§ 1. Introduction

Following almost ten years of incubation, solid state radiation detectors have, in recent years, achieved increasing emphasis and use in low energy nuclear physics. Such detectors depend on the production of free-charge carriers in crystals by the interaction of incident particles with bound electrons. Solid-state detectors are analogues of the well-known gaseous ionization chamber. In an ionization chamber, the incident particle produces electron-ion pairs; in a solid, the incident particle produces electron-hole pairs. Detection of the incident particle is then a problem of collection of the liberated charge by application of an electric field.

An important difference between the solid and the gas is that many more electron-hole pairs are produced in the solid than electron-ion pairs in the gas per unit energy loss of the particle. This leads to a smaller fractional statistical fluctuation in the number of carriers produced and hence to potentially higher resolution in the measurement of the incident particle energy. Other features also make the solid-state counter attractive for nuclear physics applications; among these are high density of the solid compared to a gas, small size and short pulse rise time.

Collection of the liberated charge in a solid is more complicated than in a gas. Holes and electrons may be lost by recombination in the dense plasma formed along the particle track, or by trapping of the moving carriers subsequent to their separation by the electric field. These effects, which are discussed in § 2, depend on the detailed properties of the solid, the potential distribution in the device, and the ionization density along the initial track.

The requirement of an electric field for charge collection makes it necessary that the crystal be an insulator. Otherwise high current would result, leading to excessive noise. The simplest type of crystal detector consists of conducting electrodes on opposite faces of an insulating crystal. Early attempts to produce such detectors
were disappointing because serious trapping of carriers led to inefficient and counting rate dependent charge collection. This trapping was due to imperfections in the crystals employed. In general any foreign atoms or defects in the crystal structure can seriously affect free holes or electrons.

In recent years single crystals of silicon and germanium have been produced of purity and crystal perfection many orders of magnitude better than any other available materials. These were first recognized as being potentially useful as crystal counters by McKay in 1949, who found that the previous difficulties were not present when these materials were used. However, at room temperature, silicon and germanium exhibit excessive leakage current in the presence of an electric field because they are semiconductors, not insulators. Two methods have been employed to raise the effective resistivity of these materials to a level high enough for them to be usable as detectors. One method is to introduce certain impurities, such as gold, which produce extremely high resistivity at low temperatures. The adverse trapping effects of such impurities, combined with the inconvenience of cooling the detector, cause this

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**Fig. 1. Cross-section of a typical diffused $n^+p$ junction radiation detector**

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method to be relatively unattractive. The second method employs a reverse biased diode.¹⁸

A common type of diode structure used as a particle detector is illustrated in Fig. 1. The figure depicts a diffused counter having a thin, ≈ 0.1 µm, heavily doped n-type layer on a p-type crystal. This is designated an \textit{n}+\textit{p} junction.* The layer at the surface is n-type with a high concentration of free electrons and practically no free holes. The material inside is p-type with an excess of holes and very few electrons.

In the presence of a reverse bias voltage, as shown in the diagram, free electrons and holes are swept out of a layer between the n and p regions to form a depletion region. Under these conditions current flow through the device is greatly reduced since neither the n or the p region can supply carriers of appropriate sign. This results in the exposure of a slice of material in which a space charge exists since the charges on the ionized donor and acceptor impurities are no longer balanced by charges of mobile carriers. For this reason the depletion region is also called the space charge layer. The thickness of this space charge or depletion layer is proportional’s to $\sqrt{pV}$ where $p$ is the base material resistivity and $V$ is the bias voltage.

The depletion layer is the sensitive region of the detector. The number of hole-electron pairs produced in the depletion layer is proportional to the energy expended by the incident particle in this region. These pairs are swept out by the electric field, resulting in the collection of a quantity of charge in the external circuit.

If the incident particle traverses the depletion layer and enters the undepleted region beyond, it will produce hole-electron Pairs in that region also. Electrons from these pairs are minority carriers in the p-type base material. Some of these will diffuse to the depletion layer and be swept across, thus contributing to the signal. In 1 µsec collection takes place by this process from a depth of ≈ 20 µm beyond the depletion layer. Pairs are also produced in the thin front diffused layer of the detector. Again some of the minority carriers, in this case holes, can diffuse to the depleted region and be swept across. It is found that for detectors with diffused-layers of ≈ 0.3 µm collection can take place from roughly half this thickness.¹⁴

Associated with the depletion layer there is a capacitance $C = KA/4\pi w$, where $A$ is the junction area, $K$ is the dielectric constant, and $w$ is the depletion layer thickness. As will be noted in § 3, this capacitance has an important bearing on the signal-to-noise ratio.

Before discussing detailed behavior and applications of semiconductor particle detectors, it is instructive to consider the ultimate energy resolution of such devices. The average energy $\mathcal{E}$ required to produce an electron-hole pair is 3.55±0.1 eV.**

* The general diode characteristics which will be considered for the \textit{n}+\textit{p} junction also apply to \textit{p}+\textit{n} diffused junctions and to surface barrier junctions.

** Determinations of $\mathcal{E}$ for silicon have been made for \textit{γ}-rays,¹⁸ electrons,¹⁸ protons,¹⁸ α-particles,¹⁷ heavy ions¹⁷ and fission fragments. With the possible exception of fission fragments,¹⁹,²⁰ $\mathcal{E}$ is independent of energy and particle type. A calculation of $\mathcal{E}$ by Shockley gives a value¹¹ of 3.5 eV, in good agreement with observation.

in silicon and 2.94 ± 0.15 eV in germanium. An incident particle of energy $E$ will produce $E/\epsilon$ electron-hole pairs. The number of pairs produced by a 5 MeV particle in silicon is, therefore, $1.43 \times 10^6$. For a gaussian distribution the statistical fluctuation in this number is $\pm 1.2 \times 10^3$, leading to a full width at half maximum of 10 keV. This may be compared with a similar limitation of 27 kilovolts for a gas ionization chamber, and more than 100 kV for a scintillation detector. Such a comparison however is not strictly correct. Fano has pointed out that for the case in which the incident particle comes to rest in the sensitive region of the counter the ionization events should not be treated as completely independent since the primary particle must lose the exact amount of its initial energy. This causes the distribution to be non-gaussian and the mean square fluctuation in the number of pairs produced to be changed by a factor $F$, commonly called the Fano factor. This effect reduces the statistical fluctuation below that indicated by the above simple comparison (which assumes a Fano factor of unity) and is dependent on the properties of the stopping material. A Fano factor of 0.22 has been measured for argon gas, while observations by Blankenship indicate a value for silicon of less than 0.5. Although relative comparisons of the limiting resolutions of different types of detectors must include these factors, it is unlikely that future determination of their values will alter the resolution advantage of semiconductors over gas devices.

An attempt is made in the following sections to describe important properties and applications of semiconductor particle detectors. For more detail than is possible in this brief review the reader is referred to the references cited in each section.

§2. Charge collection

The main features of the process of charge collection in solid-state detectors can be illustrated by considering the case of a silicon junction diode. Similar considerations apply to other materials and structures.

On entering a detector, an ionizing particle creates a trail of hole-electron pairs. Pairs produced in the depleted region of the diode drift under the influence of the electric field. This motion of the carriers is superimposed on their random thermal motion. The drift velocity is given by $V = \mu \phi$ where $\mu$ is the carrier mobility, differing

13 W. C. Dunlap, Jr., ref. 12, p. 136.
The energy $E$ will be a fluctuation of 10 keV. In silicon, the hole and electron mobilities are approximately 500 cm$^2$ sec$^{-1}$ volt$^{-1}$ and 1500 cm$^2$ sec$^{-1}$ volt$^{-1}$, respectively.\textsuperscript{26} The mobility is constant for carrier velocities up to $\approx 10^6$ cm sec$^{-1}$, and decreases for higher velocities.\textsuperscript{26} An upper limit for the carrier velocities is $\approx 10^7$ cm sec$^{-1}$, and this, together with the depletion layer thickness, sets a lower limit on the charge collection time. Neglecting possible self-shielding effects along the particle track, which will subsequently be shown to be important for densely ionizing particles such as fission fragments, the collection time in thin detectors is of the order of nanoseconds. However, the signal rise time is often dictated by the resistance and capacitance of the device\textsuperscript{27, 28} and is usually in the range 10 to 100 nsec for thin devices.

In moving across the depletion layer, carriers may become trapped at imperfections in the crystal lattice.\textsuperscript{29} These imperfections may be structural defects or chemical impurities, and may or may not have an electrical charge. The trapping cross-sections of such imperfections depend on complex factors that are not well understood and can vary greatly from one type of imperfection to another. The mean time which a carrier spends trapped on an imperfection depends on its binding energy relative to $kT$, the thermal energy of the lattice. The presence of ‘deep traps’ can, therefore, seriously affect the motion of free carriers. Even though trapped carriers may be subsequently released, they may be too late to contribute to the signal because of the short clipping times used in nuclear particle counting.\textsuperscript{20}

A free electron which has been captured by an imperfection may be released by thermal excitation, or may fall into an unoccupied state in the bound electronic structure of the crystal. Stated differently, the imperfection can capture an electron and then capture a hole, resulting in the annihilation of both carriers.\textsuperscript{31} The efficiency for this recombination process depends on the binding energy for electrons on the imperfection, and on the concentration of both electrons and holes in the vicinity.

Recombination and trapping, the two processes interfering with charge collection, are characterized by a mean lifetime $\tau$ for which a carrier is free to move. Since the velocity of a carrier is $\mu \frac{E}{F}$, the distance it can travel in its lifetime is $\mu \tau$. This quantity is known as the trapping length, and $\mu \tau$ as the mobility-lifetime product.

In a pn junction the absence of free carriers in the sensitive region severely limits recombination, so that the dominant mechanism leading to poor charge collection might be expected to be trapping. Efficient charge collection is achieved only when the trapping length is large compared to the sensitive thickness of the device. In silicon diodes the lifetimes are rarely so short as to make trapping losses serious.

\textsuperscript{26} F. J. Morin and J. P. Maita, Phys. Rev. 96 (1954) 28.
\textsuperscript{29} H. M. Mann, J. W. Haslett and G. P. Lietz, IRE Trans. on Nucl. Sci. NS-8 (1961) 151.
For example, in 10 000 Ω·cm silicon, a carrier lifetime as short as 1 μsec would produce only ~0.5% charge loss. However, if a region of the crystal is damaged, or if the crystal is heavily doped with a material producing deep traps, such as gold, the carrier lifetime can be as short as a few nanoseconds and appreciable losses will occur.

The way in which the trapping length is involved in charge collection can be seen with the aid of Fig. 2. Here an ionizing particle has just entered the detector surface from the left, creating a trail of hole-electron pairs of density \( N(y) \) per unit length. It is assumed that the depletion depth \( w \) exceeds the particle range \( R \) and that the electric field, \( \mathbf{E} = -\frac{d\mathbf{V}}{dx} \), is a known function of position. The electrons created in the segment \( y \to y + \delta y \) move from right to left under the action of the field \( \mathbf{E} \). In moving a distance \( \delta x \) in time \( \delta t \), their number decreases by the fraction \( \delta t/\tau_e \) for an electron lifetime \( \tau_e \). (This lifetime is that of a carrier in the depletion region and will in general be much shorter than that quoted by materials manufacturers who measure lifetime under quite different conditions.) But \( \delta t = \delta x/\mu_e \mathbf{E}(x) \) where \( \mu_e \) is the electron mobility. Consequently, the amount of charge reaching \( x \), a finite distance from \( y \), is

\[
\Delta Q = qN(y) \delta y \exp \left( - \int_y^x dx/\mu_e \mathbf{E}(x) \right)
\]

where \( q \) is the electronic charge. It is often asserted on the basis of an energy argument that if charge \( \Delta Q \) falls through a fraction \( \mathbf{V}/\mathbf{V} \) of the potential across a detector, charge \( \Delta Q_x = \Delta Q \mathbf{V}/\mathbf{V} \) will be transferred around the external circuit. Cavalleri et al.\(^{33} \) have shown that this is, in general, not true since it neglects the effect of the interaction energy between \( \Delta Q \) and any bound space charge that may exist inside the device. For closely spaced parallel plate geometry, which includes the majority of junction particle detectors, \( \Delta Q_x = \Delta Q \mathbf{Ax}/\mathbf{W} \) independent of the space charge distribution inside the device. For the general case of any electrode configuration, the external charge transfer can be found by defining a field \( \mathbf{E}_0 \), the field that would exist in the

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\(^{32}\) W. D. Davis, Phys. Rev. 114 (1959) 1006.

\(^{33}\) G. Cavalleri, G. Fabri, E. Gatti and V. Svelto, Nucl. Instr. and Meth. 21 (1963) 177.
A detector if the boundaries of the depletion region, and the applied voltage, remained fixed but the space charge were zero. It follows from superposition that the simple energy argument can then be applied using $E_0$ instead of $E$. Returning to eq. (1) the charge $\Delta Q$ therefore makes a contribution of $\Delta Q/\delta x/V$ in moving a further distance $\delta x$ across the device, if $V$ is the detector bias voltage. The total contribution from the electrons that started from the segment $y \rightarrow y + \delta y$ is therefore

$$qV^{-1} N(y) \delta y \int \exp \left\{ - \frac{\int F(x) dx}{\mu_e \epsilon_0(x)} \right\} \phi_0(x) dx$$

and the entire electron contribution from the incident particle is given by

$$Q_{el} = qV^{-1} \int_N \exp \left\{ - \frac{\int F(x) dx}{\mu_e \epsilon_0(x)} \right\} \phi_0(x) dx \, dy.$$  \hspace{1cm} (2)

The contribution from the holes follows similarly as

$$Q_{eh} = qV^{-1} \int_N \exp \left\{ - \frac{\int F(x) dx}{\mu_h \epsilon_0(x)} \right\} \phi_0(x) dx \, dy.$$  \hspace{1cm} (3)

The total collected charge is the sum of the hole and electron contributions.

An important application of eqs. (2) and (3) is that of short-range particles incident on a thick detector having a uniform internal field, e.g. $\alpha$-particles being detected by a thick p-i-n device. In this case $F(x) = F_0(x) = V/w$ and $N(y) \approx N_0 \delta(y)$, where $\delta(y)$ is the Dirac delta function. The contribution from eq. (2) vanishes, as it should since it is the holes that make the long trip across the detector. Equation (3) yields the entire signal, and shows that the charge collection efficiency $\eta$, the ratio of the collected to liberated charge, is

$$\eta = Q_{el}/Q_{tot} = \{1 - \exp \left( - \frac{w}{\mu_e \epsilon_0} \right) \} \mu_h \epsilon_0/w.$$  \hspace{1cm} (4)

But $\mu_h \epsilon_0$ is the hole trapping length $l_h$, and eq. (4) shows explicitly the importance of the ratio $l_h/w$. Expanding eq. (4) for $l_h \gg w$ yields $\eta \approx 1 - w^2/2 \mu_h \epsilon_0 V$ which indicates the difficulty in obtaining good collection from thick devices. In general, holes and electrons have different trapping lengths. The serious polarization effects which plagued the early crystal counters were due to very short hole trapping lengths, resulting in a space charge from the trapped holes which impeded further charge collection.

Charge loss by recombination, depending as it does on the presence of both holes and electrons, is of importance only along the track of a densely ionizing particle. For a short time a dense cloud of equal numbers of holes and electrons exists in this region, leading to the possibility of recombination. Along the particle track the fractional carrier loss by recombination is given by

$$\frac{\delta n}{n} = \frac{\delta t}{\tau_{re}}$$

where $\tau_{re}$ is the recombination lifetime and $\delta t$ is the plasma time, the time during

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* It should be noted that these integrals are stated incorrectly in ref. 34.

which the track is held together by its own electrostatic forces. This time depends on the ionization density along the track and on the applied electric field. Measurement of pulse rise times for fission fragments indicates that the plasma time in this densely ionizing case may be as long as $10^{-7}$ sec at moderate field strengths.

The recombination lifetime decreases monotonically with increasing carrier density. For certain types of imperfections and for carrier densities $\approx 10^{18}$ carriers $\times$ cm$^{-3}$ or greater the lifetime may become comparable to the plasma time. Under these circumstances an appreciable fraction of the charge will be lost by recombination along the initial track. Since imperfections may be introduced during device fabrication the importance of this recombination effect depends on the details of the fabrication process. The plasma time decreases with increasing electric field. Consequently, by application of high electric fields it is possible to achieve efficient charge collection even in detectors having short recombination lifetimes.

In devices exhibiting recombination or trapping, the magnitude of charge loss may vary in different regions of the detector leading to poor energy resolution. Such effects become less pronounced as the ionization density is decreased or as the electric field is increased.

Non-uniformities in collection efficiency can arise from inhomogeneity in the bulk material, or, in the case of diffused junctions, from non-uniform distribution of impurities diffused in from the surface. Similar effects can also be produced by radiation damage.

§3. Detector noise

Collection of the liberated charge is a necessary but not sufficient condition for obtaining the optimum energy resolution. It is also necessary to minimize the detector noise. This noise is generated by fluctuations in the leakage current flowing through the device. These leakage currents arise both from the detector surface and from the detector volume.

Volume, or bulk, leakage is produced by the inverse of the carrier recombination process discussed in § 2. An imperfection captures a bound electron from the lattice, thus producing a free hole, and subsequently releases the electron which is then a free carrier. This carrier generation process, therefore, produces hole - electron pairs.

When such generation processes occur in the depletion layer, the holes and electrons are swept apart rapidly by the field, and the imperfection is available to repeat the process. This is called space-charge generated leakage current, and is serious only in cases of short lifetime material, or in very large detectors since this current is proportional to the depleted volume. Under normal conditions these currents are $< 10^{-6}$ A $\cdot$ cm$^{-3}$.

If the carrier generation occurs in the undepleted material, carriers must diffuse

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to the depletion layer before they can be affected by the field and add to the observed leakage. This is called diffusion current\(^{38}\) and is usually negligible \(< 10^{-8} \text{ A} \cdot \text{cm}^{-2}\).

Surface generated leakage currents arise in the region where the high electric field in the depletion layer comes to the detector surface, as shown in Fig. 1. This region is also of primary importance in determining the detector breakdown voltage. Surface leakage currents usually dominate the performance of semiconductor detectors and for this reason they have been studied in some detail.

![Fig. 3. Effects of different ambient atmospheres on the reverse leakage current of an n+p junction (ref. 39)](image)

Buck has investigated the effect of various surface treatments on junction detectors and has found that the reverse leakage current is related to the breakdown potential.\(^{39}\) Such effects for an n+p detector are shown in Fig. 3. Even larger variations can be produced by other chemical treatments. Boiling in deionized water produces a lower surface leakage current and a lower breakdown voltage, while soaking in concentrated hydrofluoric acid produces higher breakdown potentials and higher leakage currents. Analogous effects occur for detectors made with n-type base material, except that the direction of a given effect is reversed. In these cases, wet nitrogen produces low leakage and low breakdown and dry oxygen leads to high leakage and high break-

\(^{38}\) W. C. Dunlap, Jr., ref. 12, p. 154.

down. Within limits the surface can be chemically adjusted to an optimum condition. Usually the resulting state is a compromise between the desire for a low leakage current and a high breakdown potential. In addition to the chemical treatments described by Buck, arsenic glass and chemically doped epoxy resins have been used to adjust the surface at the junction edge. A method to reduce the effect of high surface leakage current by using a guard-ring structure has been described by Goulding and Hansen. In this device, shown in Fig. 4, the leakage and signal currents flow through different paths.

![Figure 4: An n+p junction guard-ring structure for minimizing the effect of surface leakage current (after ref. 41)](image1)

![Figure 5: An encapsulation method for protecting the edges of a junction from ambient change (ref. 42)](image2)

After achieving a desirable surface condition, the junction edge must be protected from further changes due to ambients such as water vapor, mercury vapor, ions, etc. Various methods of protection have been employed. In the encapsulation method described by Jackson et al., a transistor can is sealed to the junction surface such that most of the junction remains exposed while the junction edges are protected from ambient changes. This requires, however, that the diffusion at least under the seal be \( \approx 2 \mu m \) thick. Coatings of arsenic glass or apiezon wax around the junction

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edge, which slow down effects of ambient changes, have also been used. Silicon dioxide films grown on the base silicon before diffusion of the phosphorus have succeeded in producing very stable large area diffused junctions.\textsuperscript{44} In this device, shown schematically in Fig. 6, the edge of the junction is buried under the oxide film. Oxide passivation combined with independent control of the surface potential at the SiO\textsubscript{2}-Si interface as by prediffusion of gallium\textsuperscript{45} has succeeded in producing detectors with controlled junction properties and good long term stability.

\textbf{Fig. 6.} Idealized cross-section of an oxide masked diffused junction radiation detector

§ 4. Radiation damage

Radiation can produce lattice defects in the single crystals used in semiconductor detectors. The number and importance of these defects depend critically on the mass, charge and energy of the incident particles\textsuperscript{3} as well as the nature of the detector structure employed. The effect of these imperfections is to reduce both \( \mu \) and \( \tau \). This results in a reduction of the trapping length \( \mu \tau \) (see § 2) and an increase in the space-charge generated leakage current (see § 3). Use of the lowest resistivity material in which the desired depletion layer thickness can be obtained reduces the effect of radiation damage both by providing high electric fields, which aid charge collection, and by restricting the depleted volume, which reduces space charge current generation. No systematic study of the effect of radiation damage on detectors has yet been undertaken but Dearnaley and Whitehead\textsuperscript{47} report a slight increase in leakage current in a surface barrier detector after \( \approx 10^8 \) 5.5-MeV \( \alpha \)-particles \( \cdot \text{cm}^{-2} \), and a degradation of resolution after \( 2 \times 10^9 \) \( \alpha \)-particles \( \cdot \text{cm}^{-2} \) at low collecting fields. Halbert\textsuperscript{18} also reports degradation after \( \approx 10^9 \) \( \text{N}^{14} \) ions \( \cdot \text{cm}^{-2} \) with energies between 2 and 26 MeV. Sensitivity to fast neutrons has been found by George and Gunnersen,\textsuperscript{48} and also by Klingensmith,\textsuperscript{47} who reports degradation after \( 5 \times 10^{11} \) fast neutrons \( \cdot \text{cm}^{-2} \), and by Babcock\textsuperscript{49} who has observed changes in device leakage currents and \( \alpha \)-particle pulse height after \( \approx 10^{12} \) n \( \cdot \text{cm}^{-2} \). Degradation with slow neutrons depends sensitively on the packaging and environment of the detector because of damage due to \( \beta \)-particles from neutron capture products in the package. By careful consideration of the mounting and environment, large area \( p \text{-} n \) junctions have been used for weeks in a

\begin{itemize}
\item \textsuperscript{44} T. C. Madden and W. M. Gibson, Rev. Sci. Instr. 34 (1963) 50.
\item \textsuperscript{45} W. L. Hansen, F. S. Goulding and R P. Lothrop, Univ. of Calif. Lawrence Radiation Lab. Report UCRL-10578 (December 4, 1962).
\item \textsuperscript{46} G. Dearnaley, IEEE Trans. on Nucl. Sci. NS-10 (1963) 106.
\item \textsuperscript{47} G. Dearnaley and A. B. Whitehead, Nucl. Instr. and Meth. 12 (1961) 205.
\item \textsuperscript{48} G. George and E. M. Gunnersen, Conf. on Nucl. Chemistry, Oxford, Sept. 1962.
\item \textsuperscript{49} R. V. Babcock, IRE Trans. on Nucl. Sci. NS-8 (1961) 98.
\end{itemize}
thermal neutron flux of $\approx 10^9$ n · cm$^{-2}$ sec$^{-1}$ without apparent degradation.$^{50}$ In $\gamma$-ray fluxes of $4 \times 10^5 \text{ n}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$ Raymo et al.$^{51}$ observed high leakage currents, leading to poor resolution.

Lithium drift detectors are specially radiation-damage sensitive because of their low internal fields and consequent short trapping lengths. An added problem arises from the tendency of lithium to precipitate out on radiation produced vacancies.$^{52}$ Such effects have been studied by Mann and Yntema$^{53}$ and by Coleman and Rodgers.$^{54}$

§ 5. Electronics

The signal from a semiconductor detector is a quantity of charge $Q$ proportional to the energy expended by the incident particle in the sensitive region of the detector. This charge flowing into the external circuit produces a voltage signal $Q/C_t$ where $C_t$ is the total circuit capacitance, i.e., that of the detector, $C_D$, together with the stray capacitance, $C_s$. However, $C_D$ is a function of the counter bias voltage, in the case of a junction detector; consequently the output signal will be bias-dependent if a voltage amplifier is employed. This can be overcome by the use of an integrating preamplifier configuration, as shown in Fig. 7. A number of such systems have been described.$^{41,55-57}$

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Fig. 7. Integrating preamplifier configuration employed to minimize the effect of variations of the detector capacitance $C_D$. The charge liberated in the detector by an incident particle is represented by $Q$, and charge calibration is accomplished with a pulse generator and a calibrated capacitor $C_c$.

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57 J. L. Blankenship and C. J. Borkowski, IRE Trans. on Nucl. Sci. NS8 (1 961) 17.
In such preamplifiers, the output signal $V_0$ is given by $-Q/C_t$ to a good approximation, provided that $G_0C_t \gg C_L$, where $C_t$ is the feedback capacitor and $G_0$ the open loop gain. Therefore the output voltage is proportional only to the input charge, and is independent of the input capacitance.

The signal energy is $Q^2/2C_t$, and as $C_t$ increases the signal energy decreases, reducing the signal-to-noise ratio. (The application of feedback does not alter this situation except to add a small capacitance, namely $C_R$, to $C_t$ in computing $C_t$.) Hence, the signal-to-noise ratio is a function of the input capacitance even though the signal amplitude is not.

![Fig. 8. Calculated noise line width as a function of detector capacitance $C$, detector leakage current $i_L$ and amplifier time constants (ref. 41)](image)

The signal-to-noise ratio depends on the noise generated by leakage currents in the detector and shot noise, grid current noise, etc., in the amplifier input tube. The importance of these various noise sources has been investigated by Goulding and Hansen⁴¹ who have produced the useful graph, containing all these factors, shown in Fig. 8. It is assumed here that the input tube is a WE 417A, that the amplifier employs one integrating and one equal differentiating time constant, and that the detector leakage current has a white noise spectrum.

Given a preamplifier operating as shown in Fig. 7, the reserve gain is $G_R = G_0C_t/C_L$. If the open loop rise time is $\tau_o$, the closed loop rise time, assuming one dominant internal time constant, will be $\tau_c = \tau_o/G_R = \tau_oC_t/G_0C_t$. The rise time therefore depends on the input capacitance. As the input capacitance increases, both the noise and the rise time suffer, and this, for a particular integrating preamplifier, is shown in the graphs of Fig. 9 due to Fairstein.

It is important to note that the design of preamplifiers for optimum noise performance depends critically on the capacitance and leakage currents of the detectors with which they are to be employed. For detectors of a few pF capacitance, and
leakages of nanoamperes or less, tubes operating under starved conditions\textsuperscript{58} (low voltages and currents), and field effect transistors\textsuperscript{59} can yield line widths < 2 keV. High capacitance detectors dictate the use of conventional bipolar transistors\textsuperscript{58, 60} or tubes operating under normal conditions.

Consideration has also been given to other amplifying systems, e.g., parametric amplifiers, but they do not seem to offer any distinct advantage at this time.\textsuperscript{61}

A useful feature of charge sensitive amplifiers is the ease of charge calibration. This is usually carried out, as shown in Fig. 7, by applying accurately known voltage pulses, from a precision pulse generator, to a small stable calibrated capacitor connected to the preamplifier input. In this way each voltage pulse $V_p$ from the pulser injects a known quantity of charge $Q_c = V_p C_0$. This allows energy calibrations to be checked,* and also noise contributions to be evaluated since the line width from the pulse generator will result only from detector and amplifier noise, and will be independent of particle beam spread, inhomogeneous collection efficiency, etc. A similar technique can be employed to measure the detector capacitance by injecting voltage pulses of known amplitude in series with the detector ground connection, and hence quantities of charge $V_p C_D$ per pulse.

As with all radiation detectors, considerable importance attaches to the precise pulse shaping systems used in the main amplifier.\textsuperscript{30} The effects of various of these

\* It may be useful to remember that $e = 3.5 \text{ eV \cdot \text{ pair}^{-1}}$ for silicon corresponds to $4.6 \times 10^{-14}$ coulombs per MeV of energy deposited in the sensitive volume.

\textsuperscript{58} J. L. Blankenship, Oak Ridge Nat. Lab., private communication.


\textsuperscript{60} T. L. Emmer, IRE Trans. on Nucl. Sci. NS-8 (1961) 140.

systems have been analyzed in detail. If high resolution is desired it is apparently a good compromise to employ equal 1 μsec differentiating and integrating time constants. At high counting rates, or for fast coincidence work, 1 μsec double delay line pulse shaping has proved useful despite a noise disadvantage.

In view of the excellent statistics of charged particle ionization in semiconductor detectors, fast timing may be carried out even though the signal rise times are often quite long because of the device-RC. Zero cross-over timing applied to double clipped wave forms affords a convenient way of achieving accurate timing with slowly rising signals.

§ 6. Detector types

6.1. Diodes

As noted in the introduction, the extreme purity and crystalline perfection obtainable in silicon and germanium allow these materials to be employed as radiation detectors for high resolution measurement of particle energies. A reverse biased diode structure is most often employed to reduce leakage currents to manageable levels. For germanium, thermal generation of carriers across the 0.66 eV band gap requires that diodes be cooled to reduce this source of leakage current. The inconvenience of cooling has resulted in major emphasis on the use of silicon because its band gap of 1.09 eV allows diode structures to be used at room temperature. The starting materials in detector fabrication are usually high purity vacuum-floating-zone refined single crystals. The largest commercially available floating-zone refined material at the present time has a diameter of ~4 cm. Production of very high resistivity (10 000 Ω · cm p-type or 4 000 Ω · cm n-type) zone refined silicon is a difficult matter, and so far no method exists for making it at will. However, such material has occasionally been produced, and has been used to achieve depletion layer thicknesses of ~2 mm.

Slices are cut from the crystal, usually perpendicular to its long dimension, forming discs with thicknesses ranging up to 10 mm. These slices are lapped with fine abrasive to remove cutting damage and then chemically etch-polished to expose an undamaged crystal surface. These and subsequent steps outlined here are mainly standard semiconductor fabrication techniques which have been extensively described elsewhere.

To make phosphorus-diffused counters, the wafers are introduced into an oven and heated in the presence of phosphorus. The phosphorus is present in a carrier gas. Suitable temperature and time schedules then give diffused layers of desired thickness, e.g., 10 minutes at 900° C results in an n⁺ layer ~0.3 μm thick. Similar techniques are employed for diffusion of boron or gallium into n-type material to form p⁺n junctions.

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46 R. L. Chase, ref. 30, p. 166.
Following the diffusion step the wafers are slowly cooled, the edges etched, and suitable electrical contacts made to the p and n regions.

The main alternative fabrication technique that has been employed is that of forming surface barrier junction diodes. In these devices, n-type base material is employed. Following the chemical etch, which is quenched with deionized water, the surface is washed with deionized water and allowed to stand in air for several hours. Gold is then evaporated onto the crystal surface, making contact in a way that is not well understood.

It is usually not difficult to make electrical contact to the front face of either diffused or surface barrier diodes because of the high conductivity of this region. For diffused junctions, alloyed contacts of indium or gold are sometimes used for hermetic seals or mechanical stability, but it is often sufficient to use a spring wire contact across which a small capacitor has been discharged in the forward bias direction. For surface barrier detectors, attachment of a thin metal ribbon to the evaporated gold film or extension of the evaporated film onto an insulating layer containing a metal contact is usually used. The properties of the contact on the back of a junction detector are also important due to the requirement that it not inject carriers into the sensitive region of the device. Successful non-injecting contacts have been made using diffused, alloyed and surface barrier techniques. Whichever type of junction is employed, the thickness of the depletion layer is proportional to $\sqrt{\rho V}$, where the factor of proportionality is different for n-type base material. (This result is only true for abrupt junctions. Graded junctions exhibit a $\rho V$ dependence.) The connection between thickness, bias and resistivity has been displayed in a very useful form by Blankenship, whose nomograph, somewhat extended, is shown in Fig. 10.

6.2. LITHIUM DRIFT COMPENSATION

The high mobility of lithium ions in silicon and germanium may be used to increase greatly the semiconductor resistivity. In this technique, due to Pell, lithium is used...

* It is interesting to note that other dense metals, e.g., nickel, have also been used successfully, but Andrews has found that the light metals with low work functions, Al, Be, Mg, do not form rectifying junctions on n-type material. This indicates that the metal may play a more fundamental role than simply making contact to a chemical inversion layer.

** In the case of almost intrinsic material between two heavily doped contacts, forming a $p^+ - i - n^+$ structure, the diode nomogram does not apply. In that case, the i region is depleted throughout for biases of only a few volts.

to produce almost exact compensation of low resistivity p-type starting material. The 
resistivity may be raised in this way close to the intrinsic value,72,73 and compensated 
thicknesses of over a centimetre have been produced.74

Lithium is first diffused into the surface of p-type material producing an n+p junc-

Fig. 10. Silicon diode nomograph, computed using carrier mobilities of 1500 and 500 for electrons 
and holes respectively (ref. 25) and range-energy data from ref. 70 (after Blankenship, ref. 67).

This nomograph does not apply to lithium-drifted devices

tion. This is then heated to increase the lithium mobility and a reverse bias voltage is applied. Lithium ions drift in the depletion layer under the influence of the electric field in a manner that tends to compensate the excess donor impurities in that region. It can be shown that the compensation of a given volume of semiconductor requires the expenditure of a proportional amount of energy. This energy appears as Joule heating in the drifting wafer, and the rate at which drifting proceeds is therefore limited by the capacity of the cooling system employed. A number of automatic techniques have been used to facilitate the drifting process\textsuperscript{74-76} which becomes very time consuming for deep drifts, e.g. ten days to produce approximately a one centimeter thickness of compensated silicon.

Because only low voltages need be applied to lithium drift devices to obtain thick depletion layers, the surface leakage and breakdown problems are reduced. The larger sensitive volumes obtained, however, cause space-charge generated leakage currents to become more important, and in some cases dominant.\textsuperscript{77} This leakage is very temperature dependent and can be drastically reduced by cooling. A more serious difficulty is the motion of the lithium at room temperature in the absence of a high reverse bias voltage. The lithium effectively 'undrifts' and may move to a surface and be lost or may precipitate out in the crystal. This problem, which is much more serious in germanium\textsuperscript{78} than silicon, requires storage under reverse bias voltage at low temperatures or possibly loading of the crystal with oxygen before fabrication to reduce the lithium mobility by formation of the LiO\textsuperscript{+} complex.\textsuperscript{71}

6.3. Conductivity Counters\textsuperscript{*}

Addition of gold to silicon in small concentrations introduces traps which result in extremely high resistivity at low temperatures. Heat treatment to 1000°C sometimes introduces imperfections of unknown origin which have similar effects. Use has been made of such deep trap material for detectors\textsuperscript{11,79}.

Unfortunately, the existence of these deep levels also reduces the carrier lifetimes,\textsuperscript{80} resulting in inefficient charge collection and poor energy resolution.

Other semiconductors such as gallium arsenide and cadmium sulfide which exhibit very high resistivity at room temperature have also been used for particle detection.\textsuperscript{80,81} Imperfections in these materials, however, result in excessive and often inhomogeneous

\textsuperscript{*} A detailed account of the operation and properties of conductivity counters is given in ref. 3.

\textsuperscript{78} J. L. Blankenship and C. J. Borkowski, IRE Trans. on Nucl. Sci. NS-9 (1962) 181.


\textsuperscript{81} M. Borisov and M. Marinov, in Nuclear Electronics 1 (International Atomic Energy Agency, Vienna, 1962) 363.
carrier trapping and recombination. It is unfortunately true that the material purity and crystalline perfection required for high resolution particle detectors will probably limit the application of materials other than silicon and germanium for several years. The use of high atomic number semiconductors for γ-ray measurements, or other devices using special semiconductors will, therefore, necessarily await substantial advances in material purification techniques.

6.4. INTERNAL GAIN DEVICES

A number of attempts have been made to provide charge gain within the detector itself. The simplest method involves operation of a junction detector at such a high bias that avalanche multiplication occurs. This effect has been observed but does not seem very promising since it is hard to stabilize, and the high fields involved lead to serious surface leakage problems.

Another possibility that has been investigated is that of combining the detector with a transistor structure. However, this again suffers from the problem of gain instability and also exhibits slow response although these are probably not inherent difficulties.

Other suggestions have been made regarding possible gain mechanisms, e.g., impact ionization at low temperatures, but so far none of these appear particularly promising.

§ 7. Application to nuclear physics

The use of semiconductor nuclear particle detectors has already had a considerable impact on the field of low-energy nuclear physics and it is expected that these devices will play an even more important role in the future. It is the intent of this brief account to point out the chief advantages and limitations of these detectors as applied to nuclear physics experiments. The references given in this section are not exhaustive, but rather have been selected as being illustrative of the application under discussion.

Advantages:
(a) Excellent energy resolution
(b) Linear response over a wide range of particle types and energies
(c) Insensitivity of pulse height to counting rate
(d) Fast pulse rise time
(e) Windowless operation
(f) Variable sensitive thickness
(g) Selectivity for charged particles
(h) Small size and ease of handling
(i) Insensitivity to magnetic fields
(j) Ability to operate at low temperatures
(k) Ability to fabricate special structures, e.g. mosaics, annular devices and position sensitive detectors

Disadvantages:
(a) Inability to stop particles of long range
(b) Relatively short operating lifetime of, many currently available devices (due to surface degradation or radiation damage)
(c) Low output signal level
(d) Relatively slow, and particle range dependent, signal rise time for thick devices
(e) Inability to operate at high temperatures

The principal applications of semiconductor detectors to low-energy nuclear physics are listed and discussed below.

7.1. NUCLEAR REACTION CHARGED PARTICLE SPECTROSCOPY

Most of the published work involving the use of semiconductor particle detectors has been in the general field of nuclear reaction charged particle spectroscopy. In this application the advantages mentioned are particularly important. Figures 11 and 12, taken from the work of Almquist et al. indicate the results attainable in charged particle reaction spectroscopy using both singles and particle-γ-ray coincidence

Fig. 11. Spectrum of α-particles from the reaction $\text{Al}^{37}(p, \alpha) \text{Mg}^{24}$ showing α-peaks corresponding to population of the ground and first four excited states of $\text{Mg}^{24}$ (ref. 86)

techniques. Figure 11 shows an $\alpha$-particle spectrum from the reaction $^{27}$Al$^{27}(p, \alpha)^{24}$Mg with 8 MeV incident protons. The energy resolution in this experiment was limited by the target thickness. In reactions like the $(p, \alpha)$ reaction in which elastically scattered beam particles may have a range much longer than the particles of interest, the depletion layer thickness may be adjusted so that beam particles give pulse heights low enough to be outside the region of interest. This technique is not usable in the case of lithium-drifted devices, in which essentially the full thickness of the device is attained at a low reverse bias voltage). Figure 12 demonstrates the usefulness of semiconductor detectors in particle-$\gamma$-ray coincidence experiments. The upper part of the figure shows the singles $\gamma$-ray spectrum from the reaction shown in Fig. 11. The $\gamma$-ray of 1.368 MeV expected from the decay of the first excited state of $^{24}$Mg is not discernible. By setting a channel on the $\alpha_1$-group shown in Fig. 11 and displaying the pulse height spectrum of the coincident $\gamma$-rays using a $7 \times 10^{-9}$ sec resolving time, the curve shown in the lower part of the figure was obtained. This is a pure 1.37 MeV spectrum for a 5"-diameter x 4" NaI(T1) crystal.

Fig. 12. Spectra exhibiting the use of particle-$\gamma$-ray coincidence techniques (ref. 86)
Particle-particle coincidence measurements with semiconductor detectors have also proved to be a very useful technique in nuclear reaction spectroscopy. Here advantage may be taken of the high energy resolution available in both channels. This, together with the short resolving times obtainable with semiconductor detectors, make possible excellent background discrimination. Fullest advantage is taken of the wide range of energy information available from these particle-particle coincidence measurements when two-dimensional pulse-height analysis techniques are used.

High resolution heavy-ion spectroscopy is an area in which semiconductor counters have also proved useful. The saturation effects which are encountered when scintillators are used to detect densely ionizing particles are not noticeable with the semiconductor devices, and the short range of energetic heavy ions makes it possible to stop heavy ions of the highest available energy in the sensitive thickness readily obtainable in semiconductor counters.

Very short coincidence resolving times are frequently desirable in particle-particle coincidence measurements. It is often possible to use a resolving time which is short compared to the pulse rise time, especially in the case of very densely ionizing particles of high energy, such as fission fragments and heavy ions of several MeV per nucleon. Rise times vary widely depending on the electric field and the device-RC time. McKenzie and Bromley have reported a pulse rise time of $< 3 \times 10^{-8}$ sec obtained with a cooled Au-Ge surface barrier junction.

The small size and flexibility of geometry provided by semiconductor detectors are useful in angular distribution measurements, particularly when it is desirable to employ very small angular increments or to make measurements close to 0° or 180° to the incident particle beam. Bromley has reported on a semiconductor device fabricated by McKenzie (see Fig. 13) which makes it possible to detect, with high efficiency, particles which are emitted close to 180°. The object is to take advantage of the great simplification in the $(b, \gamma)$ angular correlation formalism which occurs in a reaction of the type $A(a, b\gamma)B$ when the particle $b$ is emitted at either 0° or 180° to the incident particle (‘a’) beam. The semiconductor device pictured in Fig. 13 is a silicon surface barrier junction with a $\frac{1}{4}$ in outer diameter with a $\frac{1}{8}$ in. hole through the center.

Various types of mosaic structures employing semiconductor counters have been used. Mainly these have been raster configurations used in magnetic spectrometers to replace photographic plates. In this application one has the obvious advantages of instantaneous digitization and continuous data display. Raster configur-
tions are also attractive for angular distribution measurements. When the raster contains very many individual detectors, handling the output information can be very cumbersome. An obvious but expensive way to solve this problem is to provide each element of the raster with its own preamplifier. Bilaniuk et al. have reported on a technique which greatly reduces the number of amplifiers needed to handle the output of a raster of 20 detectors. Each detector of the raster is connected as a capacitor in a lumped delay line. The originating detector is identified by the delay between the pulses from the two ends of the line and in this way unambiguous detector identification is achieved.

An ingenious position sensitive device has been constructed by Norbeck in which contacts are provided at both ends of a long narrow detector having a high sheet resistance. The way in which the charge due to an incident particle divides between the two ends of the detector can be measured and used to indicate the particle position. In principle, this technique can be extended to give two-dimensional position information by the use of three contacts mounted on a suitable device.

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Fig. 13. Special detector configuration allowing measurement of reaction products emitted close to an incident beam (J. M. McKenzie, reported by Bromley, ref. 93, p. 64)

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7.2. MASS IDENTIFICATION

A useful technique in nuclear reaction investigations is the identification of an emitted particle by the simultaneous measurement of its energy \( E \) and its rate of energy loss \( dE/dx \). The product of these two quantities* is approximately proportional to the particle mass times the square of its charge.

There are four principal advantages to be expected from semiconductor \( dE/dx \) counters\(^97,98 \) as compared with the transmission ionization chambers and proportional counters which have been used for this purpose. First, due to the higher density of the semiconductor device, it can be made much thinner than a gas counter of comparable stopping power. By placing this thin \( dE/dx \) counter close to the front of the \( E \) counter, one can use a small area semiconductor \( E \) detector without incurring particle losses from scattering in the \( dE/dx \) detector. Such losses are often serious when the much longer gas \( dE/dx \) counters are used. Second, because of the faster rise time of the semiconductor device, higher \( dE/dx \) counting rates are practical. Third, because of the higher carrier production efficiency in semiconductors, better resolution is possible in the \( dE/dx \) pulse. Fourth, these detectors can be made without windows.

Wegner\(^97 \) has reported on a \( dE/dx \) counter fabricated by phosphorus diffusion into 6000 \( \Omega \cdot \text{cm} \) p-type silicon. The thickness of the final device was 0.002", and the useful area about 0.7 cm\(^2\). Used with a semiconductor \( E \) detector and an electronic pulse multiplier, this system separated \( \text{He}^5 \) from \( \text{He}^4 \) particles in the energy region of 10 to 25 MeV, at intensity ratios up to 1000:1.

Application of oxide masked diffusions together with special etching techniques has made possible the production of reliable \( dE/dx \) detectors as thin as 15 \( \mu \text{m} \) with thickness non-uniformity of < 0.5 \( \mu \text{m} \).\(^99 \)

In addition to thickness non-uniformity and statistical limitations on resolution in \( dE/dx \) detectors, crystal orientation may also be important.\(^100 \)

An alternative mass identification scheme has been proposed by Goulding,\(^101 \) also employing two detectors, in which discrimination is based on an empirical range-energy formula. This method imposes less stringent conditions on the thickness of the \( dE/dx \) detector.

7.3. ALPHA-PARTICLE SPECTROSCOPY

Semiconductor detectors are extremely useful for a-particle spectroscopy. Although their energy resolution is inferior to the best a-particle magnetic spectrometers, their

\* This product can conveniently be formed by the use of a field effect transistor multiplier.\(^99 \)


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better geometry is attractive in experiments where the highest energy resolution is not necessary or where low counting rates or short half lives preclude the use of magnetic spectrometers. Advantages over conventional gridded ion chambers include better energy resolution, lower background, higher permissible counting rates, better time resolution for coincidence measurements, lower cost, and superior stability. The two factors of prime importance in \( \alpha \)-spectroscopy are energy resolution and peak-to-low-energy-tail ratio. Blankenship and Borkowski have attained an energy resolution (full width at half height) of 13.5 keV with a cooled gold-silicon surface barrier detector. At room temperature a line width of 15 keV has been obtained for both surface barrier and phosphorus diffused devices. Such a spectrum obtained using a surface barrier junction is shown in Fig. 14. With the same type of detector, Chetham-Strode et al. using \( \text{Cm}^{244} \), have measured the low-energy tail to be 0.15% of the main peak height at an energy about 150 keV below the main peak.

Fig. 14. Alpha-particle spectrum of \( \text{Am}^{241} \) measured with a gold-silicon surface barrier detector (ref. 67)

Fig 15. Study of correlated fission fragment energies using two semiconductor detectors in coincidence. The inset is a photograph of the two-dimensional pulse height analyzer display showing the energy surface obtained for thermal neutron fission of $^{238}U$.

7.4. INVESTIGATIONS OF THE NUCLEAR FISSION PROCESS

Semiconductor detectors have been playing an increasingly important role in nuclear fission studies. Total fission yields, angular distributions, fragment kinetic energy, and mass distributions and light charged particle emission in fission have all been studied using semiconductor particle detectors. Sub-

stantially windowless operation and the good energy resolution* have made these detectors especially valuable in such investigations; their small size and lack of response to γ-rays or low-energy neutrons have also been important. In addition, the short pulse rise times and large signals obtained from fission fragments makes these detectors useful for time-of-flight measurements of fragment velocities. Figure 15 summarizes an experiment in which two semiconductor detectors, a U²³⁵ fission source, and associated preamplifiers, were exposed to ≈ 10⁹ thermal neutrons cm⁻² x sec⁻¹. The coincident fragment energy spectra were then measured using a two-dimensional pulse height analyzer. A photograph of the analyzer display representing the energy surface is shown in Fig. 15. This experiment, which utilizes many of the advantages previously noted for semiconductor detectors, illustrates their usefulness in such studies.

7.5. ELECTRON SPECTROSCOPY

Because of the relatively small sensitive thicknesses available, semiconductor detectors have not been widely used for electron spectroscopy. However, as techniques for increasing the effective volume of the sensitive layer have become more highly developed, these devices have assumed increasing importance for this application. Measurements of electrons up to 1 MeV energy in phosphorus-diffused junctions and surface barrier junctions have been reported. In both cases line widths of 7.5 keV were obtained at room temperature. Depletion layer thicknesses up to 0.8 mm have been achieved for diffused pn junctions and 1.5 mm for surface barrier junctions by use of the highest resistivity silicon available and by control of the surface condition to allow application of the highest possible reverse bias voltage. Even thicker depletion layers can be achieved by use of the lithium drift technique. Room temperature operation of such devices usually results in significant noise due to space charge generated leakage currents. By cooling, however, noise from this source can be reduced to a level at which it is no longer dominant. Blankenship and Borkowski using a detector 2 mm thick and 0.8 cm² area cooled to 200° K have achieved a line width of 3.8 keV, as shown in Fig. 16. This result is interesting not only because of its high resolution but also because it has allowed a limit of less than 0.5 to be set on the Fano factor for silicon. While these resolutions compare unfavorably with those obtainable from magnetic spectrometers, it is useful to bear in mind that the luminosity of semiconductor systems can be very high, that the output is proportional to energy not momentum, and that all energies are recorded simultaneously.

For electron measurements the low atomic number of silicon helps to reduce effects

* Comparison of fission fragment kinetic energy spectra obtained using solid-state detectors with time-of-flight data indicates a possible pulse height defect of 5-10 MeV per fragment. This must be differentiated from the larger field-dependent defect present at low fields due to the recombination effects discussed in § 2.

due to backscattering of the incident electrons. There remains, however, a low energy tail due to backscattering. This effect interferes with detailed measurements of β-particle spectral shapes but can be minimized by use of two detectors or special configurations allowing recapture of backscattered electrons. An ingenious solution to this problem has been devised by Shera and Casper which overcomes the difficulty of backscattering leading to spectral distortions. In this instrument two small detectors are placed axially at opposite ends of a 30 kilogauss superconducting solenoid, while a thin source is placed symmetrically between them. Most of the emitted electrons, together with those backscattered from the detectors, are constrained by the field to a narrow axial tubular region. Adding the detector output signals then yields an essentially undistorted spectrum. Another advantage of this spectrometer is that the solid angle subtended by the detectors at the source is small and consequently the β-γ discrimination is greatly improved.

7.6. GAMMA-SPECTROSCOPY

Detection of γ-rays represents an almost ideal situation for a semiconductor detector from the point of view of charge collection. Dead layer and columnar recombination problems are minimized, as are difficulties associated with thin window encapsulation. Consequently, it is to be expected that at any stage of semiconductor detector technology the highest resolution will be obtainable for γ-rays. Neither is it unreasonable to

118 E. B. Shera and K. J. Casper, Western Reserve Univ., Cleveland, Ohio, private communication.
the solid angle through which the detector can see the source. This is a large, thick, 2-mm-thick lithium-drifted silicon detector. A gamma-spectrum obtained with such a detector is shown in Fig. 17.

The energy dependence of photoeffect, Compton scattering, and pair production in germanium, taken from ref. 3, is shown in Fig. 18. This indicates a pronounced

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117 C. Chasman and J. Allen, Yale Univ., New Haven, Conn., private communication.
Fig. 18. Absorption coefficients for $\gamma$-rays in germanium (from ref. 3)

Fig. 19. $\text{Bi}^{207}$ source $\gamma$-ray spectrum from a germanium lithium-drift detector (19 mm diameter and 5 mm depletion depth) (from ref. 78)
minimum in photon absorption, as opposed to scattering, at approximately 1 MeV. Compton effect is dominant in this region but the high resolution of the detectors allows sharp peaks (arising partly from multiple processes) to be readily resolved from the background. This is shown in the Bi207 spectrum of Fig. 19 taken from ref. 78. Interesting structure in the Compton edge of the two higher energy γ-rays is displayed in this spectrum as well as the spectrum of Fig. 17. This structure may be due to multiple Compton scattering or possibly arises from the momentum distributions of electrons in the various atomic and crystalline energy levels.

At lower energies, the higher photoelectric cross section leads to improved detection efficiency and peak-to-background ratios. The Co57 spectrum shown in Fig. 20 illustrates the performance of germanium devices at energies of approximately 100 kilovolts. The clear separation of the two photopeaks differing in energy by only 14 kilovolts is particularly striking.

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Fig. 20. Co57 source γ-ray spectrum from a germanium lithium-drift detector (18 mm diameter and 8 mm depletion depth) (from ref. 78)

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111 C. Chasman, Yale Univ., New Haven, Conn., private communication.
At energies above approximately 2 MeV pair production becomes important as exemplified in the $^{24}\text{Na}$ spectrum of Fig. 21. For increasing $\gamma$-ray energies the detection efficiency continues to improve, for a device of given dimensions, until the loss of energetic pairs becomes significant. A sensitive volume of 1 cm$^3$ can be expected to yield an efficiency of a few per cent for $\gamma$-rays of 5 to 10 MeV.

While performance of lithium drifted germanium devices is extremely impressive, it is important to bear in mind certain limitations. As previously pointed out the 0.66 eV band gap of germanium necessitates that these detectors be operated at low temperatures to reduce the leakage current noise. Problems are also posed by the tendency of the lithium to precipitate in the germanium crystals and to become electrically inactive. This necessitates storage at low temperatures or periodic re-drifting and re-etching of the device.

It is also important to bear in mind that the limiting velocity of carriers in germanium is approximately $10^7$ cm/sec which imposes a limit of $\approx 100$ nsec per centimeter thickness on the rise time of detector signals. Charge collection time, collection efficiency, availability of material, and practical difficulties in drifting large distances

Fig. 21. $^{24}\text{Na}$ source $\gamma$-ray spectrum from a germanium lithium-drift detector (19 mm diameter and 5 mm depletion depth) showing the 1368 keV and 2754 keV $\gamma$-ray photopeaks. The double and single-escape pair peaks associated with the 2754 keV $\gamma$-ray are present (from ref. 78)
will probably limit the sensitive volume of individual detectors to a few cubic centimeters for some time to come.

For reasons indicated in § 2 it is unlikely that germanium will be replaced for high resolution $\gamma$-spectroscopy by any higher-$Z$ semiconductor for a number of years.

### 7.7. Neutron Spectroscopy

Two principal types of neutron spectrometers employing semiconductor counters have been studied. One involves a proton radiator consisting of a thin layer of hydrogenous material either some distance in front of the counter, with collimation to examine only protons ejected directly forward, or directly on the face of the counter.$^{122}$ In the latter case information regarding the neutron energy distribution can be derived by differentiation of the recoil proton energy spectrum.

The second type of neutron spectrometer involves detection of the charged particles produced by a suitable neutron-induced reaction. In one such device the neutrons are detected by measuring in coincidence the sum of the energies of the triton and $\alpha$-particle produced in the reaction $\text{Li}^7(n, \alpha)\text{T}$. The neutron energy is equal to the sum of the energies of these two particles minus 4.78 MeV, which is the negative of the $Q$-value of the reaction. Love and Murray have reported on a neutron spectrometer of this type using sensitive areas of 0.7 cm$^2$ with $\text{Li}^4\text{F}$ layer about 150 $\mu$g $\cdot$ cm$^{-2}$ thick.$^{124}$ Slow neutrons and monoenergetic fast neutrons in the energy range 0.6 to 15 MeV were detected. An energy resolution of about 300 keV was obtained for the fast neutrons. This peak width was caused by charged particle energy losses in the $\text{Li}^4$ layer, and was approximately independent of the neutron energy. The spectrometer had an efficiency of $3 \times 10^{-3}$ for thermal neutrons, and about $10^{-6}$ for neutrons of 2 MeV energy.

Deamaley et al.$^{125}$ have demonstrated the usefulness of the $\text{He}^3(n, p)\text{T}$ reaction for neutron spectrometry. Because of the low density of the gaseous $\text{He}^3$ target material and the fact that both of the products are singly charged, the energy spread due to particle energy losses in the target is reduced. With a detector consisting of two surface barrier detectors with $\text{He}^3$ gas at 5 atmospheres pressure between them, Deamaley et al. obtained a detection efficiency of $\approx 10^{-5}$ with a neutron energy resolution of 150 keV. This type of detector has the added advantage that by varying the gas pressure the neutron efficiency-energy resolution balance best suited for a particular experiment can be used. In addition, effects due to neutron reactions in the silicon can be determined by removing the gas from the chamber. Fois with suitably spaced thresholds for neutron induced, charged particle producing reactions can also be used with standard counting diodes for neutron energy measurements.$^{126}$

In all of these methods suitable corrections must be made for the effects due to

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neutron reactions in the silicon\textsuperscript{125,127} and it has been suggested that these reactions themselves may be used to measure the energy, energy spread and intensity of neutrons from 7 to 18 MeV.\textsuperscript{128}

7.8. LOW TEMPERATURE NUCLEAR ALIGNMENT EXPERIMENTS

Semiconductor detectors are well suited for investigations involving the emission of charged particles from aligned radioactive nuclei.\textsuperscript{129} Because of their small size they can be used to determine the angular distribution of emitted particles in the small volume of a low temperature nuclear alignment apparatus. Among their advantages over scintillation crystals in this application are better energy resolution for charged particles, and the absence of a phototube which must be well shielded from the high magnetic fields employed in some nuclear alignment techniques. However, there is evidence that certain detectors can exhibit inefficient charge collection below about 40° K.\textsuperscript{130} Application of semiconductor detectors to the measurement of α-particles and fission fragments from aligned nuclei have been described.\textsuperscript{129}

7.9. SUMMARY OF SEMICONDUCTOR DETECTOR PERFORMANCE

The table below is intended to summarize the best values of energy resolution for various types of particles at various energies, which have come to the attention of the authors. Since in almost all cases comparable performance has been achieved by a number of individuals or groups, references are not given.

\textbf{TABLE}

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy</th>
<th>Resolution (FWHM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission fragments</td>
<td>50-150 MeV</td>
<td>&lt; 1.2 MeV</td>
</tr>
<tr>
<td>Heavy ions, various</td>
<td>1-10 MeV/nucleon</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>α-particles</td>
<td>~ 42 MeV</td>
<td>~ 80 keV</td>
</tr>
<tr>
<td>α-particles</td>
<td>5-6 MeV</td>
<td>~ 13.5 keV</td>
</tr>
<tr>
<td>Protons</td>
<td>11 MeV</td>
<td>~ 35 keV</td>
</tr>
<tr>
<td>Protons</td>
<td>2 MeV</td>
<td>~ 16 keV</td>
</tr>
<tr>
<td>Electrons</td>
<td>50 keV – 1.2 MeV</td>
<td>~ 4.5 keV</td>
</tr>
<tr>
<td>γ-rays</td>
<td>100 keV</td>
<td>~ 3 keV</td>
</tr>
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<td>1-3 MeV</td>
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<td>5 MeV</td>
<td>~ 8 keV</td>
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<tr>
<td>Neutrons</td>
<td>0.5-15 MeV</td>
<td>~ 150 keV</td>
</tr>
</tbody>
</table>

\textsuperscript{125} W. M. Deuchars and G. P. Lawrence, Nature 192 (1961) 1278.