Semiconductor detectors for ionizing radiation

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Following the discovery of semiconductor devices that could perform the circuit functions of thermionic valves and photoelectric cells — the transistors and photoresistors now so widely used — there has been considerable success in the last few years in the development of semiconductor devices which can be used for the detection of ionizing radiation. These detectors have some exceptionally valuable features, and it can already be said that their introduction has very considerably advanced the technique of radiation measurement. By way of introduction to future articles, in which the applications of semiconductor detectors will be discussed, the article below deals with the operation and distinctive features of these new devices.

Principles and characteristic features of semiconductor detectors

In the last six years or so, great changes have been taking place in the instrumentation used for detection and energy-measurement of charged particles, and a similar situation has recently arisen in γ-ray spectrometry. The conventional instruments for energy measurement, such as ionization chambers, proportional counters and, to a lesser extent, scintillation counters, are being superseded by detectors of an entirely different type, i.e. semiconductor counters. These solid-state detectors (fig. 1) combine small size and ready interpretation of the output signals with exceptionally high resolution of the energy of the detected particles or quanta. This high resolution is particularly useful in many branches of research in nuclear physics. The use of semiconductor detectors has for example made possible experimental analysis of certain disintegration processes whose details could previously only be assumed on theoretical grounds. Really accurate measurement of particle or quantum energy is also often important in certain investigations directed more towards practical purposes, such as process measurements using radioactive indicators, analyses by means of chemical activation, and reactor investigations.

In principle a semiconductor detector can be regarded as an ionization chamber in which the sensitive volume is a solid instead of a gas; it consists basically of a semiconductor wafer with an electrode on each side. An incident particle or quantum produces a certain ionization charge in the semiconductor, just as it would in a gas, and this gives a pulse of current in an external circuit. This in turn causes a voltage pulse to appear across a resistance included in the circuit (fig. 2). The great attraction of using a solid as the detection medium is its very much higher absorption, which en-
ables even fast $\beta$-particles to be stopped in a relatively thin layer, making it possible to measure their energy with an instrument of small dimensions. An incidental but extremely important advantage is that a semiconductor counter can be very much faster than a gas-filled ionization chamber. Of course, the solid used as the detection medium has to be a material in which the ionization-charge carriers — electrons and holes — can move freely under the influence of an electric field and in which they are not lost prematurely due to the presence of impurities or other crystal imperfections.

The first indication that a solid can act as an ionization medium was found as long ago as 1913 by Röntgen and Joffé \cite{11}. They established that an insulating crystal becomes slightly conductive when brought into the vicinity of a radioactive source. With the electrical instruments available at that time, however, it was not possible to measure the particles individually.

The first solid-state detector capable of counting particles individually, and which could be used for measuring their energy, was not reported until 1945, by Van Heerden \cite{21}. The ionization medium used was a silver chloride crystal which was held at the temperature of liquid air. The resolution, however, was rather poor.

The great advances made in this respect in recent years have mainly come about because intensive semiconductor research has made it possible to produce single crystals of silicon and germanium which combine extreme purity with a very high degree of crystal perfection. With such starting materials, and using techniques partly derived from diode and transistor manufacture and partly new, solid-state detectors can now be made that meet exacting requirements.

The chief characteristic features

The pulse spectra obtained with a semiconductor counter are very easily interpreted, because the height of the pulses is proportional to the energy of the detected particle, while moreover the proportionality factor is the same for all kinds of particles — except very heavy ones like fission products.

The pulse rise-time, i.e. the time in which the ionization charge is produced plus the time it takes to travel to the electrodes, can be very short: in certain circumstances as short as $10^{-8}$ s, and never longer than $10^{-9}$ s at the very most. As this time mainly determines the number of incident particles which the counter can handle per second, semiconductor counters show a very good performance in this respect. The short rise time is also important in the study of coincident phenomena; the shorter the rise time the more accurate is the time discrimination. This will reduce the number of situations in which two events taking place in rapid succession are mistakenly regarded as coincident.

The energy resolution, as in all ionization chambers, is determined by 1) the electrical noise from the detector and amplifier, and 2) the statistical fluctuations in the ionization process. Both effects are relatively weaker in those counters in which particles of a particular kind and energy bring about stronger ionization, i.e. in

![Fig. 2. Diagram and circuit of a semiconductor detector. The detection medium (shaded) is between two electrodes, 1 and 2, to which a voltage $V_0$ is applied. An incident radiation quantum or charged particle frees pairs of charge carriers in the detection medium. Under the effect of the electric field the charge carriers move to the electrodes, giving rise to a voltage across $R$. The effect of variations in $V_0$ is virtually eliminated by means of capacitive feedback in the amplifier (via capacitor $C_i$).](image)

![Fig. 3a. The $\alpha$-spectrum of $^{241}$Am recorded with a silicon detector for $\alpha$-particles. The particle energy $E$ is shown on the horizontal axis, and the number of pulses per energy interval of 0.25 keV is shown on the vertical axis. The width of the strongest line is about 20 keV at half height. Although the energy separation between the lines is about 45 keV (less than 1% of the particle energy) it is easy to discriminate between lines.](image)
which the average energy required for producing a pair of charge carriers is lower. Semiconductor counters owe their exceptionally high resolution principally to the very small average ionizing energy of silicon and germanium (3.6 and 2.9 eV) respectively, compared with about 30 eV for argon). For the detection of X-rays and γ-rays the resolution of the detector is in fact so good that even the best low-noise amplifiers that can now be built are barely good enough to do full justice to it. Some semiconductor counters do, however, have to be cooled, e.g. to liquid nitrogen temperature (77 °K), to limit the noise contribution from the bias current. Fig. 3 shows α- and γ-spectra recorded with semiconductor counters, and for comparison a γ-spectrum of the same radioactive substance, recorded with a scintillation counter.

The design of a semiconductor detector can readily be adapted to the nature and energy of the particles to be detected and to the purpose for which it is to be used. There are detectors for α-particles, for hard γ-radiation, for X-rays, and so on.

Another feature is that the single electrodes on each side of the semiconductor wafer can be replaced by a series of separate strips. If the strips on one side are aligned perpendicular to those on the other, the detector is divided into a large number of subdetectors, so that the place where a particle enters can be determined accurately [3] ("checker-board counter"). This approach is of interest in nuclear physics and also in various branches of nuclear engineering.

A feature useful in some types of research is the fact that semiconductor detectors can be made so thin that the particles are able to pass through them with very little loss of energy. The detector is then used, of course, not to measure the energy of the particle but the energy loss per unit path-length. This quantity is of interest in establishing the identity of an unknown particle.

The last important advantage to be mentioned is the very small effect which variations in the supply voltage have on the output signal when a suitable circuit is employed; the scintillation counter and the proportional counter, on the other hand, require highly stabilized power supplies.

In the following sections of this article we shall deal first with the processes taking place in the detection medium. We shall then briefly consider the principal effects determining the resolution and discuss the merits of various counter configurations. Finally, the characteristic features of semiconductor counters will be compared with those of proportional counters and scintillation counters.

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Fig. 3b. Part of the γ-spectrum of 166Ho, recorded with a germanium counter. Each point represents the number of pulses in an energy interval of 2 keV. A very large number of separate lines can be distinguished; the quantum energy for most of them is indicated separately. The dashed line indicates the spectrum found with a scintillation counter. (For clarity this is shown at about 100 times the measured value.)

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[3] This type of counter was developed in co-operation with a team of physicists from the Instituut voor Kernfysisch Onderzoek (Institute for Nuclear Physics Research), Amsterdam.
The ionization process in a semiconductor

When a high-energy charged particle or a quantum of radiation moves through a medium it dissipates energy in it. In the process, atoms of the medium may become ionized. In this section we shall examine more closely just how this takes place, particularly in semiconductors, and show that in a given substance the average energy \( w \) required for a single ionization is independent, in the first instance, of the nature of the particle owing to the differences of mass involved — for example a 6 MeV \( \alpha \)-particle can transfer at the most only 3 keV to a stationary electron — but even so it is usually more than sufficient to free the electron from the atom. This is known as primary ionization. A much greater part of the ultimate ionization charge is due, however, to secondary ionization. This is largely brought about by the electrons freed by primary ionization. Some electrons are also freed by the Auger effect: when an electron freed from a deeper shell by the primary radiation is replaced by an electron from a peripheral shell, the released energy is not always emitted in the form of a quantum of radiation but is sometimes transferred to another electron, which then freed by the Auger effect.

![Fig. 4. Semiconductor detector for determining directional distribution ("checker-board counter"). This detector has a series of electrodes on opposite sides in the form of strips. The direction of the electrodes on one side is perpendicular to that of the electrodes on the other side (see mirror image; the line crossing this is the lower edge of the mirror, twice reflected).]
leaves the atom. If we assume that the primary and secondary ionizations take place one after the other, we can represent the situation arising after each of the two phases in a semiconductor by an energy band diagram like that in fig. 5.

Ionization by $\gamma$-particles or accelerated electrons takes place basically in the same way. Owing to the equality of the masses involved, however, a single collision can result in a much greater part of the energy (up to 100%) being transferred to a stationary electron.

A charged particle travelling at very high speed also loses some of its energy through the emission of electromagnetic radiation. The intensity of the radiation is proportional to the square of the atomic number of the medium. For electrons in germanium this effect only becomes of significance when the particle energy is greater than 10 MeV. For heavy particles it can be entirely disregarded, since it only becomes noticeable in the GeV region.

Because of the relatively high density of solids the range of particle radiation in them is very much smaller than in gases. For example, the range of 1 MeV $\beta$-particles in silicon is 2 mm, compared with 3.75 m in air; the range of 10 MeV $\alpha$-particles — the highest energy particles emitted by the nuclides known at present — is only about 70 $\mu$m in silicon. A thin wafer of the detection medium can therefore be used; for $\alpha$-detectors this need only be very thin.

The ionization due to $\gamma$- or X-radiation differs from that due to charged particles in that the primary ionization is brought about by three different effects: the photoelectric effect, the Compton effect and pair formation. In the photoelectric effect the quantum energy $E$ is imparted entirely to the freed electron. In pair formation an electron and a positron (positively charged electron) are created, which together receive the energy $E = 1.02$ MeV. In the Compton effect a variable part of the quantum energy is transferred to the electron. The probability of the occurrence of these processes is a function of $E$ and of the atomic number $Z$ of the ionization medium. The probability of the photoelectric effect, for instance, is proportional to $Z^2 E^{-3.5}$. It thus increases sharply with increasing $Z$ and decreases sharply as $E$ is increased. The probability of pair formation is proportional to $Z^2$, and increases slightly with increasing $E$, initially in proportion to $E = 1.02$ MeV, but less at greater $E$. Because both effects increase with increasing $Z$, the relatively heavy germanium ($Z = 32$) is preferable to silicon ($Z = 14$) for a $\gamma$-detector. Gamma radiation penetrates deeper into the substance than particle radiation of the same energy. For energy measurements on $\gamma$-quanta of about 1 MeV the semiconductor layer must be several mm thick.

**Relation between ionization charge and energy**

In a fairly wide range of energies the ionization charge, within the accuracy of measurement, is proportional to the energy of the particles (quanta) and independent of the nature of the radiation. This independence is understandable when we consider that ionization is entirely due to electrons for $\gamma$-quanta and $\beta$-particles and very largely due to electrons for heavy particles.

The average energy $w$ required for a single ionization is, as we have seen, much lower in solid-state detectors than in gases, but it is still considerably greater than the energy gap $\Delta E$. For germanium $w = 2.9$ eV, against $\Delta E = 0.65$ eV; in silicon $w = 3.6$ eV, against $\Delta E = 1.1$ eV. There are two reasons for this inequality: 1) part of the energy of the freed electrons is used for lattice vibrations and 2) electrons whose energy has decreased to less than $\Delta E$ can no longer cause ionization, so that this residual energy plays no part in the ionization process. In any case, then, $w$ will be greater than $\Delta E$.

For heavy particles there is in theory some deviation from linearity in the relation between $E$ and the ionization charge, because these particles can no longer cause ionization when $E$ has dropped to a value which is still well above $\Delta E$. For $\alpha$-particles in silicon this threshold value is about 1 keV. Although this is a large multiple of $\Delta E$, it is nevertheless such a
small fraction of the normal initial value of $E$ that the deviation is not detectable in the experimental results. If the ionization medium is a gas, this threshold value may be very much higher, and a marked deviation is indeed found for heavy particles of not unduly high energy [4].

**From ionization charge to pulse**

We shall now examine what happens when the applied field causes the ionization charge to move towards the electrodes. This determines the form of the pulse observed in the external circuit in the detection of a particle. We shall assume to begin with that none of the ionization charge is lost on the way, that the detection medium has a large energy gap (so that, in the natural state, there are virtually no free charge carriers in the medium), and that no charge carriers can penetrate into the medium from the electrodes.

In every ionization event two charge carriers of opposite sign are produced. When an electric field is applied (due to a voltage $V_0$) the freed positive and negative charge carriers (each with a total charge $Q_i$) move away from one another and a charge is induced in each of the two electrodes 1 and 2 (fig. 2). If the two kinds of charge carrier have become separated by a distance equivalent to a potential drop of $AV$, then the induced charge [5] has a magnitude of $Q_iAV/V_0$. The voltage across the resistor $R$ (fig. 2) at that moment is $(Q_i/C)(AV/V_0)$, where $C$ is the capacitance of the electrode 2 with respect to earth. Now if the time constant $RC$ is large compared with the time in which the ionization charge is collected at the electrodes, then the final value of the voltage across $R$ — i.e. the height of the voltage pulse — is equal to $Q_i/C$, hence proportional to $Q_i$ and independent of $V_0$. (If the charge collection time is not short with respect to $RC$, then the proportionality with $Q_i$ remains but the final value is lower than $Q_i/C$ and no longer independent of $V_0$.)

The above picture of a semiconductor detector is, of course, over-simplified: some charge carriers from the electrodes will always penetrate into the medium, and even without this the medium in the natural state contains a certain number of free charge carriers.

In counters for particle and gamma spectrometry, which should therefore have a very high energy resolution, these effects must be suppressed as far as possible. In counters, on the other hand, which are only required to measure the average intensity of a stream of particles (quanta), such as counters for dosimetry, there may be advantages in a ready flow of charge carriers from the electrodes (injection contact), since the sensitivity can be increased by this [6]. Counters with injection contacts are called conduction counters, and the others are known as barrier-layer counters.

In the following we shall be concerned purely with barrier-layer types, unless otherwise stated.

A complication may arise from the effect in which clouds of positive and negative charge carriers, as soon as they are separated by the electric field, are in principle neutralized by charge carriers of opposite sign which come from the surroundings and from the electrodes. This neutralization varies exponentially with time. The time constant $\tau_{rel}$, the dielectric relaxation time, is equal to $\varepsilon/\sigma$, where $\varepsilon$ is the dielectric constant and $\sigma$ the conductivity of the material. The above treatment of the charge collection applies, strictly speaking, only for $\tau_{rel} = \infty$. In detectors in which the natural material contains hardly any charge carriers, and where none can come from the contacts, the neutralization is virtually negligible.

**Life of charge carriers and pulse height**

In the foregoing we have assumed that all charge carriers freed by the incident radiation do in fact reach the electrodes. In reality a number of them will not, but will be trapped on the way and may even recombine. Obviously, there will be less probability of their recombining if the travelling time of the charge carrier — maximum value equal to the carrier transit time — is short compared with its average life. For a group of charge carriers that has to cover the whole distance $d$ between the electrodes it has been calculated that a fraction $[1-(1-\exp(-d/\mu F))]\mu F/[d]$ are lost. In this expression $F$ is the electrical field strength, assuming the field to be uniform, and $\mu$ the mobility of the charge carriers. At a given $d$ and $F$ the product $\mu F$ therefore determines the magnitude of the loss. It should be remembered here that $\mu F$ does not in general have the same value for holes and electrons. The greatest signal loss is found when the particle to be detected is incident at a place such that the charge carriers with the lowest $\mu F$ value have to travel through the whole crystal.

Since the signal loss depends on the place of incidence, pulses produced by particles of identical $E$ do not all have the same height. For a good energy resolution, therefore, the signal loss must be kept relatively small. It follows from the formula just given that we must make $\mu F$ large with respect to $d$, i.e. $d/\mu F$ small with respect to $\mu$. (If this condition is satisfied, the expression for the relative loss approximates very closely to $d/2\mu F$.)

If we now reduce the condition above to $d/\mu F \ll \tau$ we see at once the relation to the qualitative approach at the beginning: since the velocity of a charge carrier is $\mu F$, $d/\mu F$ is the carrier transit time, and therefore, taking a value for $\mu$ corresponding to that of the lowest charge carriers, $d/\mu F$ is the maximum value $t_{e \max}$ of the charge collection time. The condition for a relatively small signal loss is simply $t_{e \max} \ll \tau$. 
Pulse rise-time

If we wish the detector to have a very high resolution in time and if we require it to be able to handle a high count-rate without the pulse height being seriously affected by the superposition of pulses, we must obviously try to obtain the shortest possible pulses. It is comparatively easy to reduce the pulse decay time: this can be done electronically, e.g. by differentiation. The rise time, however, is entirely determined by one of the processes that takes place in the detector itself: the collection of the charge. The ionization process usually takes place much faster.

We have seen that the collection time is at the most \( d\mu F \) (or \( d\mu V_0 \)). Depending on the design of the detector, values are found between \( 10^{-5} \) and \( 10^{-8} \). On the other hand, the duration of the primary ionization process — i.e. the time that elapses between the entry of the particle and the moment at which it causes no further ionization — is only about \( 2.5 \times 10^{-18} \) s for a 5 MeV \( \alpha \)-particle in silicon, and the duration of the secondary ionization process, which may be similarly defined, is of the same order of magnitude.

To obtain a short rise time it is therefore necessary to impose on the maximum charge collection time \( t_c \) a condition similar to that laid down for obtaining a small signal loss, the difference here being that the absolute value of \( t_c \) must be small. This is the case if \( d \) is small and if \( \mu \) and \( V_0 \) are large. The requirement for large \( V_0 \) indicates that the breakdown voltage of the counter should be as high as possible.

In the above we have tacitly assumed that the ionization charges are not dense enough to seriously affect the field in the detection medium by polarization. With heavy particles, however, which produce a very dense charge cloud, polarization may indeed occur (fig. 6). Inside the cloud the field strength \( F \) is then initially very small, and does not assume an appreciable value until the cloud has thinned out due to ambipolar diffusion of the charge carriers — at right angles to the direction of the field — and the loss of peripheral charge carriers.

It is evident that in such a case the collection of the ionization charge will not be so fast. For a 5 MeV \( \alpha \)-particle, incident perpendicular to the field direction, and a field strength of 1000 V/cm we have calculated that the collection time \( t_c \) can be lengthened at the most by \( 0.3 \mu \). Usually, however, this time is much less, so that the effect is not particularly serious.

It should not be concluded from the above that the recombination loss associated with the delay is of no significance. In a dense charge cloud — a region therefore where the concentrations of both kinds of charge carrier are very high — the probability of recombination is much greater, and hence \( r \) is much smaller than in a rarefied cloud. The recombination loss for heavy particles is therefore already greater than for light ones, so that a longer collection time is more serious here. Since the magnitude of the recombination loss will differ from case to case, the polarization effect adversely affects the resolution. This is one of the reasons why the resolution for \( \alpha \)-particles is not as good as for \( \beta \)-particles of the same energy.

Energy resolution

In the preceding section we have already indicated that the resolution is limited when the collected charge, and hence also the height of the output pulse, depends to some extent on the place where the particle is incident. In this section we shall consider two other causes of fluctuations in the pulse-heights, namely phenomena which occur in the detector itself and moreover directly depend on the configuration of the detector (dimensions, nature of contacts) as well as on the nature of the detector material \([7]\). These are: 1) fluctuations in the ionization charge, and 2) fluctuations in the bias current through the detector, the "dark current".

The fluctuations in the ionization charge come about because only a part of the energy of an incident particle is used for ionization processes, the rest of the energy being used to set up excitations such as lattice vibrations. Since excitations are probability processes, the ionization charge produced by particles of identical energy will show statistical fluctuations. If the average ionization charge of a number of mono-energetic parti-
cles is expressed by the number of pairs of freed charge carriers \( N_0 \); then the standard deviation \( \delta N_0 \) in this number is equal to \( \sqrt{F^*N_0} \). The relative standard deviation is thus given by:

\[
\frac{\delta N_0}{N_0} = \sqrt{\frac{F^*}{N_0}} = \sqrt{\frac{F^*}{E^*} - \frac{1}{E}}. \quad (1)
\]

In these expressions \( F^* \) is a constant, called the Fano factor \([8]\), which depends on the material and on the type of radiation; \( \nu \) and \( E \) are again the average ionization energy and the energy of the incident particle, so that \( N_0 = \frac{E}{\nu} \). One of the advantages mentioned in the introduction for the semiconductor detector can readily be derived from eq. (1): there is a relatively small spread in \( N_0 \) because the average ionization energy is low. Moreover, measurements have shown \([9]\) that the Fano factor for semiconductors is also relatively small \((F = 0.1 \text{ to } 0.15 \text{ compared with } 0.2 \text{ to } 0.3 \text{ for gas ionization chambers})\). Using eq. (1) to calculate the relative standard deviation in the ionization charge of particles of 5 MeV in silicon, we find \( 3 \times 10^{-4} \), which corresponds to 1.5 keV. Calculating from this the half-height width of the pulse-height distribution — this width is 2.36 times as large as \( \delta N_0/N_0 \) and is often used as a measure of the resolution — we find 3.5 keV.

As in other semiconductor devices, in nuclear radiation detectors the bias current is a factor that calls for careful attention with regard to noise. The noise in the bias current has almost entirely the character of shot noise. This is obvious for the part of the bias current originating from the contacts. In the part due to thermal generation of charge carriers in the detector material, the generated charge carriers disappear very quickly from the detector volume because of the effect of the electric field, so that scarcely any recombination takes place, the transit time being short compared with the average life of the carriers. There is consequently no generation-recombination noise, but only a noise contribution from the generation process separately. This noise however also has the character of shot noise.

Another point to be noted about the current noise is that noise-smoothing due to space charge — as in thermionic valves — hardly occurs at all because the concentration of charge carriers is too low.

These considerations indicate that in calculating the output signal fluctuations which result from the bias-current noise we may start with the relationship \([10]\):

\[
\sigma^2 = 2e\left\langle dI \right\rangle_f. \quad \ldots \ldots \ldots (2)
\]

Here \( \sigma \) is the effective value of the shot noise in the bias current in the frequency band \( df \), \( e \) is the absolute charge of the electron and \( I \) the bias current in the detector. It is found that these fluctuations are relatively small when \( \sqrt{N} \), the square root of the number of free charge carriers in the counter, is small compared with the ionization charge \( N_0 \). What this means in practice can best be seen from an example. An \( \alpha \)- or \( \beta \)-particle of 5 MeV produces \( 1.5 \times 10^9 \) pairs of charge carriers in silicon. If we now require a signal-to-noise ratio of at least \( 1000:1 \), then \( N \) must not be greater than \( 5 \times 10^9 \). Now in extremely pure silicon at room temperature the concentration of charge carriers is already between \( 10^{11} \) and \( 10^{12} \text{ cm}^{-3} \). In a counter of not excessively small dimensions this means that \( N \) would be much too great if no special measures were taken to reduce it. In the following section we shall consider what measures can be taken.

Detector configuration

Semiconductor detectors can be divided into two basic groups with different electrical configurations: detectors with injection contacts — conduction counters — and detectors with blocking contacts — barrier-layer counters. This classification has already briefly been mentioned. The nature of the contacts affects nearly all the questions relating to the type and operation of the detectors, one of the most important being the manner in which the number of free charge carriers \( N \) is reduced to improve the signal-to-noise ratio. We shall therefore begin with a brief account of both kinds of detector, commenting briefly on the requirements to be met in both cases by the semiconducting material.

We shall then leave the subject of conduction counters, which have been very little used up till now, and devote the rest of this section to the different types of barrier-layer counter, and to the question of which type is most suitable for a given form of radiation.

Since conduction counters have injection contacts, the concentrations \( n \) and \( p \) of the free electrons and holes do not depend on whether or not an electric field is present: charge carriers leaving the detection medium under the effect of such a field are immediately replaced by others entering through the other contact. The values of \( n \) and \( p \), and hence \( N \) itself, cannot therefore be affected by means of the field. In these detectors the bias current depends entirely on the nature of the detector material and not at all on the contacts.

In barrier-layer counters, on the other hand, \( N \) is certainly affected by the applied voltage, because charge carriers drawn away from the medium are only replaced to a very limited extent. Where signal-to-noise ratio is concerned a barrier-layer counter is therefore in principle preferable to a conduction counter made of the same material.

In order for the field in a counter of any kind to be reasonably uniform, the space charge should be nearly equal to zero everywhere inside it. In conduction coun-
ters this happens automatically because free charge carriers can flow unimpeded to neutralize bound charges. In barrier-layer counters, however, the space charge is zero only when the detection medium contains no bound charges, that is to say when it is an intrinsic semiconductor, or when the positive and negative bound charges are equal and thus neutralize each other. (In the last case, also, a semiconductor is often said to be “intrinsic”, because the holes and electrons have the same concentration, so that the Fermi level also lies half-way up the energy gap.)

The materials suitable for use as the detection medium are at present few in number: for barrier-layer counters the choice is practically limited to germanium and silicon. The usefulness of these two substances is due to the following circumstances:

1) The charge carriers have a long life (0.1 to 1 ms) and at the same time a high mobility. The product $\mu t$ is therefore so large that, without any great loss, the ionization charge can be collected in a layer as thin as 1 cm. In other semiconductors the carrier life is generally much shorter ($10^{-7}$ to $10^{-8}$ s).

2) Considerable advances have been made in the production of large single crystals of well defined and readily processed germanium and silicon.

For conduction counters, however, silicon and germanium are unfortunately not so suitable, for reasons that will presently appear. First of all, we shall consider the conduction counter in somewhat more detail, and then we shall confine our attention to the barrier-layer counters.

Conduction counters

In a conduction counter the concentrations $n$ and $p$ of the negative and positive charge carriers respectively are equal to those present in the medium in the absence of an applied voltage. The well-known equation:

$$np \propto \exp(-\Delta E/kT)$$

then applies. The product $np$ is usually represented by $n_0^2$. If bound charges are present, $n$ and $p$ must also meet the neutrality condition:

$$n + N_b = p + N_d.$$  \hspace{1cm} (4)

Here $N_b$ and $N_d$ are respectively the concentrations of the singly charged negative and positive impurity centres.

It follows from eq. (3) that the sum $n + p$ is smallest if $n = p$, i.e. if $N_b = N_d$. Quantitatively, at room temperature $n + p$ is smaller than $10^6$ cm$^{-3}$ — for a counter of 1 cm$^2$, i.e. a counter in which $N = n + p$, this corresponds approximately to the requirement for a signal-to-noise ratio of 1000:1 — only if the energy gap is larger than 1.65 eV and the difference between $N_b$ and $N_d$ is smaller than $10^6$. Materials which satisfy this condition, and in which the charge carriers have sufficiently long life, are not yet available. For the present the only choice is to make do with materials of smaller energy gap, but this implies that cooling must be applied in order to reduce $n_0^2$. In the hypothetical case in which $N_b = N_d = 0$, Si would have to be cooled to $-75$ °C, and Ge to $-140$ °C.

Even the purest germanium and silicon monocrystals that can be made at present do not at this temperature satisfy the condition that $N_b - N_d$ should be less than $10^6$ in a not too small volume. Further measures therefore have to be taken, such as:

1) reducing the temperature much further than would be necessary in the intrinsic case. A greater number of impurity centres will then change to the uncharged state. The extent to which it is necessary to cool the material in order to achieve a significant reduction of $N_b$ and $N_d$ depends, of course, on the location of the impurity levels. In silicon, for example, the boron atoms present as impurities give rise to impurity levels that are only 0.045 eV above the conduction band, and this necessitates cooling to between $10^0$ and $20$ °K.

2) reducing the difference between $N_b$ and $N_d$ means of appropriate doping. Use can then best be made of substances that have impurity centres lying approximately at the centre of the forbidden band, i.e. at the height where the Fermi level should be. The quantity of dope used is then less critical. A difficulty with this method is that impurity levels of this kind constitute effective recombination centres, and thus shorten the life of the carriers.

Earlier in this section it was stated that intrinsic material (type I) should be used for a barrier-layer counter to obtain uniformity of the field. It is clear from the above that the same requirement holds in principle for conduction counters, but now for the purpose of obtaining a minimum noise level.

A familiar example of the method mentioned under 2) is the doping of $N$-type silicon with gold, producing electron traps which are located 0.54 eV below the conduction band ($\Delta E = 1.1$ eV). If the gold concentration has three times the value that $N_a$ previously had, then $n \approx p$ in a wide temperature range [12]. Counters that work reasonably well have been made with a material of this kind [13].

References:


**Barrier-layer counters**

In barrier-layer counters the charge carrier concentration is mainly determined by the contacts and the applied voltage, and to a much lesser extent by the nature of the material. The requirement that intrinsic material should preferably be used is not in the first place due to noise considerations. The significance of the energy gap will be discussed presently.

An important question here is how to obtain contacts that have an adequate blocking action. As a rule, this can be achieved by doping. In our counters the anode is generally a semiconducting surface layer of strongly N-type material, and the cathode a thin layer of strongly P-type material. In the latter material there are very few electrons in the conduction band, and therefore the P contact cannot supply a large number of electrons in a short time. The same applies to the N contact with respect to the holes. Fig. 7 shows the band diagram of a P-I-N system of this type when a voltage has been applied to it.

To get some idea of the charge-carrier concentration in the I-region when a voltage has been applied to the counter, one must first realize that the free charges in this region partly originate from the electrodes and partly from thermal generation. In practice sufficiently good blocking contacts can be obtained to make the contribution from the electrodes negligible, leaving only the thermal generation to be reckoned with. The electron carrier concentration resulting from this depends on the speed at which the freed charge carriers leave the detection medium under the effect of the electric field.

In our case thermal generation via an impurity level predominates — i.e. generation in two steps. If the impurity levels lie at the centre of the forbidden zone — the most unfavourable case — the number of pairs of charge carriers generated per cm³ is \( n_t/2\tau \), where \( \tau \) is again the life of the carriers. The number of pairs \( G \) generated in the whole counter volume is thus \( n_t A d/2\tau \), where \( A \) is the surface area. On the other hand, the average time that an electron remains in the detector is equal to \( d/2\mu_0 F \). For a hole this time is \( d/2\mu_0 F \). The number of charge carriers is now equal to \( G \) times this average time, so that, with \( F \) again put equal to \( V_0/d \), we find for the sum of the number of holes and electrons:

\[
N = \frac{d^3 A n_t}{4V_0} \left( \frac{1}{\mu_n} + \frac{1}{\mu_p} \right).
\]  

(5)

Applying this to a silicon counter (\( n_t = 10^{10} \text{ cm}^{-3} \) and \( \tau = 10^{-9} \text{ s} \)) with a thickness \( d \) of 5 mm, a surface area \( A \) of 1 cm² and an applied voltage \( V_0 \) of 500 V, we find \( N = 1.7 \times 10^6 \), which is an acceptable value. In germanium, because of the smaller energy gap, \( n_t \) is higher \((10^{13} \text{ cm}^{-3})\) and in the conditions mentioned \( N \) is higher than desirable. To make \( N \) sufficiently low the material therefore has to be cooled.

We shall now consider the situation when the detector material is not intrinsic but to a certain extent P-type or N-type. Fig. 8 illustrates the case where the detection medium is weakly P-type. The counter configuration has now in fact degenerated to a P-N junction. The volume within which the field is reasonably strong and in which the ionization charge can thus be collected (the effective volume) is reduced to the barrier layer. Although charge carriers freed outside the barrier layer have a chance to diffuse towards the barrier layer and make their contribution there, this contribution is rather small, for one reason because of the relative slowness of a diffusion process.

It should not be concluded from the above that the sensitive layer of counters with a P-N structure is necessarily extremely thin. From the equation for the width \( B \) of a depletion layer

\[
B = \sqrt{\frac{2e(V_0 + V_d)}{eN_a}},
\]

(6)

a depletion layer width of 0.5 mm is found for extremely pure silicon with a concentration \( N_a \) of \( 10^{12} \text{ cm}^{-3} \), at an applied voltage of 200 V. (Equation (6) is appli-
cable if the concentration of impurity centres in the N-region is much greater than that in the P-region. The diffusion voltage $V_d$ is negligible compared with 200 V.)

The last configuration to the mentioned is the one in which the depletion layer of a metal-semiconductor contact is used instead of the depletion layer of a P-N junction. The metal generally used is gold.

Method of making a P-I-N configuration

To make a P-I-N configuration we start from a single-crystal wafer of fairly pure P-type germanium or silicon (resistivity about 500 $\Omega$ cm). Lithium is thermally diffused at a few hundred degrees centigrade to a depth of about 0.2 mm on one side of the material. Lithium acts in this as a donor. At the surface, where the lithium concentration is high, the material thus changes into an N-type semiconductor (fig. 9a).

Since the lithium ions occupy interstitial sites in the lattice, they are to some extent mobile. When a reverse voltage is applied to the resultant P-N junction, at a temperature of say 125 ºC, the lithium ions in the region around the P-N junction, where the field strength is relatively high, begin to move towards the P-region. After a certain time the situation shown in fig. 9b is obtained: a large I region has been produced. The reason for this is briefly as follows. As long as the acceptors present are not exactly compensated by lithium, the field in the material is not homogeneous, and the lithium ion current varies from place to place in the crystal in such a way that the differences in concentration are levelled out.

This attractive method is unfortunately not applicable for the preparation of I material for conduction counters: after obtaining the P-I-N configuration the P and N layers cannot be removed. These layers are not only necessary for the production of the I layer; they are also required for its maintenance, at least when there is an electric field.

Some practical examples of barrier layer counters

Fig. 10 shows a diagrammatic representation of a semiconductor detector for $\alpha$-particles. The material used is silicon. Since the range of $\alpha$-particles is relatively short, a P-N junction or a blocking metal-semiconductor contact with a depletion layer width of 0.1 to 0.2 mm is sufficient in $\alpha$-counters. The particles are incident through one of the electrodes, which must be very thin in order to minimize energy losses. The spec-

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trum shown in fig. 3a was recorded with a counter of this type. A photograph of the counter can be seen in the lower photograph of fig. 1.

Because of the much greater range of high-energy $\beta$-particles, a $P-N$ junction is not adequate for measuring their energy, and in this case a counter of $P-I-N$ structure with an $I$ layer a few millimetres thick (fig. 11) should be used.

Counters with $P-I-N$ structure are also needed for the detection of $\gamma$-radiation. In this case, as mentioned above, germanium is to be strongly preferred because of its higher atomic number. The spectrum shown in fig. 3b was recorded with a germanium $P-I-N$ detector.

As $\gamma$-quanta can penetrate a relatively long way into light materials without any interaction taking place, $\gamma$-counters can be completely encapsulated and thus protected from atmospheric effects.

As mentioned in the introduction, extremely thin semiconductor detectors are employed in particle-identification systems. In systems of this kind separate detectors are used for measuring the energy $E$ of a particle and the energy loss per unit path length, $dE/dx$. For identifying the nature of the particle, use is made of the fact that the product $EdE/dx$ is proportional to $mZ^2$ and largely independent of $E$ (fig. 12). For protons, deuterons, tritons and $\alpha$-particles, for example, the ratios of these products are $1 : 2 : 3 : 16$. The energy loss per unit path length is measured with the thin semiconductor detector mentioned above, in which the particle loses relatively little energy (upper photograph fig. 1). In fact, of course, $dE/dx$ is not measured, but $\delta E/\delta$, where $\delta E$ is the energy loss. When the particle has passed through this detector it is stopped in the other, enabling $E$ to be measured.

The thickness of the $dE/dx$ detector is chosen between 25 to 250 $\mu$m depending on the nature of the experiment. A $P-N$ detector with a high enough applied voltage to make the depletion layer extend to the other side of the layer forms a particularly suitable $dE/dx$ detector. For $E$ measurements a silicon $P-I-N$ detector is generally employed.

Apart from the electrical structure of the detector — $P-N$ or $P-I-N$ — the geometrical structure can also be varied in many ways. We have already mentioned the “checker-board counter”, which can be used to perform very accurate directional measurements in a short time (fig. 4). With these detectors, which are divided into some 40 subdetectors per cm$^2$, a resolution of about 1$^\circ$ can be achieved in a directional measurement with a distance of only 8 cm between source and detector. It is also possible to design $dE/dx$ detectors as checker-board counters if required.[14]. There

![Fig. 10. Configuration of an $\alpha$-detector, consisting of a $P-N$ junction with a relatively wide barrier layer (width $B$).](image)

![Fig. 11. In detectors for energy measurement on $\gamma$-quanta or long-range particles (high-energy $\beta$-particles) a $P-N$ junction is not sufficient; such detectors should have a $P-I-N$ configuration.](image)

![Fig. 12. Spectrum of $mZ^2$ values ($m = $ nuclear mass and $Z = $ atomic number) obtained in measurements made with a particle-identification system on a beam containing protons, deuterons and tritons; we have taken $mZ^2 = 1$ for the proton. The value of $mZ^2$ is calculated for each incident particle from the product of the particle energy $E$ and the energy loss per unit path length $dE/dx$. These two quantities are measured with separate detectors.](image)
are other detectors in which a beam of particles is passed through a central hole; this arrangement can be used to detect particles scattered backwards from a target situated some distance further on.

Comparison with proportional counters and scintillation counters

Linearity and energy resolution

We have seen that the pulse height in semiconductor counters is proportional to the particle energy and independent of the type of radiation, except for very heavy particles such as fission products. Proportional counters are also highly linear, but the proportionality factor for these is not entirely independent of the type of radiation. Scintillation counters are linear for γ-radiation, but not for α particles, for example, and the type of radiation here also has some effect.

The resolution of semiconductor counters in the detection of β- and γ-radiation is largely determined by the noise and is therefore to some extent independent of the energy. At an energy greater than about 0.5 MeV statistical fluctuations in the ionization charge begin to become significant and the line width increases in proportion to √E. In proportional counters and scintillation counters the resolution is primarily determined by fluctuations in the multiplication mechanism; these fluctuations are also proportional to √E, but the proportionality factor is considerably greater.

By way of illustration to the foregoing, fig. 13 shows the resolution, for X-rays and γ-rays, of a semiconductor counter, a proportional counter and a scintillation counter as functions of √E. In this figure the line width at half height is again used as a measure of the resolution. The resolution of the semiconductor counters is seen to be better than that of the other two except for soft radiation, where the amplifier noise predominates.

It may be recalled here that the average ionization energy w for germanium and silicon is only a few electron-volts (2.9 and 3.6 eV respectively) and the Fano factor 0.1 to 0.15 as against w=30 eV and F*=0.2 to 0.3 for gases. A direct comparison with the scintillation counter is of course not possible, as this does not measure the ionization charge; it is however possible to characterize the relative spread in the output signals by fictitious values for w and F*. These are very high: 300 eV and 1 respectively.

In the detection of α-radiation with semiconductor counters the resolution is partly determined by the fact that a relatively large number of recombinations take place in the ionization track owing to the high carrier densities involved; their number fluctuates, largely because of the inhomogeneous distribution of the recombination centres. The resolution here is about 20 keV. Although for α-radiation the resolution is therefore rather worse than for β- or γ-radiation, it is still three times better than that of the detector previously used for α spectroscopy, the ionization chamber. This advantage is due to the lower ionization energy, which results in a better signal-to-noise ratio.

Pulse rise-time

The rise time of the pulses obtained with semiconductor counters depends on the thickness of the sensitive layer, on the applied voltage and on the temperature, and lies between 10^{-6} and 10^{-5} s. Scintillation counters are in general somewhat faster: depending on the nature of the crystal and on the photomultiplier tube, rise times in these counters are between 10^{-9} and 10^{-6} s.

![Fig. 13. Comparison of the X-ray and gamma-ray resolution of semiconductor counters (curve 1), proportional counters (curve 2) and scintillation counters (curve 3). The half-height width of the pulse-height distribution obtained with a good counter for monochromatic radiation is plotted against the square root of the quantum energy E. Except for very small values of E, the semiconductor counters are superior. The horizontal part of curve 1 represents amplifier noise.](image)

Proportional counters have a rise time of about 10^{-6} s; they are therefore generally somewhat slower than semiconductor counters. It should be remembered here that the rise time of a proportional counter is not a measure of the maximum count rate that can be handled; this is appreciably lower than would follow from the rise time because, after very pulse, it takes some time before the generated ions have disappeared again. Ionization chambers are very much slower: these have a rise time of not less than about 10^{-3} s, owing to the low mobility of positive and negative gas ions.

Other features

In solids the range of charge particles is much shorter than in gases and the absorption of γ-rays is much greater. These effects enable semiconductor counters to be very much smaller than proportional counters and...
yet still be useful for a wide range of energies. Complete semiconductor counters are even smaller than scintillation counters, which have to be used in conjunction with a light-guide and photomultiplier tube.

The small dimensions of semiconductor counters are a great advantage in various applications, such as in medical and biological experiments. On the other hand, for measurements on very large specimens, or on specimens that cannot be situated close to the detector, the small size is a disadvantage, because much of the emitted radiation is then no longer incident on the detector. This disadvantage can usually be overcome by using more than one detector, and placing them around the specimen. It also appears likely that in the future it will be possible to make larger semiconductor counters than at present.

Semiconductor detectors have the considerable practical advantage of not requiring a well-stabilized voltage source. If they are connected, as shown in fig. 2, to an amplifier with capacitive negative feedback, the height of the output pulses from the amplifier will be largely independent of the variations in the voltage $V_0$ across the detector. The reason for this is that variation of $V_0$ causes a change in the capacitance $C$ of electrode 2 with respect to earth such that the change in the height of the pulses across $R$ is exactly compensated by the change in the ratio $C/C_t$ ("charge amplification").

Finally, we should mention again that semiconductor counters can be produced in a wide variety of forms. This makes it possible to adapt them more easily and more effectively than other detectors to the requirements of specific experiments.

It will be apparent from what we have said that semiconductor detectors are preferable to other types for several types of measurement. Some examples have been specifically mentioned. In nuclear physics, the advent of the semiconductor detector has brought about a considerable advance in spectroscopy and in particle identification. We have also seen that the directional distribution of radiation emitted as a result of a nuclear reaction can be determined very much faster with a semiconductor counter, with no sacrifice of accuracy.

In radiochemistry also, which mainly requires the detection of $\gamma$-rays, semiconductor counters are often to be preferred. This applies both for purely scientific research and for applied radiation chemistry such as activation analysis. In such applications the very high energy resolution of semiconductor counters often permits a simplification of procedures.

Summary. Germanium and silicon counters with P-N and P-I-N configurations are extremely useful for detecting and measuring the energy of $\gamma$-quanta and high-energy charged particles. Except with very heavy particles these semiconductor detectors are highly linear and have a particularly high resolution (about 20 keV for $\alpha$-radiation, only a few keV for $\beta$- and $\gamma$-radiation). The pulse height depends only on the quantum energy (particle energy) $E$ and not on the nature of the radiation. With extremely thin detectors it is also possible to measure $dE/dx$ and thus identify unknown heavy particles. The construction of the device is readily adaptable to specific requirements; to measure directional distributions, for example, a detector can be divided into numerous subdetectors (checker-board counter). The resolution is higher for larger values of the charge carrier life compared with the transit time in the counter, and for lower bias current. A P-I-N detector combines a large detection volume with a small bias current.