Silicon Carbide Radiation Detector for Harsh Environments

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Abstract

We used commercial of the shelf (COTS) silicon carbide (SiC) ultraviolet photodiodes for measuring gamma dose rates at high temperature. We tested them with Co-60 gamma dose rates between 0.03 mGy(Air)/s and 3 Gy(Air)/s. The diodes show excellent sensitivity, high signal to noise ratio, and good linearity. They had been operated at temperatures up to 200° C with negligible changes of the dark and the radiation induced current. Gamma irradiation up to a total dose of 1080 kGy(Air), 32 MeV proton irradiations up to a fluence of 8.5×10^{12} cm^{-2}, and 14 MeV neutron irradiations up to 4.1×10^{12} cm^{-2} demonstrate their radiation hardness. These results and the ability to measure the proton as well as the neutron dose rate after a calibration with Co-60 gammas show that COTS SiC diodes can be used as radiation detectors in harsh environments.

I. INTRODUCTION

Semiconductor radiation detectors offer several important advantages over other types of detectors such as gas-filled counters. Faster charge-collection times of these solid-state detectors provide them with the ability to process higher counting rates. Their compactness allows the measurement of intensity variations over small distances. However, the use of conventional semiconductor detectors, made of germanium (Ge) or silicon (Si), in harsh environments is limited by radiation damage to these materials and by temperature constraints. There exist different approaches to increase the radiation hardness of solid state silicon detectors:

1. Cooling ordinary silicon detectors,
2. Lowering the initial bulk resistivity of the silicon (i.e. increasing the initial as-grown defect concentration) [1],
3. Using a better-suited detector bulk material.

Concentrating on the last point such a better material should have the following properties:

A large bandgap and a high atomic displacement threshold energy, which gives improved radiation hardness.

A high electron and hole mobility, which leads to fast signal collection.

A high resistivity, so that no dopants are needed.

A low dielectric constant, which lowers the capacitance and therefore the noise.

It should be mono-crystalline to have a good charge collection efficiency [2].

It should have a high thermal conductivity, in order to have good cooling properties.

It should be a commercially available product.

So several studies on the properties of commercially available SiC as a material for radiation detection have been initiated [3, 4]. Its high band gap energy (3.2 eV) and displacement threshold energy (21.8 eV) [5] should lead to a detector capable of operating at elevated temperatures and in high radiation fields.

The purpose of this work is to demonstrate the possibility to use a commercial SiC ultra-violet (UV) sensitive photodiode as a radiation detector, which can be utilised in harsh environments including nuclear reactors. The used SiC diode was proven to be a radiation hard UV detector [6].

II. EXPERIMENTAL SET-UP

The devices under test were 6H-SiC photodiodes manufactured by Cree Research Inc. and encapsulated by IFW Jena, Germany. The commercial types are available in different sizes and with different UV blocking filters. We used JEC 1 ISHT with an active size of 1 mm^2, but without window (hermetically closed) in order to minimise background current from UV light. The dark current is in the order of 1 fA according to the manufacturer. They were specified to work at temperatures up to 250° C.

A Keithley 617 electrometer has been used to apply a bias voltage and to read the induced current. The temperature could be controlled and measured online. The temperature range was between 23° C and 200° C. For each type of measurement we tested 3 diodes.

Gamma irradiation tests were carried out with our Co-60 irradiation facilities "GAMMAMAT TK 1000" and "GAMMAMAT TK 100". Their maximum activity are 22 TBq (600 Ci) and 520 GBq, respectively. The dose rate could be changed by changing the distance between detector

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and source from 2 to 150 cm. Therefore the achievable dose rates are between a few Gy(Air)/s and a few tens of µGy(Air)/s. They were measured with a calibrated ionisation chamber, type IC10, manufactured by Wellhöfer Dosimetry. The SiC diodes were also irradiated with 32 MeV protons at the cyclotron "JULIC" of the Research Centre Jülich [7] and with 14 MeV (D-T)-fusion neutrons at the SAMES TB 4 neutron generator of the Fraunhofer-INT. The proton flux was measured with a small ionisation chamber, type IC04, manufactured by Wellhöfer Dosimetry, and it was calibrated with Co-60 gammas. The neutron flux during the irradiation was monitored with two calibrated uranium-238 fission chambers, type FC4A from Centronic Inc.

III. RESULTS

A. The Effects of Bias Voltage

Initial characterisation of the SiC diodes was performed before radiation testing of the detectors. Figure 1 shows the dark current - voltage characteristic. The dark current is only in the range of 10 to 50 fA for bias voltages below 20 V. As a consequence the signal to noise ratio during irradiation will be high, even with low signal amplitudes.

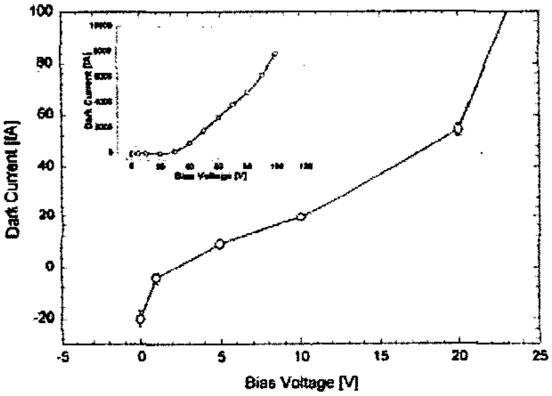

Figure 1: Dark current - voltage characteristic of a JEC 1 ISHT SiC diode at room temperature.

The active layer thickness of a diode is proportional to the square root of the applied (reverse) bias voltage [8]. As an external voltage is applied to the diode, the active region grows until the maximum active layer thickness is reached. At this point the diode is said to be fully depleted and the applied bias voltage is referred to as the depletion voltage. Further increase in the applied voltage can not result in any more growth of the active layer thickness.

Figure 2 shows the effect of the applied (reverse) bias voltage on the signal current at a gamma dose rate of about 30 mGy(Air)/s. The gamma-induced current increases with increasing reverse bias voltage. This can be attributed to the widening of the diode's active layer, because for the same dose rate more ionisation is produced in a bigger volume.

As an outcome of the initial characterisation the bias voltage was fixed at 20 V for all further radiation testing, because at this point the signal to noise ratio (S/N) is nearly optimal. At lower voltages the S/N should be higher because of the smaller dark current, but these values (below 20 fA) are stable only after 5 to 10 minutes of settling time after any change of any experimental parameter (voltage change, beam on/off, etc.).

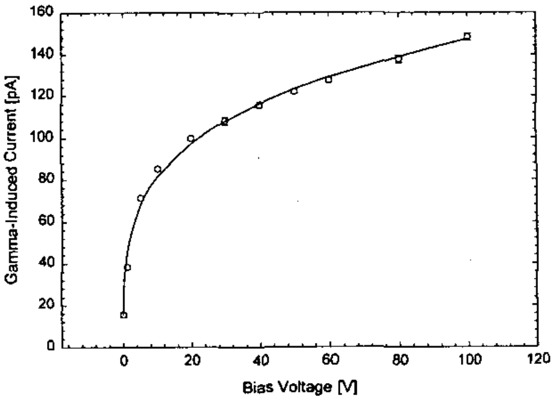

Figure 2: Increase of the gamma-induced current in a SiC UV-sensitive photodiode with increasing bias voltage at room temperature. The gamma dose rate was 30 mGy/s.

B. Response to Radiation

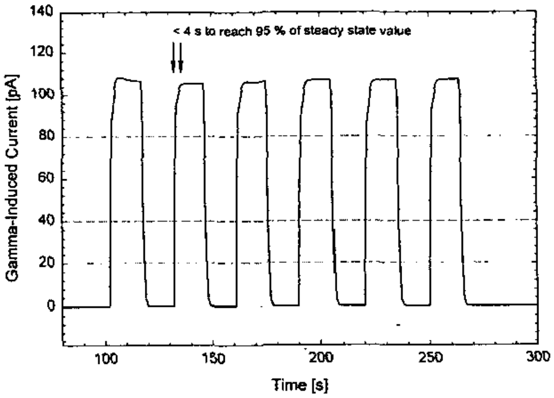

Figure 3: Response of a SiC diode to 6 successive gamma irradiations of 15 s duration at room temperature. The dose rate was 30 mGy(Air)/s. The applied bias voltage was 20 V.

Figure 3 shows the gamma-induced current versus time at room temperature of the SiC diode. The device under test (DUT) is exposed with a dose rate of 30 mGy(Air)/s for 6 successive radiation periods. A short time is required before the current reaches a stable value. This is partly due to the fact that it takes about 0.3 s to move the gamma source into or out of the shielding container. It was found that the settling time (time to reach 95 % of the steady state value) is less than 4 s. This is suitable for applications with slowly changing dose rates.

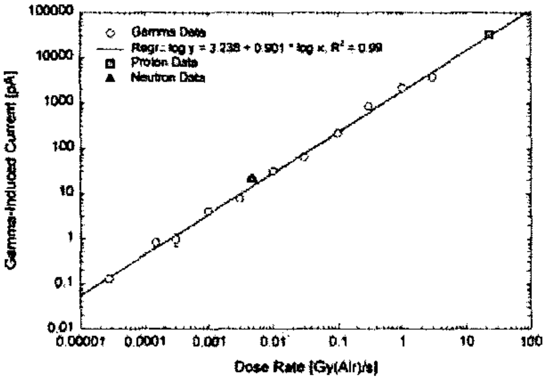

Figure 4: Gamma-induced current of a SiC photodiode as a function of gamma dose rate at room temperature, with an applied bias of 20 V. The gamma-induced current is linear in the log-log plot over nearly 6 orders of magnitude. Corresponding values for proton- (deduced from fig. 11) and neutron-induced current (from fig. 12) are plotted in this figure.

From these measurements we could deduce a lower limit of the detectors sensitivity (collected charge per absorbed dose) which 1.2 nC/Gy(Air) at 3 Gy(Air)/s. Whereas the lower limit of the signal to noise ratio is 25 at 28 µGy(Air)/s. This is shown in figure 5 where the temporal response of the diode for the above mentioned dose rates at room temperature is shown.

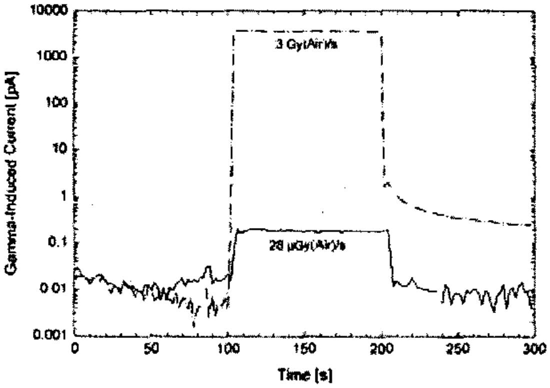

Figure 5: Temporal response of a SiC diode at two different dose rates, showing the high signal to noise ratio. The applied bias voltage was 20 V.

C. Temperature Effects

Additional experiments were performed to study the detector response with changing temperature. Firstly the change of the dark current with temperature was studied before irradiation and after a total dose of 20 kGy(Air). Therefore the diode was heated up to 250° C and the dark current was monitored while it was cooling down to room temperature. This measurement was made with a bias voltage of 20 V. The result for the temperature range between 30 and 150° C is shown in figure 6. There is only a small change for temperatures below 100° C but at higher temperatures the dark current increases exponentially. So if one wants to measure dose rates at temperatures above 100° C the use of this detector is limited to application where either small temperature variations or high dose rates, e.g. > 0.01 Gy/s, occure. Over the measured temperature range the dark current rose about 50 fA after a dose of 20 kGy(Air)

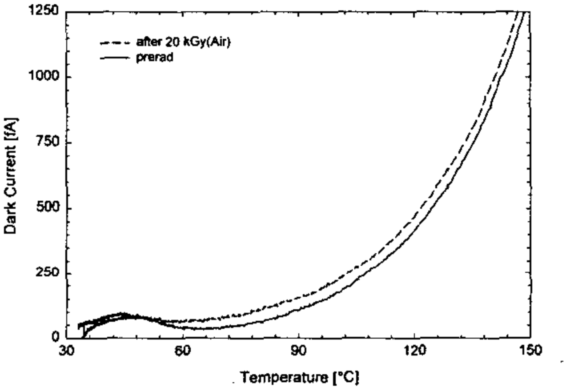

Figure 6: Effect of temperature on the dark current of a SiC diode before irradiation and after a total dose of 20 kGy(Air). The applied bias voltage was 20 V.

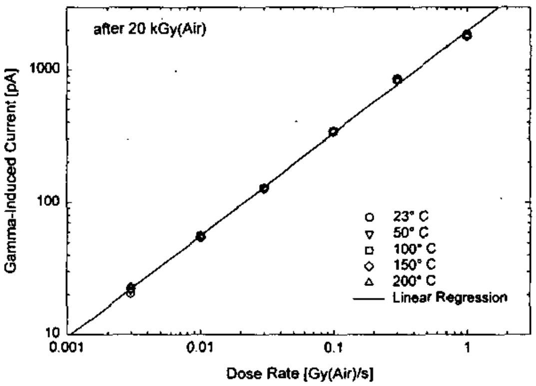

Figure 7: Effect of temperature on the linearity of the detector response after a total gamma dose of 20 kGy(Air). The applied bias voltage was 20 V.

Secondly the linearity of the detector response was measured before irradiation and after a total dose of 20 kGy(Air). These tests were done at 5 constant temperatures between 23 and 200° C. Results are shown in figure 7. No significant changes were observed.

These results demonstrate that the response of a SiC diode to gamma radiation is nearly unperturbed by temperature in the studied range. This could be expected due to the wide bandgap energy of SiC.

D. Radiation Hardness

The radiation hardness of SiC diodes was studied with two types of radiation. The tests were performed at room temperature and with an applied bias voltage of 20 V. At first they were irradiated with Co-60 gammas up to a total dose of 870 kGy(Air). During that test the gamma-induced current only decreased by 10 % and seems to reach a plateau after a total dose of 500 kGy(Air). This is shown in figure 8.

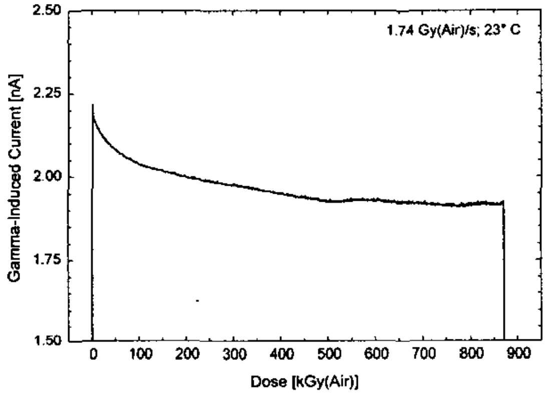

Figure 8: Decrease of the gamma-induced current of a SiC diode during gamma irradiation with an applied bias voltage of 20 V.

Secondly the gamma-induced increase of leakage current was studied. In figure 9 there are shown two irradiations. One from 0 to a total dose of 10 kGy(Air) and one from 0 to 870 kGy(Air). During the first irradiation the dark current increased from 0.013 to 0.2 pA and during the second one from 0.007 to 1.4 pA. Furthermore it can be seen that the radiation-induced increase of the leakage current after 10 kGy(Air) rapidly (within 2000 s) anneals to pre-irradiation levels. Whereas after the second (longer) irradiation no annealing was observed.

In a third step the total dose effect on the linearity of the detector response was studied. The results are shown in figure 10. As can be seen, there is no major effect of the total dose on the linearity of the detector response after 1080 kGy(Air). This could be expected after the results from the previous radiation hardness tests (slight decrease of the signal amplitude, see figure 8, and slight increase of the leakage current, see figure 9).

In [6] JEC 0.1 SiC diodes (same type but only 0.1 mm^2 active area) were irradiated with 32 MeV protons. This is shown in figure 11. During the time-intervals I 1, 2 and 3 (shaded in fig. 11) their UV-sensitivity was measured in order to test their radiation hardness as a UV detector used in proton environments. During that irradiation the proton-induced current was monitored and it nicely follows the proton flux up to a fluence of 8.5×10^{12} cm^{-2} (except for the time-intervals I 1, 2 and 3 when the UV light was on).

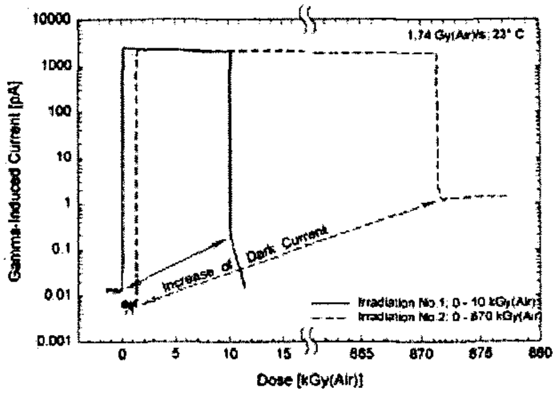

Figure 9: Increase of dark current during two gamma irradiations up to 10 and 870 kGy(Air) respectively. The applied bias was 20 V.

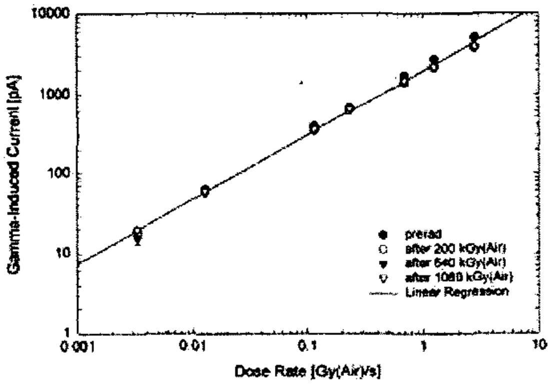

Figure 10: Linearity of the detector response before and after several total dose values. The applied bias was 20 V, and the temperature was 23° C.

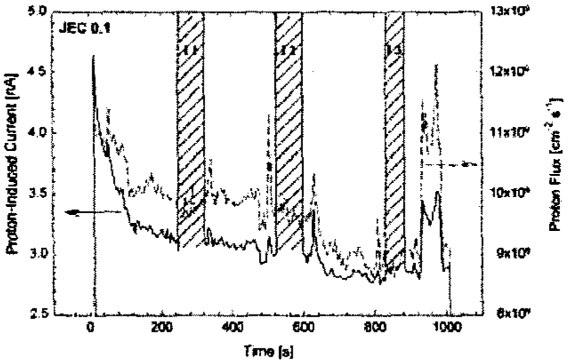

Figure 11: 32 MeV proton flux and proton-induced current in a SiC diode JEC0.1 at room temperature.

The SiC diodes were also irradiated with 14 MeV neutrons. The neutron-induced current in the SiC diode was measured online. The behaviour of its signal amplitude should be an indication for the effect of neutron radiation on the radiation sensitivity of a SiC diode. The results are shown in figure 12 up to a total neutron fluence of 4.1 x 10^{12} cm^{-2}. The irradiation was interrupted every 30 minutes for 5 minutes to study the effects of neutrons on the leakage current.

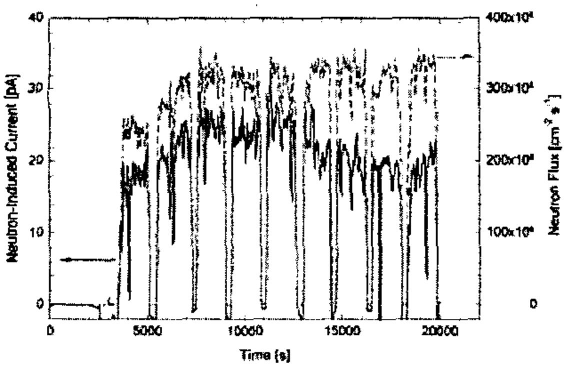

Figure 12: 14 MeV neutron flux and neutron-induced current in a SiC diode at room temperature. The applied bias was 20 V.

Up to a total neutron fluence of about 2.2 x 10^{12} cm^{-2} (after 12500 s) the signal amplitude follows the temporal behaviour of the neutron flux identically. After that fluence the signal began to decrease by about 20 % until the end of the irradiation while the neutron flux was nearly constant. In figure 12 there is no evidence that 14 MeV neutron radiation has an effect on the dark current at least up to a total fluence of 4.1 x 10^{12} cm^{-2}.

So SiC diodes of this type can be used as radiation detectors up to a total gamma dose of 1000 kGy(Air), to a 32 MeV proton fluence of nearly 10^{13} cm^{-2} or to a 14 MeV neutron fluence of about 4.1 x 10^{12} cm^{-2} without major degradation. This could be expected because of the high displacement energy in SiC.

E. Radiation Dosimetry

The good agreement between particle flux (proton as well as neutron) and particle-induced current brought up the following question: "Is it possible to use SiC diodes also as particle radiation dosimeter based on a calibration with Co-60 gammas?".

A proton-induced current of 32 nA (ten times the current from fig. 11) at a flux of 9 x 10^9 cm^{-2} s^{-1} is also induced by a Co-60 gamma dose rate of 25.5 Gy(Air). From these two values a proton energy loss in SiC of 17.7 MeV cm^2 g^{-1} can be derived. This is in good agreement with published data of 15.8 MeV cm^2 g^{-1} [9].

Whereas a neutron-induced current of about 20 pA at 2.5 x 10^8 cm^{-2} s^{-1} (see figure 12) corresponds to a Co-60 gamma dose rate of about 5 mGy(Air)/s. The division of both values result in a fluence dose conversion factor of 2 x 10^{-11} Gy cm^2 which is in good agreement with a derived kerma factor of 1.88 x 10^{-11} Gy cm^2 for SiC (published kerma factors are 1.30 x 10^{-11} Gy cm^2 for Si and 2.46 x 10^{-11} Gy cm^2 for C [10]).

This strongly supports the opinion of using SiC diodes as detectors for any kind of radiation. And after calibration at a Co-60 gamma source it is possible to measure the ionising dose applied by protons and neutrons.

IV. CONCLUSIONS

The possibility to use a commercial SiC UV photodiode as a radiation detector has been investigated. We found:

- that the small dark current in combination with a large radiation-induced current (sensitivity) gives a high signal to noise ratio.
- that the detector response is linear over 5 orders of magnitude of gamma dose rate.
- no evidence of temperature effects on the performance of the SiC detector for temperatures below 200° C.
- that the detector performance is nearly unchanged up to a total gamma dose of 1000 kGy(Air), a 32 MeV proton fluence of 8.5 x 10^{12} cm^{-2}, or a 14 MeV neutron fluence of 4.1 x 10^{12} cm^{-2}.
- that after a calibration with Co-60 gammas it can be used as a proton or a neutron radiation dosimeter.

These results demonstrate the potential of SiC COTS photodiodes as radiation (ionising and particle) detectors for use in applications where intense radiation fields and high temperatures are expected.

And last but not least in [6] it was shown that their initial function as a UV detector can also withstand harsh environments.

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