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Temperature dependence of commercial 4H-SiC UV Schottky photodiodes for X-ray detection and spectroscopy

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ABSTRACT

Two commercial-off-the-shelf (COTS) 4H-SiC UV photodiodes have been investigated for their suitability as low-cost high temperature tolerant X-ray detectors. Electrical characterisation of the photodiodes which had different active areas (0.06 mm^2 and 0.5 mm^2) is reported over the temperature range 0 °C to 140 °C together with measurements of the X-ray photocurrents generated when the detectors were illuminated with an ^{55}Fe radioisotope X-ray source. The 0.06 mm^2 photodiode was also investigated as a photon counting spectroscopic X-ray detector across the temperature range 0 °C to 100 °C. The depletion widths (at 120 V reverse bias) of the two diodes were found to be 2.3 μm and 4.5 μm, for the 0.06 mm^2 and 0.5 mm^2 detectors respectively, at 140 °C. Both devices had low leakage currents (< 10 pA) at temperatures ≤40 °C even at high electric field strengths (500 kV/cm for 0.06 mm^2 diode; 267 kV/cm for 0.5 mm^2 diode). At 140 °C and similar field strengths (514 kV/cm for 0.06 mm^2 diode; 269 kV/cm for 0.5 mm^2 diode), the leakage currents of both diodes were < 2 nA (corresponding to leakage current densities of 2.4 μA/cm^2 and 0.3 μA/cm^2 for each diode respectively). The results demonstrated that both devices could function as current mode detectors of soft X-rays at the temperatures < 80 °C and that when coupled to a low noise charge sensitive preamplifier, the smaller diode functioned as a photon counting spectroscopic X-ray detector at temperatures ≤100 °C with modest energy resolution (1.6 keV FWHM at 5.9 keV at 0 °C; 2.6 keV FWHM at 5.9 keV at 100 °C). Due to their temperature tolerance, wide commercial availability, and the radiation hardness of SiC, such detectors are expected to find utility in future low-cost nanosatellite (cubesat) missions and cost-sensitive industrial applications.

1. Introduction

Recently, many materials have been investigated for use in high temperature photon counting X-ray spectrometers. Compared with narrower bandgap materials, e.g. Si (E_g =1.12 eV) [1], wide bandgap materials, e.g. GaAs [2,3] (E_g =1.42 eV [4]), $Al_{0.8}Ga_{0.2}As$ [5] (E_g =2.09 eV [6]), 4H-SiC [7,8] (E_g =3.27 eV [9]), diamond [10] (E_g =5.5 eV [11]), and $Al_{0.52}In_{0.48}P$ [12,13] (E_g =2.43 eV [14]), can have better performance when operating at higher temperature. With high quality material available and well-developed fabrication technology, SiC detectors are especially attractive for such applications. Furthermore, they are also radiation tolerant [15], which can be essential in space science and exploration missions [16,17].

The performance of SiC Schottky diode X-ray detectors has been investigated extensively over the past 15 years, with the first measurements of X-ray detection with Schottky junctions on epitaxial SiC being reported in 2001 [18]. SiC was first shown to be suitable for X-ray detection and spectroscopy at high temperatures (100 °C) in 2002 [19], a more detailed study of the same work with improved results was subsequently reported in 2004 [20]. More recently, results have been reported showing energy resolutions as good as 233 eV FWHM at 5.9 keV at 100 °C using ultra-low-noise preamplifier electronics and high-quality semiconductor material [21]. Moreover, the ultra-low leakage current achievable with SiC detectors has stimulated the development of ultra-low-noise charge-sensitive preamplifiers [22]. Whilst such results are superb and demonstrate the suitability and high technology readiness level of the material and the excellent quality of the researchers' preamplifiers many researchers may not have access to such facilities, yet still desire to make photon counting X-ray spectrometers using low-cost commercial-off-the-shelf components for applications such as university-led Cubesat missions and industrial monitoring devices.

Previously, results have been reported showing that commercial-off-the-shelf 4H-SiC photodiodes (sold as UV photodetectors by a standard electronics retailer) could be repurposed as X-ray detectors for use at room temperature [23]. Here, the electrical and X-ray

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detection characterisation of these detectors are reported at temperatures up to 140 °C.

2. 4H-SiC UV photodiodes

SiC UV Schottky photodiodes of two different active areas (0.06 mm^2 and 0.5 mm^2) were purchased from a standard electronics retailer. The photodiodes were manufactured by sglux SolGel Technologies GmbH, Berlin, Germany [24,25]. The UV windows of the TO-18 packages were removed as Ref. [23]. At a temperature of 24 °C, the capacitances of 0.06 mm^2 photodiode and 0.5 mm^2 photodiode (excluding package, 0.67 pF) were 2.1 pF and 9.8 pF, respectively, at 100 V reverse bias. The leakage currents were 0.2 pA and 6 pA, respectively, at 100 V reverse bias [23]. The calculated depletion widths were 2.5 µm (0.06 mm^2 diode) and 4.5 µm (0.5 mm^2 diode) based on the devices' capacitances at 150 V reverse bias.

3. Experiments

3.1. Electrical characterisation

3.1.1. Capacitance-voltage measurements

The capacitances of the two photodiodes were measured as functions of applied reverse bias across the temperature range 0 °C to 140 °C. In turn, each photodiode was installed in a TAS Micro MT climatic cabinet for temperature control. The capacitance measurements were made using an HP 4275 A Multi Frequency LCR meter with an AC test signal of 60 mV rms magnitude and 1 MHz frequency; a Keithley 6487 Picoammeter/Voltage source was used as the external voltage supply. Measurements of the devices' capacitances as functions of temperature were made from 140 °C to 0 °C, with a decrement step size of 20 °C. To ensure thermal equilibrium, the devices were allowed to stabilise at each temperature for 30 min before measurements were started at each temperature. The devices were reverse biased from 0 V to 120 V, in 1 V increments. National Instruments Labview software was used to automate the measurements.

Since the devices were supplied packaged, in order to separate the capacitances of the diodes from the capacitances of the packaging, two sacrificial packaged devices (one for the 0.06 mm^2 photodiode; one for the 0.5 mm^2 photodiode), had their bond wires intentionally broken. The capacitances of the packages with the dice still mounted in each package, but the bond wires removed, were measured across the temperature range using the same procedure as was outlined above. The capacitances of the packages were independent of applied bias but dependent on temperature. The results are presented in Fig. 1.

To determine the capacitances of the photodiodes themselves, the package capacitances (presented in Fig. 1) were subtracted from the capacitances measured with the photodiodes wire-bonded. The device capacitances as subsequently determined, and the depletion width of each diode implied by those capacitances are shown in Fig. 2, for the 0.06 mm^2 and the 0.5 mm^2 photodiodes at the temperature of 20 °C and 100 °C, respectively. Fig. 2 showed the 0.06 mm^2 diode has been fully depleted (2.30 ± 0.03) µm at more than 90 V reverse bias and the 0.5 mm^2 diode has been fully depleted (4.49 ± 0.02) µm at the reverse bias of more than 110 V. Two contributors can explain the recorded increases in the capacitances of these devices with increased temperature. One is an increase in charge density in the depletion layer with increased temperature; a similar effect was previously found in abrupt p^+-n diodes and attributed to an effect where the trap density with an energy level near the centre of the bandgap contributed to a measured increase in capacitance with temperature. Thus, there may have been an increase in the excess donor concentration (N_d) with temperature, with the capacitance of the device at each temperature being expressed by,

$$C = \sqrt{\frac{q\epsilon_s N_d}{2(V_D - V)}} \quad (1)$$

where q is the elementary charge, ϵ_s is semiconductor permittivity, V_D is the diffusion voltage, and V is the external bias voltage [26]. The other contributor is the progressive ionization of previously non-ionised donors in a thin region around the depletion layer with

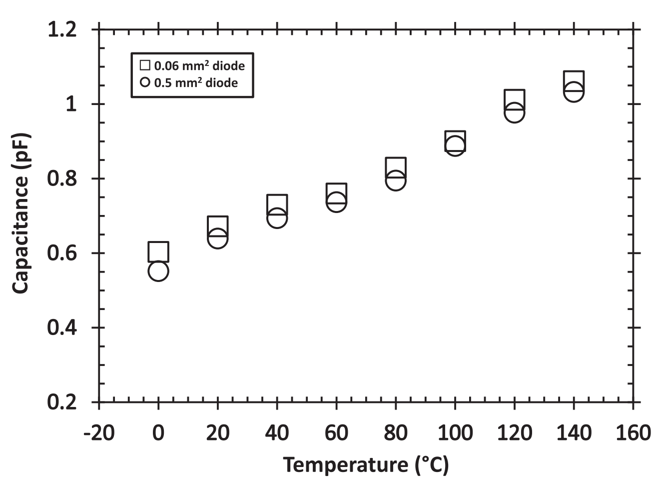

Fig. 1. Measured capacitances of the detectors' packages as functions of temperature for the 0.06 mm^2 diode (open squares) and 0.5 mm^2 diode (open circles).

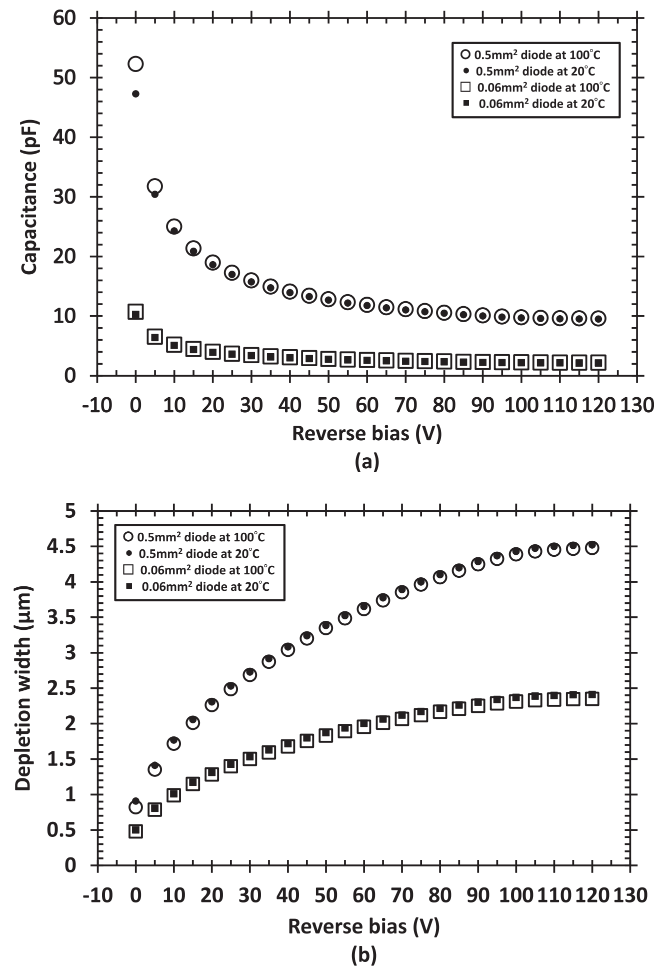

Fig. 2. (a) Measured capacitances of 0.5 mm^2 (open circles 100 °C and solid circles 20 °C) and 0.06 mm^2 (open squares 100 °C and solid squares 20 °C) photodiode as functions of applied reverse bias. (b) Calculated depletion width of 0.5 mm^2 (open circles 100 °C and solid circles 20 °C) and 0.06 mm^2 (open squares 100 °C and solid squares 20 °C) photodiode as functions of applied reverse bias.