coefficient for that process. Integration gives:

$$I = I_0 \exp(-\alpha x)$$

(6)

where $I_0$ is the incident flux, $I$ is the flux at depth $x$ in the solid and $\alpha$ is the total absorption coefficient. Experimental values for the absorption coefficient as a function of energy are shown in Figs. 5 and 6 for silicon and germanium, respectively.

In some applications interactions in surrounding material may contribute undesirable background and peaks in a spectrum. Here care must be taken in the design of the detector holder and in interpretation of the spectrum. A typical $\gamma$-ray spectrum is shown in Fig. 7.

2.4 Neutral Particles

Neutral particles such as neutrons do not interact directly with electrons in a detector to produce signals that are characteristic of the absorbed energy. Generally speaking, the energy of these particles must be transferred to a charged particle in some way (e.g., by knocking on a proton in a hydrogen-rich blanket or an atom in the semi-
conductor detector) in order to permit spectroscopy using semiconductor detectors. Protons and heavier particles, however, do interact in detectors by displacing atoms from their lattice sites. This is one of the main sources of radiation damage as discussed in the next section.

2.5 Radiation Damage

Semiconductor detectors are particularly susceptible to radiation damage since the detector material is always in the form of a single crystal and any charge trapping which might occur at defects seriously degrades performance. Furthermore, detector materials are generally of very high resistivity and the doping which can result from nuclear reactions changes the material resistivity and, therefore, the depletion layer thickness.

Radiation damage occurs when the particle energy is dissipated by displacement of atoms of the detector material or when nuclear reactions occur between the incoming particle and nuclei in the detector. Neutrons are particularly effective at producing radiation damage since they lose no energy by ionization and they have no Coulomb barrier to penetrate in order to react with the nuclei of atoms in the detector. A single neutron of 1 MeV energy may transfer as much as 133 keV to a silicon atom. Slow neutrons do not impact sufficient energy to silicon atoms to produce knock-on damage, but such neutrons are very effective at transmuting elements.
For example, $^{30}\text{Si}$ which constitutes 4% of silicon is converted by the process:

$$^{30}\text{Si} + n \rightarrow ^{31}\text{P} + \beta$$

and the resulting phosphorus acts as a donor in the semiconductor. This process is sometimes employed deliberately as a mechanism to achieve very homogenous doping (see Volume II, Chapter 1).

Heavy charged particles, such as protons, $\alpha$-particles and heavy ions also produce damage but the competing energy-loss mechanisms make damage from these particles a less serious problem than from neutrons in most applications.

From a practical point of view it is important to know the radiation dose at which damage becomes important. Unfortunately, the wide range of types of detector and radiation and the different sensitivities of measurement in different applications make a general statement of a damage threshold impossible. For example, damage in a thin highly-doped detector may not be significant until it has been bombarded with $10^{12}$ electrons, but a thick high-purity germanium detector's performance may be significantly degraded after $10^7$ high-energy protons have passed through it. The temperature of the detector during irradiation and the temperature at which the detector is tested may also be important because radiation damage creation and annealing and charge trapping depend all strongly on temperature. It is also very important to know that radiation damage in detectors can be removed.
by suitable processing in many cases. Thus, high-purity germanium detector damage can be annealed at quite moderate temperatures (0 to 150°C depending on the speed and degree of recovery required). (6) Damage in lithium-drifted detectors can be cured by redrifting lithium.

3. Charge Production and Collection

3.1 Ionization

As mentioned earlier, the energy of incoming charged particles or of the electrons produced by absorption of high-energy photons is dissipated partly in phonon emission (i.e., lattice heating) and partly in ionization. Only the latter process produces a useful signal. A detailed picture of the ionization process involves consideration of the many discrete interactions which constitute the ionization shower. However, the most useful practical fact is that the total number \( N \) of the electron-hole pairs produced is a linear function of the energy dissipated and is practically independent on the type of radiation. Therefore, we can write:

\[
N = \frac{E}{\epsilon}
\]  

(7)

where \( \epsilon \) is the average energy required to produce a electron-hole pair. The value of \( E \) is a few electron volts for semiconductors, which is approximately ten times smaller than the equivalent quantity for gases. Detailed calculations of the ionization shower process lead to the predicted \( \epsilon \) dependence of \( E \) on bandgap shown in Fig. 8. (7) Obviously,
\( \varepsilon \) is smaller for semiconductors exhibiting small bandgaps, but low temperature operation, with its attendant problems, may be necessary to reduce generation current. For example germanium with a bandgap of 0.7 eV must be operated at low temperatures—usually liquid nitrogen temperature (77 K)—to reduce detector leakage current to an acceptable level.

The statistical sharing of energy losses between ionizing and phonon interactions results in a fluctuation in the signals produced by monoenergetic incident radiation (photons or charged particles). Obviously, in the impossible situation that all the incident energy is expended in ionizing processes no spread in signal amplitudes can occur. On the other hand, if phonon processes were totally dominant and ionization occurred only occasionally, normal statistics would prevail and the variance \( \sigma \) in the number \( N \) should be equal to \( \sqrt{N} \).

The actual situation lies between these extremes so we can write:

\[
\sigma = \sqrt{FN} = \sqrt{FE \frac{F}{\varepsilon}} \tag{8}
\]

and

\[
\text{FWHM} = 2 \sqrt{2 \ln 2} \sigma \tag{9}
\]

\[
= 2.35 \sigma
\]

where: \( F \) is a factor smaller than unity called the Fano factor \((8)\) whose value depends on the details of the shower process; FWHM is the full width at half maximum of the distribution in \( N \).
The smallest experimentally-measured Fano factor for germanium is $0.08^{(9)}$ and a value of $0.11^{(10)}$ has been observed for silicon. These values are somewhat larger than predicted by theory but since the theory is very sensitive to poorly known details of the shower process, the agreement is quite good.

At first sight it is surprising that the value of $\varepsilon$ is independent of the type of energy of incident radiation. However, the dominant production of electron-hole pairs occurs at the low-energy "tails" of the shower process and these are quite insensitive to the details of the high-energy processes that led to their existence. Therefore, the result is not too surprising.

3.2 Charge Collection
3.2.1 Diode Structures

In order for a charge signal to appear in the external circuit associated with a detector, the holes and electrons produced by the ionization process must be collected at the detector electrodes. To accomplish this, an electric field must be present through the sensitive volume of the detector and the strength of the field must be adequate to produce fast collection before recombination or trapping occurs.

The most common method of achieving the required electric field in the volume of a detector is to employ p-n or p-i-n junction structures biased in the reverse
direction. In the former case, the depletion layer reaches only part way through the material and the sensitive detection volume is limited to the depletion layer. In the p-i-n diode, the "intrinsic" or high resistivity bulk is totally depleted and thin p and n opposing faces provide non-injecting contacts.

Figure 9 illustrates the use of a p-i-n detector for γ-ray detection. For the sake of simplicity, we will assume that the electric field throughout the detector volume is sufficient to cause both holes and electrons to travel at their saturation velocity $v_{\text{sat}}$ ($\sim 10^7$ cm/s). This is not difficult to achieve at the low temperatures typically used for germanium γ-ray detectors where the reduction of lattice scattering yields very high mobilities ($\sim 4 \times 10^4$ cm$^2$ V$^{-1}$ s$^{-1}$) for both carriers. If we assume that the γ-ray intersects at distance $X$ (cm) from the p$^+$ contact, and that the electron-hole shower occupies a dimension much smaller than the total detector thickness $W$ (cm), the external signal will consist of two parts:

(i) That due to electrons traveling over the distance $(W - X)$ being collected in a time $t_e = (W - X)/v_{\text{sat}}$.

(ii) That due to holes traveling over the distance $X$ being collected in a time $t_h = X/v_{\text{sat}}$. The total charge signal will always be equal to $Nq$ where $N$ is
the number of electron-hole pairs originally produced and $q$ is the electronic charge. However, the rise time of the signal is dependent on the value of $X$, with the largest rise time occurring when the interaction occurs near to a contact ($t = W/v_{sat}$) and the shortest when it occurs in the middle of the detector ($t = W/2v_{sat}$).

3.2.2 Resistive Detectors

A p-n junction is not essential for achieving an electric field in the bulk material. In fact, semi-insulating or insulating materials with electrodes on opposite faces can be used as detectors. They are sometimes called resistive detectors. A number of materials ranging from cooled (770K) gold-doped silicon to CdTe and HgI$_2$ have been used in this mode. Clearly, the materials used in this manner must have very high resistivity at the operating temperature in order to reduce leakage currents to a negligible value. This implies the use of relatively wide bandgap materials in which deep trapping levels will be common. A further difficulty clearly exists in providing the required contacts since these must be able to neutralize carriers reaching the interface between the contact and detector material while, at the same time not injecting charge into the bulk. If injection can occur, preferential trapping of one carrier in the bulk will cause injection
of the opposite carrier from the contact and the charge multiplication process well known in CdS photodetectors results. The variable nature of this amplification process prohibits its use in radiation detectors. Another common feature of these resistive detectors is the phenomena of polarization which results when single carrier trapping occurs in the bulk. Here the trapping process produces charge in the lattice which reduces the electric field in parts of the bulk to a very low value and causes poor charge collection in later events.

At the present time promising results are being obtained with HgI₂ and CdTe detectors in applications where the ultimate energy resolution is not required. However, a substantial amount of work will be required before the phenomena associated with contacts and trapping are understood and controlled. For this reason, junction detectors made on simple semiconductors such as silicon and germanium are dominant in all radiation energy measurements.

3.2.3 Charge Trapping

High resolution spectroscopy demands almost perfect charge collection of carriers over distances as large as 1 cm or more. This is illustrated by the case of a germanium γ-ray detector detecting 1 MeV γ-rays. According to Eqs. 8 and 9 with a Fano factor
F = 0.08 and ε = 2.96 eV, the anticipated detector signal fluctuation (FWHM) will be 1.15 keV—or approximately 0.1% of the signal. Since γ-rays interact anywhere in the detector volume and the resulting holes and electrons travel different distances depending on the interaction point, it is obvious that any significant probability of a carrier being trapped will seriously degrade the energy resolution. Models of the effects of trapping on spectral line shape have been developed by Trammell and Walter (1969)(12), Mayer (1970)(13) and Webb et al (1968). (14) These models indicate that mean trapping lengths, the distance an electron or hole travels before getting trapped, greater than 100 cm are necessary to prevent serious spectral line distortion in typical γ-ray detector.

All deep donors and acceptors produce effective traps. For example, copper, nickel and gold all produce deep acceptor levels in Ge as do complexes of impurities and point defects such as vacancies. Defects such as dislocations (Glasow et al, 1976)(15) also produce traps. In view of the abundance of trapping possibilities, it is indeed surprising that germanium and silicon crystals can be produced which meet the demanding requirements for radiation detectors and which show virtually no spectral line degradation as compared with the ultimate expected performance.
4. Detector Structures

4.1 Introduction

The previous section indicates many of the aspects of detectors and demonstrates the essential material properties. The broad range of applications has resulted in a variety of types of detectors and a wide range of techniques has been developed associated with contacts and surface treatments. While many recipes exist and much of the art is poorly understood, we will confine ourselves here to a brief description of the dominant types of detectors.

4.2 Partially-depleted Silicon Detectors

The simplest type of radiation detector is a conventional p+-n or n+-p diode made from either p- or n-type bulk material with a thin heavily doped surface layer of the opposite type. For example, such a detector might consist of a slice of high resistivity (∼1,000 Ω·cm) p-type silicon and a thin diffused n+ layer (∼2,000 Å thick) made on one face by a relatively low-temperature (950°C) brief (∼30 min) phosphorus diffusion. The thin surface junction is then reverse biased with a voltage ∼100 volts to produce a depletion layer ∼100 μm thick. Figure 10 shows a structure of this type. Such detectors are only useful for detection of short-range charged particles (e.g., 10 MeV α-particles) whose range is smaller than the relatively small depletion layer thickness.
A more common variety of this detector is the so-called "surface barrier" detector made by forming a Schottky barrier by a metal evaporation onto the surface of a suitably etched and prepared silicon slice. Gold evaporations on n-type materials are the commonest type, although, aluminum evaporations on p-type material are also used. Palladium and platinum silicide barriers are also used with the advantage that the barrier is within the solid material and less subject to damage. Furthermore, while the operation of a gold surface barrier depends on the poorly controlled interface layer between the metal and bulk, the silicide barrier is inside the semiconductor and its behavior is well understood. These surface barrier detectors can generally be produced with very thin surface "dead" layers compared with diffused devices. Furthermore, the surface barrier process avoids high-temperature treatments which are likely to introduce unknown impurities into the silicon and which often change the resistivity. Ion implantation is also used to form thin surface junctions; this technique is rapidly becoming more widespread due to the excellent control that can be achieved. For example, controlled high-resistivity layers can be produced and the high sheet resistance of the surface layer can be used to provide sensing of the position of an event across the surface. Position-sensitive detectors of this type are very useful in many types of experiment.
The reverse leakage current characteristics of all these devices is very dependent on the electrical characteristics of the surface at the edge of the junction. Therefore, much of the art of making detectors is concerned with surface treatments and protection. Oxide passivation and masking can be used in diffused detectors but surface barriers and ion implanted devices do not lend themselves to these techniques. Therefore, various types of surface coatings are used to set the surface states and to protect them from the effects of ambient conditions. These special treatments have been developed to produce almost neutral surfaces on detectors.

Figure 11 shows cut-away views of an n⁺-p-p⁺ device with surface channels that accumulate electrons (n-type channel) or holes (p-type channel). An n-type surface channel such as shown in Fig. 11A, acts as an extension of the n⁺-face and the relatively poor junction it forms with the bulk causes the device to exhibit high-leakage current. If the surface is p-type, as in Fig. 11B, the leakage will be low at low voltages, but the junction at the point where the p-type surface meet the heavily doped n⁺-layer exhibits a low breakdown voltage. These simple arguments indicate the need for relatively neutral surfaces.

The depletion layer thickness \( W \) of a junction or surface barrier detector is given by:

\[
W = \sqrt{\frac{2K_0(V_D + V_O)/q}{N_A - N_D}} \quad (10)
\]
where $K = \text{dielectric constant of the bulk material} \ (K_{Si} = 12; \ K_{Ge} = 16)$

$K_0 = \text{permittivity of vacuum} \ (8.85 \times 10^{-14} \text{ C V}^{-1} \text{ cm}^{-1})$

$V_D = \text{diffusion (built-in) potential} \ (S_{Si} \approx 0.7 \text{ V}, \ Ge \approx 0.2 \text{ V})$

$q = \text{electronic charge} \ (1.6 \times 10^{-19} \text{ C})$

$|N_A - N_D| = \text{net-acceptor (or donor) concentration} \ (\text{cm}^{-3})$.

This equation assumes that the thin $p^+$- or $n^+$-contact is very heavily doped so the penetration of the depletion layer into them is negligible.

4.3 **Totally-depleted Silicon Detectors**

In the type of detector discussed in the previous section, the depletion layer, whose thickness can be calculated from Eq. 10, is assumed not to penetrate through the bulk material. Therefore, part of the original wafer material remains undepleted. In E or transmission detectors, which are designed to sample the energy loss in a small portion of a particle's track, the presence of this "dead" material is obviously not acceptable. Therefore, in such detectors, the depletion layer is made to occupy the whole bulk and the back of the depletion layer terminates on a highly-doped surface layer. The need to prevent charge injection at the contacts implies that these totally depleted detectors have the form $n^+\text{-}n\text{-}p^+, \ n^+\text{-}p\text{-}p^+ \ or \ n^+\text{-}i\text{-}p^+$.

The highly-doped faces may be diffused or implanted or can be Schottky barriers. If the bulk material resistivity
is high (usually referred to as i; intrinsic) the electric field will be rather constant in the main bulk and electric field lines practically all reach from the n⁺-to the p⁺-contact.

Transmission detectors are designed for their specific application. Consequently, thicknesses as small as a few microns are required in some cases. It is also often essential that the devices have very uniform thickness since particles may traverse the detector at any point across its area. Preferential etching techniques on epitaxial n⁺-n or p⁺-p wafers have been developed for the preparation of very thin uniform wafers. These methods retain a thick surrounding silicon ring which serves to support the fragile thin detector region.

Transmission detectors are generally used as the front detector in a ΔE-E detector telescope. The signals obtained from the two detectors can be suitably processed to provide a unique identification of light charged particles (Z<10)(16) and the total signal E + ΔE provides a measurement of energy.

4.4 Lithium-drifted Silicon Detectors

The best available methods of purification of silicon yield silicon crystals with net-impurity concentrations in the $10^{11} - 10^{12}$ cm⁻³. Consequently, the depletion layer thickness that can be achieved at reasonable bias voltages (limited by surface breakdown) are restricted to values of 1 mm or thereabouts (Eq. 10). Achieving thick
sensitive regions requires the use of a compensation process. Fortunately, the lithium-drifting process discovered by Pell (1960) provides an automatic compensation mechanism whereby virtually intrinsic silicon can be produced by drifting lithium (a fast diffusing interstitial donor) into p-type material. Figure 12 shows the process. As shown in the figure, any under or over compensation is automatically corrected by the electron field gradient it causes.

The presence of oxygen in silicon crystals severely affects lithium-drifting. The formation of Li-O donors, which are relatively immobile, slows down the drift process, which is already quite slow, to an intolerable degree. Therefore, low oxygen crystals such as those produced by the vacuum float-zone process are used exclusively for lithium-drifted detectors.

Figure 12 shows a cross-section of a typical "top-hat" lithium-drifted detector. The n\(^+\)-contact is the original lithium-diffused region which formed the lithium source for the drift process. Following the drifting process, which produced the intrinsic bulk, a shallow well is etched into the drifted region and a Schottky barrier is produced on this surface by gold evaporation. The net-impurity concentration in the bulk of such a device is usually in the \(10^8/\text{cm}^3\) range when the drift process is ended at a relatively low temperature (\(\sim 100^\circ\text{C}\)). If high-drift temperatures are used, the compensation process will correct
for the charge (in the form of holes and electrons) in transit across the detector and the compensation will then be poor. The potential electric field strength and space charge in an ideally compensated device are shown in Fig. 14.

Lithium-drifted silicon detectors are used for charged particle and X-ray spectroscopy. In the latter case, the detector is used at low temperature (770K) to reduce leakage current. These detectors are the essential element in X-ray fluorescence spectrometers so widely used now for elemental analysis of samples (Fig. 15).

From a practical point of view the thickness of lithium-drifted silicon detectors is limited to about 0.5 cm. This limits the range of particles that can be analyzed but, fortunately, 0.5 cm of silicon is sufficient for a broad range of applications. In fact lithium-drifted silicon detectors have been the dominant tool in charged-particle nuclear spectroscopy over the past 15 years.

4.5 Lithium-drifted Germanium Detectors

The fifth-power dependence (Eq. 2) of γ-ray absorption by photo effect on the atomic number of the absorber results in silicon detectors being of little use for γ-ray spectroscopy. However, the lithium-drift process works well for germanium too and permits the fabrication of the large volume germanium (Ge(Li)) detectors which are the outstanding tool in γ-ray spectroscopy.
The two basic geometries shown in Fig. 16 are employed. In planar devices lithium-drifting is usually terminated before the germanium slice is completely drifted through, so a layer of the original p-type germanium remains to form a p-type contact for the detector. This layer is sometimes removed and a metal Schottky barrier is employed to provide a non-injecting contact. The coaxial geometry, which involves drifting inward from a lithium-diffused region on the outside of a cylinder, produces the large-volume detectors required for high-efficiency γ-ray detection. Sensitive volumes up to 200 cm$^3$ have been produced by this process.

Low-temperature operation is essential for germanium detectors to reduce the thermally-generated bulk leakage current to a value that is acceptable from the point of view of noise. Liquid nitrogen is usually used to provide cooling to 77°K, although, studies have shown that operation at temperatures up to approximately 150°K is possible. It should be noted that cooling of lithium-drifted germanium detectors is essential at all times because the room-temperature mobility of lithium in germanium is high enough to result in loss of the compensation in the drifted region in a few minutes at room temperature. If a detector is maintained with bias at room temperature, lithium-drifting occurs at a fairly high rate.
The surfaces of germanium detectors are very sensitive to contamination. Consequently, such detectors are normally maintained in a vacuum cryostat pumped to low pressure (~10^{-6} torr). Cryo-pumping is convenient since the same liquid nitrogen used to cool the detector can also provide the cooling required for a molecular sieve cryo-pump. Ion-getter pumping is also used in cryostats.

4.6 High-Purity Germanium Detectors

The high mobility of lithium ions in germanium at room temperature causes severe problems in handling lithium-drifted germanium detectors during etching and mounting operations. While these difficulties are faced and solved in single detector systems they rapidly become prohibitive in multi-detector systems. Furthermore, either unintentional or deliberate warm-up of lithium-drifted germanium detector systems results in severe detector degradation in a very short time. These considerations stimulated the development of high-purity germanium for use in radiation detectors. Equation 10 shows that a net-impurity concentration $2 \times 10^{10}$ cm$^{-3}$ is required if 1 cm of germanium is to be depleted at 1000 V bias. Therefore, a purity level of 1 part in $2 \times 10^{12}$ is necessary.

Achieving this goal has required the development of new zone refining and crystal growing techniques. Furthermore, new methods of analyzing very pure materials were adopted. The most notable analysis technique has been photoelectric
spectroscopy which has permitted determination of shallow impurities (type, element and approximate concentration) at concentration levels well below the $10^{10}$ cm$^{-3}$ range. With the aid of these techniques, growth of germanium crystals with net-impurity concentrations below $2 \times 10^{10}$ cm$^{-3}$ has become a practical proposition and a number of sources of such material now exists. Using this material the techniques for making both planar and coaxial detectors have been developed. Beside the advantages of room temperature handling and storage further advantages have been demonstrated for these high-purity germanium detectors:

i) Since no undepleted material is present in these detectors, slow pulses produced by diffusion of carriers form undrifted material into the drifted region of Li-drifted detectors are absent.

ii) The lack of undepleted material in the case of coaxial detectors improves the Peak/Compton ratio.

iii) Repair of damage in high-purity germanium detectors can be accomplished by a simple thermal annealing cycle whereas redrifting is necessary in Li-drifted detectors.

iv) Coaxial detectors with p$^+$ on the outside and n$^+$ on the inside can be produced. The predominance of hole trapping in radiation damaged germanium makes such detectors far less sensitive to radiation damage than detectors made with n$^+$ on the outside and p$^+$ on the inside (as is the case in Li-drifted detectors).
These advantages are rapidly resulting in high-purity detectors replacing lithium-drifted detectors in many applications.

4.7 CdTe and HgI₂ Detectors

Where energy resolution is not a dominant consideration resistive detectors as described in 3.2.2 can be employed. Notable work on detectors of this type has focused on CdTe\(^{(19)}\) and HgI₂.\(^{(20)}\) Wide application of such detectors will depend on a better understanding of trapping, polarization and other problems and on solving these problems. However, a number of applications (e.g., nuclear reactor monitoring, medical probes) have been studied and these detectors are being applied to some degree in these areas.

5. Signal Processing

The signals produced by semiconductor detectors consist of individual short current pulses occurring randomly in time. The signal processing problem consists of measuring the integral of the current in each pulse with the highest possible accuracy. Noise analysis is quite different in this application than in normal systems where the analysis is carried out in the frequency domain. Here it is more appropriate to work in the time domain. The signals may be very small. For example, X-ray spectroscopy using such detectors may involve the measurement of events depositing less than 1 keV in the detector and therefore producing a signal consisting of less than 300 electron-hole pairs. Furthermore, these signals must be measured with a FWHM spread of approximately
10% corresponding to a variance ($\sigma$) of less than 40 electrons. This spread includes all contributing factors such as the statistical fluctuations in charge production in the detector, fluctuation (noise) in the detector leakage current and noise in the signal amplifier. This example illustrates the severe demands placed on the signal processing electronics. The scope of this section does not include a detailed treatment of the subject of signal processing electronics and reference should be made to suitable texts. (21) No discussion of detectors would be complete without a brief outline of the basic aspects of the detector signal processing channel.

The key element in the signal processing system is the input amplifying element. In a well-designed system its noise is dominant and that of later stages is negligible. Junction field-effect transistors (FET's) have proven to be by far the best input elements. Many types of junction FET can be cooled to low temperatures to reduce their noise well below their room temperature values.

Three basic types of noise are present in a system:

(i) **Parallel noise:** due to shunt components (e.g., high-value resistors) and leakage currents in the input circuit. Leakage currents include detector leakage and FET drain-gate leakage components. An important parallel noise source may be loss in feed-throughs such as the gate insulator of the FET header. For this reason, FET's are often mounted in special low-loss headers for this application.
The effect of parallel noise on the signal/noise ratio becomes stronger as the measurement time is increased. This results from the integration of charges on the capacitance of the input circuit which produces noise "steps" at the input. This type of noise is frequently referred to as "step" noise.

(ii) **Series noise**: fluctuation in the current flow through the FET channel can be represented in a circuit model as being due to a series voltage generator in the gate lead. This series noise component consists of impulses (therefore, sometimes called "delta" noise) and its effect on signal/noise increases as the measurement time is decreased. When these first two noise sources are combined it is clear that an optimum measurement time exists which gives maximum signal/noise when the two components are equal. Obviously, this optimum depends on the relative magnitude of the two components which depends in turn on the particular components used.

(iii) **1/f noise**: this type of noise is characterized by its effects on the signal/noise ratio tending to be independent of the measurement time. It can arise from any sources such as insulators in the input circuit and from generation-recombination processes in the FET channel. This latter source is temperature dependent and it is a major problem in attempts to cool many types of FET. Specific traps produced by uncontrolled impurities are known to act as centers for the generation-recombination process.
The second key element is the pulse-shaping network used to define the "measurement time" referred to in the previous paragraph. In its simplest form this consists of a single RC differentiator and integrator. The detector charge pulse gives a voltage step at the system output whose rise and fall times are determined by the pulse shaper. More complex pulse shapers (e.g., containing multiple integrators) are used to optimize the signal/noise ratio while maintaining the measurement time within constraints imposed by the required counting rate performance. Long measurement times are often prohibited by the possibility of two input events recurring within the measurement time.

6. Concluding Remarks

As indicated in the Introduction, semiconductor radiation detectors present quite unique problems compared with other semiconductor devices. Despite this fact, their special features are so important that they have become a major tool in a wide range of scientific and industrial applications. Furthermore, the special requirements particularly in regard to material quality and purity have led to developments which have been important in other semiconductor work. A good example is the research on electron-hole droplets which uses the high-purity germanium developed for detectors.

7. Acknowledgment

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References


Figure Captions

Fig. 1. Extrapolated range-energy curves for electrons in silicon and germanium. Courtesy of Berger and Seltzer (1964).

Fig. 2. dE/dx for electrons in silicon and germanium. Courtesy of Berger and Seltzer (1964).

Fig. 3. Range-energy curves for protons (p), deuterons (d), tritons (t), $^3$He and $^4$He in silicon a) and germanium b). Courtesy of Williamson et al., (1966).

Fig. 4. dE/dx for protons (p), deuterons (d), tritons (t), $^3$He and $^4$He in silicon as a function of energy. Courtesy of Williamson et al., (1966).

Fig. 5. Total absorption coefficient $\alpha$ for photons in silicon.

Fig. 6. Total absorption coefficient $\alpha$ for photons in germanium.

Fig. 7. Gamma-ray spectrum produced by the decay of $^{60}$Co. Two photopeaks appear at 1.16 and 1.33 MeV. The corresponding Compton edges are located near 680 and 800 keV respectively.

Fig. 8. Average energy for electron-hole pair production versus bandgap.

Fig. 9. Collection of charge from a point of interaction inside diode structure.

Fig. 10. n$^+$-p-diode; structure, charge distribution, electric field and potential.

Fig. 11. Cutaway view of a n$^+$-p-p$^+$ device with a lightly n-type(A) and a lightly p-type(B) surface.

Fig. 12. Lithium drift process. A: Lithium is diffused into a p-type semiconductor. B: Under a reverse electric field
the lithium ions have drifted and compensated the region

W. C: Some faulty process produces an excess of lithium
in the drifted region W. D: The excess lithium concentration
produces a drop in the electric field which will correct
the lithium distribution.

Fig. 13. Cutaway view of a lithium drifted p-i-n silicon diode.

Fig. 14. n⁺-i-p⁺ diode; structure, change distribution electric field
and potential.

Fig. 15. X-ray fluorescence spectrum of a freeze dried blood specimen.
The lead Lα and Lβ peaks correspond to a 0.5 ppm lead
concentration in the original sample.

Fig. 16. Planar and coaxial Ge(Li) detectors.
Figure 2

GERMANIUM

SILICON

ENERGY (MeV)

de/dx (K\text{eV} \text{M})
Figure 3a
Figure 3b
Figure 4

Varying DE/dx in keV/micron of Si

- ALPHA
- TRITON
- DEUTERON
- PROTON

Energy in MeV
Figure 5

**Graph Description:**
- **Absorption Coefficient (cm⁻¹)**
- **Gamma-Ray Energy (MeV)**
- **Graph Legend:**
  - **Total**
  - **Compton Scattering**
  - **Photoelectric**
  - **Pair Production**

**Graph Notes:**
- The graph illustrates the absorption coefficient as a function of gamma-ray energy for different processes:
  - **Compton Scattering**
  - **Photoelectric**
  - **Pair Production**

**Graph Scale:**
- Absorption Coefficient: 0.01 to 10
- Gamma-Ray Energy: 0.01 to 10 (MeV)
Figure 6
Figure 7
Figure 8

Diamond

Experimental

Theoretical

Materials:
- SiC
- PbO
- CdS
- GaP
- GaAs
- CdTe
- Si
- Ge
- PbS
- InSb

Band Gap Energy (eV)

XBL 706-1193
Figure 9

NEGATIVE DETECTOR BIAS

ELECTRON CONTRIBUTION

HOLE CONTRIBUTION

TOTAL

\[ \frac{Q(W-X)}{W(C_D + C_{IN})} \]

\[ \frac{QX}{W(C_D + C_{IN})} \]

\[ \frac{Q}{C_D + C_{IN}} \]
Figure 11

SURFACE PROPERTIES OF JUNCTION (SECTIONED VIEWS)

MUB-6971
FIG 2B ILLUSTRATING THE LITHIUM DRIFTING OPERATION
Figure 14
LYPHOLIZED WHOLE BLOOD

5 x 10^3 COUNTS 10^6 COUNTS

COUNTS

ENERGY

Figure 15
Figure 16

a) LITHIUM DIFFUSED N⁺ REGION
   DRIFTED REGION
   ORIGINAL P-TYPE MATERIAL
   METAL CONTACT

b) LITHIUM DIFFUSED N⁺ REGION
   DRIFTED REGION
   ORIGINAL P-TYPE MATERIAL
   METAL SURFACE-BARRIER

c) LITHIUM DIFFUSED N⁺ REGION
   DRIFTED REGION
   ORIGINAL P-TYPE MATERIAL
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