Radiation Effects in Ultraviolet Sensitive SiC Photodiodes

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Abstract

We tested SiC photodiodes with Co-60 gammas, 32 MeV protons and 14 MeV neutrons. The UV-photocurrent decreased to about 50 % of its initial value at a total gamma dose of 40 kGy(Air). Nearly the same decrease was observed during proton irradiations of 9×10^{12} cm^{-2}. But after a neutron fluence of 1.5×10^{13} cm^{-2} the signal was still 85 % of that before irradiation. It is shown that the decrease of the photocurrent is caused by darkening of the glass window. Some of the colour-centres could be annealed with the intense UV-light of a deuterium lamp. Furthermore hydrogen treatment of the photodiode reduces the radiation effects by about 20 %.

I. Introduction

Sensors for the detection of ultraviolet (UV) light are of great interest in space investigations, high temperature plasma research, spectral analysis, medicine and other fields of science and technology. In spaceborne systems UV sensors are used to determine the earth's ozone layer thickness, e.g. the "Global Ozone Monitoring Experiment" (GOME) onboard ESA's remote sensing satellite ERS-2, or to analyse the spectral emission of the sun in the UV range, e.g. the US-Navy's "Solar Ultraviolet Spectral Irradiance Monitor" (SUSIM) onboard of the "Upper Atmosphere Research Satellite" (UARS). For such space applications detectors made of silicon carbide (SiC) would advantageous because SiC devices show several attractive features such as lower leakage current from thermally-generated carriers, operation at elevated temperatures and a greater radiation hardness than most other semiconductors, e.g. Si or GaAs [1-4]. Some of the properties of the different SiC polytypes compared to Si and GaAs are shown in table 1.

II. Gamma Irradiations

The devices under test were 6H-SiC photodiodes manufactured by Cree Research Inc. and encapsulated by IFW Jena, Germany. They are available in different sizes and with different UV blocking filters. They reach their maximal sensitivity of 0.1 A/W at about 275 nm, and their dark current is less than 1 fA.

All tests were performed at ambient conditions in air. During our first test sequence total dose tests were performed at a Co-60 source up to 50 kGy(Air) with a dose rate of 0.3 Gy(Air)/s. The dose rate in air during the irradiation tests were measured with a calibrated ionisation chamber IC10. For simplicity all further doses are given in Gy(Air). 2 of 4 devices were biased during the irradiations, but no differences were observed compared with unbiased diodes. We measured the spectral sensitivity in the range from 200 nm to 400 nm with a bias of 10 V and the dark current at different reverse voltages of 0, 5, 10, 15 and 20 V before and after irradiation. In the case of the spectral sensitivity measurement we used a SiC-photodiode to monitor the total UV-light output of the spectrometer. So we were able to compare each spectrum with each other and to find the changes.

Even after a total dose of 50 kGy(Air) we found no increase in the dark current. That means, it was still in the range of 10 fA which is the uncertainty of our current measurement technique. But we found a noticeable decrease of the spectral sensitivity (see figure 1). The decrease was only $(45 \pm 5)\%$ after 15 kGy(Air) and $(61 \pm 3)\%$ after 50 kGy(Air) at a wavelength of 275 nm. The uncertainties are the standard deviation of all measured devices. The results are very promising for their use in satellites because a total dose in the order of 10 kGy(Air) is high even for the most severe orbits with the sensor placed on the outside, without any shielding. The devices showed no annealing at room temperature because after storage of 4 weeks at room temperature the measured spectra were the same as directly after the exposure to 50 kGy(Air).

Table 1:Properties of SiC polytypes. Silicon and GaAs properties are shown for comparison [6].

	Si	GaAs	6H-SiC	4H-SiC	3C-SiC
Bandgap [eV]	1.1	1.42	3.0	3.2	2.3
Breakdown Field at 10^{17} cm^{-3} [MV cm^{-1}]	0.6	0.6	3.2	3	> 1.5
Electron Mobility at 10^{16} cm^{-3} [cm^2 V^{-1} s^{-1}]	1100	6000	370	800	750
Saturated Electron Drift Velocity [cm s^{-1}]	10^7	10^7	2×10^7	2×10^7	2.5×10^7
Thermal Conductivity [W cm^{-1} K^{-1}]	1.5	0.5	4.9	4.9	5.0
Hole Mobility at 10^{16} cm^{-3} [cm^2 V^{-1} s^{-1}]	420	320	90	115	40
Commercial Wafers	12"	6"	1.375"	1.375"	none

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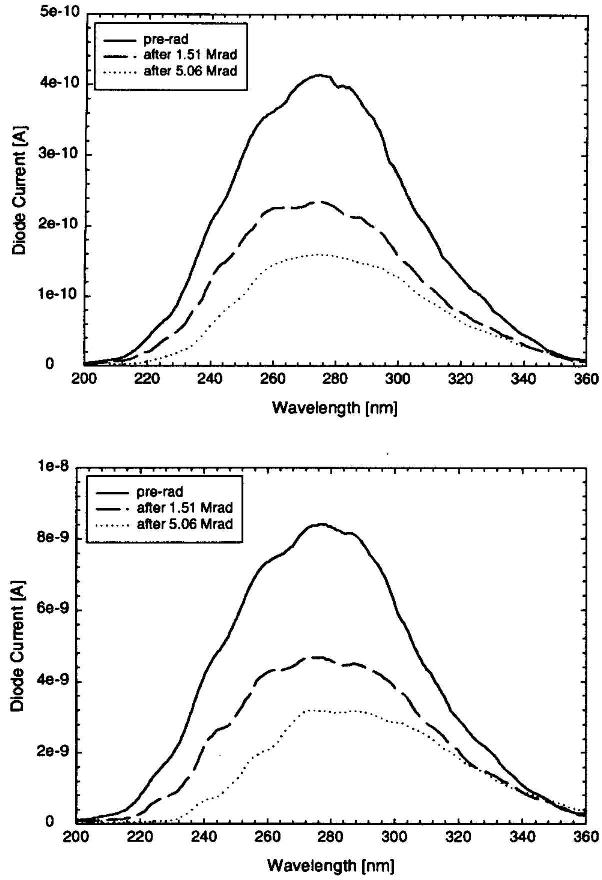

Figure 1: Decrease of spectral sensitivity for different types of SiC photodiodes. Above is the type JEC 0.1 which has an active area of 0.25 x 0.25 mm^2, below a JEC 1 with a size of 1 x 1 mm^2.

Afterwards we measured the UV-photocurrent online. The photodiodes were illuminated with the light of a deuterium lamp via an UV-resistant optical fibre, which was loaded with hydrogen in an autoclave at 150 bar to increase its UV-resistance [5]. The results are shown in figure 2 (circles). The photocurrent decreases to about 50 % of its initial value after 40 kGy(Air). In order to find whether the photodiodes themselves degrade or if it is only increase of UV-absorption in the glass window we opened a device and irradiated it without window (figure 2, squares). This diode only exhibits a decrease to about 90 % of its pre-irradiation photocurrent after 40 kGy(Air). Furthermore we irradiated the window alone and measured its UV-transmission. The reduction of 20 % at 20 kGy(Air) (figure 2, triangles) corresponds to the extra signal decrease of the photodiodes with windows. The results confirm the assumption of a reduction of the UV-transmission in the window.

While we were illuminating the diodes with UV-light during the gamma tests we observed that the intense light with its high energy photons annealed part of the introduced colour centres (e.g. 15 % at 40 kGy(Air), see figure 3). This effect is well-known as photobleaching in optical fibres [7].

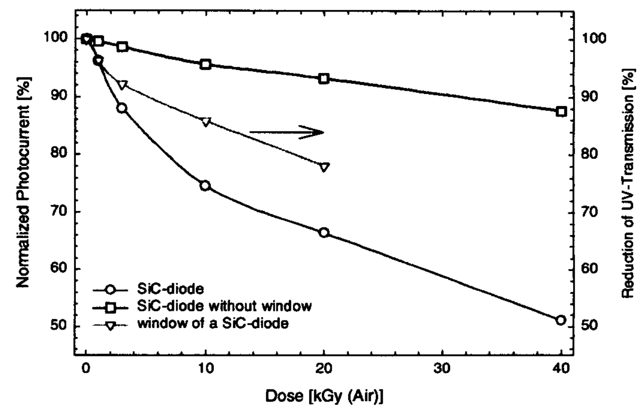

Figure 2: Reduction of photocurrent during Co-60 gamma tests of JEC 0.1 UV-photodiodes (circles and squares). But most of the decrease of the photocurrent could be explained by darkening of the glass window (triangles).

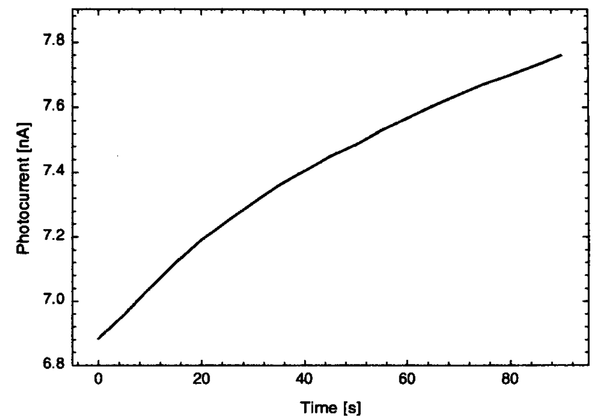

Figure 3: Up to 15 % of the produced colour centres (here after a total dose of 40 kGy(Air)) could be annealed with intense UV-light (photobleaching).

It is known that the radiation resistance of optical quartz fibres could be enhanced by treating them in an autoclave with hydrogen [5]. So we did the same with a photodiode in order to harden the glass window. We put it in an autoclave at 150 bar for one week and did the same total dose test as with the other ones. The results are shown in figure 4. The H_2-treated diode shows 16 % less signal reduction than the untreated one after a dose of 40 kGy(Air).

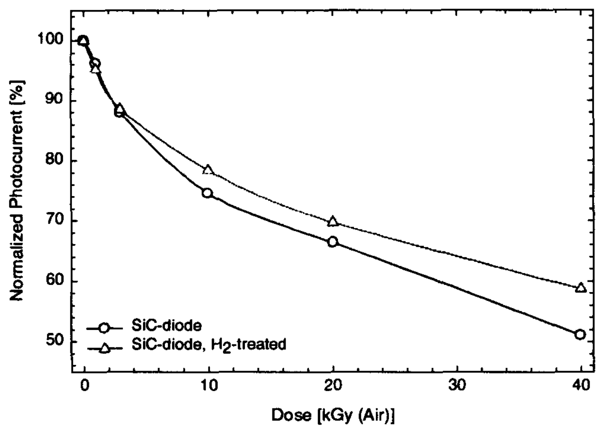

Figure 4: Hydrogen-treatment (triangles) hardens the glass window compared to the untreated window (circles).

III. Particle Irradiations

Detectors used onboard earth observation satellites, that usually fly in low earth orbits with high inclination (e.g. polar orbits for measuring the ozone layer thickness over the poles), also have to withstand a high degree of proton irradiation. The same is true when they should be used for solar observations.

We therefore tested the photodiodes with 32 MeV protons at the cyclotron "JULIC" at the Research Centre Jülich, Germany [8]. Their range in SiC is about 6 mm which was high enough to penetrate the diodes. We irradiated the devices with a flux of about 10^{10} cm^{-2} s^{-1} up to a fluence of nearly 10^{13} cm^{-2} which corresponds to an ionising dose of about 20 kGy(Air). We performed the same online measurements of UV-photocurrent as we did during the Co-60 total dose tests. We found that the photocurrent was reduced to 56% of its initial value after a fluence of 8.5 x 10^{12} cm^{-2} (see figure 5).

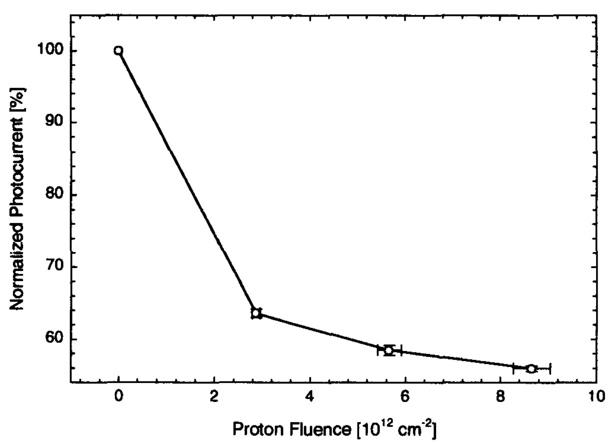

Figure 5: Reduction of photocurrent during 32 MeV proton irradiation of JEC 0.1 UV-photodiodes.

In order to compare the effects of different particle we also measure the response to 14 MeV neutrons. The flux was about 4 x 10^{12} cm^{-2}s^{-1}. The total fluence was 1.5 x 10^{13} cm^{-2} which corresponds to an ionising dose of about 360 Gy(Air). The photocurrent was only reduced to about 84 % of its pre-rad value (see figure 6).

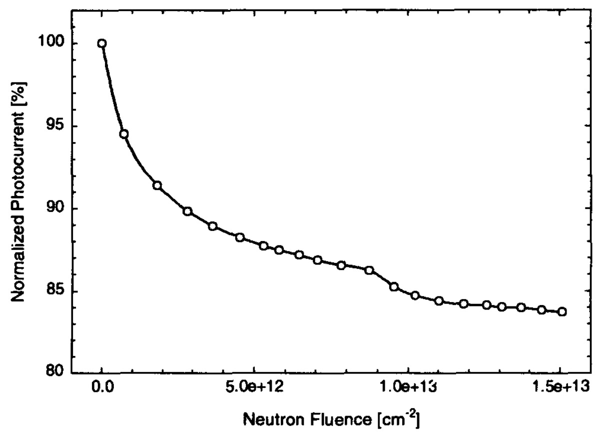

Figure 6: Reduction of photocurrent during 14 MeV neutron irradiation of JEC 0.1 UV-photodiodes.

IV. Comparison of the Effects of Proton and Neutron Irradiations

In an unordered material such as glass ionisation is the primary concern which leads to an increase of light absorption through the production of colour-centres. Whereas in a semiconductor displacement is the main damage effect which reduces the sensitivity of the photodiode through the shortening of the minority carrier lifetime [9, 10]. Displacement damage is proportional to the non-ionising energy loss (NIEL) and do not depend on the specific particle [11]. The protons also applied an ionising dose of nearly 20 kGy(Air) to the window of the diode whereas the neutron dose was only 360 Gy(Air). Under the assumption that the same ionising dose applied by protons or gammas introduce the same amount of colour-centres the effect of the protons can be corrected for the darkening of the window. A gamma dose of 20 kGy(Air) reduced the UV-transmission to 78% of the pre-rad value (see figure 2). For the neutrons this effect should be negligible because of the low dose.

$$\frac{NIEL_P \cdot \Phi_P}{NIEL_N \cdot \Phi_N} = \frac{D_P}{D_N} \quad (1)$$

In equation (1) $NIEL_P$ is the NIEL of 32 MeV protons, $NIEL_N$ the NIEL of 14 MeV neutrons, Φ_P and Φ_N their fluences and $D_{P,N}$ their induced displacement damage (here the reduction of photocurrent). The NIEL (in terms of mass stopping power) of 32 MeV protons is about 3.5 times of that of 14 MeV neutrons in n-GaAs according to [12]. If this ratio is nearly the same for SiC equation (1) leads to:

$$\frac{3.5 \cdot 8.6 \times 10^{12}\ \mathrm{cm}^{-2}}{1.5 \times 10^{13}\ \mathrm{cm}^{-2}} \quad = \quad 2.0, \qquad (2)$$

whereas the ratio of the proton to the neutron induced damage is 2.15. So the displacement damage appears to be similar (in terms of damage per unit NIEL).

V. Conclusions

We have shown that SiC UV-photodiodes can be used on board of satellites that fly in mixed particles environments. The commercial version JEC0.1 that we tested exhibit most of the degradation of the photocurrent due to darkening of the glass window (approximately 80%). This is shown by the comparison between Co-60 gamma and 32 MeV proton irradiation of covered and uncovered samples. Whereas the remaining 20 % come from displacement damage where proton and neutron irradiation showed the same reduction of photocurrent per unit NIEL.

Furthermore we found that some portion of the introduced colour centres in the glass window were annealed by photobleaching due to the high energy UV-light.

Also it was shown that the glass window could be hardened by treating it with hydrogen in an autoclave.

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