Analysis of trapping and detrapping in semi-insulating GaAs detectors

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To investigate the trapping and detrapping in SI-GaAs particle detectors we analyzed the signals caused by 5.48 MeV alpha particles with a charge sensitive preamplifier. From the bias and temperature dependence of these signals we determine the activation energies of two electron traps. Additional simulation and measurements of the lifetime as a function of resistivity have shown that the EL2+ is the dominant electron trap in semi-insulating GaAs.

1 Introduction

GaAs Schottky diodes made of commercially available undoped semi-insulating (SI) LEC (Liquid Encapsulated Czochralski) material work well as radiation detectors. However, many studies on SI-GaAs detectors denote an incomplete charge collection efficiency (CCE)[1]. This signal loss seems to stem from carrier trapping due to deep levels defects. In addition the CCE is further reduced due to an incomplete penetration of the electrical field at low bias voltages[2]. In the first part of this paper we analyze the shape of signals caused by 5.48 MeV alpha particles (241Am) as a function of bias voltage and temperature for low, medium and high ohmic SI-GaAs substrates. In the second part an attempt has been made to explain the variation of the charge collection efficiency on the resistivity of the materials, which was also reported from B. Berwick et al.[3].

2 Experimental Method

The detectors studied in the present work were made on undoped SI-GaAs 3” wafer obtained from various manufactures. The detectors are 2 or 3 mm in di-
ameter, 200 µm thick with circular Schottky pads. The back contact (Schottky or Ohmic) covers the entire wafer. The details of the contacts are described elsewhere[4]. The resistivity was determined from the I-V characteristic using the Norde plot[5].

Charge collection efficiency was measured for irradiation with alphas (\(^{241}\text{Am}\)). The spectroscopy chain includes an Vitrom (559-064) charge sensitive preamplifier with a rise time of 10 ns and a decay time of 240 µs followed by an OR-TEC 579 amplifier-shaper with gaussian shaping and a time constant of 500 ns. For trapping and detrapping measurements the output of the preamplifier was read out with a digital scope with 500M samples/s and band width of 100 MHz. For temperature dependent measurements the Schottky diodes are placed in an oven with a temperature stability of about 0.1°C.

3 Results and Discussion

Figure 1 shows the shape of the measured signals from of GaAs detectors irradiated with alphas from the Schottky contact, applying a positive voltage to the back contact. The signal is than (Ramo’s theorem [6]) dominated by the motion of electrons rather than holes. We observe signals similar as reported by ref. [7] with a fast rise time and a long exponential decay. The height of the fast part of this signal increases with increasing bias voltage. The dependence of the time constant of the slow exponential decay $\tau$ as a function of bias can be seen in figure 2. If we interpret the slow components as a detrapping from defects the decrease of $\tau$ can be explained by field enhanced emission (Poole-Frenkel effect [8]). The observed dependence of $\tau$ on the resistivity $\rho$ is in contradiction to the circuit model proposed by ref.[7] where $\tau$ is given by

$$\tau = \rho \varepsilon \frac{L}{w}$$

where $L$ and $w$ denotes the thickness of detector and space charge region. Additional we have shown in a previous paper [9] that the space charge density beyond the Schottky contact increases with increasing resistivity which results in a small space charge region and increasing electrical field at the same bias voltage. Taking into account this variation of the electric field the decrease of the detrapping time as a function of resistivity can also be explained by the Poole Frenkel effect. If we have a closer look on the amplitude of the slow component we observe a decrease with bias and resistivity (figure 3). From temperature dependent measurements at a constant bias voltage assuming a

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similar theory as for PICTS (Photo Induced Current Spectroscopy) [8] the
detrapping time is given by

\[ \tau = \frac{\exp(E_c - E_T/kT)}{\gamma_n \sigma_n T^2} \]  

(2)

with an activation energy \( E_T \), capture cross section \( \sigma_n \) and coefficient \( \gamma_n \), we have determined two electron traps. The activation energies are \( E_{T1} = 0.352 \pm 0.025 \) eV and \( E_{T2} = 0.51 \pm 0.07 \) eV (figure 4). A determination of the capture cross section is not possible because of the time shift caused by Poole Frenkel effect. From comparison with the values given in the literature the \( E_{T1} \) and \( E_{T2} \) can be associated with the EL6 and EL3 (table 1)[10].

Table 1

| Trap | Activation energy (eV) this paper | Activation energy (eV) lit. | Capture cross section (cm\(^2\)) lit. | Concentration \(10^{15} \) (cm\(^{-3}\)) lit. |
|------|----------------------------------|-----------------------------|---------------------------------------|-----------------------------------|
| EL6  | 0.352 ± 0.025                    | 0.32-0.33                   | 2.0 \(10^{-14}\)                      | 1-20                              |
| EL3  | 0.051 ± 0.07                     | 0.58                        | 0.8-1.7 \(10^{-13}\)                 | 0.5-2.0                           |

The capture cross sections of both defects are in the \(10^{-13} - 10^{-14} \) cm\(^{-2}\) range and the concentrations in melt grown GaAs are in the range of \( 0.5 \cdot 10^{14} \) to \( 2 \cdot 10^{16} \) cm\(^{-3}\) as reported by M. Skowronski [10]. After the detrapping of the EL6 and EL3 we still not have 100% CCE, this means there is still a signal loss due to trapping. This trap must have a capture cross section and concentrations in the same range as the two defects we observed directly and a slower detrapping time constant. If we assume a similar capture cross section and the same influence of the Poole Frenkel effect on the emission, the activation energy must be larger then for the measured EL3, because if the energy is smaller we will expect a detrapping in the temperature range we measured, with a time constant of a few \( \mu \)s. The EL2 has an activation energy of 0.8 eV, the concentration of the ionized state is in the range of \( 10^{15} \) cm\(^{-3}\) [11] and for electric fields higher than \( 10^4 \) V/cm a capture cross section of \( 8 \cdot 10^{-14} \) cm\(^2\) is published by G. Martin et al. [12]. This good agreement with claimed properties of the deep level and also the observed influence of the CCE on the EL2\(^+\) concentration [15] favour the EL2 to be the dominating electron trap in SI-GaAs. Therefore we analyze in the following the CCE as a function of the EL2\(^+\) or rather the resistivity.

Figure 5 shows the CCE of detectors obtained with low, medium and high ohmic SI-GaAs substrates. The CCE as a function of bias voltage rises rapidly and saturates for high voltages. Simulations [2] and measurements [13] of the field penetration as a function of bias voltage have been shown a linearly increase of the width of the high field region with bias. From this we can
conclude that the observed saturation of the CCE is due to the limitations caused by the mean free drift length of electrons. For electric fields higher than $10^4 \text{ V/cm}$ [2] we can assume a constant drift velocity and therefore a constant mean free drift length. Under this assumption we calculate the mean free drift length of the electrons $\lambda_e$ using

$$CCE = \frac{\lambda_e}{d} \left[ 1 - \exp \left( -\frac{d - x_0}{\lambda_e} \right) \right] + \frac{\lambda_h}{d} \left[ 1 - \exp \left( -\frac{x_0}{\lambda_h} \right) \right]$$ (3)

where $\lambda_e$ and $\lambda_h$ denotes the drift lengths of electrons and holes, $d$ the detector thickness and $x_0$ represents the generation point of electron hole pairs. Estimated a drift velocity $v_{\text{drift}}$ of $1 \cdot 10^7 \text{ cm/s}$ we can extract the lifetime $\tau_e$ of the electrons from the plateau value of the CCE at high voltages using

$$\tau_e = \frac{\lambda_e}{v_{\text{drift}}}.$$ (4)

As shown above there is no significant signal loss to the EL3 and EL6 at this condition which means the lifetime is independent of this two traps.

The electron lifetime as a function of resistivity is shown in figure 6. We observed a fast decrease from about 45 ns for a resistivity of $0.4 \cdot 10^7 \text{ }\Omega\text{cm}$ down to 0.8 ns at $8.9 \cdot 10^7 \text{ }\Omega\text{cm}$. To investigate the influence of the EL2+ on the electron lifetime we calculate in the first step from the resistivity the position of the Fermi level in the bulk material assuming a mobility of $8000 \frac{\text{cm}^2}{\text{V}\cdot\text{s}}$ for electrons and $380 \frac{\text{cm}^2}{\text{V}\cdot\text{s}}$ for holes using:

$$n = \frac{1}{q \rho \mu_e} + \sqrt{\left( \frac{1}{q \rho \mu_e} \right)^2 - \frac{n_i^2}{\mu_e \mu_h}}$$ (5)

and

$$E_F = \frac{kT}{q} \ln \left( \frac{n}{N_v} \right)$$ (6)

Knowing the Fermi level position $E_F$, the energy niveau of the level $E_{EL2} = 0.69 \text{ eV}$ [14], the concentration $N_{EL2} = 1.2-1.8 \cdot 10^{16} \text{ cm}^{-3}$ (typical for LEC material [15]) and electronic degeneracy $g = 0.84$ [14] we determine the ionized density of the EL2 trap according to

$$N_{EL2+} = N_{EL2} \left( 1 - \frac{1}{1 + g^{-1} \exp \left( \frac{q(E_{EL2} - E_F)}{kT} \right) \right)} \right)$$ (7)
The change of the ionization due to the formation of the space charge region can be neglected, because the space charge density is in the range of $10^{11}$-$10^{12}$ cm$^{-3}$ in comparison to $N_{EL2^+} \sim 10^{14}$-$10^{15}$ cm$^{-3}$.

Under the assumption that one single trapping center is prevailing, the electron lifetime should be inversely proportional to the density of ionized EL2 (Schockley-Read-Hall statistics):

$$\tau = \frac{1}{\sigma \langle v_{th} \rangle N_{EL2^+}} = \frac{1}{\sigma \langle \sqrt{m_{eff}/m} \rangle N_{EL2^+}}$$

(8)

with $\sigma_n$ being the capture cross section and $\langle v_{th} \rangle$ the mean thermal velocity. Because of the high electric field we must take into account the increase of the effective electron mass $m_{eff}$ due to field enhanced occupation of the second minimum in the conduction band of GaAs, which results in a lower thermal velocity than without electric field. For the capture cross section we use the above mentioned value of $8 \cdot 10^{-14}$ cm$^2$. Table 2 summarizes all parameters of the simulation.

Table 2
Parameters of the simulation.

| Parameter                  | Symbol | Value          |
|----------------------------|--------|----------------|
| Concentration of the EL2   | $N_{EL2}$ | $1.6 \cdot 10^{16}$ cm$^{-3}$ |
| Energy level of the EL2    | $E_{EL2}$ | 0.69 eV         |
| degeneracy                | $g$    | 0.84           |
| Temperature               | $T$    | 296 K          |
| capture cross section      | $\sigma$ | $8 \cdot 10^{-14}$ cm$^2$ |
| effective electron mass    | $m_{eff}$ | 1.2            |
| electron mobility          | $\mu_e$ | $8000 \frac{cm^2}{Vs}$ |
| hole mobility              | $\mu_h$ | $380 \frac{cm^2}{Vs}$ |

Using this parameters we obtain a good agreement with the experimental data (figure 6). This simulation also explains the decrease of the slow signal height of the detrapping component at low voltages as a function of resistivity. For material with a short EL2$^+$ trapping time more electrons are captured by the EL2 and less can be trapped by the EL6 and EL3. In the other case of low resistivity material with only a small concentration of EL2$^+$ the signal loss due to the EL6 and EL3 exceed that of the EL2$^+$.  


4 Conclusion

We report a new technique to investigate detrapping in SI-GaAs particle detectors, which is similar to PICTS measurements. This technique allows to determine directly the electron traps responsible to a signal loss in particle detectors. Therefore we have identified the EL6 and EL3 as electron trapping centers. A comparison of measurements and results of a simple simulation shows that the EL2$^+$ is the dominate electron trapping center in SI-GaAs and responsible for the dependence of the electron lifetime on the resistivity of the materials.

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Fig. 1. Measured output signals from GaAs detectors irradiated with alpha particles on the front for different bias voltages.
Fig. 2. The time constant of the slow exponential decay as a function of the bias voltage for different materials.
Fig. 3. Amplitude of the slow exponential decay as a function of bias voltage for different materials.
Fig. 4. Arrhenius plots of the time constant of the slow exponential decays measured at bias voltages of 40 V and 80 V (MCP90).
Fig. 5. The charge collection efficiency as a function of the bias voltage for different materials.
Fig. 6. Comparisons of the measured and simulated dependence of the electron lifetime on the bulk resistivity.