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Muon track induced current measurements in semi-insulating GaAs

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ABSTRACT

We report on preliminary muon-track-induced current measurements in semi-insulating (SI-) GaAs. At $T = 70\,\mathrm{K}$, after simultaneous treatment of the sample by muon irradiation and a strong electric field (a square wave with $|E| > 10\,\mathrm{kV/cm}$ and the polarity changed every $\frac{1}{50}\,\mathrm{s}$) for approximately 2 h, the sample is transferred to a metastable-like state which is characterized by increased life-times for non-equilibrium electrons and holes. The sample can be returned to the original state by heating up to 250 K. Our results for SI-GaAs suggest a muon-track-induced electric-field-assisted neutralization process for the deep traps.

1. Introduction

Semi-insulating (SI-) GaAs has been found to be one of the most promising materials for the fabrication of radiation detectors, and is used in high-energy physics, in X-ray digital imaging and in the medical field [1]. That is why studies of SI-GaAs under radiation (in our case by the muon beam) and under the influence of applied electric fields are of significant practical importance.

Our recent RF μSR experiments in electric fields have revealed a metastable behavior of commercial SI-GaAs samples [2]. After the treatment of the sample by the muon beam at $T = 70\,\mathrm{K}$, together with a strong alternating electric field (square wave with $|E| > 10\,\mathrm{kV/cm}$ and the polarity changed every $\frac{1}{50}\,\mathrm{s}$) for 2 h, the diamagnetic RF amplitude measured in longitudinal fields (LF) of $H \sim 1500-2000\,\mathrm{Oe}$ at $T \sim 100-140\,\mathrm{K}$ increases (and reaches 80% of the apparatus asymmetry) when compared to the "virgin" sample. The sample can be returned to the original state (with reduced RF diamagnetic asymmetry) by raising the temperature above 250 K.

Results for non-relaxing LF asymmetry measured in both the virgin and treated sample states are presented in Fig. 1. The increase in the diamagnetic fraction can be explained by two mechanisms, either muonium ($\mu^+ + e^- = \mathrm{Mu}$) captures an excess electron and forms Mu^- or it captures an excess hole and forms Mu^+. The idea of the muon-track-induced current measurements is to make a link between microscopic charge transport (muonium charge dynamics) and macroscopic time-of-flight measurements of the injected (by the muon track) carriers and to check if there is a change in the bulk properties of the sample when μSR data show a metastable-like behavior.

To study the non-equilibrium charge transport in the metastable GaAs we have performed muon-track-induced current measurements in two geometries. In the standard setup muons were stopped close to the center of the 0.5 mm thick GaAs wafer, while in the second we used a degrader to stop the muons as close as possible to the incoming electrode. In the standard geometry both electrons and holes can drift to an appropriate electrode, while in the second the charges are generated in a relatively narrow layer close to the surface. In this case, if a positive polarity is applied to the incoming electrode, the track holes will make the main contribution to the recorded current and, in contrast, if a negative polarity is applied the recorded current is mainly due to the track electrons.

2. Experimental

Studies reported here were performed using a commercial high resistivity ($\rho \sim (1.6-1.8) \times 10^8\,\mathrm{Ohm} \times \mathrm{cm}$, n-type conductivity, electron mobility $\sim 5000\,\mathrm{cm^2/V\,s}$) SI-GaAs substrate (0.5 mm thick, (1 0 0) crystallographic axis perpendicular to the surfaces) purchased from the American Xtal company. The sample was cut to $2 \times 3\,\mathrm{cm}^2$ size, and silver electrodes of 80 nm thickness were deposited on both surfaces of the sample using the DC magnetron sputtering technique, thereby making two Schottky contacts.

A kapton degrader was mounted on a supporting frame inside the thermal shield of the standard CCR cryostat. The frame was

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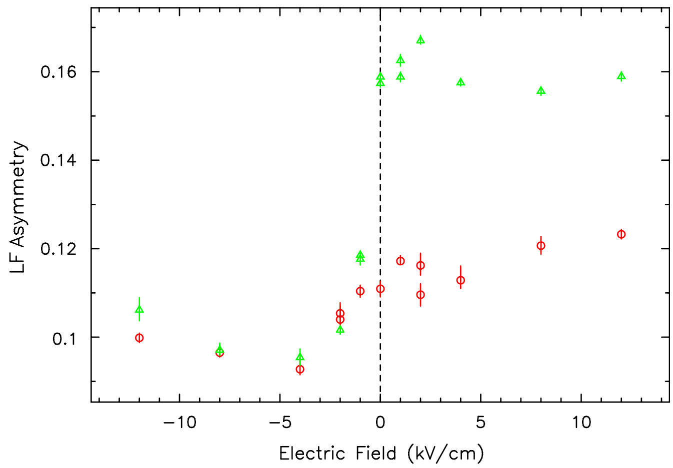

Fig. 1. Electric field dependence of the non-relaxing LF asymmetry measured in $LF = 1837$ Oe for GaAs at $T = 120$ K. Circles—virgin sample. Triangles—sample after the treatment. For this particular temperature, the non-relaxing LF asymmetry approaches the diamagnetic RF asymmetry [2]. The positive electric field points parallel to the muon beam.

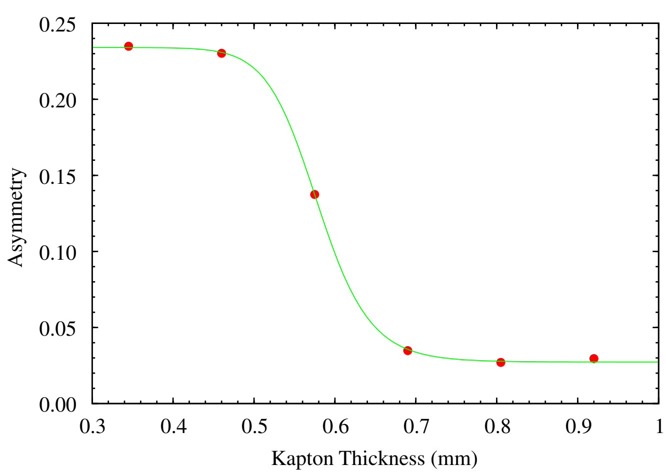

Fig. 2. Diamagnetic asymmetry measured in the silver sample holder covered by Kapton foils.

constructed such that its position could be altered without braking the spectrometer vacuum, allowing us to measure spectra with the degrader either in beam ('degrader in') or out of beam ('degrader out') while keeping all other conditions (temperature, EF, RF) unchanged.

The degrader was adjusted to stop the muons as close to the surface of GaAs sample as possible (see Fig. 2 for details), and a thickness of 0.7mm was found to be optimal. Scaling the data from the Fig. 2 by the Kapton to GaAs density ratio allows us to estimate the muon range for the two conditions: $Z_{out} = 0.17$ mm for the degrader out geometry, $Z_{in} = 0.03$ mm for the degrader in geometry. The pulsed structure of the muon beam at the ISIS Facility at Rutherford Appleton Laboratory allowed us to record the time evolution of the muon-track-induced currents. Current vs time spectra were recorded using a Tektronix oscilloscope, simultaneously with the collection of μSR spectra in LF + EF fields. Fig. 3 presents muon-track currents recorded for the degrader out state (muons stopping at a distance from both electrodes). Fig. 4 presents muon-track currents recorded for the degrader in state (where muons stop close to the incoming electrode). The positive electric field points parallel to the muon beam, and nominal electric fields (applied voltage divided by the thickness of the sample) are given in the labels.

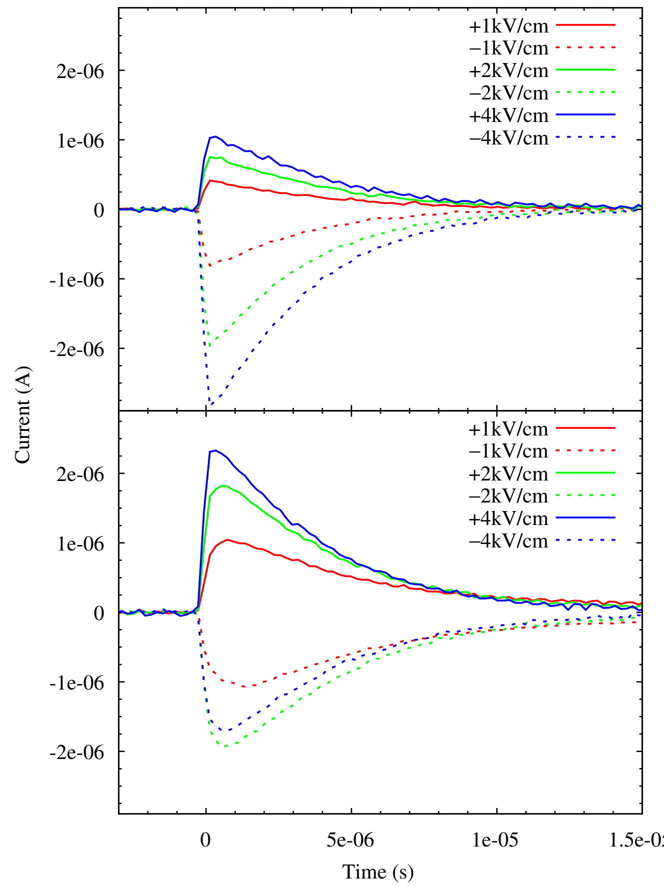

Fig. 3. GaAs: $T = 120$ K. Muon-track-induced currents recorded for the degrader out state. Top: virgin sample. Bottom: sample in the enhanced state (after the treatment of the sample by the electric field).

Even in low fields, $E \sim 1$ kV/cm, the typical drift velocities of electrons and holes in GaAs are of the order $V_{drift} > 10^6$ cm/s. This will result in typical time-of-flight times of about $t_{drift} \sim d/V_{drift} < 50$ ns (where $d = 0.05$ cm is the thickness of the sample) which is comparable with the ISIS muon pulse width $\delta t \sim 80$ ns, and explains why we cannot readily resolve the drift times of the free carriers. Moreover, the simplified type of the preamplifier used for these measurements resulted in a typical RC decay (with $RC \sim 5 \times 10^{-6}$ s, where $R = 10$ kOhm is the input impedance of the preamplifier and C is the parasitic capacitance) that is clearly seen at long times in all the plots in Figs. 3 and 4, independent of the state of the sample and of the muon implantation depth. One can see that the early time behavior of the currents is completely different for the original (top in Figs. 3 and 4) and treated (bottom in Figs. 3 and 4) states of the sample. For the treated state, the current is delayed by $\sim 1-2 \times 10^{-6}$ s which is significantly larger than for either the electrons/holes drift times or the muon pulse width. A possible explanation would be that for the treated sample the life-time of the non-equilibrium carriers is increased, and then this broad current peak can be attributed to ambipolar diffusion of the carrier plasma [3]. The observation of this delayed peak requires carrier life-times in excess of a microsecond. This scenario is also supported by the charge collection data presented in Fig. 5. The charge collection efficiency increases in the treated sample. This effect is clearly