INTERSTRIP SURFACE EFFECTS IN OXIDE PASSIVATED ION-IMPLANTED SILICON STRIP DETECTORS

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An investigation is reported into charge sharing effects for highly ionising particles penetrating the interstrip gap for ion-implanted silicon strip detectors. It is found that under certain conditions anomalous polarity pulses are induced on adjacent strips. This effect is analysed with a model that takes account of the surface charge trapped on the Si–SiO₂ interface between the adjacent strips.

1. Introduction

Silicon strip detectors have, for a number of years, been used as active targets in high energy physics [1] where the excellent spatial resolution attainable by modern semiconductor fabrication techniques makes them particularly suitable for accurate vertex determination and flight path direction measurements.

In contrast to the minimum ionising particles detected in high energy applications, heavy ions of energy \( \approx 10 \text{ MeV/A} \) will deposit large amounts of energy within the detector. The resulting higher ionisation density will generate intense internal fields which may give rise to charge sharing effects from the region between strips, although no such problems have been reported in previous work using minimum ionising particles [2]. This paper reports some results of an investigation to specifically determine charge sharing characteristics for highly ionising particles.

2. Experimental procedure

The detector used for this investigation was an oxide passivated, ion-implanted, silicon strip detector supplied by Enertec (Strasbourg). It consisted of 25 aluminium strips of 1.8 mm width and 200 \( \mu \text{m} \) separation evaporated on a 42 mm \( \times \) 50 mm slice of 5 kΩ cm resistivity, n-type silicon and was manufactured using the planar process [3]. A schematic cross section of the construction between two adjacent strips is shown in fig. 1.

The performance of the detector was evaluated using the IBIS (intense bunched ion source) accelerator at AERE, Harwell. The machine was used in its microbeam mode [4] with 3 MeV alpha particles. Under normal operating conditions it can produce a beam of cross sectional dimensions better than 10 \( \mu \text{m} \times 10 \mu \text{m} \) which is ideal for probing this interstrip structure. However, due to the extremely small beam current required to allow exposure directly onto the detector surface (\( \approx 10^{-16} \text{ A} \)) the beam profile did not approach this value. From experimental results it was concluded that the beam had an intense spot with one sharply defined edge of \( \approx 5 \mu \text{m} \) but an extended tail on its opposite edge. This tail was wider than the interstrip gap but narrower than the individual strip width. The detector was mounted on a mechanical scanning mount allowing it to be positioned relative to the microbeam with an accuracy of 1 \( \mu \text{m} \).

For this investigation four adjacent strips were biased to their full depletion voltage of \( \approx 40 \text{ V} \) with reference to the earthed rear connection. The microbeam was then scanned across the front surface of the detector, between the two centre strips, sharp edge first, by moving the detector mount assembly in steps of 25 \( \mu \text{m} \). Energy spectra from singles events from each strip were recorded for each position, along with the spectra of any pulses which occurred in coincidence in both strips.

3. Results

Fig. 2a shows a typical energy spectrum of the alpha particles when the beam illuminated only one strip, i.e.,
Fig. 1. Cross-sectional details of detector between two adjacent strips. The numbered arrows refer to fig. 3.

Fig. 2. Typical energy spectrum of 3 MeV alpha particles incident on (a) the strip only and (b) the strip and interstrip gap.
Fig. 3. Energy spectrum from one strip as the beam is moved towards it, sharp edge first, from the centre of the interstrip gap. The approximate location of the edge for each position is shown in fig. 1.

height spectrum from one strip. On further investigation it was found that these anomalous-polarity pulses always occurred in coincidence with a normal-polarity pulse in the adjacent strip. Furthermore, it was observed that these coincident normal-polarity pulses were smaller than a full energy pulse and contributed to the lower energy satellite peak in fig. 2b. In order to explain this lower peak consider the spectrum taken at the centre of the interstrip gap (i.e. fig. 3b) which exhibits a strong lower energy peak. It is the pulses contributing to this peak which are in coincidence with the anomalous-polarity pulses from the adjacent strip. This leads to the conclusion that these coincident pulses of opposite polarity originate from the region between the strips and more specifically from the volume below the central region where there is no p⁺ implantation.

When one looks at a two-dimensional plot of the anomalous-polarity pulse amplitude signal from one strip against the coincident normal-polarity pulse amplitude from its neighbour as shown in fig. 5, it can be seen that the reduction below the full-energy charge for a normal-polarity pulse is about equal to the charge of the coincident anomalous-polarity pulse. This is not then charge sharing but could be due to the imposition of equal anomalous-polarity charges on both strips simultaneously, added to the normal collected charge. Prompted by these results a number of other simple

Fig. 4. A typical anomalous negative polarity pulse height spectrum.

Fig. 5. A two-dimensional plot of coincident normal-polarity (x-axis) vs anomalous-polarity (y-axis) pulse heights. This was taken using an ²⁴¹Am alpha source rather than the IBIS beam, so is not expected to correspond in all details with figs. 2–4.
tests were performed on the detector to try and shed more light on the mechanism producing these coincident pulses.

It was found that they disappeared when the bias was removed from one of the central strips and that the number of consecutive negative pulses from one strip, before a negative pulse from the other strip occurred, did not follow any identifiable pattern. To check whether these pulses were due to a difference in the voltage applied to the central strips the voltage on one was lowered by 10 V (a quarter of the full depletion voltage) to try and enhance the rate of negative pulses in either strip. This had no effect. It was also noticed that there was a threshold bias voltage below which the negative pulses disappeared. This may indicate that the growth of the depletion layers from the p+ regions could be an important factor in their production. Using a fast-timing coincidence circuit the time difference between the coincident positive and negative pulses was found to be less than resolution of the setup (~ 2–3 ns).

The anomalous-polarity effect was also present when the detector was illuminated with a 252Cf source whose fission fragments have a range comparable to that of the alpha particles used, but which deposit ~ 90 MeV.

When the detector was illuminated with electrons from a 207Bi source no anomalous-polarity pulses were observed. These electrons have a range of approximately 1 mm in Si and the full energy peak observed in the spectra was presumably due to the increased likelihood of large angle scattering within the detector. This lack of anomalous pulses seems to agree with the recent tests at CERN [2] where no anomalous effects were seen or reported when the detector was being used as a transmission detector. With 5.5 MeV alpha particles from an 241Am source illuminating the rear of the detector the anomalous effect was also absent suggesting that it arises from the front surface only. There was, however, a normal–normal coincidence rate of < 1% of the individual strip singles rate which was attributed to charge sharing following the diffusion of the hole cloud as it travelled through the detector towards the strips.

This absence of negative pulses with transmitted ionising particles may be due to their ionisation density in the volume between the adjacent p+ regions being much smaller than that of the highly ionising particles stopping near the front surface.

4. Analysis of observations

The behaviour of p–n junctions of this type under charged-particle irradiation is a topic of current interest in electron device design and is receiving some attention from a number of authors [6]. In his paper on surface barrier detectors Kraner [5] identified similar anomalous-polarity pulses with charge injection from the aluminium strip contact due to the perturbation of the local field by the ionising particle. A crude calculation shows that the maximum instantaneous concentration of electron–hole pairs resulting from a 5.5 MeV alpha particle is of the same order as the fixed space charge in the p+ region of full depletion (~ 5 × 10^{18} cm^{-3}) so that the field would indeed be perturbed. However, there is no known mechanism to instantaneously separate these associated concentrations of holes and electrons in order to generate the perturbing field necessary to cause charge injection. An alternative explanation is required. The computer simulations of Hsieh et al. [6] predict that an anomalous charge collection funnelling effect will be of increasing importance with higher resistivity substrate and be a strong function of junction bias. However, we have developed a rather different model from the viewpoint of charge induction rather than charge injection which seems to explain many of the observed effects.

5. Proposed model

Between the strips is a highly insulating surface layer of SiO_{2}, and the depleted junction extends underneath this layer. Leakage (and also ionisation) causes current to flow across the junction, and a steady flow of holes arrives at the strip side, to be collected by the strips.
Because the interstrip gap is highly insulating, there can be no net flow of current to this area, so a positive charge must be built up at the surface of the insulating layer, sufficient (in the equilibrium state) to repel further holes arriving in the interstrip gap. This charge is distributed symmetrically about the midpoint of the gap (point X in fig. 6). The assumption is that this positive charge is sufficient to cause a local field reversal so that the potential, measured across the junction from X, falls locally to a minimum value between the strips, close below the surface, before the normal potential rise across the junction then commences. Between the strips there will be a saddle point in the potential map, as sketched in fig. 6.

6. Hole sharing

One effect of the hump in the potential between the strips is that when hole-electron pairs are produced by an ionising particle in the interstrip gap, the holes are driven towards the nearest strip by the field gradient, depending on which side of the saddle they were created. Therefore, there will be a strong tendency for the holes to be collected on one or other of the strips, rather than divided between them. Only from a very restricted band of positions, right on the interstrip centre, will holes from a track be divided between the strips, as suggested in fig. 7a. A sharp division of charge between strips is observed experimentally. This would give ideal characteristics for the detector if all the electrons from all tracks were to travel to the anode for collection. However, this does not happen as we will see.

7. Electron trapping

When a particle track occurs near the centre of the interstrip gap, the electrons will be pulled towards the potential hump at X, rather than towards the anode, if they were created on the reversed-field side of the potential saddle point. This will be particularly likely for electrons in the tracks of short range highly ionising particles such as 3 MeV alphas (range approximately 10 μm). For more penetrating particles, or for tracks which occur near one strip or the other, some of the electrons will be pulled towards the anode. But the model implies that over a finite area around X, all the electrons created by an alpha track lie in this anomalous reverse-field region and all move to X, as shown in fig. 7b. There is no electrode here to conduct them away; if they remain trapped at this point for a time long compared with the pulse-shaping times of the electronics, or if they immediately recombine at this point with a trapped positive charge, the effect of the net signals at the detector electrodes will be exactly the same, a charge deficit will arise in the signal which depends on the charge which has been induced on the corresponding electrode by these electrons. Consider first a “normal” full-energy signal produced by a track passing through, or close to the edge of a strip. The track produces a charge +q of holes −q of electrons. All the holes are collected on a strip and all the electrons travel away from the influence of the strip to the anode, resulting in a net charge q flowing between the strip and the anode and zero charge on adjacent strips. There may be a transient pulse electrostatically induced on the adjacent strip but its net charge will integrate to zero.

However, if the track is between the strips, and the electrons become trapped at X, the result is very different. The charge −q carried by the electrons is electrostatically coupled entirely to the two strips, and hardly at all to the anode, because of the geometry (the anode is much further away). The induced charge flow from each strip is −½q if we suppose that the charge has ended up symmetrically between the strips at X (figs. 7c and d). As all the holes will usually be collected by one strip, the resulting net charge flow from that strip is +q −½q, of +½q, i.e. a pulse or normal polarity but halved amplitude. As there is no hole collection on the adjacent strip, the net charge flow from it is −½q, i.e. an anomalous-polarity pulse of half amplitude. Many such signal pairs were observed in this experiment.
It is worth emphasising that the anomalous pulse is due entirely to induced charge: no electrons or holes are collected by that strip, but the incompletely collected ionisation from the particle track results in a charge \(-q\) ending up near the strip and inducing a charge \(-\frac{1}{2}q\) to flow out from it and into the external circuit (see fig. 7e, regions C and F).

It appears from the measurements that trapping of all electrons occurs for tracks over a significant fraction of the interstrip gap, near its centre (i.e. regions CDEF in fig. 7). Outside these regions the nearer to a strip a track occurs the smaller is the fraction of the electrons that are trapped. The trapped charge \(-\Delta q\) then becomes progressively smaller than \(q\). Assuming still that all the trapped electrons migrate to the midpoint \(X\), the net signal on the nearer strip would be \(q - \frac{1}{2}\Delta q\), and on the further strip \(-\frac{1}{2}\Delta q\). This is exactly the correlation that has been observed experimentally and corresponds to regions B and G of fig. 7e. For tracks near the edge of the strip, and for all tracks that pass through the strip, complete collection is expected, and \(\Delta q = 0\). This corresponds to regions A and H of fig. 7e.

A correlation diagram (fig. 8) has been developed from fig. 7e and shows how the simultaneous pulses from adjacent strips correlate for tracks in various regions of the interstrip gap. This shows remarkable agreement with the observed correlation reported in this paper.

To summarise, the following effects are well explained by the model:

1. The sharp splitting of signals between the strips.
2. The peaks at \(\frac{1}{2}\) and \(-\frac{1}{2}\) of normal pulse height.
3. The fact that simultaneous normal-polarity pulses are never seen: one is always reversed.
4. The detailed form of the correlation function between simultaneous pulses from adjacent strips.

In addition it seems likely that some of the "peculiar effects" of reversed-polarity pulses described in ref. [5] might be caused by a similar charge-trapping mechanism, though many details of that measurement differ from the present one, and a weaker effect of the same variety would be anticipated.

8. Conclusion

The existence of interstrip surface effects in oxide passivated ion-implanted silicon strip detectors has been identified. They seem to be important only for highly ionising nontransmitting particles and arise from a volume beneath the \(\text{SiO}_2\) passivation layer between the main \(p^+\) implantation regions under each strip. The effect gives rise to anomalous-polarity pulses and anomalous peaks in the energy spectrum of the ionising particle. They have been observed in a number of different strip detectors of different design and from different manufacturers but all of which have been produced by the planar technique incorporating ion implantation. It is clear from these results that although strip detectors have a number of advantages over more conventional detectors for a range of applications, care must be taken when incorporating them into certain experiments, especially those involving fission fragments and other highly ionising radiation.

References

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