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Performance of bulk SiC radiation detectors

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SiC is a widegap material with excellent electrical and physical properties that may make it an important material for some future electronic devices. The most important possible applications of SiC are in hostile environments, such as in car/jet engines, within nuclear reactors, or in outer space. Another area where the material properties, most notably radiation hardness, would be valuable is in the inner tracking detectors of particle physics experiments. Here we describe the performance of SiC diodes irradiated in the 24 GeV proton beam at CERN. Schottky measurements have been used to probe the irradiated material for changes in I-V characteristics. Other methods, borrowed from III-V research, are used to study the irradiated surface include AFM (atomic force microscope) scans and Raman spectroscopy. These have been used to observe the damage to the materials surface and internal lattice structure. We have also characterised the detection capabilities of bulk semi-insulating SiC for a radiation. By measuring the charge collection efficiency (CCE) for variations in bias voltage, CCE values up to 100 % have been measured.

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1 Introduction

In high energy physics, experiments have shown that the degradation of Si over the lifetime of a detector may be quite significant [1]. Even with the use of defect engineering and annealing techniques it is necessary to increase bias voltages for operation after irradiations and still the CCE is reduced. Recently, in an attempt to move beyond the limitations of Si, research has been carried out into the use of different materials as detector media. Much work has gone into materials that are supposed to be more radiation hard than Si, such as GaAs and related compounds and the widegap materials such as SiC and diamond [2]. These are expected to be more resistant to radiation due to high atomic binding energies within the material.

However, development has been slowed by the need to produce suitably high quality material. In SiC material quality is limited mostly by micropipes (a hollow core super-screw dislocation with Burgers vectors >2c) which cause a virtual eradication of the Schottky barriers of devices fabricated on the material. Also present are other non-hollow screw dislocations that can cause a reduction in breakdown voltage by around 5-35 % [3]. As the quality of available material has increased, so research into applications has advanced. Presently the material is used in UV detectors. A number of other applications are being investigated which take advantage of the chemical inertness and temperature stability of the material in hostile environments. However work to date on detectors for high energy particles has been more limited [4].

Initial work on n-type SiC from Cree has suggested that the amount of damage induced in SiC by relativistic, 24 GeV, protons is insignificant in terms of structural changes when using completed devices [5]. We used Schottky characterisation of irradiated devices to probe changes in barrier height and leakage current. The greatest observable effect is due to surface changes, shown by the degradation in characteristics. We have used AFM scans of the irradiated surfaces to look at the change in surface topography and Raman Spectroscopy scans to observe the surface crystal structure. These show no change in internal crystal structure compared to large changes in the surface roughness. The effect of these changes in surface roughness and subsequent changes in device performance, i.e. barrier height and leakage current are unimportant for the current work as only completed devices are used, with the interface already having been formed. We also report on the CCE of Schottky barrier SiC detectors for Am^{241} a radiation. Tests were carried out for a range of bias voltages, applied in both forward and reverse directions.

2 Radiation damage characterisation

The main reason for testing SiC as a detector material is to exploit its potential radiation hard properties. We fabricated a number of diodes on 4-H n-type SiC from Cree, with a carrier concentration of $\sim 10^{18}$ cm^{-3}. Two sets were produced. One consisted of a series of completed Schottky/Schottky diodes using 100 nm evaporated Au. The other set had only a back face ohmic contact applied, 100 nm of Ni annealed at 1100^o C. Both sets of samples were irradiated in the 24 GeV proton beam line at CERN. The incomplete devices then had a Schottky contact applied to the irradiated surface. Leakage current and barrier height measurements were taken for both sets of samples, as shown in Fig.1. It is clear that the level of degradation in the characteristics is markedly greater in the devices which were irradiated before completion. We found that the unprotected surface was roughened by the bombardment, with features of 10's of nm being produced, as shown in Fig.2. The surface roughness increases rapidly, until by a dose of $\sim 10^{13}$ p/cm^2 the feature size is ±200 nm. The feature size then reduces until by a dose of $\sim 10^{14}$ p/cm^2 it has smoothed out to ±10 nm, but still with sharp rather than smooth features. This tends to indicate a 'stochastic averaging' of the features produced by the bombardment as a large number of collisions take place.

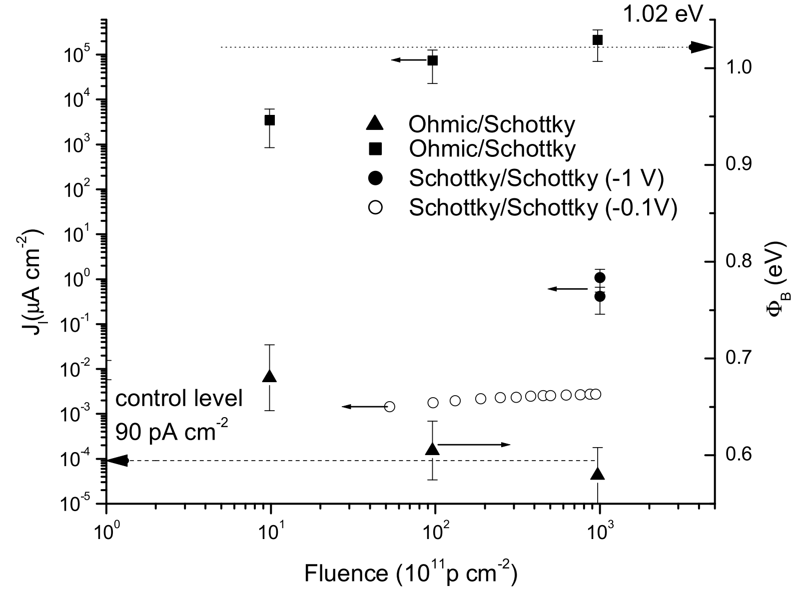

Fig. 1. Leakage measurements and barrier height measurements for 24 GeV proton irradiated SiC. Schottky/Schottky diodes were completed before irradiation, ohmic/Schottky had Schottky contact applied to irradiated surface

The damage caused by the radiation was only apparent on the surface. As

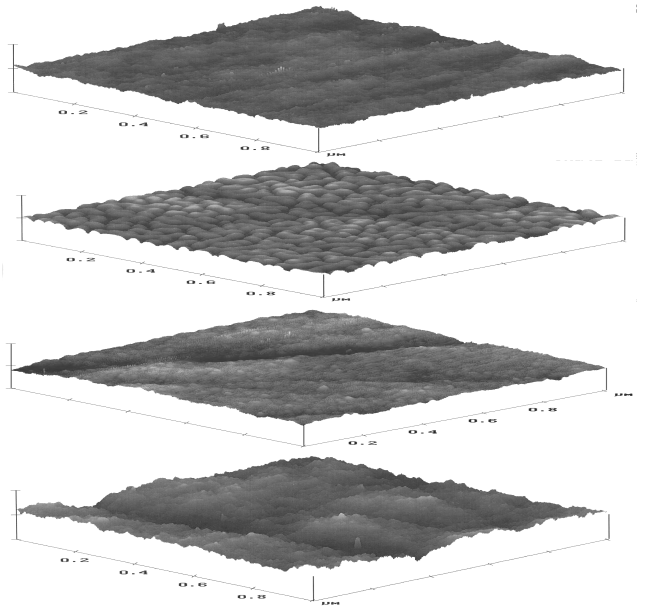

Fig. 2. AFM scans of irradiated SiC. Feature sizes range from (i) un-irradiated ±4 nm, (ii) 9.8x10^{11} p/cm^2 ± 60 nm, (iii) 9.6 x10^{12} p/cm^2 ± 200 nm, and (iv) 9.7 x10^{13} p/cm^2 ± 10 nm.

shown in Fig.3, Raman spectroscopy suggested no significant change in sub-surface lattice structure between pre- and post-irradiation. A comparison spectrum is included here from Burton et al [6]. The scans are differentiated only by finer features in the post-irradiation scan, as a consequence of more accurate measurement equipment. This suggests that the high binding energy of the SiC has ensured the internal structure was not affected adversely by the bombardment, as this would have been revealed as a broadening or displacement of the phonon peaks.

3 I-V characterisation of devices

In order to reduce the leakage currents still further detectors were made using bulk semi-insulating (S.I.) 4H SiC from Cree Research. This had a resistivity of $>10^5\Omega$cm. The material was thinned to $\sim$100 μm. Contacts to the S.I. SiC are formed from a different recipe than those for n-type SiC. Due to the slightly p-type, effectively intrinsic, nature of the material a modification of the contacting recipe is required for good I-V characteristics. For the experiments using the S.I. material the contact scheme used is 100 nm e-beam evaporated Ni annealed at 1100^o C for 30 s for Schottky contacts with ohmic contacts being made from 50 nm Ti / 50 nm Au e-beam evaporated and left un-annealed. The surfaces were prepared for contact deposition using a standard solvent clean with warm acetone and warm IPA (iso-propyl-alchohol) to de-grease the surfaces. This was followed by a standard de-oxidisation etch, 5

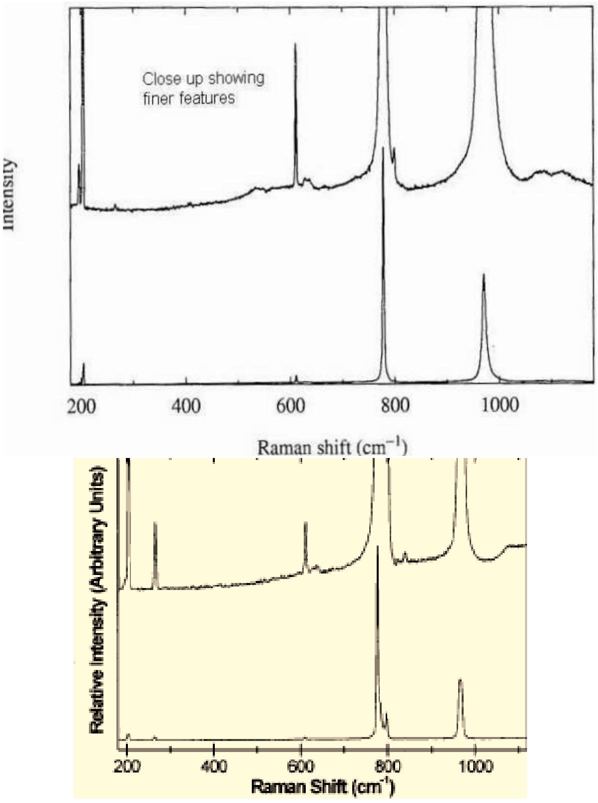

Fig. 3. *A(top)*: Raman spectrum for the SiC piece which was irradiated at 9.7 x10^{13} p/cm^2. *B(bottom)*:Comparison spectra from Burton et al[6]. Both show prmiry features with insets showng closer detail of features.

min in a solution of 4:1 H_2O:HF (hydrofluoric acid), to remove the SiO_2 layer and ensure good electrical contact to the SiC. I-V measurements were performed on the diodes using a Keithley 237 electrometer and a manual probe station. They indicated an ideality factor for the Ni, Ti/Au diodes of 1.7 and barrier height of $\sim$1.8 eV [7]. Measurements were taken over the range ± 1000 V. Plotting the I-V curves after a number of tests it became apparent that there was a variation in the material response, as seen in see Fig.4. To try to understand this a plot was made of the current leakage at -100 V over a range of humidity levels. This is shown in Fig.5. Surface leakage currents affecting I-V measurements have been reported by Dubbs et al [8] who used flowing nitrogen to control them. The data suggests a dependence on conduction via surface states on humidity. For future I-V characterisation of devices it is better to passivate the surface using a dielectric layer, for example Si_3N_4. However the effect that this will have on the detection properties is possibly small as all measurements of CCE are taken in vacuum. The I-V characteristics themselves indicated that good low noise operation should be possible, as shown in Fig.6 which is the full plot of the diode I-V measurements at 45 % humidity. The I-V plot shows a reverse current of -2.5 nA at -1000V. When properly bonded the current drawn by a detector is very low, producing low noise devices.

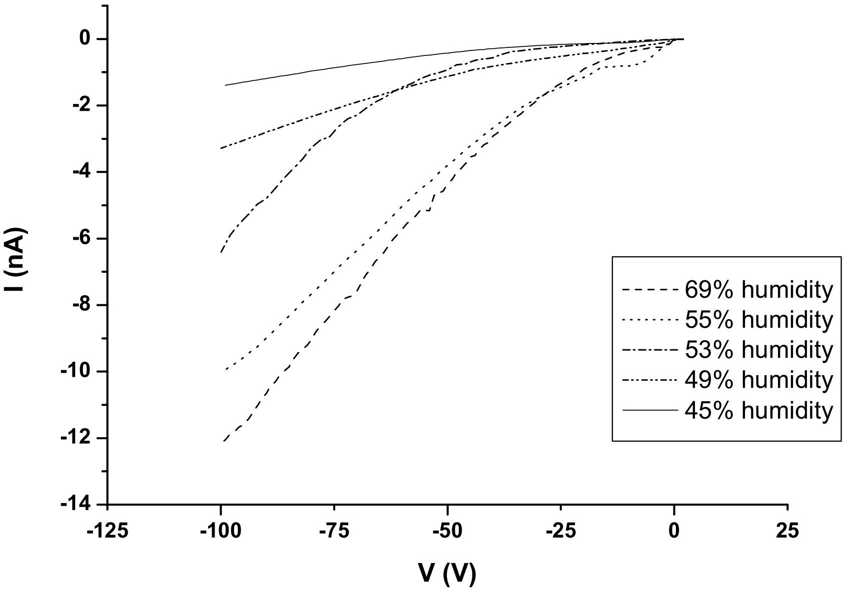

Fig. 4. Reverse current plots for 500um pad from 0- -100V for different humidity levels.

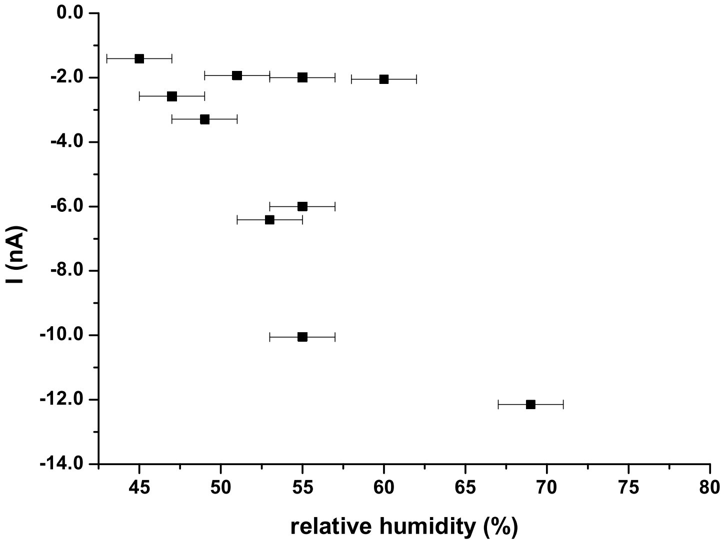

Fig. 5. Fitting points to exponential decay at -100V for a range of humidities.

4 Spectra of Am^{241}

Two sets of diodes were produced to allow comparison of forward and reverse bias CCEs. These were bonded to a holder with Au wire and tested with an

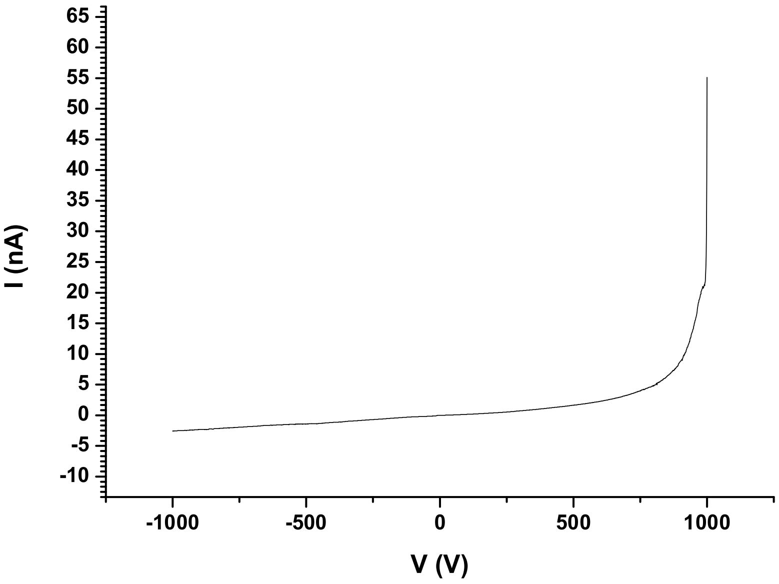

Fig. 6. I-V plot for annealed Ni pad and un-annealed Ti/Au back contact, relative humidity is 45%.

Am^{241} 5.48 MeV α source in a vacuum of ~23 mbar. The spectra obtained from the test shown in Fig.7 are from a forward biased detector. This has a full face Schottky back contact of 100 nm annealed Ni, and an ohmic front

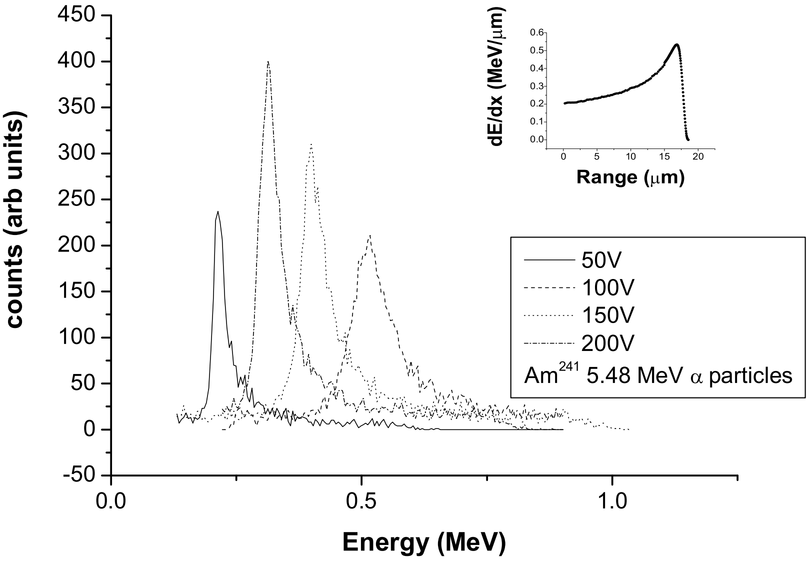

Fig. 7. SiC line spectra for a 5.48 MeV Am^{241} α source over range of bias voltages, collecting electrons at the pad, inset TRIM data showing range of patricles in SiC.

pad of 50 nm Ti/ 50 nm Au. Operating in this fashion the device is collecting electrons at the pad. These spectra were taken using a single diode at a range of bias voltages. The CCE for each voltage level is given. The CCE calibration is with respect to a large area Si diode calibrated using a spectroscopic source. The low CCE value for each of the three voltage levels suggests that most of the charge is being lost. For example compare with Nava et al [4] who used thin lightly n-doped epitaxial films achieving 100 % CCE for 2 MeV α and $\sim$70 % for 5.48 MeV α particles. The range of the a particles is $\sim 18 \mu$m as shown by the inset SRIM [9] data. The relatively low field strength coupled with a low hole mobility < 100 cm^{2}V^{-1}s^{-1} mean that most of the available charge is recombining before being detected.

A second set of diodes was fabricated from 400 mm thick SiC which were designed to be reverse biased, with an ohmic back contact and a Schottky front contact, which collects holes at the pad. Barrier height and ideality values were comparable to the first set of devices. CCE values were collected for high voltage runs, as seen in Fig.8. This has a 100 % CCE when operating

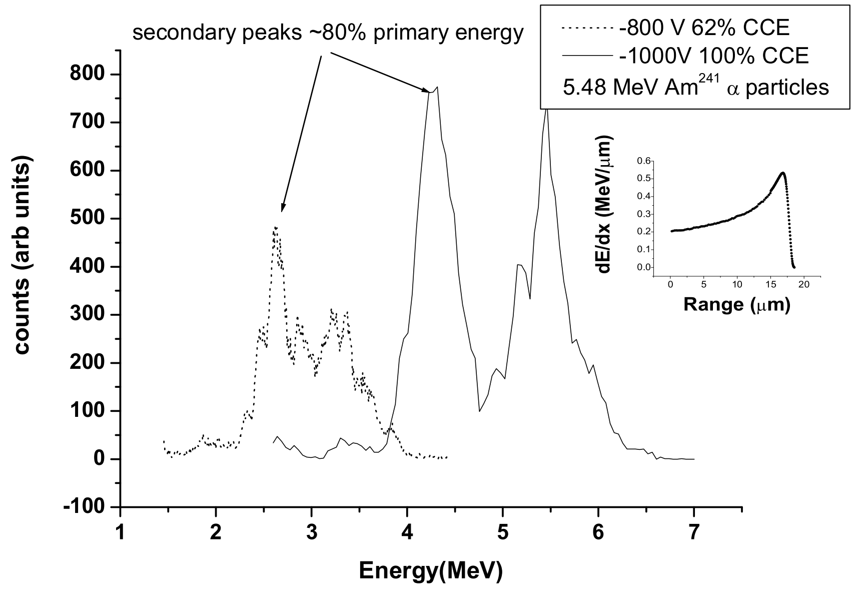

Fig. 8. SiC line spectra for a 5.48 MeV Am^{241} α source over range of bias voltages, collecting holes at the pad, inset SRIM data showing range of patricles in SiC

at -1000V using the same Am^{241} source as before in a vacuum of 23 mbar. The vast increase in the CCE from the initial set of devices may be attributed to the higher value of the electron mobility $\sim$900 cm^{2}V^{-1}s^{-1} meaning that most of the charge is being swept through the bulk of the device. The low mobility holes have only a short distance, 18 μm, to travel and so again are swept out. The electric field corresponds to $\sim$25 kVcm^{-1} which is far below published values of the breakdown field of > 2 MVcm^{-1} [10] for this type of material. The reason for the secondary peak is not understood at present although diffusion of charge generated from outside the diode area may be a possibility.

5 Summary

The present work has looked at the viability of currently available bulk S.I. SiC for use as detector material. The data from the irradiation of samples suggests that there is some resistance to radiation damage, changes in leakage current being minimal when measuring fully completed devices. The structural changes caused when relativistic protons bombard the material also appear minimal. We have shown that it is possible to use SiC as a semiconductor detector medium, by achieving 100 % CCE for an Am^{241} 5.48 MeV α source with reverse biased Schottky barrier diodes.

A number of issues still must be addressed before SiC is acceptable as a detector material. The problem of energy resolution may be a limiting factor in the operation of detectors. The large energy needed to create an electron hole pair, 8.4 eV [10], implies that SiC will always be of limited use for low energy detection or where energy peaks are very close together. However the main area were the use of SiC is targetted in this paper is in high energy, high radiation damage environments. In this case the detector properties of the material appear to be very suitable.

Acknowledgements

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