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THE SEMICONDUCTOR SURFACE BARRIER FOR NUCLEAR PARTICLE DETECTION

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A simple and reliable technique for the preparation of surface barrier detectors in silicon and germanium is described The performance and electronic requirements of these directors are discussed and compared with those of diffused junction counters Many properties of semiconductor detectors are of great value in nuclear physics and an outline is given of their advantages and limitations Some special configurations for fission studies, dE/dx counters and neutron detection are described

CONTENTS

1. Introduction

There has arisen recently a widespread interest in the detection of nuclear particles by means of semiconductor devices. Such detectors have shown very good energy resolution and linearity, coupled with a fast rise time, compact size, and a relatively low sensitivity to background gamma-rays and neutrons. Other advantages are their low cost, simple power supply requirements, and adaptability to special applications. In fact, experience gained so far suggests that semiconductors in one form or another may ultimately replace most other types of particle detector.

Basically the principle of operation is similar to the gaseous ion chamber. An electric field is established across a medium of low conductivity. When a charged nuclear particle penetrates the medium, collisions occur, producing ion pairs in the case of the gaseous chamber or electron-hole pairs in the solid lattice. Ideally the charges are separated by the field and collected at the boundaries, producing an electrical pulse which can be amplified and recorded. Recombination of the charges before collection must be avoided, so the medium must have a high carrier mobility, must be free of defects, and capable of withstanding a high collecting field without breakdown. The earlier crystal counters of materials such as diamond, ZnS, and CdS, were not satisfactory in this respect. On the other hand germanium and silicon can be made to satisfy these requirements, and several other materials such as gallium arsenide show promise of being suitable in the near future.

The simplest arrangement would be to have a block of semiconductor between parallel electrodes so that a uniform electric field could be set up throughout the whole volume. This has been termed a bulk conductivity counter and charge produced anywhere throughout the volume of the block is collected. In practice the conductivity of the most suitable materials is too great, due to impurity and thermally generated carriers, but by using extremely pure material at a very low temperature the conductivity has been reduced[1,2]) sufficiently to allow an adequate collecting field to be established. Alternatively the impurity conductivity in some cases has been reduced by counter-doping, as in gold-doped silicon[3]) and oxygen-doped gallium arsenide[4]), but at the expense of shortened carrier lifetime and corresponding loss of collection efficiency.

So far the bulk conductivity counter has not been as practicable as those employing the depletion layer effect which occurs in a semiconductor diode. This exists between an n-type or donor-rich region and a p-type or acceptor-rich region of a semiconductor. A shallow volume of the interface is depleted of carriers, leaving the impurity atoms ionized, positive in the n-region and negative in the p-region. The strong dipole field which results will rapidly collect any electron-hole pairs created in the interface by a charged nuclear particle. A voltage applied in the reverse-biased direction will extend the depletion layer thus increasing the volume which is effective for particle detection. In materials having a small gap between valence and conduction bands, cooling reduces the number of thermally generated carriers.

If the whole of the sensitive volume is to be accessible to nuclear particles, the n-p interface must be formed close to the surface of the crystal. One way in which this may be accomplished is by the shallow diffusion of a doping impurity of one type into a crystal having a weak impurity concentration of the other type. Diffused junctions have been employed as detectors by a number of laboratories[5–8]) with results which are a considerable improvement over more conventional methods. A second approach is to employ the surface barrier which forms spontaneously on clean silicon and germanium. The surface readily oxidizes and surface states are formed which behave predomi-

[1]) P E Gibbons and D. C Northrop, Nature 188 (1960) 803

[2]) F J Walter, J W T Dabbs and L D Roberts, Rev Scient Instr. 31 (1960) 756

[3]) J D Van Putten and J C Van der Velde, I.R E Trans NS-8 (1960) 124

[4]) Harding, Hilsum, Moncaster, Northrop and Simpson, Nature 187 (1960) 405

[5]) G. L Miller, W. L Brown, P F Donovan and I M Mackintosh, B N L Report 4662 (1960)

[6]) S S Friedland, J W Mayer, J M Denney and F Keywell Rev Scient. Instr 31 (1960) 74

[7]) J M McKenzie and J B S Waugh, I.R E Trans TS-7 (1960) 195

[8]) G. Amsel, P Baruch and O Smulkowski, Nucl Instr and Meth 8 (1960) 92

nantly as electron acceptors. Electrical connection to the surface layer is made by evaporating a thin layer of metal, usually gold, over a certain area. A reverse bias applied to this electrode extends the depletion layer, or barrier, into the semiconductor to a depth of as much as a millimetre.

Several methods of preparing surface barrier detectors have been reported[9,10,11]) but we feel that there is still need for a detailed account of a reliable technique which can be readily adapted to the requirements of most experiments. At Harwell, we have concentrated attention on the surface barrier detector[12]), because it has a simpler construction and potentially better performance than a junction prepared by diffusion. A comparison of the two types of detector will be attempted in section 6.

2. Construction Techniques

The technique is quite straightforward but requires a vacuum evaporation system and a fume cupboard. Extreme cleanliness is essential at all stages because impurities present in high resistivity silicon and germanium represent only a few parts in 10^{10}. The crystals should not be touched with bare hands, for instance.

Zone-refined crystals of silicon have been obtained from several firms, cut to the required size and lapped to a fine matt finish with aluminium oxide of about 7 microns grain size. Our procedure is then as follows.

(1) While not essential, it is good practice to clean the crystals prior to etching by boiling for a few minutes in concentrated nitric acid.

(2) The crystal is then put in a polyethylene beaker, and about 20 cc of CP-4A is added, the mixture being kept ice-cold. Etch-pit formation has been observed if the temperature is allowed to rise. CP-4A is a standard solution used in semiconductor processing, and consists of:

concentrated nitric acid	2 volumes
glacial acetic acid	1 volume
40% hydrofluoric acid	1 volume.

Chemicals should be of analytical reagent purity, mixed in clean polyethylene apparatus, and allowed to stand for 30 minutes before use. Fresh etch must be made up for each day's requirements. This step must be carried out with due care in a fume cupboard as HF produces serious burns on the skin and is highly toxic if inhaled. Five to ten minutes in the etch bath should be sufficient to produce a mirror-like finish on the silicon surface. In some cases uneven etching has been observed and is attributed to the presence of strain dislocations. Such crystals

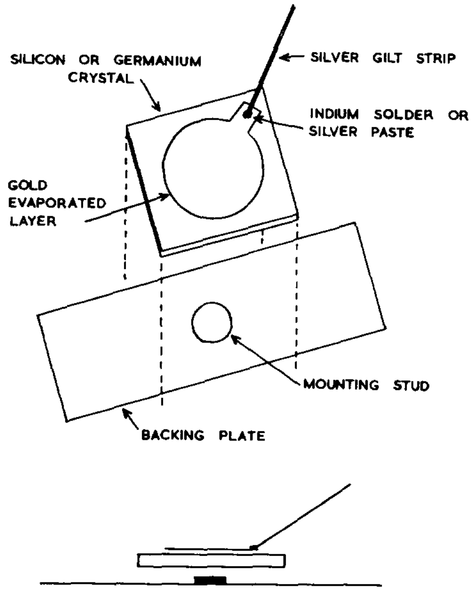

Fig 1 Construction of surface barrier detector

do not make good detectors. Bubbles which occur on the surface during etching should be removed by occasional agitation, and we have recently found supersonic agitation very effective at this stage for removing bubbles.

(3) Demineralised water is run into the etch and the crystal is washed by alternate dilution and decanting, avoiding exposure of the silicon during the early stages of the procedure. A dark stain results if this precaution is not taken. The crystal is transferred to a clean polyethylene beaker and

[9]) J L Blankenship and C J Borkowski, I R E Trans. NS-7 (1960) 190

[10]) J L Blankenship and C J Borkowski, I R E Trans NS-8 (1961) 17

[11]) F J Walter, J W T Dabbs, L D Roberts and H W. Wright, O R N L report CF-58-11-99 (1958)

[12]) G Dearnaley and A B. Whitehead, A E R E report R-3278, and R-3437 (1960)

washed several more times with demineralised water. This beaker must be used for no other purpose. A water conductivity cell can be employed at this stage to verify that the washing is complete. The crystal is then dried on pure tissue, and allowed to stand for 3–6 hours to undergo the initial oxidation process. The work of Green and Maxwell[13]) shows that the oxidation is initially rapid, followed by a slow adsorption.

(4) A mica mask is prepared for the evaporation. A convenient shape is the keyhole as shown in fig. 1 which provides a small gold area for the front contact leaving a circular area free. The purpose of the mask during evaporation is to define the area of the counter and avoid deposition of gold on or near the crystal edges. The mask is then cleaved to ensure that the faces which are in contact with the crystal are perfectly clean, and the crystal is lightly clipped between them.

(5) The masked crystal is then mounted in the vacuum evaporator so as to deposit gold on the face which has the best finish. The gold is evaporated at a pressure of less than 10^{-4} mm of Hg. For most purposes a film of about 75% light transmission, corresponding to 20–40 micrograms per square centimetre, is satisfactory. If the gold layer is to be of minimum thickness, for example for a fission detector, it is convenient to mount a small quartz strip with electrodes beside the crystal. The surface resistivity of the film deposited on the quartz can then be monitored. We are indebted to Mr. M. Nobes (A E.R.E.) for suggesting and constructing this arrangement.

(6) The crystal is then removed and placed on pure tissue in a covered box. We have found, as has Blankenship[9]), that it is better to age the dectectors for a few days after deposition of the gold before making the connections. This is presumably to allow the full development of the surface oxide which appears to take place through the thin gold.

(7) A second gold evaporation is made, this time with the circular counting area shielded, forming a thicker deposit on the small tab to which electrical connection is to be made. This avoids the possibility of the organic binder in the silver paste penetrating and damaging the surface layer. It is known from studies by Buck[14]) that organic contaminants cause deterioration in shallow junctions on N-type silicon, while water vapour improves them, in respect of leakage current. Conversely, water vapour is deleterious to junctions on P-type silicon. We have sometimes found an increase of leakage current over a period of months, and restored the behaviour by scraping away the contact and making a new one elsewhere. The double evaporation of gold should avoid this trouble.

(8) The crystal is then cemented on to the required mount which may simply be a small plate of metal with fixing holes. Kovar is recommended as it has a coefficient of thermal expansion similar to that of silicon. Johnson, Matthey FSP 43 flake silver paste† has proved satisfactory. In order to give a long surface leakage path and avoid the possibility of cement on the edges of the crystal a dimple can be pressed into the plate or a small spacing disc inserted as shown in fig. 1. The silver paste contact is only slightly rectifying, presumably due to the effect of its organic constituents on the surface inversion layer, thus despite the symmetrical preparation of the etched crystal the finished unit is a diode. A more nearly ohmic contact can be obtained by nickel plating but the present method proves simpler and is satisfactory for most purposes.

(9) Front contact to the gold is made by a short length of silvergold alloy galvanometer suspension strip, cemented to the gold tab with a small drop of FSP 43. The paste should be sufficiently fluid to wet the gold but on no account should it be allowed to flow on to the uncoated silicon.

(10) The whole assembly is maintained at approximately 80°C for a few hours to set the conducting cement.

The device is then complete and ready for testing. The success rate of this method is very high and most of the differences in performance of detectors are believed to be due to characteristics of the semiconductor starting material. Thus a good detector

† This is a new resin-based two-component paste which gives a stronger bond than the FSP 36 used hitherto

13) M Green and K H Maxwell, J Phys and Chem of Solids 13 (1960) 145

14) T Buck, Proc of N A S Conference, Asheville (Sept 1960) to be published

can be reground and remade satisfactorily, while inferior detectors remain poor after reprocessing. Fig. 2 shows a photograph of a pair of detectors.

The procedure for germanium is identical to that described above for silicon except that (i) the etch may be used at room temperature, and (ii) the method of making electrical connections is altered. Silver paste tends to fracture when cooled, so that it is better to make a solder connection, both to the base and to the gold layer, with indium (m.p. 155°C) as a solder.

3. Pulse Amplification

The energy loss per electron-hole pair in silicon is 3.6 eV so that the charge liberated by a nuclear particle is 4.4×10^{-14} coulomb per MeV lost in the barrier. A typical counter capacitance is of the order of 20 pF yielding voltage pulses of about 2 mV per MeV. Counters with large sensitive areas have much higher capacitance and correspondingly lower voltage signal. Both of these types require amplifiers with high gain and very low noise. On the other hand, small, high resistivity counters with very deep barriers can have a capacitance of as little as 1 pF and would give best performance with a very low input capacity amplifier.

The circuit resembles that for an ion chamber (fig. 3). For minimum noise the load resistor should be as high as possible without causing undue pile-up of pulses under operating conditions. With a high impedance amplifier the decay time of the pulse is governed by the counter and stray capacitance together with the load resistance. If the amplifier has a low input impedance, this will govern the pulse decay.

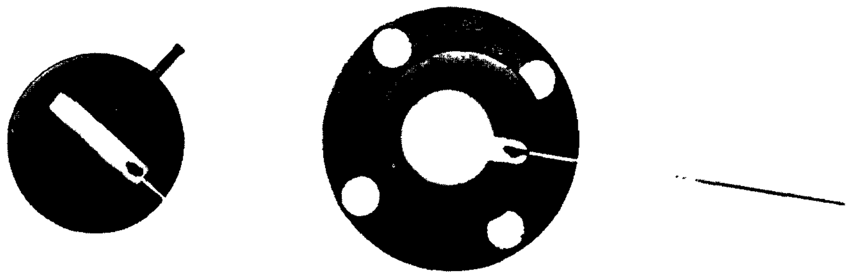

Fig 2 Two completed detectors The unit on the left is slitshaped for use with a magnet spectrometer

The amplifier used at Harwell for most applications has been the A.E.R.E. type 1430, which is a conventional 2 Mc/s voltage amplifier, with a 6AK5 first stage. The signal to noise ratio with such an instrument is usually adequate, but the pulse height stability is limited by variations in the effective capacitance of detector and input circuit. Any change in current through the detector alters the detector bias, and thus its capacitance, while

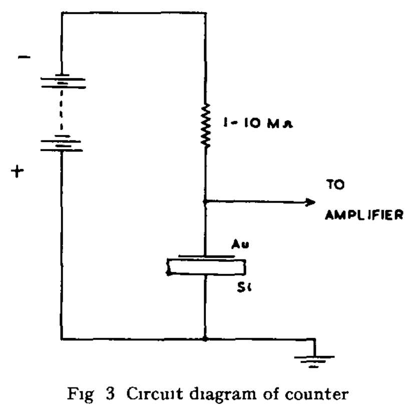

Fig 3 Circuit diagram of counter

McKenzie[15]) has found that heater voltage variations alter the effective input capacitance of the amplifier, due to variations of space charge. To overcome this, charge sensitive amplifiers employing feedback through a small capacitance to the input grid have been designed by Gatti[16]), Blankenship[10]) and Chase[17]).

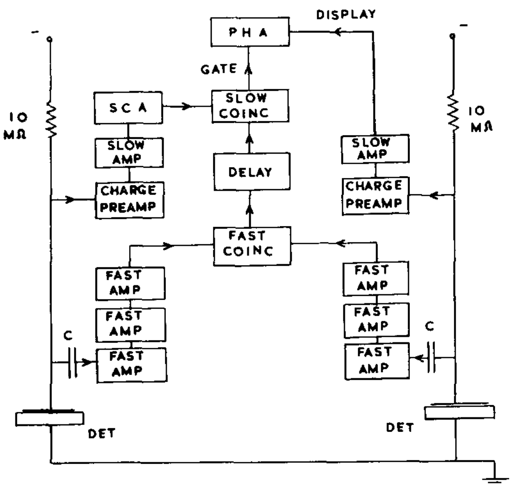

Fig 4 Block diagram of coincidence counting system
Amp = amplifier
S C A = single channel analyser
Det = detector
Coinc = coincidence unit
P H A = pulse height analyser
C = coupling condenser, about 500 pF

In order to utilise the fast rise-time of the detectors, an amplifier of higher bandwidth is required, but the signal to noise ratio, and the stability of gain are then inferior. Thus with the A.E.R.E. type 2002A 200 Mc/s amplifier the noise level is around 0.5 mV. In many cases it is possible to use a combination of fast and slow amplification, so that fast coincidence measurements can be made simultaneously with high resolution pulse-height analysis. An example of such an arrangement is shown in fig. 4.

The time for collection of charges in the detector itself is generally of the order 10^{-9}–10^{-8} sec in silicon detectors, and less than 10^{-9} sec in germanium detectors. However, there is a time-constant associated with the transfer of charge into the amplifier due to the resistance of the undepleted silicon in series with the detector capacitance. The existence of this effect was brought out in a discussion with J. W. Mayer, who has since verified it experimentally[18]). It is necessary to minimise this effect in fast applications by choosing a silicon wafer thickness no more than the depletion layer depth required. There is some advantage in detectors of N-type material, in that the carriers of higher mobility electrons make the transit through the weaker field region near the base electrode, and hence the charge collection time can be shorter by a factor of 3, the ratio of carrier mobilities.

Frequently there may be present a high background of small unwanted pulses, e.g. from electrons or elastically scattered particles, and the pile-up of such pulses may interfere with the observations. Then it is necessary to use a small load resistor, and short amplifier time-constants. The size of electron pulses is minimised by working with a depletion layer no deeper than is necessary to stop the particles under investigation.

4. Characteristics of Gold-Silicon Detectors

4 1 REVERSE CURRENTS

This is a somewhat variable quantity, sensitive to the amount of surface contamination. The work of Buck[14]) has shown that organic vapours cause higher leakage in the case of P-type surface layers. We have therefore tested counters under good vacuum conditions with adequate vapour trapping by liquid nitrogen. However, it is quite possible to operate counters satisfactorily in the presence of air or, presumably, many other gases. Measurements by Buck (private communication) on one of our detectors show a relatively smaller amount of variation in reverse leakage under various ambient conditions than for diffused counters on P-type base material.

A good detector should have a reverse current less than 0.3 $\mu A/cm^2$ at 50 volts bias. This corresponds with the space-charge generated current

[15]) J M McKenzie and G T Ewan, I R E Trans NS-8 (1961) 50

[16]) C Cottini, E Gatti, G Giannelli and G Rossi, Il Nuovo Cimento 3 (1956) 473

[17]) R L Chase, W A Higinbotham and G L Miller, I R E Trans NS-8 (1961) 147

[18]) J W Mayer and C T Raymo, I R E Trans NS-8 (1961) 157

in the volume of the barrier, which is proportional to $\sqrt{V}$, where V is the bias voltage. Fig. 5 shows some typical results in agreement with this, and we infer that the surface leakage current is relatively small. At a fairly critical reverse bias break-down occurs, manifested by a marked fluctuating increase in current accompanied by severe electronic noise. With some detectors over 500 volts bias has been applied before any sign of this, but 200 volts is a more typical limit. Cooling the units reduces the leakage and increases the breakdown potential, and by such means Blankenship[10]) has applied 2100 volts bias to surface barrier detectors.

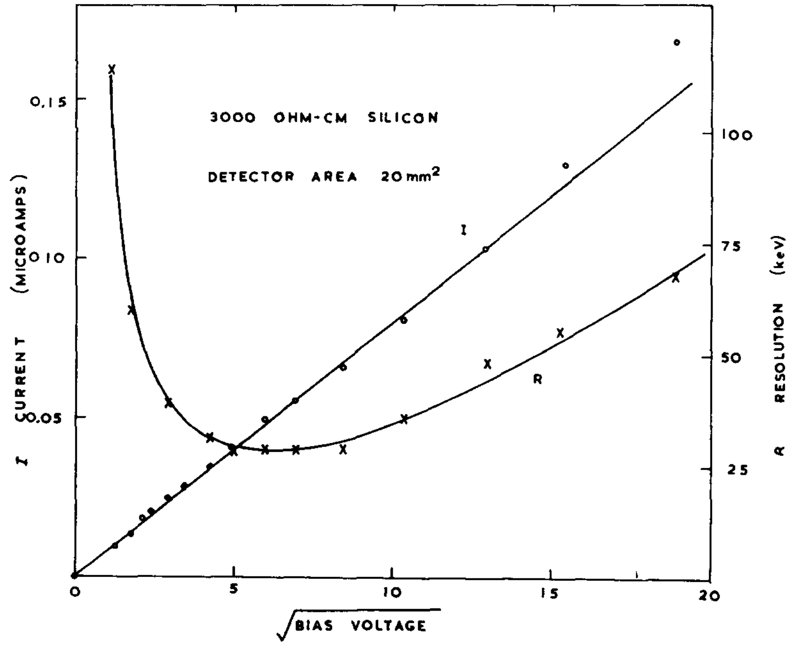

Fig 5 Reverse current and resolution as a function of (bias voltage)$^{\frac{1}{2}}$

Due to effects such as dislocation density and uniformity of impurity concentration (which controls the uniformity of barrier depth), different crystals behave in different ways. We find there is often little connection between the magnitude of the leakage current at low bias, and the breakdown potential. Possibly a non-uniform barrier depth leads to early breakdown without causing large current at lower bias.

We have studied some alternative methods of making the base contact to the detector, and find that it may have a marked influence on the reverse current. A method[10]) in which the back of the silicon wafer is protected during the etching process so as to retain a lapped surface results in a good ohmic contact to the silicon either by subsequent evaporation of a gold layer, or by a silver pasted connection. However, the leakage current is greater than that observed following our normal procedure, and if the detector is lapped again and remade by the method described in section 2, the current is reduced. Similar effects have been observed by R.B. Owen at A.E.R.E. when the back crystal surface is roughened by an air-blown abrasive before making the base contact.

It seems likely that carriers are being injected at the base contact and owing to their long lifetime in the bulk silicon some of them are able to diffuse across the crystal to the depletion layer. The damaged surface will contain a large number of sites at which electron-hole production can occur.

The effect of this process is found to be much more pronounced in thin slices of silicon, as would be expected. Therefore the lifetime should be made high at both surfaces by symmetrical etching, and the area of the base contact should be kept small, as in the procedure we advise.

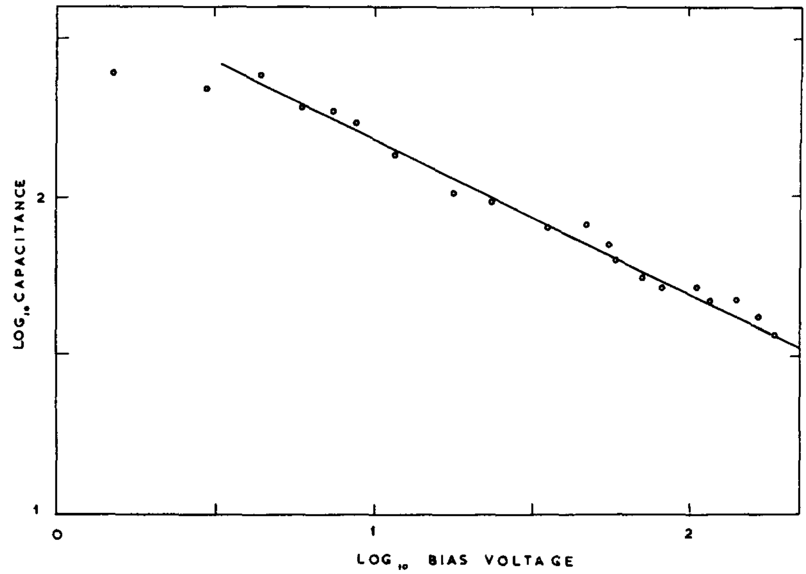

Fig 6 Detector capacitance as a function of bias voltage (logarithmic scale) The points are fitted with a straight line of slope 0 49 $\pm$ 0 01 in the region above 4 volts bias

4 2. CAPACITANCE

The surface barrier acts as a shallow insulating region between conductors, in a medium of high dielectric constant, and the capacitance is inversely proportional to the barrier depth. The capacitance can be measured by the change in pulse height produced by connecting a standard comparable capacitance in parallel with the detector, while it is exposed to monoenergetic alpha particles.

In an abrupt junction, such as we expect for a surface barrier, the capacitance should be proportional to (bias voltage)$^{\frac{1}{2}}$, and in N-type silicon integration of Poisson's equation leads to the formula $C \approx 1.8 \times 10^4/\sqrt{p(V + V_0)}$ pF/cm^2 after insertion of constants and boundary conditions. Here p is the resistivity in ohm cm, V is the applied bias voltage, and V_0 is the intrinsic potential between surface and interior of about 0.6 volts. Measurements on a fairly large area (2 cm^2) detector up to 200 volts bias show a $V^{-(0{,}49+0{,}01)}$ power law in agreement with expectation (fig. 6). The stray capacitance was here determined by extrapolation of the straight line obtained by plotting capacitance against $V^{-\frac{1}{2}}$.

4 3. BARRIER DEPTH

For practical purposes this is the distance from the front electrode over which efficient carrier collection can be achieved, and it is most directly measured by the linearity of pulse height with particle energy. When the particle penetrates beyond the region of the barrier field, carriers are lost by recombination, and linearity ceases. Different types of particle of the same energy give the same pulse height up to an energy at which they penetrate the barrier. This method gives more information than capacitance measurements, since non-uniformity of impurities across the crystal can lead to a non-uniform barrier depth, which becomes apparent from measurements with accelerated particles.

Figs. 7 to 9 show results of scattering protons of different energies, from the Harwell Van de Graaff and Tandem Generators, into detectors at various bias voltages. The turnover is not abrupt, showing that there is not a sharp boundary to the barrier. Some charge diffuses to the barrier, and is collected, so that the value of barrier depth obtained will be

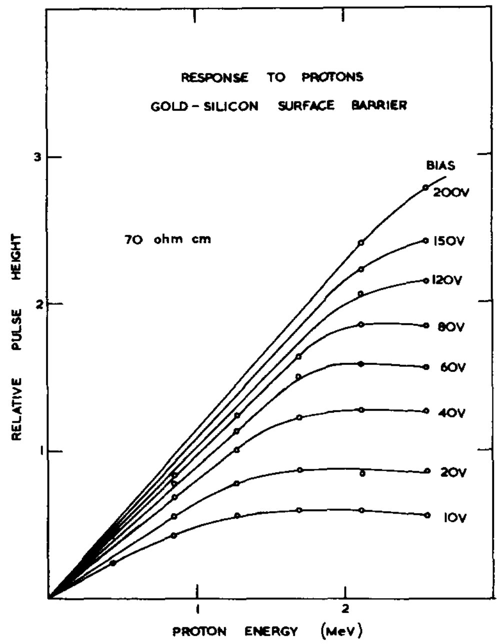

Fig 7 Response of 70 ohm cm silicon detector to protons of various energies as a function of bias voltage

dependent on the amplifier bandwidth. Equal integration and differentiation time constants of 0.8 μsec were used in these measurements.

Some earlier measurements[19]) with material which had a resistivity at the surface of 1900 ohm cm are invalidated by the fact that the resistivity changed by a factor of 5 through the 1 mm specimen. Resistivity measurements on both faces of the crystal are now made.

In N-type silicon, the barrier depth d is given by $d \; \Omega \sqrt{\rho(V+V_0)}/1.8$ microns, where the symbols are as in § 4.2. If $V >> V_0$ the barrier depth is proportional to $\sqrt{V}$, as is the electric field at any given depth. Blankenship[20]) has given a useful nomogram relating barrier depth, bias and resistivity.

4 4 ENERGY RESOLUTION

Several factors influence the resolution of a counter.

(i) *The statistics of the electron-hole pair formation.* If the number of pairs is related to the incident

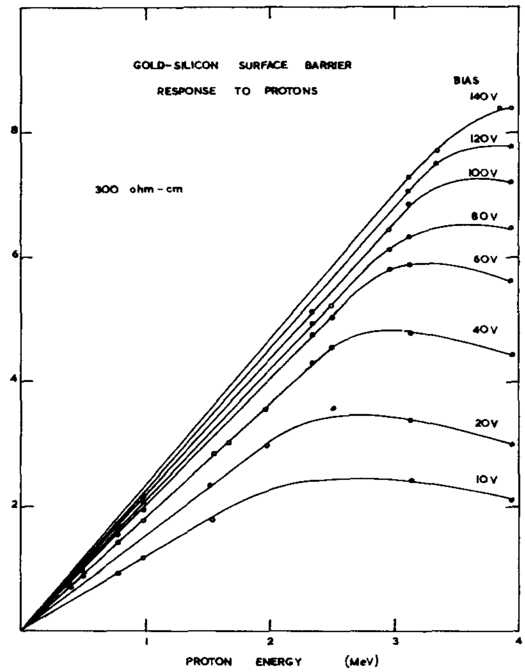

Fig 8 Response of 300 ohm cm silicon detector to protons of various energies as a function of bias voltage

particle energy by a constant $W \approx 3.6$ eV independent of particle energy, as all evidence suggests, then this is unlikely to limit detector performance. The advantage over gas counters is here apparent, the number of events being 8–10 times greater in the solid detector.

(ii) *Recombination effects.* Some small fraction of the carriers will inevitably encounter recombination sites before being collected, and if this fraction varies over the crystal the pulse height will be a function of the position of the ionized track. Initially as the carriers begin to be separated there will be a strong mutual field between the electrons

[19]) G Dearnaley, I R E Trans NS-8 (1961) 11
[20]) Contribution to Nucleonics 18 (1960) 98

and holes, diminishing as they diffuse away from the track. At a certain stage the externally applied field will become predominant, and collection will take place governed by the normal carrier mobility. An increased field reduces the time for both these processes, and so shortens the time in which recombination is possible. The minority carrier lifetime in high-quality silicon is around 1 msec, but if the impurity concentration is non-uniform, and there are local dislocations around which impurities tend to cluster, there will be regions of much lower lifetime, and carriers may be lost during transit times as short as 10^{-8} sec. However, in diffused junction counters a marked reduction in lifetime follows the heating process necessary for diffusion. Multiple peaks from monoenergetic alphas have been observed in such counters much more commonly than in surface barrier counters[21]), with consequently often poorer resolution. Further evidence that such effects are linked to poor carrier lifetime is provided by radiation damage observations (see also § 4.8), in which multiple peaking becomes apparent after bombardment with charged particles.

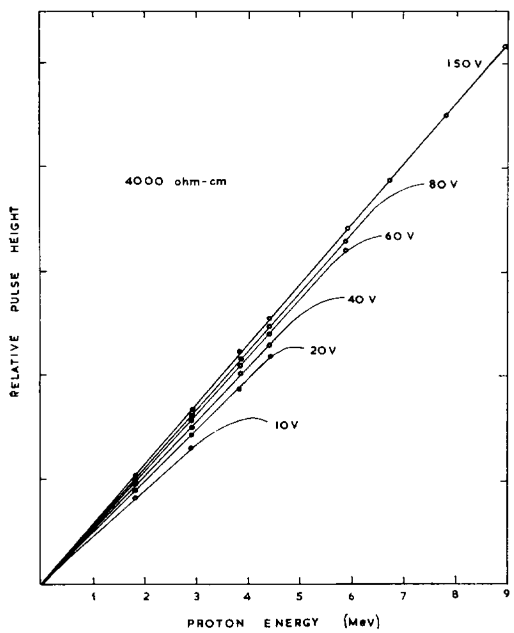

Fig 9 Response of 4000 ohm cm silicon detector to protons of various energies as a function of bias voltage

(iii) *Detector noise.* This arises from fluctuations in the detector leakage current, which is a function of the applied bias. The detector acts simply as a reverse-biased diode, which has been studied before in this respect[22]). The noise consist of shot noise due to fluctuations in the bulk leakage current, and two types of flicker noise characterized by a $1/f$ frequency dependence. One is due to surface noise arising from fluctuations in the density of recombination centres at the diode surface, and the other is leakage noise due to a conducting film by-passing the junction at its perimeter. Flicker noise is very dependent on the ambient atmosphere. The contributions of these noise sources vary with detector current.

At low bias voltages the detector noise is usually less than the amplifier noise, which then limits performance, and for which the amplifier time constants must be optimised. At high bias the detector noise becomes dominant and we find that the signal to noise ratio is improved by shorter (equal) time constants.

(iv) *Amplifier noise.* This arises principally from shot noise and grid current noise at the input stage. There is a certain time constant, dependent upon tube characteristics and input capacitance, for which the sum of these noise contributions is minimised, and this determines the optimum conditions at low detector bias. A detailed study of amplifier noise in these applications has been given by Fairstein[23]) and Goulding[24]).

At A.E.R.E. we have used the conventional 1430 amplifier, and so far this has limited the resolution attained to about 16–18 keV (i.e. 0.35% for a 5.4 MeV alpha). Fig. 10 shows the response of a 30 mm^2 detector to Am^{241} alphas. The vertical lines indicate the expected positions and intensities of the lines, normalised to the main peak.

Such voltage-sensitive amplifiers are, however,

[21]) Discussion at N A S Conference, Asheville (Sept 1960) (to be published)

[22]) See for example Van der Ziel, Fluctuation Phenomena in Semiconductors (Butterworths, 1959)

[23]) E Fairstein, I R E Trans NS-8 (1961) 129

[24]) F S Goulding and W L Hansen, U C R L Report 9436 (1960)

inferior to charge-sensitive configurations as mentioned in § 4.3. With a cascode charge-amplifier, Blankenship[9]) has reported a resolution of 14 keV for 5 MeV alphas.

Not all counters give such high resolution, however, probably for a variety of reasons. Inferior

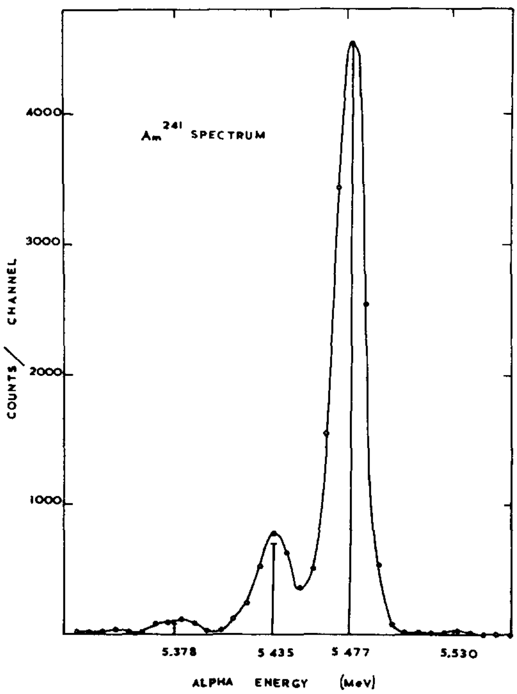

Fig 10 Resolution of Am^{241} alpha spectrum in a silicon detector of 30 mm^2 area (3000 ohm cm resistivity, bias 60 volts) The vertical lines show the expected positions and intensities of the lines normalised to the main peak The resolution is 17 keV or 0 3 % in energy

silicon can be the cause of a high detector current, producing noise which is apparent in the absence of any charged particles, while nonuniform trapping causes a spread in pulse height. Surface contamination of the detector can cause surface leakage noise. Such surface effects cause a variation in performance with time, whereas the bulk effects remain constant, provided radiation damage or overheating does not occur.

(v) *Practical considerations.* When detectors are used in conjunction with an accelerator to detect particles from a nuclear reaction, there is some spread in particle energies at the detector due to its angular acceptance. Target thickness may also limit the resolution.

There is an optimum detector bias for best resolution (fig. 5), since the voltage signal increases as the capacitance is reduced by increasing bias, but the leakage current increases. However, other considerations will generally determine the bias voltage used to obtain a barrier depth to suit the relevant particle energy. Bias of 200 volts often gives us a resolution still better than 50 keV, and in the highest resistivity N-type material available (around 10000 ohm cm) this produces barriers almost 1 mm deep, sufficient to stop 11 MeV protons, or 40 MeV alphas.

4 5 PULSE RISE-TIME

The mobility of electrons in silicon at room temperature is about 1300 cm^2/volt sec while that of holes is approximately one-third that value. For a given barrier depth and bias the charge collection time can thus be calculated, and typical values lie between 10^{-9} and 10^{-8} seconds. As the range of the ionising particle will in general be less than the barrier depth, the electrons make the longer transit. Here incidentally is a slight advantage of surface barrier detectors over P-type diffused junction counters, in which the slower carriers make the longer transit. The simple approach neglects the separation time of the electrons and holes, during which they must diffuse until the collecting field can overcome their mutual attraction. This time can be appreciable in the densely ionised tracks of fission fragments[5]).

Measurements were made at A.E.R.E. on the rise-time of pulses from 5 MeV alphas in a barrier $\approx 120\ \mu$ deep formed by 72 volts bias in 1000 ohm cm silicon. After amplification by two type 2002A distributed amplifiers in series pulses of 0.4 volts amplitude were observed with a rise-time of 6×10^{-9} sec on a Tektronix type 517A oscilloscope. The rise time of the system was not appreciably less than this, so that the result is in accordance with the calculated rise time of 3×10^{-9} sec.

4 6 WINDOW THICKNESS

By this is meant the effect of any insensitive layer at the surface of the detector.

Extrapolation of pulse height against energy calibrations for alpha particles of energies down to 300 keV show no appreciable intercept. Measurements by R. Segel (priv. comm.) on one of our detectors, in which 1.8 MeV alphas were injected at 0° and 45° showed that the dead layer was $< 0.05\ \mu$ of silicon, or equivalent.

Low energy C^{12} ions, of 200 keV, have been detected with good agreement with the proton energy calibration. This was carried out by bombarding a thin foil of carbon with alphas, and detecting the scattered alphas and recoiling carbon ions. This again shows that the dead layer must be $< 0.03\ \mu$ of silicon.

Such figures are consistent with the thickness of the gold film, and the expected thickness of the oxide layer, of the order 10 Å. The results are significantly better than those for most diffused junction counters.

4 7 SENSITIVITY TO GAMMA-RAYS

Gamma-rays produce photoelectrons, Compton electrons, and pairs in the silicon itself and in surrounding material. Because of the low atomic number of silicon the photoelectric process and pair formation are unfavoured.

In the case of a shallow barrier the sensitive volume is so thin that electrons lose negligible energy before escaping from it, and thus gamma-rays produce only small pulses with low efficiency. Barriers as deep as 1 mm however have shown much greater efficiency and pulse height for electrons and gamma-rays. Donovan[25]) and McKenzie[15]) have reported good resolution for these radiations up to a few hundred keV. Pile-up of unwanted small pulses can be minimised by the precautions mentioned in section 3.

4 8 SENSITIVITY TO NEUTRONS

Neutrons can produce pulses in a surface barrier detector by three possible means

(i) (n,p) and (n,α) reactions in silicon. Known reactions occurring[26]) are·

Si^{28}(n,p) $Q = -3.86$ MeV. Percentage abundance $= 92\%$. The cross-section[27]) rises from 0.02 barns at 5 MeV to 0.40 barns at 8 MeV falling to 0.22 barns at 14 MeV.

Si^{28}(n,α) $Q = -2.66$ MeV.

Si^{29}(n,p) $Q = -3.20$ MeV. Percentage abundance $= 4\ 7\%$. The cross-section is 0.10 barns at 14 MeV.

Si^{30}(n,α) $Q = -4.19$ MeV. Percentage abundance $= 3.1\%$. The cross-section is 0.05 barns at 14 MeV.

The reactions induced in Si^{28} are clearly the most important, due to the large cross-section and isotopic abundance.

(ii) Reactions in the gold layer. Charged particle emission is inhibited by the high atomic number. Capture followed by emission of a 412 keV gamma-ray is the only effect which might be observed, but the yield is very low for film thicknesses of 50 μ g/cm^2 or less.

(iii) Recoil protons ejected from adsorbed hydrogen and water vapour in the surface, and neighbouring surfaces. Gold has a very low adsorption and is particularly suitable in this respect.

Measurements have been made, with A. T. G. Ferguson, on the response of a detector mounted in a gold-lined evacuated chamber and exposed to a flux of $\approx 10^5$ neutrons/cm^2 sec at different energies. At 2 MeV neutron energy the spectrum observed in the detector corresponds to a low yield of protons recoiling out of a thick layer, and this is attributed to residual hydrogen and water in the chamber walls. A lower background level could be obtained by vacuum-baking all the components, then introducing the detector in a dry-box. The response of semiconductor counters to low energy neutrons is made low by their high purity, which ensures the absence of any bulk contamination by hydrogenous materials.

At 6.3 MeV neutron energy the spectrum is very different, and is shown in fig. 11. The Si^{28}(n,p) cross-section is known[27]) to be large at this energy, ≈ 0.2 barns, and the Si^{28}(n,α) reaction, not previously observed, appears to have a cross-section

[25]) P F Donovan, G L Miller and B M Foreman, Bull Amer Phys Soc 5 (1960) 355

[26]) P M Endt and J C Kluyver, Rev Mod Phys 26 (1954) 95

[27]) R J Howerton, U C R L Report 5226 (1958)

almost as great. In fig. 11 the arrows indicate the expected positions of proton and alpha groups to known levels in Al^{28} and Mg^{25} respectively, and there is obvious correspondence with the spectrum observed. The resolution is inevitably poor since particles from reactions induced near the barrier boundaries may escape.

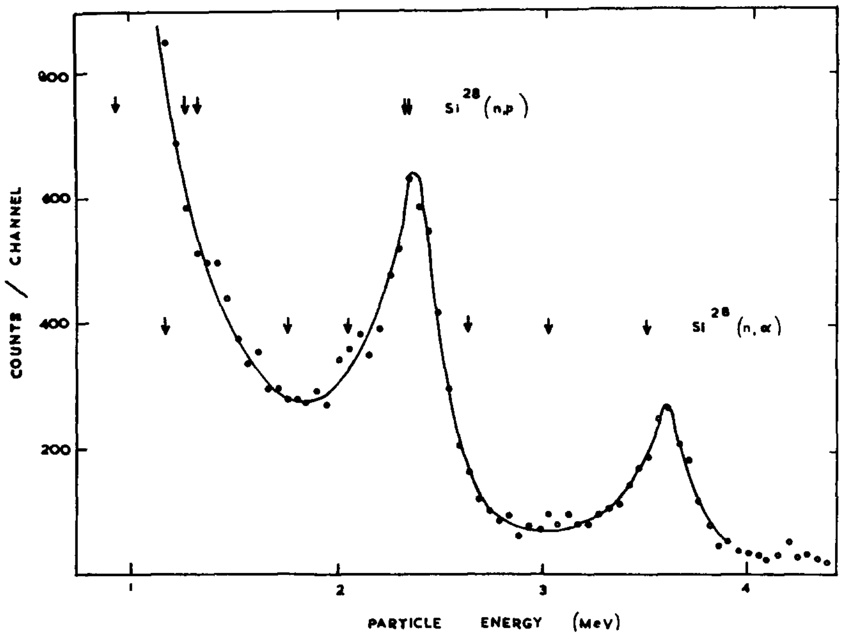

Fig. 11 Spectrum observed in a silicon detector under a high flux of 6 2 MeV neutrons. The arrows indicate possible charged-particle transitions to known energy levels

These reactions impose a limitation on the usefulness of silicon detectors, of any type, in a flux of fast neutrons, especially in the region of 8 MeV, where the $Si^{28}(n,p)$ cross-section peaks. The response to neutrons can, however, always be minimised as for gamma-rays by simply adjusting the barrier depth to be no greater than is necessary. As we shall see in § 5.5., there are advantages here in the use of germanium detectors.

4 9 RADIATION DAMAGE

Lattice defects are known to be produced in semiconductors by bombardment with alphas, deuterons, neutrons and electrons. In silicon this results in an increase in resistivity due to the trapping of carriers in levels formed near the middle of the band gap. The presence of these trapping centres lowers the lifetime of minority carriers and leads to a greater reverse diode current, due to the possibility of transitions via the intermediate defect states. The possibility that the useful life of a detector may be limited by radiation damage must therefore be considered.

Measurements by Klingensmith[28]) on several surface barrier detectors exposed to fission neutrons indicate that deterioration is not appreciable up to about 5×10^{11} fast neutrons/cm². Above this dose the resolution worsens and multiple peaking appears in the spectrum for monoenergetic alphas, while after 10^{13} neutrons/cm² the pulse height is much reduced. These measurements were made for a low bias of 6 volts in 3000 ohm cm silicon, and so correspond to a low collecting field. We would expect that recombination effects would be reduced

[28]) R W Klingensmith, I R E Trans NS-8 (1961) 112

by using higher fields, and the life of detectors might then be appreciably greater.

Little information seems to be available on damage by charged particles, so an empirical measurement was made to assess this. Several detectors of around 1000 ohm cm silicon were exposed

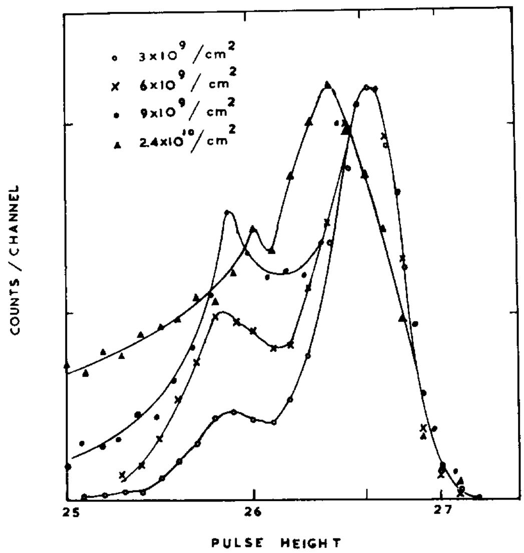

Fig 12 Alpha-particle spectrum in a silicon detector after various amounts of irradiation by 5 MeV alphas

to a high flux of 5.5 MeV alphas from a source of Am^{241}. Since the region of damage will be limited by the alpha range to about 0.003 cm it is to be expected that damage effects will be most apparent for a barrier depth only slightly greater than this, produced by only 2 volts bias. The resolution was measured by replacing the strong source by a weak one of good resolution. At this low bias the initial resolution of the detectors was about 1.5%.

After 10^8 alphas/cm^2 a slight increase of reverse current could be observed, and after 10^{11} alphas/cm^2 the current had increased by 3 μ A/cm^2 at 2 volts bias, from a very small initial value. This corresponds to a reduction in mean carrier lifetime to ≈ 1 μsec. There was a significant variation around these figures for different detectors. The resolution began to deteriorate after 2×10^9 alphas/cm^2 and soon a secondary peak of lower pulse height began to appear, increasing in size with further damage, as shown in fig. 12. In one detector, three peaks became visible, merging together as the resolution progressively worsened. These effects were strikingly similar to those observed by Klingensmith for neutron damage. After 10^{11} alphas/cm^2 the resolution in different counters had deteriorated to between 6% and 15% at 2 volts bias. At a higher bias of 20 volts the resolution was only increased to 3–4%, and multiple peaking was never apparent.

The most serious damage is expected to be near the end of the alpha particle range, owing to the heavy ionisation and likelihood of nuclear collisions. It is just in this region that the carriers are produced in a relatively weak field, which must overcome the forces between the electron and hole plasmas as they begin to separate. Recombination may under these conditions become possible before the charges can be collected, and local regions of low carrier lifetime may be the cause of multiple peaking. The effects are not seen at higher bias voltages because the carriers are produced in a much stronger field, and recombination is less likely. Variations between detectors are then due to differences in the initial carrier lifetime and in the uniformity of distribution of recombination centres.

There was some evidence that the peaks tended to merge on allowing the detector to stand at room temperature, without further damage. A period of 24 hours at 120°C produced no improvement un resolution.

The assistance of Dr. Jan Kuperus, (on attachment from Rijks Universiteit, Utrecht) is gratefully acknowledged in these measurements.

4 10 USEFUL LIFE OF DETECTORS

At A.E.R.E. detectors have been used over periods of 15 months without deterioration, and without more protection than a covered box when not in use. Measurements on one such counter, by R. Segel, have shown that its characteristics remain essentially unchanged over this time. Some detectors have shown increased noise and leakage current after a time, and in some cases this has been found to be associated with the front contact, since the counters were restored by making a new contact elsewhere. Other cases of deterioration have been due to surface contamination caused by a visible film of grease or amalgamation of the gold with mercury. The use of nickel instead of gold for the evaporated film overcomes this if it is for some reason impossible to trap the mercury vapour. A period of surface breakdown caused by contamination while the bias voltage is applied can produce permanent damage.

We have not observed the deterioration under vacuum which some groups have experienced, especially with high resistivity counters. Some counters of 1000 ohm cm silicon have been operated for two months under vacuum with no apparent ill effects.

Radiation damage may under some circumstances limit the useful life, for instance in applications to neutron spectrometry inside a reactor. A difficulty is caused by the low efficiency of some such devices[29]) for fast neutrons, ($\approx 10^{-6}$) since $\approx 10^{12}$ fast neutrons/cm^2 can produce appreciable damage.

4 11 PHOTOSENSITIVITY

All detectors exhibit photoconductivity, and they should therefore be tested and used in reasonably dark conditions.

4 12 EFFECT OF A MAGNETIC FIELD

A transverse magnetic field will deflect the electron paths in a surface barrier, but no effect on the detection of 5 MeV alphas was observed in a field of 3000 gauss parallel to the surface. From formulae given by Shockley[30]) an appreciable effect would not be expected below about 50000 gauss, in silicon. This characteristic is valuable when the detectors are used in conjunction with a magnetic spectrometer.

5. Characteristics of Gold-Germanium Detectors

5 1 REVERSE CURRENT

Owing to the lower band gap of germanium, it is necessary to cool detectors made with it to the region of liquid air temperatures in order to reduce the intrinsic conduction by thermal carriers. All the measurements described here were made at 77° K.

The reverse current is somewhat more variable with germanium than with silicon detectors, possibly because the cooling required may cause condensation of contaminants on the surface. Another factor is the apparently greater surface conductance of the surface layer on germanium compared with silicon. This was already known from the work of Brown[31]) and is confirmed by two effects we have observed. First, if the whole crystal face is exposed to alpha particles, then as well as the fast-rising pulses of good resolution there are also pulses of lower amplitude which rise in several microseconds. These pulses disappear if the uncoated germanium is masked by a collimator, and they are attributed to collection by the unbiased surface barrier which exists on the germanium, followed by diffusion through the surface layer to the gold electrode. Secondly, measurements with a guard-ring type of structure show that there is usually an appreciable surface conductance between separate gold electrodes. This surface conductivity influences the design of a multiple detector of germanium (§ 8.4).

It has been possible to apply 200 volts reverse bias to a gold-germanium detector without breakdown, but this is not easily reproducible and more often 50 volts is the limit.

5 2. BARRIER DEPTH

Owing to the greater stopping power of germanium compared with silicon, the same barrier depth will stop particles of about twice the energy. Also, due to its lower melting point, it is rather more easily zonerefined and lower uncompensated donor densities can be obtained. For these reasons it has been possible to achieve linearity of pulse height with proton energy to over 6 MeV for only 40 volts bias (fig. 13). For comparison, it would require a resistivity of 10000 ohm cm in silicon to give the same performance.

5 3 ENERGY RESOLUTION

The best resolution obtained at A.E.R.E. has been 20 keV for 5.4 MeV alphas. The resolution seems to be rather more consistently good with germanium detectors than with silicon, probably owing

[29]) T A Love and R B Murray, O R N L report CF 60-5-121 (1960)

[30]) W Shockley, Electrons and Holes in Semiconductors (Van Nostrand, 1950) p 214

[31]) W L Brown, contribution to "Semiconductor Surface Physics" ed R H Kingston (Penn Univ Press, 1957)

to the greater carrier mobility and lower likelihood of recombination effects.

5 4 PULSE RISE-TIME

The mobility of electrons and holes is much greater in germanium at 77°K than in silicon at room temperature, and is of the order 1.5×10^4 cm^2/volt sec, so that the anticipated pulse rise time is around 5×10^{-10} sec. It is again important to minimise the time constant due to the detector capacitance and its base resistance. It has been verified by P. Orman, at A.E.R.E., by means of a sampling oscilloscope, that the rise time of 5 MeV alpha pulses in a gold-germanium detector is less than 3×10^{-9} sec.

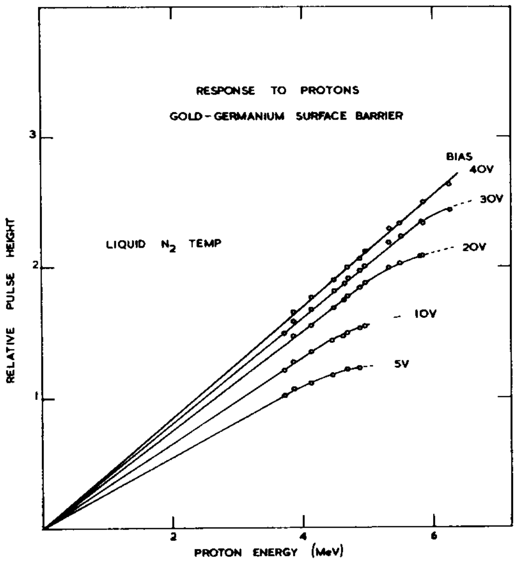

Fig 13 Response of germanium detector at 77° K to protons of various energies as a function of bias voltage

5 5 SENSITIVITY TO NEUTRONS

Known (n,p) reactions induced in germanium isotopes are[27]:

Ge^{70}(n,p) $Q = -0.82$ MeV.

Isotopic bundance = 20.5%, cross-section $\sigma = 0.014$ b at 1.8 MeV, 0.09 b at 14 MeV.

Ge^{72}(n,p) $Q = -3.2$ MeV.

Isotopic abundance = 27.4%, cross-section $\sigma = 0.06$ b. at 14 MeV.

Ge^{73}(n,p) $Q = -0.71$ MeV.

Isotopic abundance = 7.6%, cross-section $\sigma = 0.13$ b at 14 MeV.

Other isotopes present in the natural element are Ge^{74} (36.7%) and Ge^{76} (7.7%), but the (n,p) thresholds for these neutron-rich isotopes will be well over 5 MeV. In spite of the rather low thresholds for some of these reactions, it can be seen that the higher atomic number of germanium, 32 compared with 14 for silicon, is effective in inhibiting charged particle emission. Alpha particles will be even less favoured.

The result is that, as we have found qualitatively, germanium counters produce a lower background from a flux of fast neutrons compared with silicon counters of the same barrier depth, a fact which may sometimes be a considerable advantage. Another factor of three is gained because the depletion layer thickness required to stop protons of a given energy contains three times fewer nuclei in the case of germanium.

6. Comparison of Surface Barrier and Diffused Junction Counters

There have been some unjustified criticisms of the performance of surface barrier counters compared with diffused junction counters, and these should be dispelled.

Earlier techniques[7]) in which synthetic resin was employed to encapsulate the crystal before etching give unreliable results because of the difficulty of washing the etch away from small crevices at the silicon-resin boundary. Also, impurities from the resin may enter and contaminate the silicon at the edge of the barrier, leading to deterioration with time. We find that the present technique gives detectors with a very stable characteristic and long life.

A second criticism has been that the N-type silicon used for surface barriers is not available to the degree of purity possible for P-type silicon. This is true, as a rule, since the boron impurity which is the most difficult to remove is an acceptor. However, a small degree of compensation provides

N-type material of high resistivity which still retains a lifetime in the millisecond region. The supply of 3500 ohm cm N-type silicon seems as plentiful as 10000 ohm cm P-type, which, because of the ratio of 3 in carrier mobilities, is the equivalent in uncompensated carrier density and hence in barrier depth.

We must rule out the objection that less is known about conditions at the crystal surface compared with the interior, and hence that we should not make use of its properties. The detectors have shown themselves to perform extremely well, and the study of them is itself already providing information regarding the surface states of semiconductors.

Perhaps a valid criticism is that surface barrier units are less easily protected in a metal can than the diffused counters. The surface film is more easily damaged in handling, and the present construction methods are less suited to industrial production than to laboratory preparation. This, however, is probably not an insuperable obstacle if there are merits elsewhere.

Turning to the advantages of the surface barrier counter, we have at once a much simpler construction, easily carried out in most laboratories. There is no heating process and hence the lifetime is not degraded. The thickness of the gold film is not critical, and is easily made uniform, whereas the shallow diffusion must be carefully controlled to give a counter that is to be essentially windowless. The window of a surface barrier counter is always extremely thin. Because of the higher carrier lifetime the bulk leakage current is lower in surface barrier counters, especially for large area units. Surface barrier counters have been operated successfully with an area of 6 cm^2 on germanium and 3 cm^2 on silicon.

The simplicity of the evaporation method allows a variety of structures to be made with ease, and some of these are outlined in section 8.

Finally, we must not overlook possible combinations of both techniques. D. A. Bromley[32]) has pointed out that a surface barrier could be formed on a deep-diffused N-type layer on high-resistivity P-type silicon. This would produce a thin dE/dx counter integral with an energy counter. Such a unit would seem to have valuable possibilities.

7. Applications to Nuclear Physics

In the light of the performance of surface barrier detectors in a variety of experiments at Harwell, we may summarise the advantages and disadvantages which have become apparent.

The excellent energy resolution, down to 20 keV

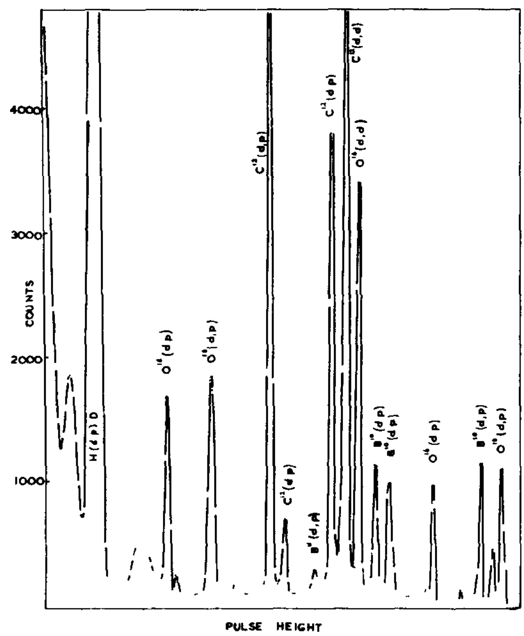

Fig 14 Spectrum resulting from the bombardment of a thin target containing carbon, boron and oxygen with deuterons of 5 0 MeV

even with conventional types of amplifier, enables them to be used in place of magnet spectrometers for the investigation of charged particle reactions and scattering processes in many cases, (fig. 14). The whole spectrum is displayed by pulse height analysis, instead of by slow scanning by variation of the magnetic field, so that effects due to changes in the target under bombardment are less serious. The linearity of response makes calibration simple.

The low cost of the detectors, if prepared by a laboratory technique such as that described, and the simple requirements for voltage supplies enable

[32]) D A Bromley, Proc of N A S Conference, Asheville (Sept 1960) (to be published)

numbers of them to be used in laboratories without extensive facilities.

Compactness of size of the counters enables them to be mounted easily so as to rotate about a target, and although they may be relatively small, they can be brought close to a target in order to subtend an appreciable solid angle. The detector can be made in a slit shape to minimise the energy spread due to the spread in azimuthal angle. Detectors can be mounted at angles very close to 180°, a region which has not been accessible for magnetic analysis, so that high resolution data is usually lacking. Often stripping reactions show interesting behaviour at these large angles. Bromley[32]) has described an annular detector designed so that the particle beam can be directed through it, to give symmetrical detection at 180°. Such an arrangement brings great simplification to the analysis of angular correlation experiments.

A number of detectors can be used simultaneously for the measurements of an angular distribution of charged particles, under identical beam and target conditions. The problem of handling the amount and precision of data which can then be obtained is considerable, but multi-track magnetic tape equipment enables simultaneous storage of information to give counter angle and pulse height.

Detectors can be employed singly or as a multiple system in conjunction with a magnetic spectrometer, so that simultaneous high resolution in momentum and energy is then possible. Their low sensitivity to magnetic fields is a significant advantage over scintillation counters.

The excellent signal to noise ratio obtainable allows the detection of particles of very low energy. The detectors are essentially windowless.

It is possible to control the thickness of the sensitive region, by means of the applied bias, and thus discriminate between particles of different range. This is easily performed by remote control, and does not affect the energy resolution as does the use of stopping foils. The fact that the sensitive thickness can be suited to the particles investigated enables the response to background gammas and electrons to be minimised.

The low response to neutrons (below about 5 MeV) due to the absence of hydrogenous material is very valuable, for instance in polarisation experiments. Fast neutrons can cause a considerable background, however, though again this can be minimised by suitable choice of barrier depth. Germanium detectors have some advantages here.

The fast rise time is important in coincidence measurements, but it is then difficult to make use of the good detector resolution owing to the small size of the detector output. Fast amplifiers have too poor a signal to noise ratio, but it is possible to employ simultaneous slow amplification as suggested in section 3.

Most use of the counters has been made for the detection of low energy particles, of range less than the depletion layer thickness, but the detectors may not be without applications to high energy physics. Here they behave as dE/dx counters, in which the energy loss for all minimum ionising particles is about 400 keV/mm (in silicon). The pulses are therefore of small size, and require considerable amplification, which leads to difficulties due to electrical pick-up and radiation background near large accelerators. There is a spread in pulse height amounting to 20–30%[33]) owing to the statistical fluctuations in energy loss, the Landau effect. It would seem that bulk conductivity counters hold more promise for this field, in the future.

Similar considerations apply to the detection of fast electrons for which the resolution is good up to a few hundred kilovolts[15]). At higher energies the output becomes essentially independent of energy, due to the broad minimum in the rate of energy loss. In tracer experiments and activity measurements some features of semiconductor counters, such as their small size, will probably be advantageous.

Further applications are made possible by elaborations of the detector design, and some of these will be described in the next section. It is already clear that in the design of any experiment in nuclear physics the possible advantages of semiconductor detectors, of the various types, must be considered.

[33]) G L Miller, B M Foreman, L C L Yuan and P F. Donovan, I R E Trans NS-8 (1961) 73

8. Special Configurations

The design of the surface barrier detector is easily modified to meet special requirements, and its versatility is illustrated by some variations which have been studied at A.E.R.E.

8.1 FISSION DETECTOR

If a thin film of fissile material, such as uranium oxide, is evaporated on to the gold layer, fission fragments emitted from it can be detected. Such a structure was first described by McKenzie and Bromley[34]). If two such counters are spaced a short distance apart, the coincidences corresponding to collection of both fragments can be recorded and the pulse heights added in such a way as to yield the mass spectrum. The use of solid counters eliminates the need for the self-supporting thin film of fissile material required for ionization chambers. Experiments with such an arrangement of surface barrier detectors have been carried out at A.E.R.E. by Melkonian[35]) and Gooding[36]). The performance was as good as the best published results by other means, and it was possible to study the influence of neutron energy on the mass spectrum. Some preliminary measurements on ternary fission were made with array of three detectors, and the fission cross-section of uranium was studied with a square array of counters. Their compactness and the small amount of scattering material present is of particular advantage, while the high speed allows shorter resolving times and less pile-up from alpha-activity.

During this work it was found that the ratio of pulse heights corresponding to the peaks of the fission energy spectrum was lower by a few percent than the value obtained by time-of-flight measurements. It has been shown that this is not due to a detector "window", by measurements with a detector at 90° and then 45° to the source. It seems most likely to be due to recombination effects enhanced by the very high density of ionization caused by fission fragments. The work of Miller, Brown and Donovan[5]) has shown the existence of "ambipolar" effects by which the rise-time of pulses from fission fragments is extended to about 4×10^{-8} sec. Similar nonlinear behaviour has since been reported by Joyner *et al.*[37]).

8.2 FAST NEUTRON DETECTORS

Several types of fast neutron detector are under investigation at A.E.R.E., with special regard to their use for neutron spectrum measurements inside low powers reactors or other integral systems.

One type has been described by Love and Murray at O.R.N.L.[29,38]) and makes use of the $Li^6(n,\alpha)H^3$ reaction. Two close and parallel surface barrier counters are exposed to a thin film of Li^6F in an evacuated chamber. In the units constructed at A.E.R.E. it has proved simple to evaporate Li^6F on to the gold surface of one of the detectors, taking care to mask the counter during the process so that the fluoride does not extend beyond the area of the gold. The alpha particle and triton from the neutron-induced reaction are counted in coincidence, and addition of the pulses gives an output proportional to the neutron energy added to the reaction Q, which is 4.7 MeV. Resolution of 70 keV has been obtained for this summed pulse for thermal neutrons. At higher energies this resolution improves, but the reaction cross-section becomes low, and the efficiency of the detector falls to $\approx 10^{-6}$ at 3 MeV. With such a low efficiency there is danger of radiation damage occurring before the experiment is complete. At neutron energies above about 8 MeV the background due to $Si^{28}(n,p)$ and (n,α) reactions becomes serious, despite the coincidence condition, for it is possible for a charged particle produced in one crystal to cross to the other.

In collaboration with Dr. S. B. Wright at A.E.R.E., studies are now being made of a similar unit in which the Li^6F is replaced by He^3 gas. The reaction then involved is $He^3(n,p)H^3$ which has a Q of only 770 keV and the added advantage of a larger cross-section in the region of a few MeV neutron energy. The pressure of He^3 can be adjusted to suit different conditions, a higher pressure being allowed at higher energies to give increased efficiency without too much energy loss taking

[34]) J M McKenzie and D A Bromley, Phys Rev Letters 2 (1959) 303

[35]) E Melkonian, A E R E Report R-3524 (1960)

[36]) T J Gooding, Proc Phys Soc London (to be published)

[37]) W T Joyner, H W Schmitt, J H Neiler and R J Silva, I R E Trans NS-8 (1961) 54

[38]) T A Love and R B Murray, I R E Trans NS-8 (1961) 91

place in the gas. A pressure of 1–5 atm of He^3 is to be used, but the volume of the detector can be quite small. Owing to the fast pulses, pile-up from possible tritium contamination of the He^3 is less important than in an ion chamber. There is, of course, the possibility of background due to random coincidences fron recoiling He^3 ions following elastic collisions, but this is minimised by a short coincidence resolving time.

The third type of neutron detector being investigated makes use of recoil protons from a thin hydrogenous radiator. The cross-section for this process remains high in the MeV region and the counter does not suffer from over-sensitivity to thermal neutrons, which is a disadvantage of the other types. At energies above 5 MeV, however, difficulties arise from the Si^{28}(n,p) and (n,α) background. There are two forms of recoil detector in one, recoils at all angles to the incident neutron direction are detected, giving a uniform spectrum up to the neutron energy, while in the second the protons are collimated with respect to a neutron beam, giving a single peak. In the isotropic flux of a reactor only the first method is possible.

Measurements have been made with both types of recoil counter exposed to monoenergetic neutrons produced from the 5 MeV Harwell Van de Graaff generator by protons on a thin tritium target. A radiator of 250 μg/cm^2 glyceryl tristearate was evaporated on to a gold disc in front of a silicon surface barrier, and a collimator consisting of four spaced gold discs drilled with many holes could be interposed. The whole unit was in an evacuated tube. With the collimator in place the yield of protons from the radiator was reduced with respect to a background of protons due to adsorbed hydrogen and water on the surfaces exposed to the detector. It would be difficult to detect neutrons below 1 MeV in the presence of a flux at higher energies, due to this background. With the collimator removed good spectra for recoil protons were obtained (see fig. 15) over a range of energies down to 400 keV neutron energy, but below this energy the thickness of radiator which can be tolerated must be reduced. In both cases the pile-up of electron pulses due to the gamma-ray flux contributed to the spectrum in the region corresponding to protons below 200 keV. The background was

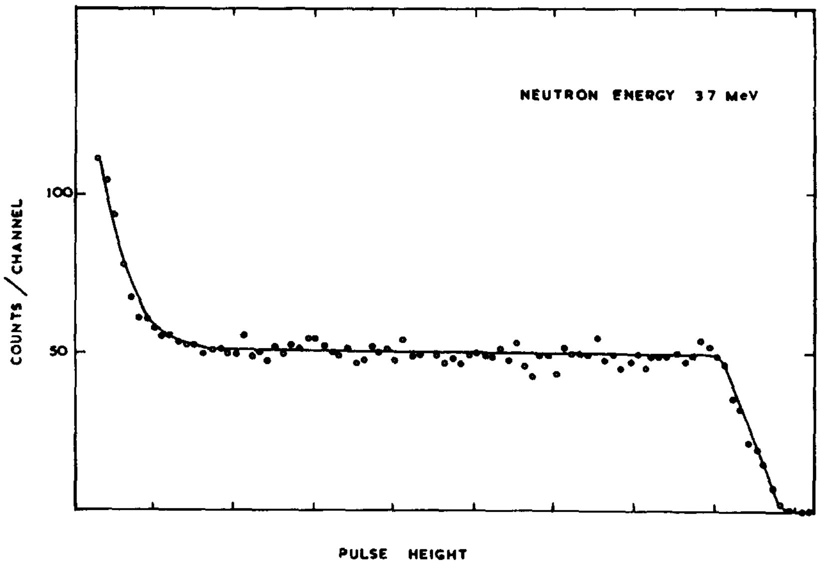

Fig 15 Spectrum observed in a proton-recoil detector with a radiator of 800 μg/cm^2 glyceryl tristearate exposed to monoenergetic neutrons of 3 7 MeV

measured by reversing the radiator disc and recording the spectrum for the same neutron flux.

A simpler and more accurate arrangement is shown in fig. 16. Here two semicircular detectors are prepared by evaporation through a mask on to a single disc of silicon, and contacts are attached in the

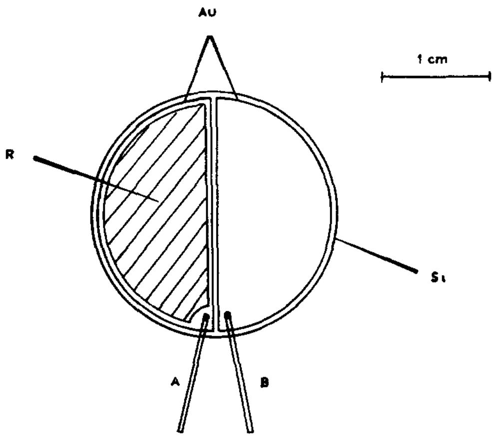

Fig 16 Suggested form of proton-recoil detector for simultaneous measurement of neutron flux and background

Si = silicon disc
Au = two semicircular gold-coated areas
R = hydrogenous radiator evaporated on gold layer
A, B = leads to contacts

usual way. It can be verified at this stage that both counters yield the same spectrum due to electron pulse pile-up and recoil protons from adjacent surfaces under a combined neutron and gamma-ray flux. Then the radiator of glyceryl tristearate is evaporated on to the gold layer of one semicircular counter. The difference in the spectra then obtained is due to recoil protons from the radiator.

The neutron spectrum is obtained from the proton recoil distribution by differentiation, and this places much greater demands upon the accuracy of the initial spectrum. Making allowances for this for typical spectra, Dr. Ferguson finds that the equivalent efficiency is still greater for the proton recoil detector than for those making use of the He^3 or Li^6 reactions. Further work is in progress, and it is hoped to publish the results of this study at a later date.

8 3 THIN dE/dx DETECTOR

It is possible to make a very thin transmission detector in which a particle loses in general only a small fraction of its energy. The most important application of this is in the discrimination between different types of particle of the same energy. This is performed with a thin counter followed by a deep barrier counter so giving simultaneous measurement of dE/dx and energy. Another possibility with thicker wafers is to build up a stack of counters in series so that linear response can be obtained up to energies no longer limited by the depth of a single depletion layer.

At A.E.R.E. slices 0.012 cm thick of 300 ohm cm silicon were etched and coated with gold on both faces. Contact to the gold was made by gold-silver strip cemented in the usual way with silver paste. Application of a sufficiently high bias voltage then produces a field extending throughout the whole volume. This condition was tested by irradiating with 5.5 MeV alphas first one side of the detector and then the other. The particle range in silicon is only 20% of the wafer thickness so that complete collection of the carriers produced proves the full penetration of the field. This was achieved at 30 volts bias. More recently thinner slices of 0.005 cm thickness were obtained of 2000 ohm cm resistivity, and in these complete collection is achieved at under 3 volts bias. These detectors all showed excessive leakage current and noise, however, and this may be due to the proximity of the back contact which is able to inject carriers into the field region. Studies are being made of a variety of contact methods in order to overcome this effect.

Mention must be made of the excellent results obtained with thin diffused junction counters by H. Wegner[39]) at Los Alamos and which have fully demonstrated the value of such detectors.

8 4 MULTIPLE DETECTOR

If gold is evaporated on to an etched silicon crystal through a comb of fine wires, it is possible to produce a multiple detector in a single process. Separate contacts are made at the ends of the strips in the usual way. Such detectors made at A.E.R.E. with a separation of only 0.1 mm have

[39]) H E Wegner, I R E Trans NS-8 (1961) 103

been operated without interaction when used in the normal counting circuit. However, this is not usually possible with germanium, probably owing to surface conductance (see section 5) and it is preferable to construct the device from separate insulated bars[40,41]).

The problem arises of how to handle the output from such an arrangement. Parkinson[40]) has used separate transistor amplifiers for each detector, while Bilaniuk[41]) has successfully applied a method in which a delay line is formed by the capacitance of the detectors linked by inductances. The difference in time of the pulses arriving at the two ends of the line gives the location of the counter in which they originated.

Such a unit extended to at least 100 counters would supplement the use of nuclear emulsions in a broad-range magnetic spectrometer. The multi-track magnetic tape storage under development at A.E.R.E. could be adapted to record the counter location together with a digital pulse height indication.

[40]) W C. Parkinson and M O Bilaniuk (to be published).
[41]) O M Bilaniuk, A K Hamann and B B Marsh, Univ of Rochester Report No AT (30-1)-875 (May, 1960)

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