Radiation Induced Damage in GaAs Particle Detectors.

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Abstract
The motivation for investigating the use of GaAs as a material for detecting particles in experiments for High Energy Physics (HEP) arose from its perceived resistance to radiation damage. This is a vital requirement for detector materials that are to be used in experiments at future accelerators where the radiation environments would exclude all but the most radiation resistant of detector types.
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INTRODUCTION

GaAs particle detectors were developed for use in the experiments currently being designed as part of the new accelerator (the LHC) to be built at CERN, Geneva. The estimated radiation fluence foreseen for the innermost forward tracking layer of the experiment is of the order of several $10^{14}$ cm$^{-2}$ of particles, consisting of roughly equal fluxes of charged hadrons and neutrons with a typical energy of 1 MeV. This will be accumulated over the life of the experiment, which is projected to be 10 years.

GaAs had been proposed as a radiation hard detector material for tracking particles in this very forward region, where the radiation environment will be harshest and precludes the use of standard types of semiconductor radiation detectors. Extensive studies[1] have already been carried out on the resistance to radiation damage of this material using Gamma radiation. The purpose of this study was to evaluate the damage from neutrons and charged particles with particular emphasis on pions, as these are foreseen to be one of the dominant sources of damage to semiconductor particle detectors at the LHC.

MEASUREMENTS AND RESULTS

All the detectors used in this study were 3 mm diameter circular Schottky diodes with a 500 µm wide guard ring separated by 10 µm on 200 µm thick semi-insulating GaAs substrates. The detector operates as a reverse biased diode, the energy deposited by a particle creating electron-hole pairs which are swept out of the depleted region by the applied field, which create a signal in the front-end charge amplifier. The main detector characteristics of interest for HEP are the leakage current, the full depletion voltage ($V_{fd}$) and the charge collection efficiency (cce). The leakage current is measured as an I-V characteristic up to the breakdown voltage or until the diode reaches a compliance current. $V_{fd}$ is rather more difficult to measure as there is incomplete charge collection in the first place. This value is measured by looking for alpha particle detection on the back contact as the range of this type of particle is approximately 20 µm in GaAs. This effect is also seen on the I-V curve as a knee in the leakage current corresponding to an increase in the injection current from the back contact.

The cce of the device is defined as the ratio of the measured charge to the total charge deposited in the detector by the ionising particle. The deposition of energy in the bulk of the detector depends on the type of radiation used to illuminate the detector. Beta particles with an energy of over 2 MeV deposit energy uniformly along their path through the detector material with a Landau energy distribution and are known as minimum ionising particles (MIPs). The most probable value of this deposited energy is $56 \text{ keV per } 100 \mu\text{m of GaAs traversed}$. Alpha particles lose all their energy close to the surface of the material because of their short range (approximately 20 µm for 5.5 MeV alphas from Am$^{241}$). This property is very useful as it permits the contribution to the total charge collected by the holes and the electrons to be separated by illuminating the...
detector from either side. This technique has been used to estimate the mean free path for each carrier in the material.

The pion energy is at the delta resonance and results in maximum damage. The proton energy is that used to irradiate silicon detectors for similar applications to those proposed for their GaAs counterparts.

The change in leakage current as a function of irradiation is of the order of a factor of two over the range of interest for all types of irradiation (Fig.1). This change is orders of magnitude lower than that for silicon detectors. This is not a cause for concern for the use of GaAs devices in the LHC environment, as the leakage current increase would contribute, at most, a 30% decrease in signal to noise ratio - an effect which is even further reduced by the fast shaping times proposed for the LHC experiments.

The voltage at which full depletion occurs ($V_{fd}$) decreases with increasing fluence for all types of charged particle irradiation (as illustrated in Fig.2 for protons) and is consistent with a decrease in free carrier concentration similar to the donor removal effect seen in silicon before type inversion. From an initial fluence of around $2 \times 10^{13} \text{ p cm}^{-2}$, $V_{fd}$ falls by about 35% from its pre-irradiation value which is always around 1 V $\mu$m$^{-1}$ of substrate thickness for the type of detectors used in this study. At higher fluences $V_{fd}$ remains almost unchanged.

The cce for MIPs is the parameter most affected by particle irradiation. The loss of charge is due to the creation of radiation induced trapping centres in the bulk. These either trap the charge created by the traversing particle or modify the electric field within the bulk of the detector so as to enhance the trapping efficiencies of the traps present.

The cce of a 200 $\mu$m thick detector, reverse biased at 200 V, before irradiation is typically >75% which corresponds to a signal greater than 20,000 electrons.

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two stage cce dependence on fluence is similar to that observed in the dependence of leakage current as a function of fluence.

From alpha cce data it has been shown that the signal from holes falls faster with increasing fluence than that from electrons and so the MIP signal after irradiation is mainly due to the electron signal. If the bias is increased the signal begins to increase again and this is due to a further increase in the electron signal as shown in Fig[3].

The differing effects from each type of irradiation on the cce can be attributed to the differing amounts of non-ionising energy loss (NIEL) as the particles pass through the crystal lattice. Fig[4] shows the correlation between cce for 200 µm thick detectors measured at 200 V and the calculated NIEL[2,3] for the various particles used in this study. The damage attributed to each particle type has been weighted by its relative NIEL and the calculated energy loss is well correlated with the observed damage. The radiation induced defects in the crystal may be reduced by thermal annealing. Arsenic anti-site defects introduced by irradiation have been shown to anneal at temperatures above 450°C [3]. Detectors were thermally annealed at 450°C in a rapid thermal annealer after exposure to 1 x 10^{14} p cm^{-2}. The electron signal increased as shown in Fig[5] but that due to the holes hardly changed. The response to MIPs, as illustrated in Fig[6], gave an increase in cce to 50% at a bias of 300 V.

**DISCUSSION**

The radiation damage measured in GaAs particle detectors correlates very well with calculated values of NIEL for different particle types. The exponential decrease in charge collection efficiency with increasing integrated NIEL cannot easily be explained, as it depends on too many parameters which cannot be measured in isolation. In Si detectors the displacement cross section for protons, neutrons and pions has been found to be almost the same value for each particle at the energy of interest[5]. In the case of GaAs detectors this is not so and a factor of almost 4 has been measured in the damage caused by equivalent fluxes of neutrons and pions, with protons causing roughly three times more damage than neutrons.

**SUMMARY AND CONCLUSIONS**

The irradiation studies show that a large signal loss is present in the detectors at high levels of incident charged hadron fluence. This damage is consistent with increased non-ionising energy loss from the charged particle irradiation. Post irradiation annealing helps to recover some of the lost charge by annealing out an electron trap. Further studies are taking place in an attempt to improve the understanding and performance of these devices after
irradiation as their present radiation tolerance is not sufficiently hard enough for the forward regions in an LHC experiment.

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