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X-ray spectrometer with a low-cost SiC photodiode

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A low-cost Commercial-Off-The-Shelf (COTS) 4H-SiC 0.06 mm^2 UV p-n photodiode was coupled to a low-noise charge-sensitive preamplifier and used as photon counting X-ray spectrometer. The photodiode/spectrometer was investigated at X-ray energies from 4.95 keV to 21.17 keV: a Mo cathode X-ray tube was used to fluoresce eight high-purity metal foils to produce characteristic X-ray emission lines which were used to characterise the instrument. The energy resolution (full width at half maximum, *FWHM*) of the spectrometer was found to be 1.6 keV to 1.8 keV, across the energy range. The energy linearity of the detector/spectrometer (i.e. the detector's charge output per photon as a function of incident photon energy across the 4.95 keV to 21.17 keV energy range), as well as the count rate linearity of the detector/spectrometer (i.e. number of detected photons as a function of photon fluence at a specific energy) were investigated. The energy linearity of the detector/spectrometer was linear with an error <± 0.7 %; the count rate linearity of the detector/spectrometer was linear with an error <± 2 %. The use of COTS SiC photodiodes as detectors for X-ray spectrometers is attractive for nanosatellite/CubeSat applications (including solar flare monitoring), and for cost sensitive industrial uses.

1. Introduction

A large number of compound semiconductors have been studied for radiation detection and spectroscopy applications, including GaAs [1–3], AlGaAs [4–6], AlInP [7,8], CdZnTe [9,10], and SiC [11–18]. As one of the wide bandgap (4H-SiC = 3.27 eV [13]) semiconductors, SiC brings the benefits of low leakage currents across a wide range temperatures [14,19,20] and high radiation tolerance [21–24]. Thus, SiC detectors are attractive options for space missions and terrestrial applications that have mass, power, and volume restrictions, since the requirements for cooling and shielding for SiC detectors can be less onerous than for silicon detectors. Within space science and astronomy, SiC detectors may find applicability for in situ and remote X-ray fluorescence (XRF) spectrometry of planetary surfaces in high temperature or intense radiation environments [25–27], as well as for investigation of planetary radiation environments, and near-sun heliophysics and X-ray astrophysics. Terrestrial applications for such detectors include mineral analysis and machine condition monitoring.

Most work on SiC X-ray detectors has concentrated on custom-made devices. However, with the increasing commercial availability of SiC UV photodiodes, interest has been generated in repurposing SiC UV photodiodes as low-cost high temperature tolerant and radiation-hard X-ray detectors. Such use of readily available Commercial-Off-The-Shelf (COTS) technology is of potential value in budget-limited applications such as university-led CubeSat missions.

Previously, results have been reported showing that commercial 4H-SiC p-n photodiodes (manufactured by sglux SolGel Technologies GmbH, Berlin, Germany [28], and purchased from a standard electronics retailer) can be used to spectroscopically detect X-ray photons from an ^{55}Fe radioisotope X-ray source (Mn $K\alpha$ = 5.9 keV; Mn $K\beta$ = 6.49 keV) at room temperature [29] and at temperatures from 100 °C to 0 °C [30]. The geometry of the devices can be found in Ref. [31]. In this paper, we extend the characterisation of this type of photodiode (area = 0.06 mm^2) across the energy range 4.95 keV to 21.17 keV, using eight different high purity metal foils fluoresced by an X-ray tube with a Mo cathode. The photodiode was uncooled throughout the experiment and was maintained at a temperature of 33 °C. The photodiode was supplied mounted in a TO-18 package. In order to directly illuminate the device with X-rays, the UV window of the TO-18 package was removed, as shown in Fig. 1.

2. The photodiode

2.1. Current–voltage characteristics

Previous measurements of the device's current–voltage characteristics showed that its leakage current at temperatures <40 °C was too

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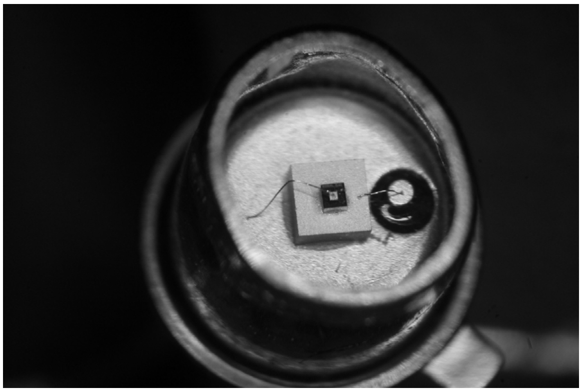

Fig. 1. Photograph of packaged 0.06 mm^2 SiC photodiode with UV window removed.

small to be measured with the available experimental set up, even when the detector was operated at high (100 V) reverse bias [30]. However, because the new X-ray measurements reported in Sections 3.1 and 3.4 of the present article used long accumulation times (14,000 s and 6 h, respectively) with the device kept reverse biased for these periods, measurements were conducted to determine the time stability of the leakage current. Using a Keithley 6487 Picoammeter/Voltage Source, a TAS Micro MT climatic cabinet, and National Instruments Labview software to automate the measurements, the photodiode's leakage current was measured as a function of time when reverse biased at 100 V for 6 h at 33 °C (the temperature at which the X-ray measurements were conducted). The measurements showed that the leakage current remained constant and low (<0.2 pA) throughout the 6 h period.

2.2. Capacitance–voltage characteristics

Measurements of the diode's capacitance as a function of applied reverse bias have been reported at temperatures from 140 °C to 0 °C, in 20 °C steps [30]. However, since the new X-ray characterisation reported in Sections 3.1–3.4 of the present article was conducted at 33 °C (a temperature at which capacitance measurements have not been previously reported for this diode), for completeness, the capacitance of the packaged 0.06 mm^2 SiC photodiode was measured as a function of applied reverse bias at 33 °C. An HP 4275 A Multi Frequency LCR meter was used, in conjunction with a Keithley 6487 Picoammeter/Voltage Source to bias the device, and a TAS Micro MT climatic cabinet for temperature control. The device was installed inside the cabinet and left to stabilise at 33 °C for 30 min before starting the measurement. The AC test voltage signal magnitude and frequency of the LCR meter were set at 60 mV r.m.s. and 1 MHz, respectively. National Instruments Labview software was used to automate the capacitance measurements.

In order to extract the capacitance of the photodiode itself, and separate it from the capacitance of the package (the photodiode and package were considered to be connected in parallel), a sacrificial device of the same type but with its bondwires removed was also measured to yield the packaging capacitance. The capacitance of the photodiode was calculated by subtracting the packaging capacitance (0.75 pF ± 0.01 pF) from the measured total capacitance of the packaged device. The depletion width, W, of the photodiode

$$W = \frac{\epsilon_0 \epsilon_r A}{C} \quad (1)$$

is inversely proportional to the capacitance, C, thus it was calculated using the measured capacitance of the photodiode (Fig. 2a) [32], where ϵ_0 was the permittivity of the vacuum, ϵ_r was the dielectric constant of 4H-SiC 9.7 [33], and A was the diode area. The measured capacitance, the calculated depletion width and the C^{-2} of the photodiode as functions of applied reverse bias at 33 °C are shown in Fig. 2, respectively. The photodiode appeared to be fully depleted at reverse biases ≥ 100 V, with the implied thickness of the depletion width = 2.69 μm ±0.04 μm at 100 V reverse bias.

Whilst a depletion layer thickness of only 2.69 μm suggests that the quantum efficiency of such a detector would be very low at X-ray energies, previous investigation of these devices showed substantially greater photocurrents than would be expected if the active region of the photodiodes was simply limited to the apparent depletion width [29,30]. Previous photocurrent measurements using an ^{55}Fe radioisotope X-ray source to illuminate the detector suggested that the thickness of the active region was 34.5 μm [30]. In addition to the epitaxial layer, part of the substrate was also considered to constitute the active region of the device; the larger than expected photocurrent that was previously measured may be attributed to the collection of the charge carriers generated around the edge of the depletion region [30]. Because the contact of the photodiode has an optical window, and assuming the top layer of the photodiode was active, the quantum detection efficiency, assuming complete collection of the charge created by the X-rays absorbed in the active region, (i.e. active region thicknesses of 2.69 μm and 34.5 μm) was computed using,

$$QE = 1 - e^{\mu t} \quad (2)$$

where μ is the linear attenuation coefficient at the particular X-ray energy, and t is the thickness of the active region [34]; the calculated quantum detection efficiencies of different thickness of the active regions of the diode are presented in Fig. 3 at X-ray energies up to 24 keV.

3. X-ray measurements

3.1. X-ray fluorescence measurements

In order to accumulate X-ray fluorescence spectra for the eight different high-purity (≥ 98.7%) metal foils (the details of which are shown in Table 1), the photodiode was connected to a custom-made low-noise charge-sensitive preamplifier with a 2N4416 Si input JFET (capacitance = 2 pF). The detector and preamplifier were housed in a single light-tight die cast box, with a 4 μm thick Al X-ray window. The detector was well centred in the middle of the window. An ORTEC 572A shaping amplifier and an ORTEC EASYMCA-8k multi-channel analyser (MCA) were connected to the preamplifier. The preamplifier and diode were installed within a LD Didactic GmbH X-ray apparatus (LD Didactic 554 800) with a Mo X-ray tube (LD Didactic 554 861) and a sample stand goniometer (LD Didactic 554 831) which was used to hold each high purity foil in turn. A custom-made aluminium-PTFE collimator (20 mm central open diameter) was used to collimate the X-rays from the X-ray tube. The sample stand goniometer was set at 45° with respect to the collimator. The detector was positioned at 135° with respect to the collimator, with the detector facing towards the focus of the circle of rotation as shown in Ref. [35]. The distance between the centre of the Mo target tube and the collimator was 40 mm ± 3 mm, the length of the collimator was 105.00 mm ± 0.02 mm, the distance between the collimator and the target stand goniometer was 43 mm ± 1 mm, the distance between the target stand goniometer and the spectrometer was 57 mm ± 1 mm, and the solid angle subtended by the detector from the position of the target stand goniometer was 0.015π sr ±0.001π sr. This geometry minimised the detection of X-rays directly from the tube whilst ensuring good detection of the fluorescence X-rays from the foils. The PTFE inner of the collimator ensured complete absorption of any fluorescence X-rays from the aluminium of the collimator. In order to eliminate any influence of humidity effects upon the detector, dry N_2 gas was flowed through the detector-preamplifier assembly throughout the accumulation of the spectra. The preamplifier was powered continuously throughout the accumulation of the spectra of the foils. The photodiode was reverse biased at 100 V to accumulate each spectrum and was only powered off when the high purity fluorescence