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Wide Bandgap Semiconductor Detectors for Harsh Radiation Environments

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Abstract

In this work two wide bandgap materials, silicon carbide (SiC) and gallium nitride (GaN), were investigated for their performance in harsh radiation environments. Schottky devices were fabricated on vanadium doped SiC (V-SiC), Okmetic semi insulating (SI) non-vanadium doped SiC, SI GaN grown by MOCVD (metal organic chemical vapour deposition) and bulk GaN. Completed devices were electrically characterised and the CCE (charge collection efficiency) calculated from pulse height spectra of ^{241}Am α particles. SI GaN samples were irradiated with estimated neutron fluences of up to 10^{16}n/cm^2 (Ljubljana), proton fluences of 10^{16}p/cm^2 (CERN), and a dose of 600 Mrad of 10 keV X-rays (ICSTM, London). V-SiC samples were irradiated up to 5 x$10^{14}\pi$/cm^2 using 300MeV/c pions (PSI).

Electrical characterisation and CCE calculations were repeated after irradiation to observe changes in properties caused by radiation induced damage.

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1 Introduction

Harsh environments present severe challenges for designers of semiconductor devices and electronics. Critical systems for nuclear reactors and position sensitive detectors for particle beams and advanced light sources are examples where semiconductor systems must exhibit a high degree of radiation tolerance [1],[2]. Stable operation with currently available silicon technology is not possible beyond fluences in excess of $\sim 5x10^{14}$fast hadrons/cm^2 [3]. However, the semiconductor tracking detectors at planned experiments at the CERN Large Hadron Collider (LHC) will be subject to fluences $>10^{15}$fast hadrons/cm^2. The proposed upgrade, possibly in in 2012, will require tracking detectors that are able to operate at fluences of 10^{16}fast hadrons/cm^2 [4]. At this fluence yearly semiconductor tracker replacement is envisaged, resulting in increased costs and excessive machine down time. A better alternative, if possible, would be the development of detectors that are intrinsically more radiation hard. A number of possible strategies for improving the radiation tolerance of systems placed in harsh environments, such as oxgenated silicon and 3D detectors, are studied within the CERN RD50 collaboration [5]. Also investigated within the RD50 collaboration is the use of other detector substrates, namely wide bandgap materials such as SiC and GaN. This paper investigates the performance of different SiC and GaN materials as a basis for radiation hard detectors. Detectors were fabricated and irradiated up to fluences of 10^{16}neutrons and protons/cm^2. The I-V characteristics and CCE of the detectors were measured pre-and post-irradiation in order to determine the effects of the incident radiation on detector performance.

2 Materials and Test Samples

Four material systems were investigated. Vanadium compensated, bulk semi-insulating (SI) 4H-SiC (V concentration $\sim 10^{18}$cm^{-3}), 550μm thick, was obtained from Cree Research. The vanadium compensation gave the material a very high resistivity, $>10^{11}\Omega$cm. Okmetic semi-insulating 4H-SiC with no vanadium doping was also obtained and the effect of the vanadium compensation assessed. Standard photolithography techniques were used to produce planar pad/guard ring structures on the two SiC materials. The SiC detectors were made in a standard parallel plate configuration by depositing Ni ohmic contacts on the back surface and Ti Schottky contacts on the front surface. Pad diameters of 250, 500 and 750μm were fabricated with 50μm spacing between the pad and guard ring. Si_3N_4 passivation of the remaining free SiC surfaces was performed to minimise surface leakage effects [6]. Completed detectors were wire bonded to a ceramic chip carrier for characterisation.

The fabricated SiC detectors were electrically characterised pre-and post-irradiation by performing current-voltage (I-V) measurements and charge collection efficiency (CCE) measurements. I-V measurements were performed using a Keithley 237 electrometer and a manual probe station. The pulse height spectra from the SiC detectors were measured with α particles from an ^{241}Am source in a vacuum of ~23mbar. Calibration of the energy scale of the observed spectra was performed using a reference Si detector. In calculating the CCE of the SiC detectors it was necessary to introduce a scaling factor to account for the difference in electron-hole pair creation energy of Si (3.62eV) and SiC (8.4eV) [7].

Bulk GaN, 450μm thick, was obtained from Vilnius University, Lithuania with a measured resistivity of ~16Ωcm. SI epitaxial GaN detectors manufactured at Tokushima University, Japan were also studied. A 2.0-2.5μm thick epitaxial layer of SI GaN was grown on a 2μm thick n-GaN buffer on a sapphire substrate [8]. The SI epitaxial GaN detectors were received with Au Schottky contacts already realised. Bulk GaN pad/guard ring detectors were made in a standard parallel plate configuration by evaporating 80nm of Pd on the front and back contacts. Pads of diameter 250μm, with 50μm spacing between pad and guard ring, were chosen as the front contact. The high density of surface defects prevented larger diameter pad structures being fabricated. The devices were again wire bonded to a ceramic chip carrier for characterisation. I-V and CCE measurements were performed on the fabricated detectors as described earlier. Again a scaling factor was introduced to account for the difference in electron hole pair creation energy of Si and GaN (8.9eV).

Devices were irradiated with 300MeV/c pions, 24GeV/c protons, 10keV X-rays and neutrons. Pion irradiations were performed at the Paul Scherrer Institut (PSI), Villigen, up to a fluence of $5x10^{14}\pi/cm^2$; proton irradiations were performed at CERN up to a fluence of 10^{16}p/cm^2 and neutron irradiations at Ljubljana, Slovenia up to a fluence of $10^{16}n/cm^2$. X-ray irradiations up to 600MRad were performed at Imperial College, London.

3 Results and Discussion

Vanadium doped SiC detectors were irradiated to fluences of 10^{12}, 10^{13} and $5x10^{14}$pions/cm^2, and to 10^{16}protons/cm^2 at the irradiation facilities stated earlier. The reverse bias J-V curves from detectors irradiated to different pion fluences, shown in fig. 1, are essentially unchanged for reverse bias voltages up to 300V. Beyond this voltage, the characteristics initially deteriorate at low fluence, but then recover at high fluence. At $5x10^{14}\pi/cm^2$ the reverse leakage current was back at the levels found for the unirradiated detector right up to 600V. Fig.1 also shows the J-V characteristics of a detector irradiated to a fluence of 10^{16}protons/cm^2. The proton irradiated detector shows almost identical J-V characteristics as the unirradiated detector.

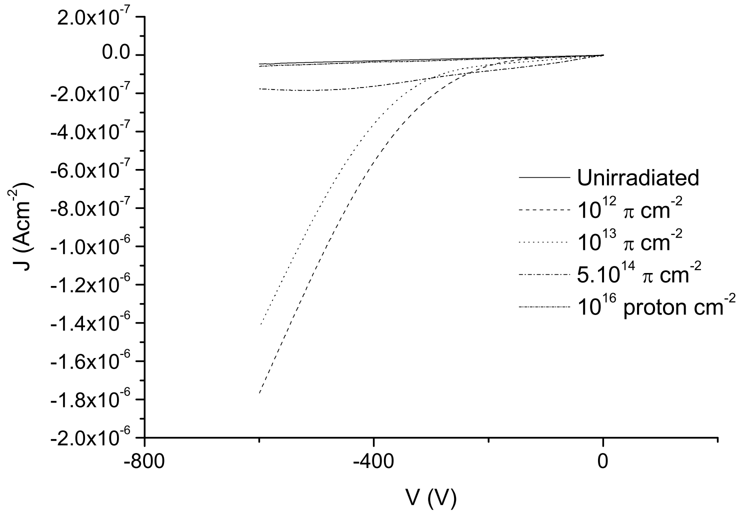

Figure 1: J-V measurements of vanadium doped SiC detectors irradiated to different proton and pion fluences

Fig. 2 shows the effect on the I-V characteristics of the detector irradiated with protons after annealing at room temperature for 6 months. The annealing resulted in an increase in leakage current which is more pronounced at high bias voltages.

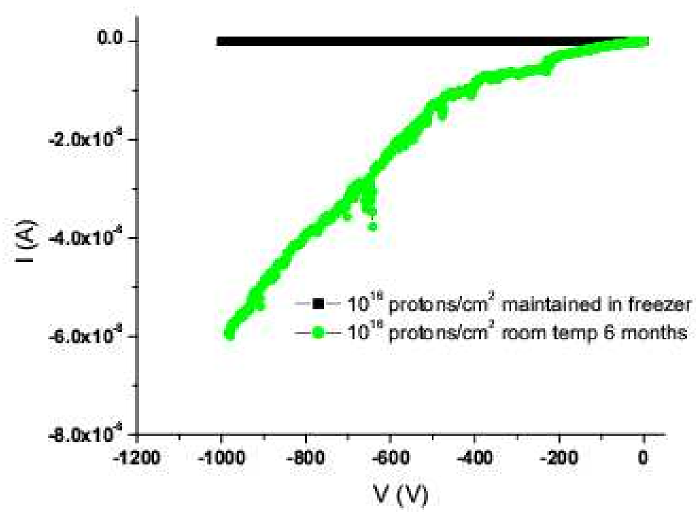

Figure 2: The effect of annealing on I-V characteristics of a vanadium doped SiC detector irradiated with a fluence of 10^{16}protons/cm^2

Pulse height spectra were measured for vanadium doped SiC detectors irradiated to $10^{12}\pi/cm^2$ and $10^{13}\pi/cm^2$. The measurements were taken to the largest reverse bias voltage before breakdown, for a given fluence. Fig. 3 shows the CCE vs bias voltage for the irradiated detectors. There is a slight deterioration of the maximum CCE due to irradiation, down from 60% to ∼50% compared to the maximum CCE of the unirradiated detectors.

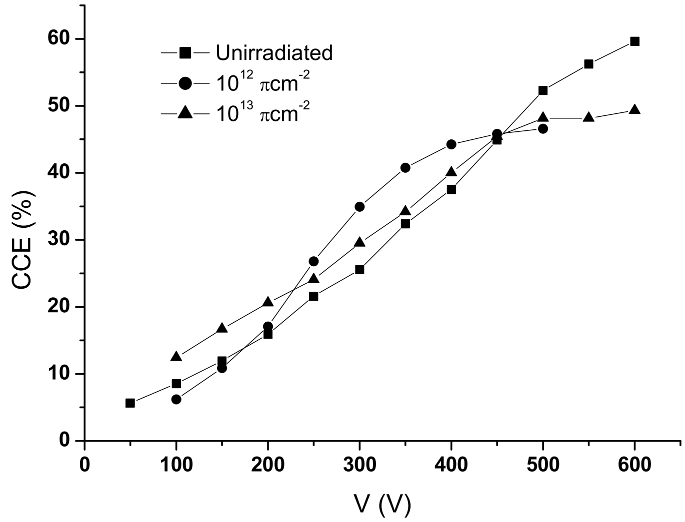

Figure 3: CCE for 5.48MeV α particles in vanadium doped SiC detectors

The low CCE of 60% of the unirradiated detectors is attributed to recombination at the vanadium centres in the material [9].

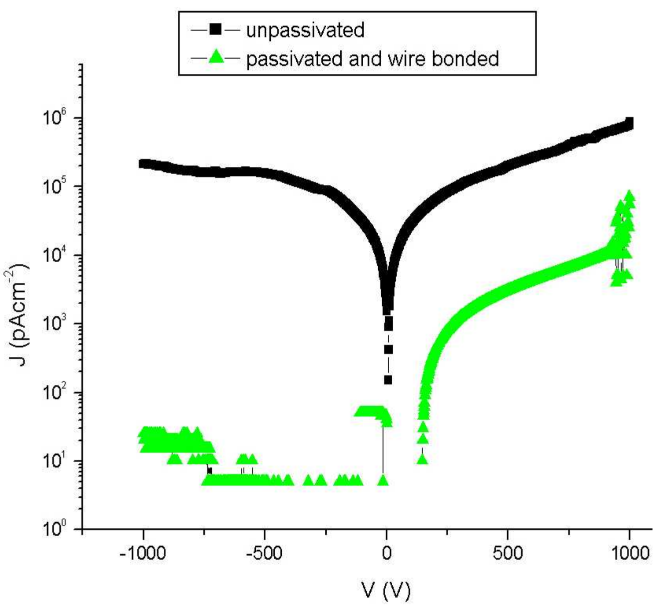

Figure 4: J-V curves of an Okmetic SiC detector

Fig. 4 shows the current density-voltage (J-V) characteristics of a diode fabricated on Okmetic SiC. Passivation and bonding of the diodes results in improved J-V characteristics. Preliminary measurements indicate a CCE of 100%, further evidence that the vanadium compensation is responsible for the relatively low CCE of the Cree SiC.

The SI GaN detectors were irradiated with 1 MeV neutrons to fluences of $5x10^{14}$, 10^{15} and 10^{16}n/cm^2, with 10keV X-Rays to a dose of 600MRad and 24GeV/c protons to a fluence of 10^{16}p/cm^2. The I-V characteristics of the irradiated detectors can be seen in fig. 5.

A non-linear increase in leakage current with fluence is observed with the neutron irradiated detectors. This behaviour has also been reported in other wide bandgap materials [10]. The CCE vs bias curves are shown in Fig. 6. In the case of X-ray irradiation, there was no measured change in the CCE compared to the unirradiated

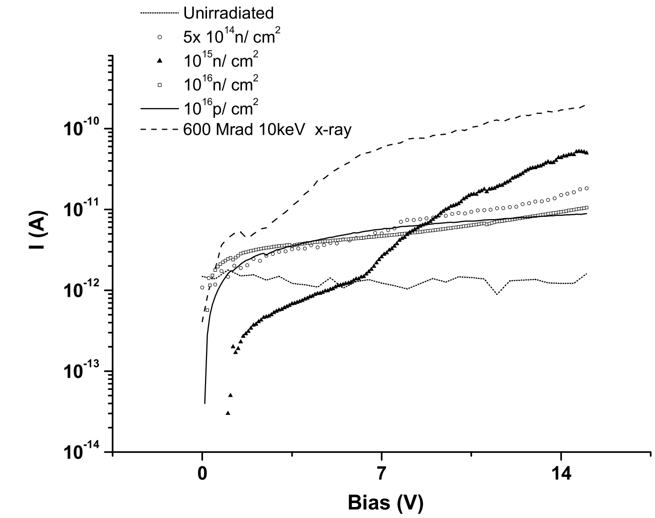

Figure 5: Measured I-V curves for epitaxial GaN detectors under varying levels and types of irradiation

detector. A CCE of ∼5% was measured for detectors irradiated to a fluence of $10^{16}/\mathrm{cm}^2$ protons and neutrons. This CCE may be improved by cooling the detectors. Fig. 7 shows the I-V curve for the bulk GaN detector. The large leakage current is thought to be attributable to inhomogeneties in the crystal. CCE measurements are yet to be made on the bulk GaN detector.

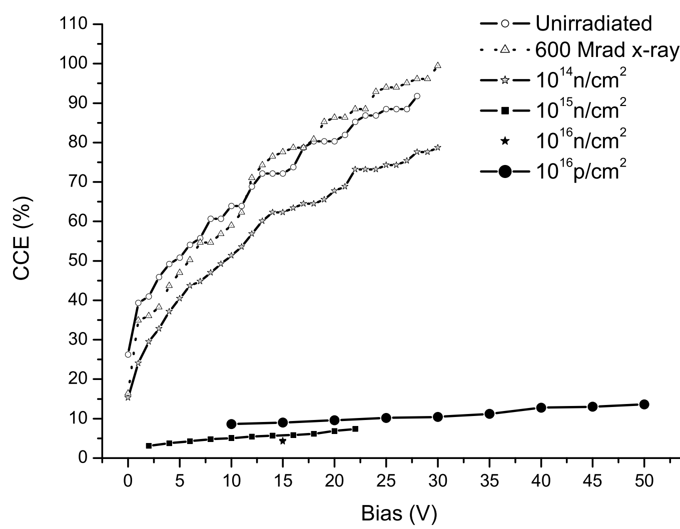

Figure 6: CCE of epitaxial GaN detectors under varying levels and types of irradiation

4 Conclusions and Summary

Wide bandgap semiconductors such as SiC and GaN show promise for use in harsh radiation environments. The low CCE of the vanadium doped SiC material is attributed to charge recombination at the vanadium centres. Inital CCE measurements on SI SiC have shown that removal of the vanadium improves the CCE to levels close to 100%. Irradiated vanadium doped SiC detectors show little degradation of CCE at pion fluences p

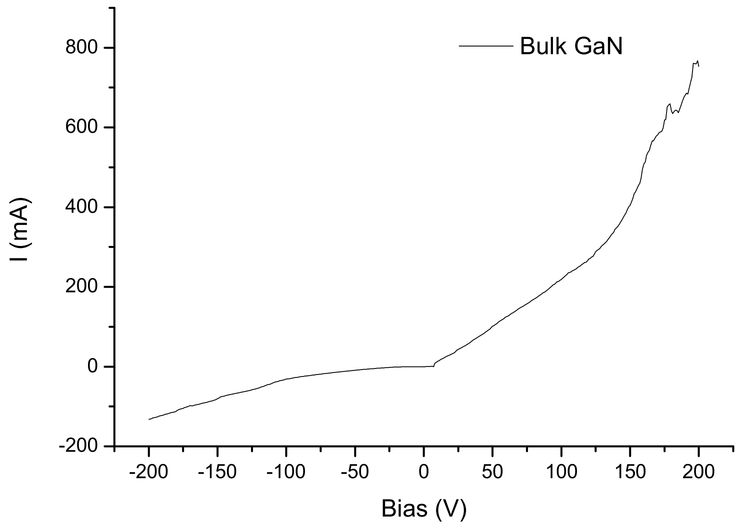

Figure 7: I-V characteristics of a bulk GaN detector

to $10^{13}\pi/\text{cm}^2$. Vanadium doped SiC detectors are able to operate effectively at relatively low bias voltages resulting in reduced power consumption when compared to Si detectors, for example [11]. The SI GaN material investigated had CCE values of ∼5% after fluences of $10^{16}/\text{cm}^2$ protons and neutrons. A number of issues need to be addressed before GaN is acceptable as a detector medium for use in harsh radiation environments. One such issue is the need to increase the amount of charge collected. Until recently, it has only been possible to manufacture epitaxial SI GaN with an active thickness of 2μm. Epitaxial SI GaN wafers with an active region of 12μm are now available. Characterisation of such material is now being carried out. Preliminary investigation of bulk GaN has shown high leakage currents. CCE measurements should asses further the potential of bulk GaN as a detector material.

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