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Review of the Physics of Semiconductor Detectors

Historically, semiconductor detectors were conceived as solid-state ionization chambers. To obtain a high-electric-field, low-current, solid-state device for detection and possibly spectroscopy of ionizing radiation, conduction counters (highly insulating diamond crystals) were first used. However, such crystals were quickly rejected because of poor charge collection characteristics resulting from the deep trapping centers in their bandgap. After the highly successful development of silicon (Si) and germanium (Ge) single crystals for transistor technologies, the conduction-counter concept was abandoned, and silicon and germanium ionizing radiation detectors were developed by forming rectifying junctions on these materials. A semiconductor detector is a large silicon or germanium diode of the p-n or p-i-n type operated in the reverse bias mode.

At a suitable operating temperature (normally ~300 K for silicon detectors and ~85 K for germanium detectors), the barrier created at the junction reduces the leakage current to acceptably low values. Thus an electric field can be applied that is sufficient to collect the charge carriers liberated by the ionizing radiation.

Detailed information on the physics of semiconductor detectors and their fabrication is available in the literature.[1] Some of the more useful basic concepts are summarized in the following sections.

Interaction of Ionizing Radiation with Semiconductor Detectors

A brief review of some fundamental concepts relating to the interaction of ionizing radiation with matter must precede a description of the operating characteristics of semiconductor detectors.

Heavy Charged Particles

Heavy charged particles lose energy by Coulomb interaction with the electrons and the nuclei of the absorbing materials. The collision of heavy charged particles with free and bound electrons results in the ionization or excitation of the absorbing atom, whereas the interaction with nuclei leads only to a Rutherford scattering between two types of nuclei. Thus the energy spent by the particle in electronic collisions results in the creation of electron-hole pairs, whereas the energy spent in nuclear collisions is lost to the detection process.

The concepts of specific ionization loss dE/dx and of range R can be used to summarize the interaction of heavy charged particles in semiconductor detectors when nuclear collisions are unimportant. The specific ionization loss measures the amount of energy lost by the particle per unit-length of its track; the range indicates how deeply the particle penetrates the absorbing material. Figure 1 shows the stopping power as a function of the energy, and Fig. 2 shows the range as a function of the energy in silicon and in germanium for alpha particles, protons, and deuterons.

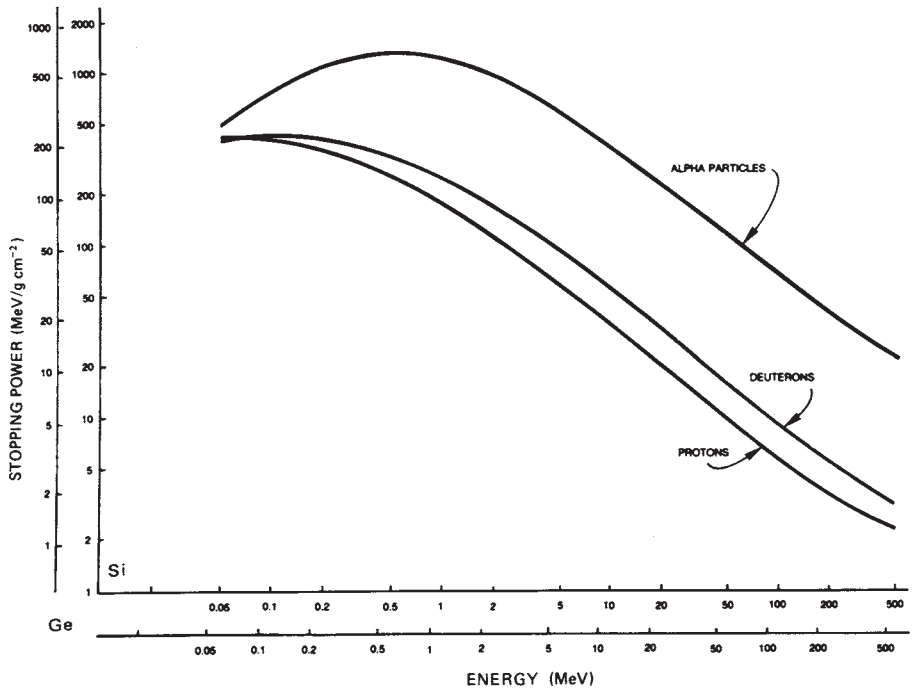

Fig. 1. Stopping Power vs. Energy for Protons, Deuterons, and Alpha Particles in Si and Ge.

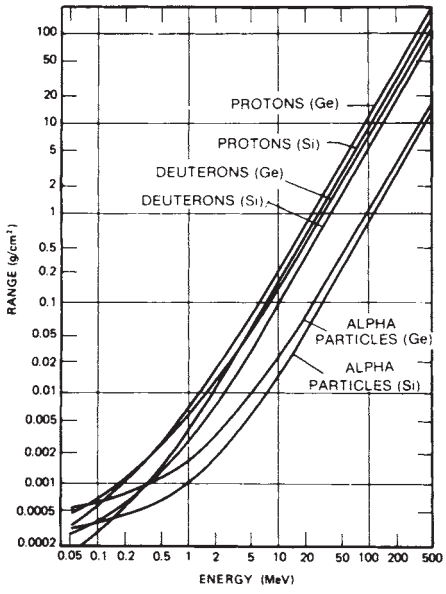

Fig. 2. Proton, Deuteron, and Alpha Particle Ranges in Si and Ge.

Review of the Physics of Semiconductor Detectors

Nuclear collisions can become an important part of the energy loss process, especially in the case of heavy ions and fission fragments. The theory describing this process is too complicated for a brief summary. We refer the reader to specialized literature such as the IEEE Transactions on Nuclear Science and the references footnoted here.[1, 2]

Finally, it should be mentioned that channeling effects (the steering of charged particles in open regions in the lattice) can reduce the specific ionization loss. Again, we refer the reader to the referenced literature for details on this particular phenomenon.[1, 2]

Electrons

The interaction of electrons with matter is similar to the interaction of heavy particles, with the following differences:

1. Nuclear collisions are not part of the interaction because of the very light electron mass.
2. At energies higher than a few MeV, radioactive processes (bremsstrahlung) must be considered in addition to the inelastic electron collision.
3. Again because of their light mass, electrons are so intensely scattered that their trajectory in the material is a jagged line; therefore, the concept of range as previously used cannot be applied. Rather, the concept of zero-transmission range is introduced. This is done by means of absorption experiments, which permit definition of the absorber thickness resulting in zero-electron transmission at a given energy. Figure 3 shows the zero-transmission range as a function of energy in silicon and germanium.

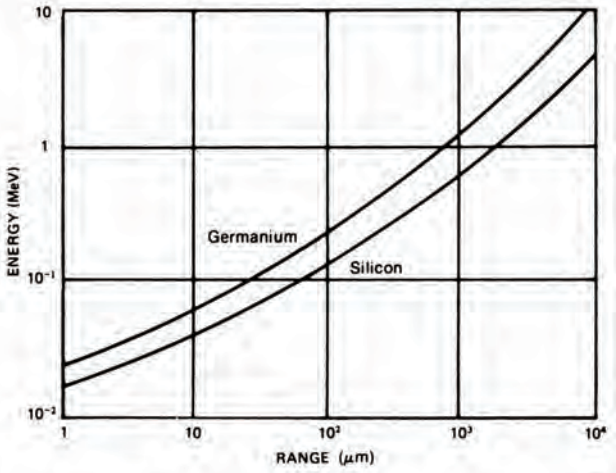

Fig. 3. Zero Transmission Range vs. Energy for Electrons in Si and Ge.

Gamma and X Rays

The interaction of ionizing electromagnetic radiation with matter is different from the processes previously mentioned, and the concept of ranges and specific ionization loss cannot be applied. Only the three most important absorption processes are considered: the photoelectric effect, the Compton effect, and the pair-production effect. The corpuscular description of electromagnetic radiation is the most appropriate for these effects, as one photon in a well-collimated beam of N_o photons disappears at each interaction. The attenuation of the photon beam can be described by a simple exponential law

$$N = N_o \exp(-\mu x), \qquad (1)$$

where N is the remaining photons in the beam after traversing distance x, and the absorption coefficient μ is the sum of three terms due to the three above-mentioned processes.

In the photoelectric interaction, the photon ejects a bound electron from an atom. All of the photon energy, $h\upsilon$, is given to the atom, which ejects the electron with an energy $h\upsilon - E_1$, where E_1 is the binding energy of the electron. The excited atom then releases energy E_1 by decaying to its ground state. In this process, the atom releases one or more photons (and possibly an electron, called an Auger electron). The cross section of the photoelectric effect increases rapidly with the atomic number Z and decreases with increasing energy.

The Compton effect is essentially an elastic collision between a photon and an electron; during this interaction, the photon gives a fraction of its energy to the electrons, and its frequency υ is therefore decreased. The cross section for this effect decreases with increasing energy, but the decrease is less rapid than for the photoelectric effect.

In the pair-production effect, a high-energy photon near a nucleus gives up its energy to produce an electron-positron pair. The photon energy goes into the rest-mass energy and the kinetic energy of the electron-positron pair. The minimum energy necessary for this effect is set by elementary relativistic considerations at the value of 1.022 MeV, an amount equivalent to two electron rest masses. The cross section P for

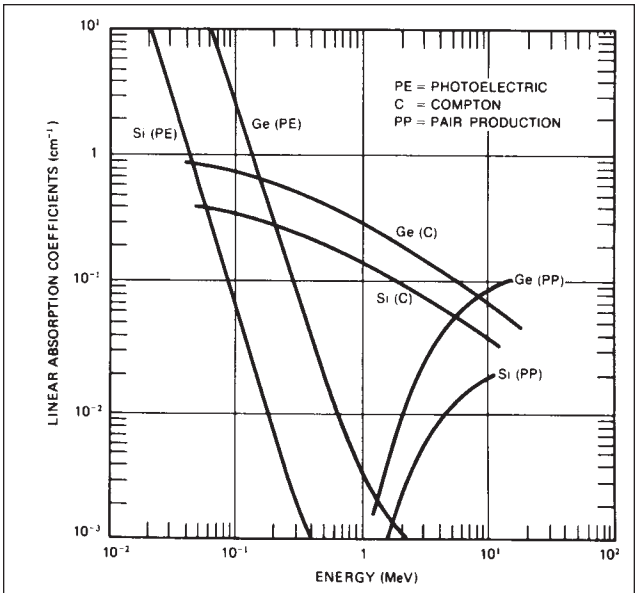

Fig. 4. Linear Absorption Coefficients vs. Gamma-Ray Energy for Si and Ge.

pair production increases with energy. Up to energies of 10 MeV, the P/Z ratio remains constant with energy.[2] At higher energies, the cross section starts to decrease for increasing values of the atomic number.

Figure 4 summarizes values of the linear absorption coefficients of the above-mentioned effects as a function of gamma-ray energy for silicon and germanium.

Creation of Electron-Hole Pairs in Semiconductor Detectors by Ionizing Radiation

Average Energy Necessary to Create an Electron-Hole Pair

The energy lost by ionizing radiation in semiconductor detectors ultimately results in the creation of electron-hole pairs. Details of the processes through which incoming radiation creates electron-hole pairs are not well known, but the average energy ε necessary to create an electron-hole pair in a given semiconductor at a given temperature is independent of the type and the energy of the ionizing radiation. The values of ε are: 3.62 eV in silicon at room temperature; 3.72 eV in silicon at 80 K, and 2.95 eV in germanium at 80 K.

Since the forbidden bandgap value is 1.115 eV for silicon at room temperature and is 0.73 eV for germanium at 80 K, it is clear that not all the energy of the ionizing radiation is spent in breaking covalent bonds. Some of it is ultimately released to the lattice in the form of phonons.

The constant value of ε for different types of radiation and for different energies contributes to the versatility and flexibility of semiconductor detectors for use in nuclear spectroscopy. The low value of ε compared with the average energy necessary to create an electron-ion pair in a gas (typically 15 to 30 eV) results in the superior spectroscopic performance of semiconductor detectors.

The Fano Factor

If all of the energy lost by ionizing radiation in a semiconductor were spent breaking covalent bonds in the detector's sensitive volume, no fluctuations would occur in the number of electron-hole pairs produced by ionizing radiation of a given energy. At the other extreme, if that energy entering the semiconductor detector that is partitioned between breaking covalent bonds and lattice vibrations or phonon production were completely uncorrelated, Poisson statistics would apply.

The variance in the number of electron-hole pairs n would then be $\langle n \rangle^2 = n$. In fact, neither of these suppositions simulates reality. As the incoming ionizing radiation gives up energy, a large shower of hot electrons is created. After many generations, the energy of these hot electrons gets close to the ionization energy necessary to create an electron-hole pair in the semiconductor detector, so that there are several possible competing mechanisms for energy loss. Thus the Fano factor F is introduced to modify the more familiar Poisson relation for this case. The equation for the variance can be written as

$$\langle n_o \rangle^2 = F \langle n \rangle^2 = Fn \, . \qquad (2)$$

In the case where there are no fluctuations in the number of electron-hole pairs, F would be zero; in the case where Poisson statistics apply, F would be equal to 1. Since the energy necessary to create electron-hole pairs in semiconductor detectors is much smaller than that of the incoming ionizing radiation, it can be concluded that F is closer to zero than to 1. The true value of F for silicon and germanium is still unknown; the conflicting theories on the subject do not lead to experimentally distinguishable results. However, by assuming a value of 0.1 for F in both silicon and germanium, satisfactory agreement with measured results is found in most cases.

By assuming a value of 0.1 for the Fano factor, the following formula gives the germanium detector resolution at LN_2 temperature:

$$\Delta E = 1.27 \sqrt{E} \qquad (3)$$

with E measured in eV.

ΔE must be summed in quadrature with the FWHM keV noise ΔN in order to obtain the measured energy resolution ΔE_S:

$$\Delta E_S = \sqrt{(\Delta E)^2 + (\Delta N)^2} \qquad (4)$$

The value of F for silicon at room temperature is of little interest because, in such conditions, other factors than fundamental statistics dominate energy resolution values. These simple formulas show that, as expected from the better statistics due to the lower value of ε, when the energy resolution is dominated by the detector contribution, germanium detectors have an advantage over silicon detectors.

Pulse Formation Process

The equivalent circuit of a semiconductor detector operated as a spectrometer is shown in Fig. 5. In most cases, effects of high resistance of the reverse-biased junction are negligible. If a zero-electric-field radiation-insensitive region is present in the detector, its impedance (a parallel RC combination) appears in series with the circuit and is indicated in Fig. 5 by the impedance Z. The impedance also accounts for any resistance (or resistance-capacitance combination) appearing in series with the contacts.

Review of the Physics of Semiconductor Detectors

When semiconductor detectors are used as spectrometers, they are invariably connected to a charge-sensitive (integrating) preamplifier with a high dynamic input capacitance. The charge-sensitive preamplifier integrates on its feedback capacitance the current signal delivered by the detector and feeds the resulting voltage signal to the filter amplifier (main amplifier). The time behavior of the current signal at the input of the charge-sensitive preamplifier is determined by the current signal's shape and by the effect of the equivalent circuit shown in Fig. 5. The effect of the equivalent circuit is usually either negligible or easily calculated, whereas detailed considerations on the charge collection process in the detector are needed to calculate the induced current signal I(t).

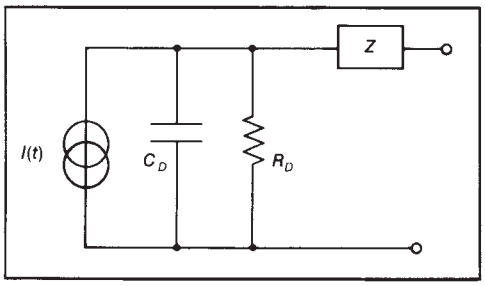

Fig. 5. Equivalent Circuit of Semiconductor Detector. Where I(t) is the current generator; C_D is the capacitance of the depletion region; R_D is the resistance of the depletion region; and Z is the series impedance.

Charge Collection Process and the Resulting Induced Current Signal

The current delivered by the signal generator I(t) is induced on the contacts of the detector by the motion of the charge carriers created by the ionizing radiation. Therefore, the first problem in determining I(t) is calculating the motion of the charge carriers in the detector's electric field. When this problem is solved, the induced charge can be calculated by electrostatic considerations.

The charge carriers created by the ionizing radiation drift to the contacts of opposite polarity, following the lines of force of the electric field established by the applied voltage. In the case of heavily ionizing particles such as fission fragments, the drift process does not begin immediately due to the creation of the charge cloud.

The electric field **E**(**r**) in the detector can be calculated from known quantities: applied bias voltage, detector geometry, and resistivity of the bulk material. Once the electric field is known, the motion of a charge carrier created at a given point $\mathbf{r}_0$ of the detector volume can be calculated by using the values for the drift velocity $\mathbf{V}_d$ as a function of the electric field **E** given in the referenced literature. Thus the differential equation

$$\frac{d\mathbf{r}}{dt} = \mathbf{V}_d[\mathbf{E}(\mathbf{r})] \qquad (5)$$

can be written for every charge carrier and can be solved if the initial positions $\mathbf{r}_0$ are known only when the charge carriers are created along a well-defined track (heavy charged particles). In the case of beta, x, and gamma radiation, the only information on $\mathbf{r}_0$ values is of statistical nature. The integration of Eq. (5) leads to **r**(t) for every created charge carrier. The charge induced by every carrier can then be calculated by electrostatic considerations. For instance, in the case of a detector with plane parallel contacts and a field **E**(x) across a distance W, the charge induced by a carrier q moving along a length Δx in the direction of the field is given by

$$\Delta q = q\frac{\Delta x}{W} \qquad (6)$$

independently of the shape of **E**(x). Equations (5) and (6) (or the appropriate induction equation) yield the contribution to I(t) of every single charge carrier and, by integration over all the created charge carriers, the total I(t) function.

Rise Time

The rise time T_t of the pulse generated by a semiconductor detector can be measured at the output of a charge-sensitive preamplifier. If the preamplifier is sufficiently fast, T_t is determined by the following factors:

1. The charge collection time T_R ,
2. The rise time of the detector equivalent circuit, in most cases a negligible quantity, and
3. The plasma time.

In most cases T_R is the dominant factor. Although a precise calculation of T_R can be quite complex, the order of magnitude of T_R can be easily obtained by the following formulas:

$$T_R \cong W \times 10^{-7}\text{s} \qquad (7)$$

for silicon detectors at room temperature, and

$$T_R \cong W \times 10^{-8}\text{s} \qquad (8)$$

for germanium detectors at LN_2 temperature.

In these formulas, W is the thickness of the depletion region measured in mm. For silicon detectors and for planar HPGe detectors, the value of W is provided with each detector. For coaxial Ge detectors, W is the radius of the cylinder (specified in the detector instruction manual).

The formulas given above are indicative only of orders of magnitude and do not give exact values.

The previous discussion did not consider trapping effects, which result in a loss of charge to the collection process and consequent distortion of the shape of the peak as observed with a multichannel analyzer.

Trapping Effects

Trapping of a charge carrier in a semiconductor occurs when the carrier is captured by an impurity or imperfection center and is temporarily lost to any charge transport process. In semiconductor detectors, it is useful to introduce the quantity τ^+ (mean free drift time):

$$\tau^+ = (N_t \, \sigma \, V_{th})^{-1} \qquad (9)$$

where

N_t = density of trapping centers,

σ = trapping cross section,

V_{th} = thermal velocity.

Note that τ^+ does not ordinarily coincide with the classical lifetime in photoconductivity theories. This is because in photoconductivity the traps are generally filled, while in a depleted detector, the traps are generally empty.

The trapped charge carrier can be reemitted in the relevant band and take part again in the charge transport process. The average time spent by a carrier in a trap is called the mean detrapping time τ_D and is strongly temperature dependent:

$$\tau_D = C \exp\left(\frac{-E_\tau}{KT}\right) \qquad (10)$$

where

C = a constant,

E_τ = activation energy of the trap,

K = Boltzmann's constant,

T = absolute temperature.

If the mean detrapping time is of the same order of magnitude as, or larger than, the electronic shaping constants, the charge carrier is lost to the charge collection process or is collected with significantly reduced efficiency. The result is poor energy resolution and peak tailing. On the other hand, if the mean detrapping time is orders of magnitude shorter than the charge collection time due to drift of the carriers, then the trap has no effect on the charge collection process. For this reason, normally used dopants such as Li, P, B, and Ga, which are shallow donors or acceptors, do not act as traps.

It can be shown that to first-order approximation, the efficiency of collection of a charge carrier subjected to trapping with a mean free drift time τ^+ is given by

$$\eta = 1 - \left(\frac{T_R}{2\tau^+}\right) \qquad (11)$$

where η is the collected fraction of the created charge.

In a modern germanium gamma-ray spectrometer the charge collection efficiency is of the order of 0.999, and as T_R is of the order of 10^{-7} s, then τ^+, according to Eq. (11), is of the order of 10^{-4} s.

As typical values of V_{th} and σ are 10^7 cm·s^{-1} and 10^{-13} cm^2 respectively, the maximum concentration of trapping centers permissible in the detector is of the order of 10^{10} cm^{-3}, corresponding to approximately 1 for every 10^{12} atoms of germanium.

Review of the Physics of Semiconductor Detectors

Plasma Effects

Of particular interest in heavy-ion spectroscopy are plasma effects. In silicon charged-particle detectors heavy charged particles produce a dense cloud of electron-hole pairs into which the electric field, created by the applied bias voltage, cannot penetrate at the onset. Only when the cloud has been sufficiently dispersed by bipolar diffusion will the charge carriers begin to drift under the influence of the electric field. This phenomenon has the following effects:

1. A delay is generated between the creation of the electron-hole pairs (which can be considered instantaneous) and the appearance of the rising edge of the charge pulse in the detector. This delay results in an additional component to the time jitter of the signal delivered by the detector.
2. The rise time of the charge signal from the detector is slowed down; this also increases the value of the time jitter.
3. Because of the existence of a dense cloud of charge in an initially zero-electric-field region, charge carriers can recombine, with consequent loss of pulse amplitude. This phenomenon is unimportant in the detection of light particles, gamma, or x rays because the probability of carrier recombination in a semiconductor region with a high electric field is negligible.

For further information on this subject see ORTEC's application note AN-40, "Heavy-Ion Spectroscopy with Surface Barrier Detectors" available on the website.

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[1] *Radiation Detection and Measurement* (2nd Edition) by Glenn F. Knoll, New York: John Wiley and Sons, 1989, and *Semiconductor Detectors*, edited by G. Bertolini and A. Coche, North Holland Publishing Co., 1968 (distributed in the U.S. by American Elsevier Publishing Co.), New York City.

[2] F.S. Goulding and R.H. Pehl, "Semiconductor Detectors," Section IIIA, *Nuclear Spectroscopy and Reactions*, J. Cerny, Ed. Academic Press (1974).

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