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Characterization of gallium arsenide X-ray mesa *p-i-n* photodiodes at room temperature

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ABSTRACT

Two GaAs mesa p^+-i-n^+ photodiodes intended for photon counting X-ray spectroscopy, having an i layer thickness of 7 μm and diameter of 200 μm, have been characterized electrically, for their responsivity at the wavelength range 580 nm to 980 nm and one of them for its performance at detection of soft X-rays, at room temperature. Dark current and capacitance measurements as a function of applied forward and reverse bias are presented. The results show low leakage current densities, in the range of nA/cm^2 at the maximum internal electric field (22 kV/cm). The unintentional doping concentration of the i layer, calculated from capacitance measurements, was found to be $< 10^{14}$ cm^{-3}. Photocurrent measurements were performed under visible and near infrared light illumination for both diodes. The analysis of these measurements suggests the presence of a non-active (dead) layer (0.16 μm thickness) at the p^+ side top contact interface, where the photogenerated carriers do not contribute to the photocurrent, possibly due to recombination. One of the diodes, D1, was also characterized as detector for room temperature photon counting X-ray spectroscopy; the best energy resolution achieved (*FWHM*) at 5.9 keV was 745 eV. The noise analysis of the system, based on spectra obtained at different shaping times and applied reverse biases, showed that the dominant source of noise is the dielectric noise. It was also calculated that there was at least (165 ± 24) eV charge trapping noise at 0 V.

1. Introduction

GaAs detectors have a number of advantages over traditional and widely used narrow bandgap semiconductor materials, such as Si and Ge. The relatively wide bandgap of GaAs (1.42 eV) results in fewer thermally generated carriers compared to narrower bandgap materials and thus, lower leakage current densities, allowing X-ray detection at room temperature and above, with good energy resolution [1]. Consequently, the cooling system that is often required for Si and Ge detectors can be eliminated. This can decrease the cost, mass, volume and power consumption of spectrometers based on the devices. Space science applications, such as future missions to Mercury (extreme thermal environment [2]), Europa's oceans (hot hydrothermal vents [3]) and Jupiter (intense radiation environment [4]), and terrestrial applications outside the laboratory environment, have restrictions on mass, power and volume, and hence may benefit from the use of GaAs or other wide bandgap detectors. Moreover, the high mean atomic number of GaAs provides higher detection efficiency for the same thickness compared with Si.

Researches have also proven a high radiation resistance of GaAs detectors to γ-rays [5,6], fast neutrons [7] and high energy electrons [8]. GaAs detectors are more radiation-resistance than Si for γ-rays, electrons and for low energy protons and neutrons [9]. As a result, GaAs is a suitable semiconductor material for radiation detection in environments which suffer from high radiation doses, such as space missions. However, it should be noted that GaAs is less radiation resistant than Si for high energy hadrons [9,10].

Results characterizing GaAs p^+-i-n^+ mesa X-ray photodiodes grown by molecular beam epitaxy have been reported for soft X-ray spectroscopy (2 μm and 3 μm i layer thickness in [11,12] respectively) and for beta particle spectroscopy (2 μm i layer thickness in [13]). In this paper, results from two fully etched 200 μm diameter GaAs p^+-i-n^+ mesa X-ray photodiodes with 7 μm thick i layers are presented. No thicker than 7 μm GaAs mesa p^+-i-n^+ diodes have been reported in the literature to date. The wafer was grown by metal organic chemical vapour deposition at the EPSRC National Centre for III–V Technologies and the devices were fabricated at University of Sheffield. The devices reported in

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this paper were randomly selected from the wafer. In Section 2, the device structure is described. In Section 3, both devices are electrically characterized in terms of their current and capacitance at room temperature and key parameters are calculated. The devices are further characterized for their visible and near infrared responsivity without any external bias applied, and the results are presented in Section 4, along with theoretical calculations. The spectroscopic X-ray photon counting performance achieved with one GaAs p^+-i-n^+ detector coupled with low-noise front-end electronics, operating at room temperature is reported and analysed in Section 5.

2. Device structure

GaAs epilayers were grown on a 350 µm thick heavily doped, n^+ GaAs substrate by metal organic vapour deposition. The thickness of the unintentionally doped *i* layer was 7 µm, and it was grown between a 1 µm *n* type and a 0.5 µm *p* type GaAs layer. The *p* and *n* type dopants used were carbon and silicon, and the doping density of both *n* type and *p* type layers was 2×10^{18} cm^{-3}. The wafer's layer structure is summarised in Table 1 and a drawing of the structure can be seen in Fig. 1. Mesa diodes with diameters of 200 µm were chemically etched using H_3PO_4:H_2O_2:H_2O as the chemical etchant. The etched depth, as measured from the top of the wafer, was 8.3 µm. The Ohmic contact of the *p* side was formed from Ti (20 nm thickness) and Au (200 nm thickness) layers.

The quantum efficiency of the devices was calculated for photon energies up to 30 keV and can be seen in Fig. 2. For these calculations it was assumed that there was a dead region at the p^+ layer, close to the surface with a width of 0.16 µm (see Section 4). The rest of the *p* layer and the *i* layer was assumed to be the active region of the devices.

3. Electrical characterization

3.1. Current–voltage measurements

Both forward and reverse bias dark current measurements as functions of applied voltage (*I*–*V* characteristics) were measured using a Keithley 6487 Picoammeter/Voltage Source. The dark current at room temperature was measured for both diodes when forward biased in the range 0 V to 1.5 V, and when reverse biased in the range 0 V to −15 V. Fig. 3 shows the forward *I*–*V* characteristics of diodes D1 and D2.

The ideality factor, *n*, and the saturation current, I_0, were both calculated from the semi-logarithm *I*–*V* characteristics of the devices. These extracted values, as well as their temperature dependence reveal the nature of the conduction mechanism (thermionic emission, diffusion, recombination and tunnelling).

There are two distinct regions in Fig. 3. The first region which corresponds to applied voltages $V_a \le 0.9$ V, is the linear region. The saturation current, I_0, was found to be $(3.12\pm0.32)\times10^{-13}$ A and $(2.58\pm0.30)\times10^{-13}$ A for diode D1 and diode D2 respectively, The ideality factor was computed to be 1.91 ± 0.01 for D1 and

Table 1
Layers structure of the GaAs p^+-i-n^+ wafer.

Material	Type	Thickness (nm)	Doping density (cm^{-3})
GaAs	p^+	10	1×10^{19}
GaAs	p^+	500	2×10^{18}
GaAs	i	7000	Undoped
GaAs	n^+	1000	2×10^{18}
GaAs	n^+ (substrate)	–	–

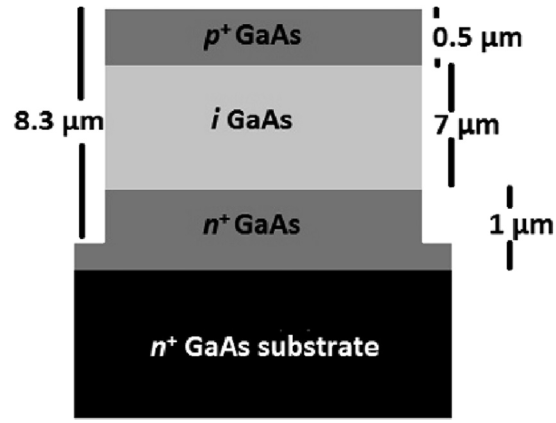

Fig. 1. Illustrative layers structure (not in scale) of the GaAs p^+-i-n^+ diode.

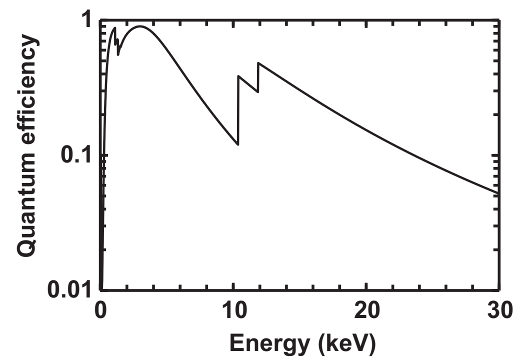

Fig. 2. Calculated quantum efficiency of the GaAs p^+-i-n^+ mesa photodiodes as a function of photon energy.

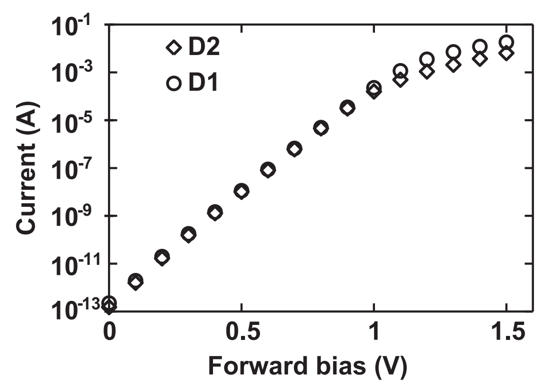

Fig. 3. Current as a function of applied forward bias of the two GaAs p^+-i-n^+ mesa photodiodes, D1 and D2, measured at room temperature.

1.89 ± 0.01 for D2. Ideality factor values close to two suggest that the recombination current dominates [14]. Further investigation of the relationship between the ideality factors of each photodiode with temperature could give a better indication of the conduction process [15]. Such measurements and analysis will be reported separately in a future manuscript. The second region of the semi-logarithm *I*–*V* characteristics which corresponds to applied voltages $V_a > 0.9$ V deviates from linearity. As the applied voltage increased, the semi-logarithm *I*–*V* characteristics of the devices bend down (Fig. 3), resulting in a non-linear relationship between the logarithm of forward current and the applied voltage and indicating that the effect of series resistance, R_s, became significant.

The reverse *I*–*V* characteristics of the two GaAs p^+-i-n^+ mesa photodiodes are shown in Fig. 4.