Correlation of the charge collection efficiency of GaAs particle detectors with material properties

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Measurements of the Charge Collection Efficiency (CCE) of radiation detectors fabricated from Semi-Insulating GaAs wafers which have different thermal histories have been undertaken. A correlation between charge collection efficiency and electrical resistivity has been observed. These are consistent with a dominant dependence of CCE with the concentration of the ionized deep donor, EL2\textsuperscript{+}.

Introduction

Radiation detectors for room temperature operation based on GaAs have been studied for many years. Devices based on LPE grown material have shown very good results, but it is difficult to produce thick layers of adequate purity to allow sufficient depletion for detection of minimum ionizing particles (mips) or gamma radiation [1]. An alternative that has been studied is the use of semi-insulating (SI) GaAs [2] which has the advantage of being readily available in thicknesses of several hundred microns and having a high resistivity (of the order of $10^7 \text{ \Omega cm}$). The SI nature of GaAs is a result of the compensation of residual acceptor impurities (primarily carbon) by intrinsic deep donor levels introduced as the crystal cools from its growth temperature or following post-growth anneals [3]. One of these electron levels, EL2, is dominant because it occurs in concentrations that far exceed all others. Since it has an ionization energy near the middle of the bandgap, it pins the Fermi level near mid-gap resulting in extremely high resistivity. Detectors based on these wafers suffer from losing some of the charge signal generated by the incident radiation [2,4]. It is believed that this degradation in performance is partly a result of carrier trapping by some of or all the intrinsic deep level defects mentioned above, together with effects due to the incomplete penetration of the electric field through the detector [5,6].

In the present paper, we present data obtained from detectors fabricated on wafers that have undergone various heat treatments in an attempt to alter the concentrations of individual traps. We conclude that the degradation due to trapping is dominated by the EL2 defect in its positive charge state.

The GaAs Samples

We have investigated GaAs samples grown by the Liquid Encapsulated Czochralski (LEC) process and which contain different concentrations of carbon. Several of these samples have undergone different thermal treatments, table 1 [7]. The GaAs particle detectors used in this study consist of a Schottky barrier-semiconductor-Ohmic contact sandwich with the thickness of GaAs being approximately 500 microns.

Concentrations of defects were measured using thermally stimulated current spectroscopy (TSC) [10]. This analysis requires optical excitation of deep levels and it is necessary to illuminate the semiconductor through the Schottky contact. Fortunately, the structures of samples for TSC defect measurements and particle detectors are identical. A circular semi-transparent Au Schottky contact 28nm thick was evaporated onto each sample. The back, ohmic, contact consisted of either
annealed Au/Ge or indium. Neither the CCE nor the TSC results depended on the composition or the thickness of the back contact.

**Defect Assessment**

In TSC the sample is cooled to 80K and donors are filled with electrons by illumination with near bandedge light. At these low temperatures donors deeper than 0.17 eV remain filled after the illumination is terminated.

The sample is then slowly warmed under reverse bias. As the temperature is increased the shallow traps empty first, followed by progressively deeper levels. Therefore, peaks in sample conductivity occur in the current versus temperature spectrum, each corresponding to different trap energies. By analysing this spectrum it is possible to extract both the activation energy and the concentrations of the levels present. This technique is limited by the onset of thermal currents so the deepest level measured in this study was 0.51eV [8].

The defect densities in these samples were very different, either as a result of heat treatments or different growth conditions (Table 2). Measurements of the concentrations of the dominant deep donor EL2, [EL2] were obtained from photoquenching the calibrated optical absorption band at a wavelength of 1 micron [9] (table 2). In addition, the resistivities of these samples were measured using a non-contacting Time Dependent Charge Measurement technique [10]. Because the resistivity of SI GaAs is extremely sensitive to temperature and there appears to be no consensus amongst substrate suppliers about which temperature to use, we have standardized our measurements at 293±0.1K.

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>SUPPLIER</th>
<th>HEAT TREATMENTS</th>
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<tbody>
<tr>
<td>1</td>
<td>MCP</td>
<td>Ingot anneal 950°C for 5hrs slow cool to room temp. Medium Carbon concentration</td>
</tr>
<tr>
<td>2</td>
<td>MCP</td>
<td>Ingot anneal 950°C for 5hrs slow cool to room temp. Low Carbon conc. (Seed end wafer)</td>
</tr>
<tr>
<td>3</td>
<td>MCP</td>
<td>Ingot anneal 950°C for 5hrs slow cool to room temp.</td>
</tr>
<tr>
<td>4</td>
<td>MCP</td>
<td>Ingot anneal 950°C for 12 hrs slow cool to room temp.</td>
</tr>
<tr>
<td>5</td>
<td>NIPPON MINING</td>
<td>Multiple wafer anneal</td>
</tr>
<tr>
<td>6</td>
<td>MCP</td>
<td>Ingot anneal 950°C for 5 hrs + multiple wafer anneal (1130°C and 830°C)</td>
</tr>
<tr>
<td>7</td>
<td>MCP</td>
<td>As for sample 2. Same ingot, sample wafer from middle</td>
</tr>
</tbody>
</table>

**Experimental**

Each detector was reverse biased at 200V and the spectrum from alpha particles irradiating the Schottky contact was taken using a standard spectroscopy chain with a shaping time of 0.5µs and recorded on a
MCA. The CCE is defined as the ratio of the measured charge to the charge deposited in the detector, assuming that the energy to create an electron-hole pair is 4.3eV [11]. The calibration is carried out using a pulser to inject charge into the input of the spectroscopy chain. An example of the CCE as a function of EL4 concentration is shown in figure 1. We immediately note that there appears to be no correlation between the CCE and the EL4 concentration. A similar lack of correlation is seen for all other observed deep levels including EL2. This failure to find a correlation is consistent with a previous report [12].

However, there is a good correlation between the CCE (at 200V) and the resistivity of the sample as shown in figure 2. The behaviour of CCE as a function of applied voltage for the sample of lowest resistivity (4x10^6 Ohm cm) and a standard is shown in figure 3.

Discussion

We have shown in previous studies that it is primarily the trapping of electrons that reduces the CCE in those circumstances where effects due to incomplete penetration of the electric field are small [13]. This trapping must be due to ionised donors or neutral acceptors having an ionisation energy above the mid-gap Fermi-level, \( E_F \). The energy level of the only known neutral acceptor in SI GaAs, the so-called RC defect [14] is degenerate with the conduction band at room temperature and is, therefore, inactive. We, therefore, believe that only ionized donors are available for trapping.

We have noted above that there is no apparent correlation between CCE and concentrations of individual deep donor levels in SI GaAs. The only parameter that is seen to correlate with CCE is sample conductivity (figure 2, noting that conductivity is the inverse resistivity). In SI GaAs with constant carrier mobility, such an increase is due to a lifting of the Fermi energy. Raising \( E_F \) has a further consequence. We note that total concentrations of EL2 defects are relatively constant from sample to sample, even after quite dramatic heat treatments (table 2). Also, \( E_F \) can be expressed in terms of the ratio of ionized to unionized EL2, by,

\[
\frac{[\text{EL2}^+]}{[\text{EL2}]} = 1 - \left( \frac{1+1/2 \exp \left( \text{EL2} - E_F \right) / kT \right)^{-1}
\]

where \( E_{\text{EL2}} \) is the energy to ionize neutral EL2 into its positive charge state and \( k \) is Boltzmann’s constant. It follows that
raising $E_F$ reduces the value of $[\text{EL2}^+]/[\text{EL2}]$ and, since $[\text{EL2}]$ is nearly constant, it reduces $[\text{EL2}^+]$. Thus the increase in CCE associated with a reduction in sample resistivity can be directly related to a concomitant diminution in $[\text{EL2}^+]$. For these reasons we believe that the major trapping centre in these detectors is the EL2$^+$ defect.

Trapping by an ionized deep donor like EL2$^+$ is hardly unexpected. However, we are aware that concentrations of EL2$^+$ probably do not exceed $10^{15}\text{cm}^{-3}$ in any of our material, a value that is comparable with concentrations of other ionized donors. Additionally, we note that published electron capture cross sections for EL2$^+$ are of the order of $10^{-13}\text{cm}^2$, a value also comparable with those of other donors [15]. Therefore, the great effectiveness for electron capture by EL2$^+$ appears to be problematic. However, it has been demonstrated that electron capture by EL2$^+$ is greatly enhanced in the presence of an electric field [16] and, indeed, such behaviour has recently been employed successfully in a model to simulate the penetration of the electric field into SI GaAs [17].

Thus, we propose that EL2$^+$ defects are very efficient electron traps in the electric fields typical in these particle detectors [17] and that their concentration is critical in reducing CCE. Trapping of electrons by EL2$^+$ defects is particularly important because de-trapping rates at room temperature are negligible compared to the typical integration time of particle detectors.

**Conclusions**

We conclude that EL2$^+$ centres are crucial in the trapping of free electrons in SI GaAs under bias. A similar mechanism has been employed to model the electric field penetration in similar devices [17]. Reducing the value of the electrical resistivity appears to be a potent way of improving CCE by reducing net concentrations of EL2$^+$ defects.

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**References**