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The spectral resolution of high temperature GaAs photon counting soft X-ray photodiodes

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Circular mesa GaAs p^+–i–n^+ diodes for photon counting soft X-ray spectroscopy have been fabricated and characterised over a temperature range of +80 to −30 °C. The spectroscopic performance of the diodes, as measured by the FWHM of the Mn K_α X-ray line from an ^{55}Fe radioisotope, is reported. In addition, we compare the GaAs diodes with previously fabricated and characterised $Al_{0.8}Ga_{0.2}As$ p^+–i–n^+ diodes of similar geometry.

1. Introduction

In recent years, there has been a renewed interest in developing compound semiconductor detectors for X-ray spectroscopy and particle detection that can operate at high temperature (>20 °C) without cooling. Removing the need for the cooling normally required by detectors in these regimes would reduce the volume and mass of the instruments into which the detectors are integrated, leading to cost savings and greater instrument robustness. Various materials have been suggested as potential high temperature semiconductors suitable for photon counting X-ray spectroscopy, including SiC [1,2], GaAs [3–8], $Al_xGa_{1-x}As$ [9] and diamond [10].

Owens et al. [3,11] have reported a number of GaAs diodes operating at +23 °C having FWHM at 5.9 keV between 0.266 and 0.66 keV. Erd et al. [12] reported the temperature dependence of the spectral resolution of a GaAs diode at 5.9 keV, for temperatures between +21 and −16 °C. However, the spectral resolution of GaAs photon counting soft X-ray photodiodes at temperatures »20 °C has not been reported.

As a part of ongoing research into high temperature soft X-ray detectors we fabricated GaAs mesa p^+–i–n^+ photodiodes and characterised their spectral resolution at temperatures from +80 to −30 °C.

Barnett et al. [13] previously reported measurements of the soft X-ray spectral resolution of $Al_{0.8}Ga_{0.2}As$ mesa p^+–i–n^+ photodiodes, with similar geometry as the GaAs devices, for temperatures between +90 and −30 °C. Comparisons of both diode types are presented.

2. Diode design

A GaAs p^+–i–n^+ diode wafer was grown on a GaAs substrate by molecular beam epitaxy. High efficiency soft X-ray detection requires a very thin entrance window and a suitably thick absorption (depletion) layer. With these in mind, the wafer was designed to have thin p^+ layer (0.2 μm) and thick i layer (2 μm). Table 1 shows the wafer details. Mesa diodes of radii 25, 50, 100 and 200 μm were fabricated from this wafer using photolithography. Fig. 1 shows the quantum efficiency for these devices at X-ray energies up to 30 keV.

Due to the high doping concentrations in the p^+ and n^+ layers, the high field region is restricted to the i layer at normal operating biases (e.g. 10 V), based on the measured capacitance–voltage characteristics. The diodes were mounted in a TO-5 package. The capacitance of the 100 μm radius GaAs detectors was measured to be 1.94 pF at 10 V before packaging by directly probing the devices and using a Hewlett Packard 4275 LCR meter with the AC test voltage signal magnitude and frequency set at 50 mV rms and 1 MHz, respectively.

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Table 1
Details of the GaAs p^+–i–n^+ wafer.

Layer	Material	Thickness (μm)	Dopant	Type	Doping density (cm^{-3})
1	GaAs	0.01	Be	p^{++}	1.0×10^{19}
2	GaAs	0.2	Be	p^+	2.0×10^{18}
3	GaAs	2	Undoped		$< 10^{15}$
4	GaAs	0.1	Si	n^+	2.0×10^{18}
5	GaAs	0.2	Si	n^+	2.0×10^{18}
Substrate	n^+ GaAs				

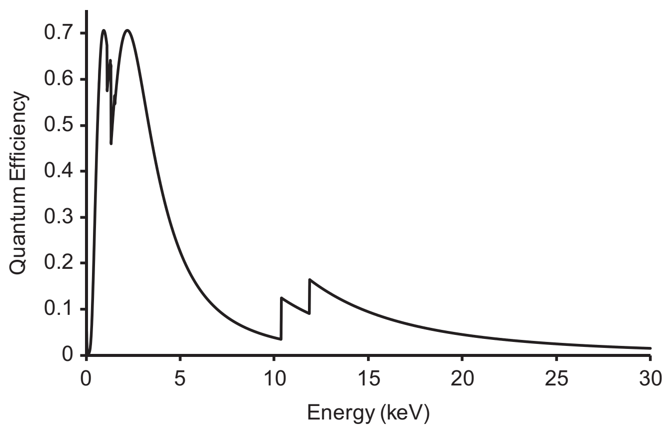

Fig. 1. Quantum efficiency of the GaAs p^+–i–n^+ diodes with varying X-ray energy. The discontinuities are the Ga and As K edges (10.367 and 11.867 keV, respectively) and the associated L edges.

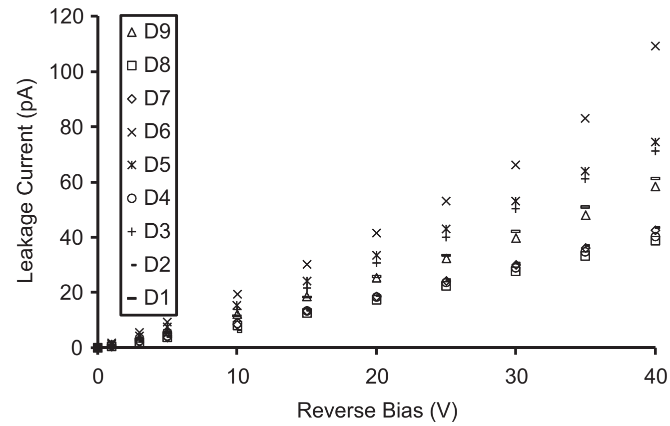

Fig. 2. *I–V* data for nine 100 μm radius GaAs diodes at room temperature in a dry N_2 environment.

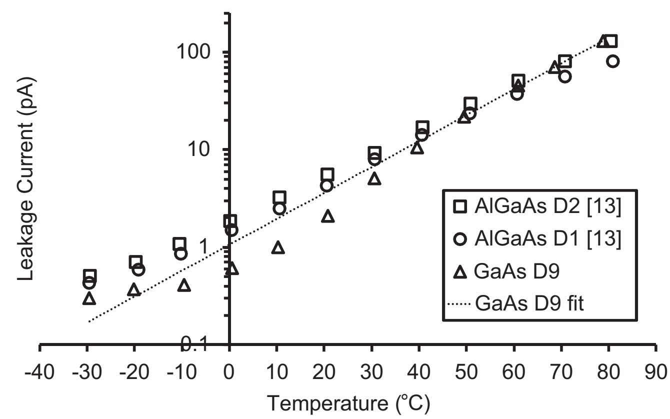

Fig. 3. The temperature dependence of the leakage current at 10 V of GaAs diode D9 (triangles), compared with the two previously reported $Al_{0.8}Ga_{0.2}As$ diodes, D1 (circles) and D2 (squares) [13]. The dotted line is the equation found to describe the temperature dependence of the leakage current at 10 V of GaAs diode D9.

3. Experiments and results

3.1. Leakage current

Leakage current under reverse bias (*I–V*) measurements of nine 100 μm radius GaAs diodes were made at room temperature. To eliminate any humidity related effects these diodes were tested in a dry N_2 environment [13].

The diodes were individually reverse biased by a Thurlby Thandar PL330QMD stabilised power supply kept at room temperature. The leakage current of each diode was amplified by a Keithley Instruments 427 current amplifier and measured by an Iso-Tech IDM 105 digital multimeter, both operated at room temperature. The *I–V* data ($\leq$40 V) for the diodes is shown in Fig. 2. For the reverse bias range shown, the leakage current's dependence on reverse bias is broadly linear (coefficient of determination, $R^2 > 0.99$) for all devices with the exception of diode D6 which shows a slight exponential trend at higher reverse biases, possibly due to slight imperfections in this device which may have arisen during fabrication or wire bonding.

At a typical operating reverse bias of 10 V, at a temperature of 20 °C, the spread of leakage currents was from 5.9 pA (current density$=1.878 \times 10^{-8}$ A/cm^2) to 19.4 pA (current density$=6.175 \times 10^{-8}$ A/cm^2). The cause of such a wide spread in leakage currents is currently unknown but probably attributable to a combination of wafer quality and/or small variations in individual diode fabrication. The current densities at 10 V for the diodes we report are higher at 20 °C than for some GaAs pixel detectors previously reported at 10 V at 30 °C ($\sim 4 \times 10^{-9}$ A/cm^2) [8].

The temperature, *T*, dependence of the leakage current of GaAs diode D9, which had a leakage current (12.2 pA) close to the mean (11.5 pA) at 10 V, is shown in Fig. 3. For comparison Fig. 3 also shows data from two previously reported $Al_{0.8}Ga_{0.2}As$ diodes [13]. Although there are some differences in the measured leakage current at high temperatures, the trend is very similar in both diode types. At the nominal operating voltage, 10 V, the temperature dependence of the leakage current for the GaAs diode is similar to that reported for the $Al_{0.8}Ga_{0.2}As$ devices [13]. A curve of the form $I=Ae^{(T/B)}$ (*I* in amps and *T* in °C) with $A=1.06 \times 10^{-12} \pm 7.4 \times 10^{-14}$ and $B=16.34 \pm 0.25$ was found to fit the GaAs D9 data (with coefficient of determination, $R^2=0.999$). Curves of the same form with $A=2.62 \times 10^{-12} \pm 2.4 \times 10^{-13}$ and $B=23.38 \pm 0.68$ with $R^2=0.997$, and $A=2.38 \times 10^{-12} \pm 1.2 \times 10^{-13}$ and $B=20.09 \pm 0.27$ with $R^2=0.999$, fit the $Al_{0.8}Ga_{0.2}As$ D1 and D2 data, respectively.

3.2. X-ray spectra

To obtain X-ray spectra measurements, the GaAs diodes were individually reverse biased at 10 V. The preamplifier used a Si JFET (Vishay Siliconix 2N4416, capacitance ~2 pF) input transistor and was connected to an Ortec 571 shaping amplifier (shaping time constant=3 μs) whose output signal was connected to a multichannel analyser (MCA). The input discriminator level of the MCA was adjusted (1.4 keV) to minimise the number of noise events. An ^{55}Fe radioisotope source (80 MBq) which gives characteristic Mn K_α and K_β lines (5.9 and 6.5 keV) was positioned 3 mm above the diode.

The X-ray source, diode and preamplifier were installed in a Design Environmental FS55-65 Temperature Test Chamber (TTC)