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Electron spectroscopy with a commercial 4H-SiC photodiode

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ABSTRACT

A Commercial-Off-The-Shelf (COTS) 4H-SiC p-n photodiode (sold as a UV detector) was investigated as detector of electrons (β^- particles) over the temperature range 100 °C to 20 °C. The photodiode had an active area of 0.06 mm^2. The currents of the photodiode were measured in dark condition and under the illumination of a ^{63}Ni radioisotope β^- particle source (endpoint energy = 66 keV). The photodiode was then coupled to a custom-made low-noise charge-sensitive preamplifier to make a direct detection particle counting electron spectrometer. ^{63}Ni β^- particle spectra were accumulated with the spectrometer operating at temperatures up to 100 °C. The quantum efficiency of the photodiode as well as the spectrum expected to be detected were calculated via Monte Carlo simulations produced using the CASINO computer program. Comparisons between the simulated and detected ^{63}Ni β^- particle spectra are presented. The work was motivated by efforts to apply COTS technologies to develop low-cost space science instrumentation; a low-cost electron spectrometer of this type could be included on a university-led CubeSat mission for space plasma physics and magnetosphere experiments.

1. Introduction

Many wide bandgap semiconductor materials have been studied for their potential utility as radiation detectors for operation in harsh terrestrial environments and for future space missions. Compared with narrower bandgap semiconductors, e.g. Si (E_g = 1.12 eV at room temperature [1]), the wide bandgap semiconductor silicon carbide (4H-SiC, E_g = 3.27 eV at room temperature [2]) has a higher breakdown field, lower intrinsic carrier concentration, and better carrier saturation velocity [1,3], which can bring benefits for high temperature operation. Moreover, SiC detectors have high radiation tolerance [4,5], which can be an important feature for both terrestrial and space applications. Therefore, SiC is expected to play a major role in future spacecraft electronics, particularly as a material for semiconductor radiation detectors used in spectrometers.

SiC was first reported as a particle detector in 1999; detectors made from a 310 μm thick semi-insulating 4H-SiC substrate and with different sizes of circular Ohmic contacts (1 mm to 3 mm diameter) were illuminated with a ^{90}Sr β^- particle source [6]. Since then, SiC has been studied intensively for particle detection. SiC particle detectors can have high charge collection efficiencies [7,8], good linear energy response, and excellent energy resolution [9,10]. SiC particle detectors have also shown stability for extended periods and suitability for operation over a wide range of temperatures (27 °C to 227 °C) [11]. Outside of particle detection, significant work developing SiC for photon counting X-ray spectroscopy has been conducted and reported with superb results [12,13]. Recently, SiC p-n photodiodes intended for UV detection have become widely commercially available. With well-developed fabrication technology and high-quality material, low-cost Commercial-Off-The-Shelf (COTS) SiC detectors open the possibility of using SiC detectors for applications such as industrial monitoring (e.g. monitoring and controlling the thickness of materials, and monitoring of spent nuclear fuel assemblies) as well as low-cost space science (e.g. as electron spectrometers to measure the energy and particle density of electrons in low earth orbit and elsewhere). Much valuable work has also been reported considering SiC detectors for use in laser-plasma diagnostics and the related fields [14–17].

Whilst larger space missions (those comparable to ESA Cosmic Vision S-, M-, and L- Class missions) are likely to continue use custom-detectors for the foreseeable future, mass-produced COTS SiC detectors, like those reported here, may be of value to groups developing CubeSat space science missions at universities and other organisations. Previously, results demonstrating the use of commercial 4H-SiC p-n photodiodes for X-ray spectrometers have been reported [18–20]. In this paper, we present work investigating such photodiodes for their suitability as detectors in electron spectrometer at temperatures up to 100 °C.

2. 4H-SiC photodiodes

The 4H-SiC UV p-n photodiode (active area of 0.06 mm^2) was manufactured by sglux SolGel Technologies GmbH, Berlin, Germany [21] and purchased from a standard electronics retailer in the UK. The 4H-SiC structure had an epitaxial layer consisting of a 0.15 μm thick p type

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layer and a ∼5 μm thick n-type layer on top of a 4H-SiC substrate. The geometry of the devices can be found in Ref. [22]. The device was packaged in TO-18 can with UV-transparent window. The window was removed as per Ref. [18] so that the device could be directly illuminated with the ^{63}Ni radioisotope β^- particle source. Despite the manufacture's stated epilayer thickness (5.15 μm), previous capacitance measurements suggested that the thickness of the device's depletion region was 2.37 μm assuming a parallel place capacitance [19]. However, the X-ray photocurrent measurements in Ref. [19] suggested that the thickness of the detector's active region extended beyond the epilayer to include a portion of the substrate, yielding an apparent active layer thickness of 34.5 μm. However, the leakage current of the detector during the X-ray illuminated measurements may have been greater than that measured before illumination. If this was the case, the photocurrent may have been smaller than the measurement indicated, and thus the thickness of the active region of the detector may have been smaller than the photocurrent measurement implied [19]. Therefore, some doubt existed at the start of the measurements reported in the present manuscript as to whether the active region of the detector was 5.15 μm, 2.37 μm, or 34.5 μm. In this present article, by illuminating the detector with β^- particles we show that the active region of the detector is 5.15 μm; i.e. equal to the manufacturer stated epilayer thickness.

3. Experiments

3.1. Measurements of the detector's leakage current as functions of applied reverse bias

The leakage current of the detector was measured as a function of applied reverse bias from 0 V to 100 V in 1 V increments, at temperatures from 100 °C to 20 °C in steps of 20 °C. To do this, the detector was installed inside a light-tight electromagnetically-shielded box inside a TAS Micro MT Environmental Test Chamber. A dry nitrogen environment (relative humidity $<$ 5%) was maintained inside the chamber in order to eliminate any humidity related effects. A Keithley 6487 Picoammeter/Voltage Source was used to bias the detector. National Instruments Labview software was used to automate the measurements. To ensure thermal equilibrium, the detector was allowed 30 min to stabilise at each temperature before measurements were started. The results are presented in Fig. 1. The leakage current of the detector at 100 V reverse bias and the highest investigated temperature (100 °C) was found to be 44.9 pA ± 0.5 pA (corresponding to leakage current density of 74.9 nA/cm^2 ± 0.9 nA/cm^2). The leakage currents of the device were $<$ 1 pA at temperatures $\leq$ 40 °C. It should be emphasised that the measured currents include the leakage current of the TO-18 can. The Keithley 6487 Picoammeter/Voltage Source had a measurement uncertainty of ± 0.4 pA; as such, the measurements at 40 °C and 20 °C shown in Fig. 1 are considered to be below the noise floor of the picoammeter.

3.2. Current mode β^- particle measurements

A ^{63}Ni radioisotope β^- particle source (consisting of a 3 μm thick ^{63}Ni layer electroplated onto an ∼50 μm thick inactive Ni foil substrate and then covered with a protective 1 μm thick inactive electroplated Ni overlayer) was placed 4.5 mm ± 1.0 mm above the photodiode to investigate the β^- particle response of the photodiode. The ^{63}Ni radioisotope β^- particle source had an active face area of 49 mm^2 and an apparent activity of 136 MBq. The resultant current was measured using the same method as was used for the leakage current measurements (see Section 3.1). The apparent measured β^- particle created current (i.e. the current measured with each device illuminated with the ^{63}Ni radioisotope β^- particle source with the previously measured leakage current subtracted) as a function of applied reverse bias for the device at temperatures from 100 °C to 20 °C is presented in Fig. 2.

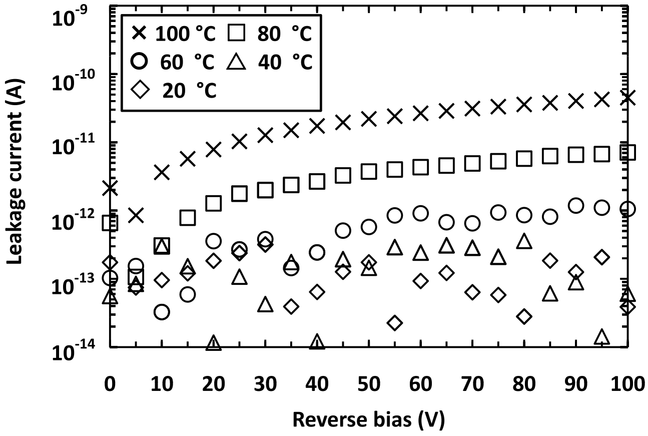

Fig. 1. Leakage currents as functions of applied reverse bias for the 0.06 mm^{2}photodiode in the range of temperature from 100 °C to 20 °C.

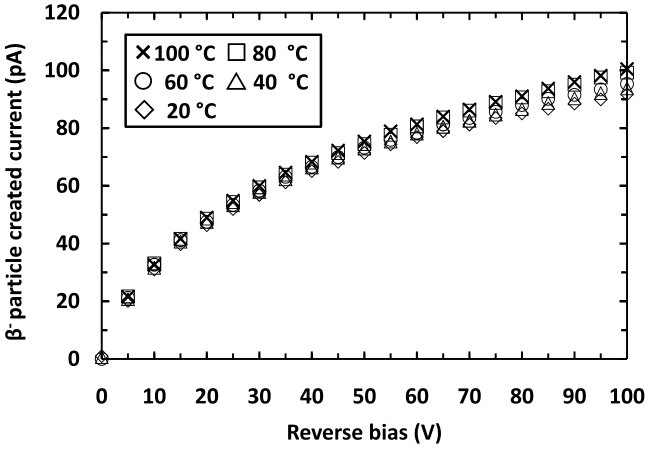

Fig. 2. Measured apparent β^- particle created currents as functions of reverse bias for the 0.06 mm^{2}photodiode in the range of temperature from 100 °C to 20 °C.

Previous X-ray measurements with the photodiode suggested that despite the detector having a stated epilayer thickness of 5.15 μm and a depletion region thickness of 2.37 μm (assuming a parallel plate capacitance) [19], collection of charge carriers created by X-rays absorbed substrate may have contributed significantly to the detected signal [19]. These previous measurements suggested that the detector appeared to have an active region which was 34.5 μm thick [19]. Therefore, to compare with the experimental results, calculations were performed to predict the β^- particle created current expected to be detected under the circumstances that the active region thickness was (a) 5.15 μm, (b) 2.37 μm, and (c) 34.5 μm. The expected β^- particle created current, I, was calculated using,

$$I = \sum_{i=1(keV)}^{end\,point=66(keV)} \frac{A}{2} E_{mi} \frac{A_{SiC}}{A_{Ni}} DE_i \frac{i}{\omega_{SiC}} \mathrm{q} \tag{1}$$

which included consideration of the apparent activity of the ^{63}Ni radioisotope β^- particle source (136 MBq), i.e. including the self-absorption, A (in units of Bq) [23], the emission probability of the ^{63}Ni radioisotope β^- particle source adjusted for self-absorption, E_{mi} (a dimensionless quantity) [24], the ratio of the area of the detector (0.06 mm^2) and the source (49 mm^2 ± 0.2 mm^2), A_{SiC}/A_{Ni} , the percentage of each electron energy deposited in the active region of the detector, considering the losses in the inactive 1 μm Ni overlayer of the source and the 4.5 mm ± 1.0 mm dry N_2 atmosphere between the source and the detector, and the quantum efficiency of the detector, DE_i (a