The charge collection response of semi insulating GaAs p-i-n detectors to alpha particles has been measured and compared to the results of a simple charge carrier drift model. The model uses an electric field distribution which had been measured using a surface probing technique. By comparing the simulated data with the experimentally measured charge collection efficiency mean drift lifetimes have been deduced for the charge carriers. The model has also been used to simulate the charge collection response of GaAs detectors to gamma rays and to minimum ionising particles.

Abstract

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I. INTRODUCTION

Particles detectors fabricated from semi insulating (SI) GaAs have been known to suffer from low charge collection efficiencies. This has been attributed to the presence of deep level traps in the material which results in the charge carriers having short drift lifetimes. Such charge trapping effects tend to increasingly influence the response of thicker (eg. >100 μm thick) detectors. The charge collection response of SI GaAs devices is further complicated by the presence of a non-uniform electric field, which consists of a high field ‘active’ region which penetrates from the blocking contact through the thickness of the detector with increasing applied bias. A quantitative understanding of this field distribution is necessary to explain the charge collection properties of GaAs detectors, due to the field dependent drift velocities of the charge carriers.

Direct measurements of the electric field distribution in SI GaAs detectors have recently been published [1] in which two independent methods were used; the first by probing the potential directly across a cleaved surface of the detector and the second using a real time imaging method. The quantitative electric field data obtained by the first method is in agreement with the data observed from the imaging technique. The measured non-uniformity of the electric field in GaAs detectors has been modelled by several groups (eg. [2,3]) in terms of the ionisation of deep levels such as EL2. A recently published model by McGregor et al. [4] which includes a field-enhanced capture rate produces field distributions which are in agreement with our data reported in reference [1].

The measured form of the field distribution can be approximated to a step function representing the high field region which penetrates through the bulk with increasing applied bias. The width of the active region increases as an approximately linear function of applied bias. In p-i-n devices of thickness 450 μm we have measured the magnitude of the field in the active region to be typically between 1.0 V/μm and 1.5 V/μm with a penetration rate through the detector of between 0.7 μm/V and 1.0 μm/V. In this paper we report results from the alpha irradiation of a p-i-n detector for which the electric field distribution has been measured in an identical device produced as part of the same fabrication batch. With a quantitative understanding of the field distribution it is then possible to compare the measured charge collection data with a model of the detector’s charge collection properties.

II. EXPERIMENTAL METHOD

GaAs devices were made in the form of circular pad detectors at Sheffield University at the EPSRC III-V fabrication facility. The p-i-n detectors were fabricated from SI GaAs with a p-type blocking contact made from diffused zinc and an ohmic contact from diffused germanium. A full description of the detector contacts is given in reference [5]. The pad detectors were 3 mm in diameter and were fixed to transmission mounts to allow irradiation of the front or rear contact. An alpha particle source of 241Am (Eα=5.48 MeV) was used to irradiate the detectors under vacuum with negative bias applied to the front contact. Charge was collected from the front contact by a Tenelec TC170 charge sensitive preamplifier, which was connected to a Tenelec TC243 shaping amplifier.

Alpha particles with an energy of 5.48 MeV penetrate approximately 20 μm into GaAs before being stopped and so deposit the majority of their energy at this distance from the detector surface. The deposited energy generates electron-hole pairs which are swept apart by the electric field. The electrons drift towards the rear contact and the holes drift towards the front contact with a velocity which is dependent on the electric field strength. If the high field region does not extend completely through the detector, a dead region will exist under the rear contact corresponding to an area of low field. Any charge carriers which are generated or enter this dead region will have a velocity close to zero and will only drift a minimal distance.

The effect of charge trapping in SI GaAs detectors is to reduce the drift lengths of the charge carriers which in turn reduces the charge induced at the detector contacts [6]. The total charge collected from a detector contact (Qcoll) can be conveniently expressed in terms of a charge collection efficiency (CCE in percent) as a ratio of the charge initially released (Q0) such that

\[
CCE = \frac{Q_{coll}}{Q_0} \times 100
\]
Because of the relatively short penetration distance of the alpha particles compared to the detector thickness, the charge collected from alpha particles incident on the front face of a 450 µm thick detector is due almost entirely to the electrons drifting towards the rear contact. Similarly, providing that the high field region extends to the rear contact, the charge collected from alpha particles incident on the rear face is effectively due to the holes drifting towards the front contact. Therefore for a relatively thick GaAs detector, comparison of CCE data for alpha particles incident on the front and rear surfaces allows the contributions to the induced charge from the electron and hole currents to be studied separately.

For alpha particles incident on the front face the data show a rise in CCE to a value of approximately 15% at -100 V, followed by a gradual increase to approximately 25% at -1000 V. The energy resolution of the alpha peaks was constant at biases below -700 V with a value of 80 ± 20 keV FWHM. This includes the measured electronic noise of 9.0 ± 0.5 keV. At bias values of -700 V and greater the electronic noise increased, reaching 31 keV at -960 V.

Pulses from alpha particles incident on the rear surface of the detector were not observed until the bias reached -600 V. Between -600 V and -700 V the measured CCE rose to approximately 60% and then continued to increase slowly reaching 66% at -960 V.

The measured CCE data allows some conclusions to be made about the passage of electrons and holes through the detector:

1. For alpha particles incident on the front face, the CCE has risen rapidly with only -100 V applied to the detector. This corresponds to the edge of the high field region extending into the bulk significantly beyond the penetration depth of the alpha particles. All the electron-hole pairs are produced within the high field region, with the electrons drifting less than 100 µm towards the rear contact before entering the low field region.

III. RESULTS FROM ALPHA IRRADIATION

The charge collection efficiency data for alpha particle irradiation of a Sheffield GaAs p-i-n detector are shown in figure 1. The detector was manufactured from a wafer of LEC ingot annealed SI GaAs supplied by Nippon Mining, with a thickness of 450 ± 20 µm and a resistivity of >1.0×10^7 Ω cm. The bias was applied up to -1000 V without breakdown occurring. The leakage current was constant at bias values up to -700 V, with a current density (at a temperature of 29°C) of approximately 2.0 µA/cm².

For alpha particles incident on the front face the data show a rise in CCE to a value of approximately 15% at -100 V, followed by a gradual increase to approximately 25% at -1000 V. The energy resolution of the alpha peaks was constant at biases below -700 V with a value of 80 ± 20 keV FWHM. This includes the measured electronic noise of 9.0 ± 0.5 keV. At bias values of -700 V and greater the electronic noise increased, reaching 31 keV at -960 V.

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Figure 1: CCE data measured for alpha particle incident on a 450 µm thick GaAs p-i-n detector

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II. As the bias is increased beyond -100 V the CCE for alpha particles incident on the front face does not significantly increase, suggesting that the mean drift length of the electrons is significantly less than the width of the high field region for biases greater than -100 V.

III. The larger CCE values observed for alpha particles incident on the rear contact indicate a longer mean drift length for holes compared to electrons.

IV. DETECTOR MODELLING

A. Alpha radiation

The detector charge collection properties were simulated by a simple drift model of the charge carriers. As input parameters the program required the electric field distribution as a function of applied bias, the electron and hole drift velocities ($v_e$ and $v_h$) as a function of electric field, and the mean electron and hole drift lifetimes ($\tau_e$ and $\tau_h$). The velocity-field functions [7] which were used are shown in figure 2. The electron velocity reaches a maximum value at a field strength of approximately 0.3 V/µm, falling to a saturated velocity of approximately $1.0 \times 10^7$ cm/s at a field strength of 3 V/µm. The hole velocity rises continually with increasing field, reaching a constant value of approximately $0.4 \times 10^7$ cm/s at a field strength of 3 V/µm.

The energy deposition of alpha particles passing through the detector is modelled using the specific energy loss function for alpha particles in GaAs. At each point along the particle’s track the number of electrons and holes which are

Figure 4: Simulated CCE data for 120 keV gamma rays incident on a 450 µm thick GaAs detector at bias voltages of 300V and 500V. The electron and hole mean lifetimes are 0.5 ns and 20 ns respectively. The upper figures show the calculated CCE distribution (in percent) as a function of depth through the detector (in microns, with the front contact at $x=0$). The lower figures show the resulting pulse height spectra.
created is calculated using a value of 4.3 eV per electron-hole pair. Each electron and hole is assigned a drift lifetime using a Monte Carlo method such that the charge carrier lifetimes are assumed to follow an exponential function, with mean drift lifetimes for the electrons and holes referred to as $\tau_e$ and $\tau_h$ respectively. Each electron and hole is tracked individually towards the detector contacts, travelling a distance $d_e$, $d_h$ calculated by the product of the charge carrier velocity and lifetime. The charge ($q_i$) induced at the front detector contact for each electron hole pair is calculated in terms of the detector width ($w$) as

$$q_i = \left[\frac{d_e}{w} + \frac{d_h}{w}\right]e$$

and the total collected charge per event is the sum of $q_i$ over the number of electron-hole pairs $N$

$$Q_{coll} = \sum_{i=1,N} q_i$$

Simulating over many events produces a pulse height spectrum for a particular bias voltage.

Figure 3 shows results from the simulation of 5.48 MeV alpha particles incident onto the front and rear surfaces of a 450 µm thick detector. The electric field distribution was taken from previously measured data as a step function of magnitude 1.0 V/µm with a penetration of 0.7 µm/V. For simulation of front incident alpha particles (figure 3a) electron mean lifetimes were chosen in the range of 0.1 ns to 10 ns. In this configuration any variation in the hole mean lifetime has a negligible effect on the CCE value and a fixed value of 10 ns was used. Similarly for irradiation of the rear contact (figure 3b) the electron mean lifetime was fixed at 10 ns and the hole mean lifetime varied over the range of 1 ns to 100 ns.

Also shown in figure 3 are the experimentally measured data. It can be seen that the experimental data provides a
good fit to the simulated values with the electron and hole mean lifetimes fixed at $\tau_e = 0.5$ ns and $\tau_h = 20$ ns. These lifetimes correspond to mean drift lengths in the high field region of approximately $d_e = 65 \mu m$ and $d_h = 360 \mu m$. The reason for the large difference observed between electron and hole lifetimes is not yet understood, however this has been seen consistently in the p-i-n detectors which we have measured and in 125 $\mu m$ thick Schottky-ohmic devices [8].

B. Gamma radiation

Using the charge carrier lifetimes extracted from the alpha radiation data it is possible to model the pulse height spectra expected from gamma radiation. Assuming a constant distribution of photon interactions through the bulk of the detector, the shape of the photopeak pulse height spectrum is critically dependent on the shape of the CCE distribution through the detector. If the CCE distribution were constant through the detector a simple gaussian shaped photopeak would be expected. However in general this not the case for a thick detector, and the pulse height spectrum will show a peak combined with a low energy shoulder of events.

For comparison, figure 5 shows similar data calculated using equal values of the electron and hole mean lifetimes of 10ns [4]. In this case the slower hole drift velocity causes the holes’ mean drift length to be less than that of the electrons and the CCE decreases towards the rear of the detector as the contribution from the hole current increases. The pulse height spectrum still contains a peak which in this case is produced by photon interactions close to the front contact of the detector. The overall CCE values are slightly greater than those of figure 4.

C. Minimum ionising particles

The detector response to minimum ionising particles (MIPs) is of particular interest for GaAs microstrip detectors. These devices are being developed as radiation hard tracking detectors for the ATLAS collaboration at the Large Hadron Collider. The energy spectrum for MIPs passing through an ideal thin detector has the form of a Landau distribution with a value for the most probable deposited energy in GaAs of 5.6 eV/$\mu m$. The charge collection response for MIPs was simulated using the drift model assuming a constant distribution of interactions through the detector. Values of the most probable CCE were obtained for detectors of thicknesses of 450 $\mu m$ and 200 $\mu m$. The response of devices of 200 $\mu m$ thickness is of particular interest since this is the specification initially chosen for the ATLAS detector. In this application the need to minimise the detector thickness in order to reduce the radiation length competes against the requirement to obtain an adequate signal amplitude.

The simulated charge collection efficiency for MIPs is shown in figure 6, produced using electron and hole mean lifetimes of 0.5 ns and 20 ns respectively. The CCE function observed from the 450 $\mu m$ thick detector rises slowly with increasing bias, reaching a maximum value of approximately 55% at a bias of -800 V. The CCE values for the 200 $\mu m$ thick detector rise more rapidly, reaching approximately 70% at a bias of -400 V reflecting the larger ratio of the mean drift lengths to the detector width. Figure 7 shows the same data
expressed in terms of the most probable pulse height; this is important in assessing the signal/noise ratio expected for a particular device. It can be seen that whilst the 450 µm thick detector ultimately produces the largest signal amplitude at high bias, the 200 µm thick detector produces significantly greater signal amplitudes for bias voltages below -500 V.

V. CONCLUSION

It has been shown that the charge collection properties of SI GaAs detectors can be well understood in terms of a non-uniform electric field distribution consisting of distinct high field and low field regions. Comparison with Monte Carlo simulations of charge collection efficiency provides good agreement with measured alpha pulse height data and indicates a longer drift lifetime for holes compared to that of electrons. The reason for this difference is not yet fully understood but work is in progress to investigate the effect of different contact types and variations in surface quality.

The effect of relatively short electron and hole lifetimes is particularly important for the pulse height response of thicker GaAs detectors to both gamma rays and minimum ionising particles. Improvements in carrier lifetimes are therefore an important ongoing area of study for tracking applications where a maximum signal size for minimum ionising particles is required.

VI. ACKNOWLEDGEMENTS

We are grateful to Mr S. Walker and Dr G. Hill for fabrication of the GaAs detectors, and for help from the staff of the EPSRC III-V facility. Thanks are also expressed to Dr Tom Davinson of Edinburgh University for his noise measurements of GaAs detectors.

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