are not very useful for the determination of the energy of gamma rays, the exponential absorption of gamma rays by matter, and the dependence of the absorption coefficient on the material of the absorber can be demonstrated. Further, it is easier to collimate a gamma-ray beam, and scattering effects are less pronounced than for electrons, so that it is possible to obtain "clean" data with only a reasonable amount of care.

The detector for measuring gamma-ray absorption could be a Geiger counter, but a scintillator is preferable because of its higher efficiency. The absorbers have now a thickness of the order of grams per square centimeter and are usually lead or aluminum; they should be placed so as to minimize scattering, a possible arrangement being shown in Fig. 5.33.

The data on Fig. 5.34 were obtained by a student† using a Cs^{137} source. The resulting values for the absorption coefficients are

$$\text{for Pb} \quad \kappa = 1/0.82\ \text{cm}^{-1} \quad \text{and} \quad \mu = 0.107\ \text{cm}^2/\text{gm}$$

$$\text{for Al} \quad \kappa = 1/4.7\ \text{cm}^{-1} \quad \mu = 0.079\ \text{cm}^2/\text{gm}$$

in good agreement with the accepted values for gamma rays of 0.662 MeV energy‡.

$$\text{Pb} \quad \mu = 0.11\ \text{cm}^2/\text{gm}$$

$$\text{Al} \quad \mu = 0.075\ \text{cm}^2/\text{gm}$$

The exponential nature of the absorption process is clearly demonstrated.

5. Solid-State Particle Detectors

5.1 General

We have seen how the gaseous ionization counters and the scintillation counters are widely used for the detection of radiation and charged particles. Recently it has been possible to use semiconductor materials for the detection of charged particles, especially those of low energy; such detectors are called "solid-state counters" after the name of the field of physics responsible for the development and understanding of semiconductors.§

In a general sense, we can think of this type of detector as a solid-state ionization chamber, having two basic advantages over a gas-filled ionization chamber:

(a) The energy required for the creation of an electron-ion pair is 3 eV (as compared to approximately 30 eV in a gas) so that stronger signals and better statistics can be achieved.

† K. Douglass, class of 1964.

‡ See, for example, *Nucleonics*, 19: 6, p. 62 (1961).

§ The scintillation counter is also a detector in the solid state!

(b) The stopping power is approximately 10^3 times that of a gas-filled device (since the detector material is so much denser), and thus it becomes possible to stop, in the *detector*, particles with energies typical of nuclear interactions. Consequently a very large number of electron-ion pairs is formed, leading to very good energy resolution. A 1-MeV proton stopping in a solid-state detector will create 300,000 electron-ion pairs, while the same proton traversing a proportional counter of 2-cm thickness would only release approximately 30 pairs.

In practice, however, it must be possible to collect the free charges (those created by the passage of the charged particle) before they recombine; this might be done, for example, by the application of an electric field in the detector material. This requirement is very difficult to meet with any of the ordinary crystals. Clearly, the material must have a high resistivity, since otherwise current will flow under the influence of the field, masking the effect of the pulse produced by the passage of the particle; on the other hand, in high-resistivity materials, the mobility of the free carriers is very low and the recombination probability high.

Even though some results have been obtained by using diamond as detector, semiconductor materials come much closer to fulfilling the requirements mentioned above. Very pure material (an intrinsic semiconductor) is used to achieve the necessary high resistivity of the order of 10^7 ohm-cm, and the detector is operated at low temperatures. Such devices are called "bulk semiconductor detectors" and have yielded only moderate results.

A great improvement occurs when a semiconductor junction† is used as the detector volume; a device of this kind is called a barrier-layer detector. The junction is made by either of the following methods:

(a) Diffusing a high concentration of *donor* impurities on a *p*-type material, usually silicon, thus creating an *n–p* junction

(b) Utilizing a thin *p*-type surface that is formed by oxidizing when *n*-type silicon or germanium are exposed to the air. This surface is so thin that it is usually coated with gold to provide a good electrical contact; thus we have a *p-n* junction.

In either case the operation is similar, but the junction is always reverse biased.

Below we will briefly discuss the diffused junction (*n-p*) type of detector; Fig. 5.35a is a reproduction of Fig. 3.29, and gives the configuration of the energy bands at an *n-p* junction, electrons being the majority carriers in the left, or *n*, region, and holes the majority carriers in the right, or *p*,

† Semiconductor junctions were discussed in Chapter 3, Section 4, and the reader may find it useful to review that material, as well as Chapter 3, Section 3.

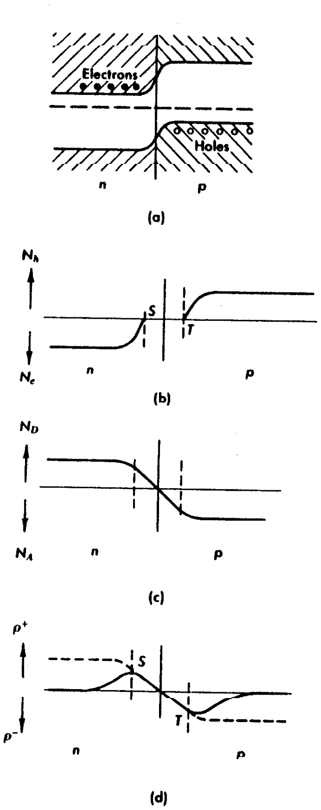

FIG. 5.35 The *n-p* semiconductor junction. (a) Position of conduction and valence bands and of the Fermi level across the junction; note the majority carriers for each region. (b) Density distribution of majority carriers on the two sides of the junction. (c) Density distribution of impurity centers on the two sides of the junction. (d) Distribution of space charge on the two sides of the junction.

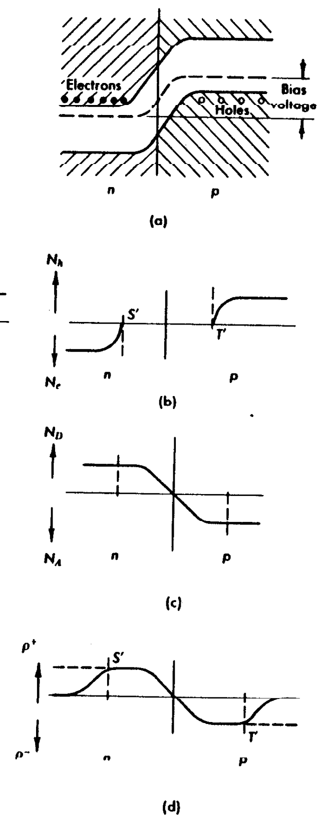

FIG. 5.36 The *n-p* semiconductor junction under reverse bias. The plots in (a), (b), (c), and (d) pertain to the same distributions as in Fig. 5.35 but under reverse bias. Note the increase of the "depletion zone," $S'T'$.

region. Clearly, electrons may not move to the right, since the conduction band is at a higher (negative) potential, and holes may not move to the left, since the valence band is now at a higher (positive) potential; as a consequence there is some *repulsion* of *majority* carriers from the junction; Fig. 5.35b shows their density distribution. We note a "depletion zone" in the region marked S–T.

Next, Fig. 5.35c shows the density of impurity centers on the two sides of the junction; that is, these centers which may be *expected* to be ionized by the passage of a charged particle. To the left the donors have given electrons to the conduction band and are left positive; to the right the acceptors have acquired electrons from the valence band and are left negative. However, these impurity centers are neutralized by the majority carriers, so that the free (space) charge distribution is the sum of Figs. 5.35b and 5.35c, as shown in Fig. 5.35d.

Thus we see that space charge exists in the region of the junction, and as a consequence an electric field (the so-called barrier) exists as well, and extends over the depletion zone. Clearly if an electron-ion pair is created in the *depletion zone*, the electric field is such as to accelerate the

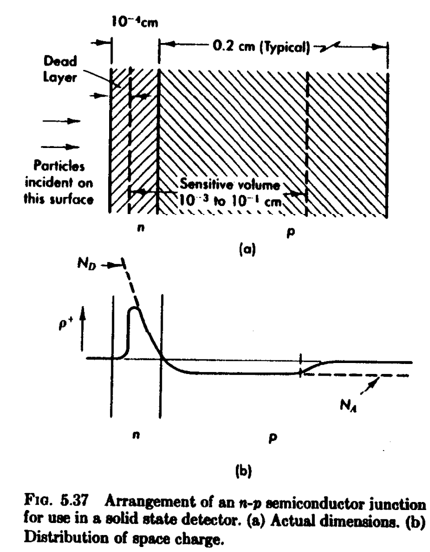

FIG. 5.37 Arrangement of an *n-p* semiconductor junction for use in a solid state detector. (a) Actual dimensions. (b) Distribution of space charge.

negative charge towards the n region, where it will have high mobility, (being a majority carrier); similarly, the hole will be accelerated towards the p region. Thus good collection efficiency is achieved.

Under reverse bias, Fig. 5.36 shows the same junction, 5.36a being the same as Fig. 3.30. Figure 5.36b gives, as before, the density distribution of majority carriers, which are now further removed from the junction, and Fig. 5.36c is exactly the same as 5.35c, giving the density of impurity centers. Figure 5.36d, however, which gives the space-charge distribution, shows that the *ionized* impurity centers have reached saturation and extend beyond the junction. Thus, most of the applied bias voltage appears across the depletion zone, which now is much more extended; the limit to this increase in *sensitive detector depth* is set by the breakdown voltage of the semiconductor material itself.

In a diffused junction, as used for a detector, the concentration of donors in the n-type material is much larger (about 10^3) than the concentration of acceptors in the p-type material. Since the total free charge must be the same on both sides of the junction, the space-charge distribution is asymmetric, as shown in Fig. 5.37b; Fig. 5.37a gives some of the physical dimensions in a realistic diffused junction; we note that most of the "sensitive volume" is in the p-type material.

5.2 Practical Considerations in Solid-State Detectors

From the previous discussion we have seen how a semiconductor junction may provide the appropriate electric field within a solid so as to collect electron-hole pairs produced by the passage of a charged particle. Multiplication such as occurs in the proportional or Geiger counter never takes place in a solid. The only way to achieve good resolution in a solid state detector is to *always* collect *all* the electron-hole pairs produced. Clearly, then, the sensitive volume of the detector must be longer than the range of the particle that is detected; it is also desirable that the dead layer at the entrance side be as thin as possible.

Since in recent detectors sensitive volumes† typical of a length of 3 mm have been achieved, the use of solid state detectors has been extended to particles of energies as high as 30 MeV. The resolution in energy is usually extremely good—that is, of the order of 0.25 percent for alpha particles (see also Fig. 5.41). The over-all size of the detector is at present restricted to a few cubic centimeters, due to the available semiconductor crystals; on the other hand, small size and the absence of need for a photomultiplier tube can be quite advantageous.

† The sensitive volume or barrier depth can be obtained from a nomograph, as given by J. L. Blankenship, "Proceedings of the Seventh Scintillation Counter Symposium, Institute of Radio Engineers, N.Y.," *Nuclear Science* 7: 2, 3 (Sept. 1960), p. 190.

It is also possible to use solid-state detectors, not as total absorption counters, but as dE/dx devices, in which case the p region is also made thin and no electrodes are placed in the path of the particle. Such detectors have been made to respond to high-energy (minimum-ionizing) particles as well. Semiconductor devices are also very useful for the detection of gamma rays. In general due to their small size, the ratio of counts in the photopeak as compared to background counts is smaller than for a scintillation crystal; however, the resolution is excellent, reaching one part in thousand.†

In practice, the construction of a solid-state detector is an art, and the attachment of electrodes to insure good ohmic contacts may be quite difficult. When germanium is used, cooling to liquid nitrogen temperatures may be required, while silicon gives good resolution at ambient temperature. The output signals are small, the voltage being determined by the capacities of the junction and of the amplifier input; the former depends on the length of the depletion zone and the area of the detector. If we assume a typical capacity of 200 $\mu\mu$F, then for 1 MeV energy loss, the signal voltage is

$$V = \frac{Q}{C} = \frac{1.6 \times 10^{-19} \times (10^6/3)}{200 \times 10^{-12}} \approx 2.5 \times 10^{-4}\ \text{V} \tag{5.1}$$

It is necessary to use a charge-sensitive preamplifier because the capacity C depends on the applied bias; thus if voltage is directly measured, severe variations in gain occur when the bias is changed. Leakage current in the crystal, and amplifier noise, set the limits of the smallest detectable signals.

Most of the hardware for solid-state detectors as well as the detectors themselves are now commercially available‡; Fig. 5.38 shows a typical setup with a feedback preamplifier. A surface-barrier silicon detector is used and operated at room temperature. Figure 5.41 gives the response ob-

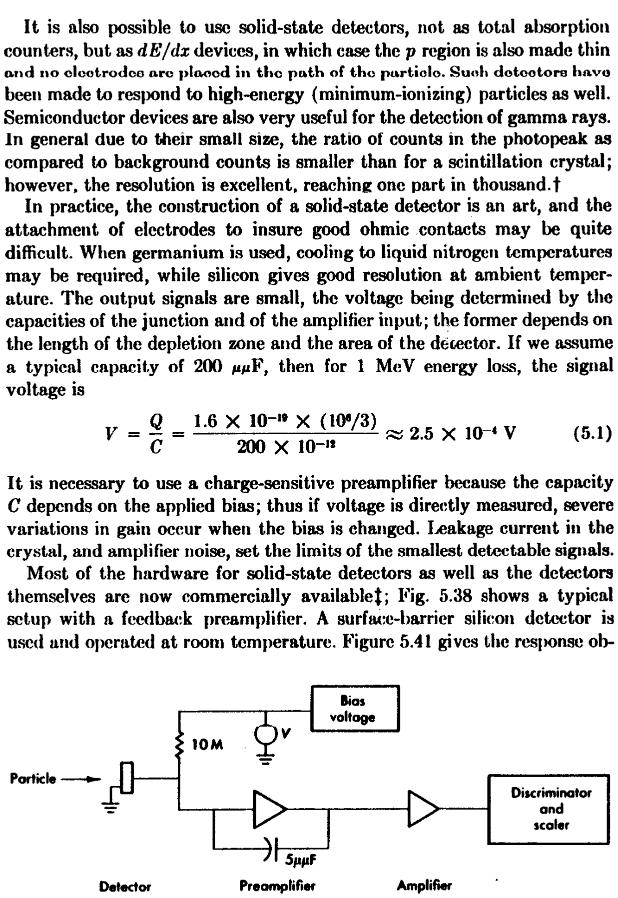

FIG. 5.38 Typical set-up for use with a solid-state detector including a feedback preamplifier.

† G. T. Ewan and A. J. Tavendale, Can. J. Phys., 42, 2286, (1964).
‡ For example, from Oak Ridge Technical Enterprises, Oak Ridge, Tennessee.

tained from polonium alpha particles of different energies (after attenuation in air).

Another recent type of solid-state detector, called *p-i-n* (positive-intrinsic-negative material), consists of a layer of intrinsic crystal placed between *p*-type and *n*-type material. Having the advantage of a much longer sensitive volume, it holds better promise for high-energy particle detection.†

5.3 Range and Energy Loss of Po^{210} Alpha Particles in Air

In Section 3 a description has been given of the method of obtaining an estimate of the range (and hence energy) of Po^{210} alpha particles in air, by means of a crude ionization chamber. With solid-state detectors, it is possible to improve on these measurements, as well as to study the rate of energy loss of the alpha particles as a function of their energy.

A collimated Po^{210} source and the detector are both placed in an evacuated vessel at a fixed distance of 15 cm, as shown in Fig. 5.39. Then air is allowed into the vessel, and as a function of the pressure we measure

(a) The number of particles counted in the detector
(b) The pulse height distribution of the output signals, namely, the energy of the alpha particles when they reach the detector

In measurements of type (a), the *same* number of alpha particles should be reaching the detector until the pressure is raised to the point where the amount of material (gm/cm^2 of air) between source and detector is equal to the range of the alpha particles; beyond that pressure the counting rate should abruptly fall to zero. Note that since the relative position of source and detector is not altered, the solid angle $\Delta\Omega$ does not change, and the

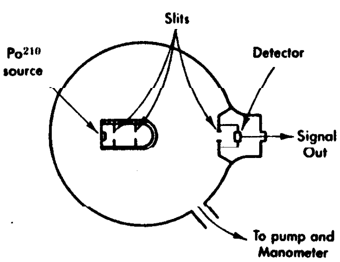

FIG. 5.39 Arrangement for the measurement of the range in air of Po^{210} alpha particles. Note mounting of the solid-state detector and source inside an evacuated chamber (see also Fig. 6.4a).

† For more details see J. M. Taylor, *Semiconductor Particle Detectors*. London and Washington, D. C.: Butterworth, 1963; also consult the current literature.

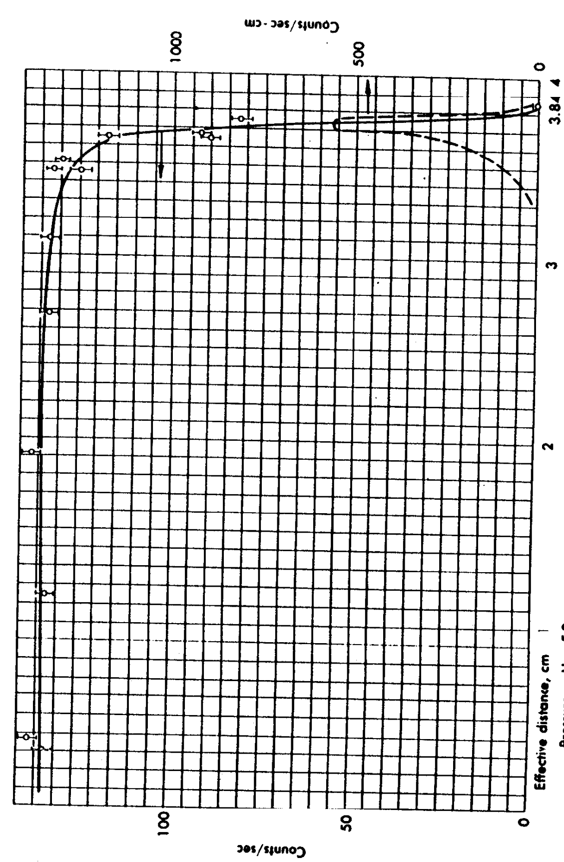

FIG. 5.40 Data on the number of counts from a Po^{210} alpha source reaching the solid-state detector as a function of the air pressure in the experimental chamber. Note that the corresponding effective distance in centimeters of air at stp is also included. The dotted curve is the derivative of the solid line; it indicates the "straggling" in the range of the alpha particles.

only variation arises from the increase in multiple scattering; this, in turn, may result in some loss of particles from the beam.

These considerations are indeed borne out by the results obtained by a student† and shown in Fig. 5.40. Here the ordinate to the left gives the counts per second while the abscissa gives the pressure of air in centimeters of mercury, or, equivalently, the effective distance of air at stp. The dotted curve to the right is the derivative with respect to distance of the counting curve and gives the range (and so-called range straggling) of Po^{210} alpha particles. We obtain a mean range of

$$R = 3.72 \pm .06 \text{ cm}$$

and an extrapolated range

$$R = 3.82 \pm .06 \text{ cm}$$

which might indicate some systematic discrepancy from the accepted value for the extrapolated range of 3.93 cm.

Turning now to the measurements of type (b), Fig. 5.41 shows the distribution of the detector pulse heights as obtained with the single channel discriminator (described in connection with the scintillation counter). Each peak corresponds to a different pressure, and we thus note that the alpha particles reach the detector with progressively less energy when they have traversed more gm/cm² of air. We set the pulse height obtained in vacuum equal to the full energy of the Po^{210} alpha particle, namely, 5.25 MeV, and use the linear characteristic of the solid-state detector to obtain

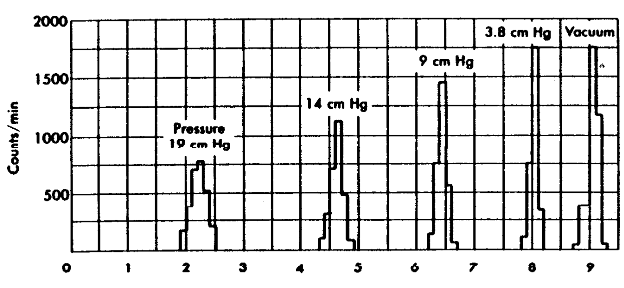

FIG. 5.41 Distribution of output pulse height of the solid-state detector for five different pressures. Note the gradual decrease of the energy of the alpha particle.

† K. Douglass, class of 1964.

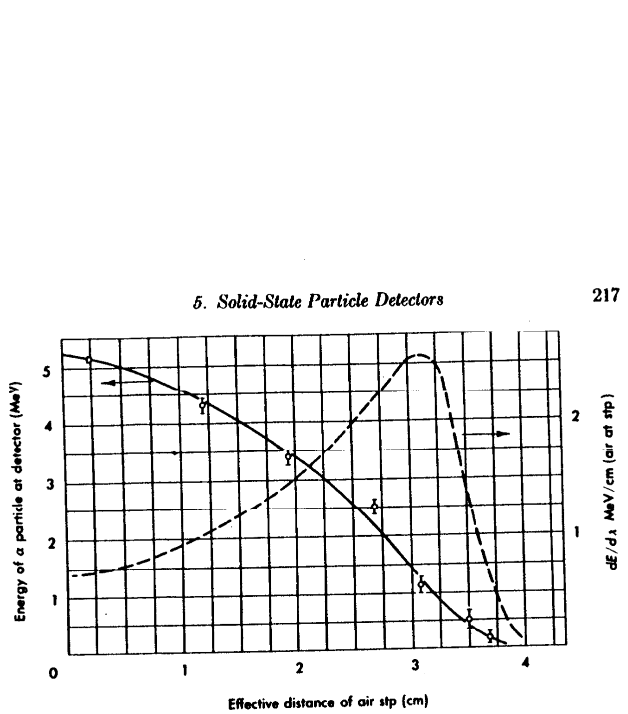

FIG. 5.42 Plot of the residual energy of a polonium alpha particle when it reaches the detector as a function of air pressure (plotted, however, in terms of the equivalent amount of air (stp) traversed). These data are obtained from distributions such as shown in Fig. 5.41. The dotted curve represents the derivative of the solid (energy) curve; thus it gives the energy loss per unit length. It is called the "Bragg curve."

the energy of the alphas as a function of material traversed. The results, obtained by a student† are given in Fig. 5.42 (solid curve).

If the derivative of the energy curve is taken with respect to distance, we obtain the energy-loss curve, dE/dx, as a function of distance, as shown by the dotted curve in Fig. 5.42. Such a curve is called a Bragg curve, and shows a $1/E$ dependence‡ as predicted by Eq. 2.10; for these very slow particles $E = \frac{1}{2}Mv^2$ and the influence of the logarithmic term of Eq. 2.10 is minimal. As the particle reaches the end of its range the energy loss dE/dx drops rapidly to zero.

From the energy curve of Fig. 5.42, we note that in air at stp the polonium alpha particle produces at the end of its range approximately 67,000 electron-ion pairs per centimeter, whereas at its full energy it produces only 20,000 pairs per centimeter; these numbers were obtained by using an average loss of 36 eV for the production of one electron-ion pair in air. More accurate results, especially close to the stopping point, can be best obtained with special ionization chambers.

† K. Douglass, class of 1964.

‡ We might plot the dE/dx curve against energy by making use of the data of the energy curve to express the distance from the stopping point in energy units.