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Gallium Arsenide detectors for X-ray and electron (beta particle) spectroscopy

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ABSTRACT

Results characterizing GaAs p^+-i-n^+ mesa photodiodes with a 10 μm i layer for their spectral response under illumination of X-rays and beta particles are presented. A total of 22 devices, having diameters of 200 μm and 400 μm, were electrically characterized at room temperature. All devices showed comparable characteristics with a measured leakage current ranging from 4 nA/cm^2 to 67 nA/cm^2 at an internal electric field of 50 kV/cm. Their unintentionally doped i layers were found to be almost fully depleted at 0 V due to their low doping density. ^{55}Fe X-ray spectra were obtained using one 200 μm diameter device and one 400 μm diameter device. The best energy resolution (*FWHM* at 5.9 keV) achieved was 625 eV using the 200 μm and 740 eV using the 400 μm diameter device, respectively. Noise analysis showed that the limiting factor for the energy resolution of the system was the dielectric noise; if this noise was eliminated by better design of the front end of the readout electronics, the achievable resolution would be 250 eV. ^{63}Ni beta particle spectra obtained using the 200 μm diameter device showed the potential utility of these detectors for electron and beta particle detection. The development of semiconductor electron spectrometers is important particularly for space plasma physics; such devices may find use in future space missions to study the plasma environment of Jupiter and Europa and the predicted electron impact excitation of water vapor plumes from Europa hypothesized as a result of recent Hubble Space Telescope (HST) UV observations.

1. Introduction

Gallium Arsenide has been the subject of much interest for its use in photon counting X-ray spectroscopic detector systems. As a wide bandgap material (1.42 eV [1]), the resulting low thermally generated leakage current density allows its use at room and high temperatures with less degradation in energy resolution compared to traditional narrower bandgap materials such as Si and Ge [2]. Another advantage of GaAs is its relatively low electron–hole pair creation energy (4.184 eV [1]) compared to other wide bandgap materials. Furthermore, GaAs has been proven to be more radiation resistant than Si for electrons [3], γ-rays [4] and low energy hadrons [5]. Moreover, high detection efficiency per unit thickness is achieved with GaAs due to its high effective atomic number.

As a result, GaAs can be used for radiation detection in harsh environments (high temperature and intense radiation environment) without the need for cooling and shielding, and with good energy resolution [2]. The elimination of the cooling and shielding system can lead to the reduction of the mass, cost, volume and power of the total detection system. Space missions and terrestrial applications with such restrictions could be benefit from the use of GaAs. Some examples include X-ray fluorescence spectroscopy missions to Mercury [6] and Jupiter [7] and X-ray fluorescence spectrometry in industrial process control applications. The use of radiation hard GaAs detectors may also be particularly beneficial for future missions to the intense radiation environment of Jupiter and its moons (doses of as high as 6 MRad [8]).

Another potential application of GaAs photodiodes is the in situ low energy (1–100 keV) electron spectroscopy at Europa along with contemporaneous UV imaging from either an orbiter or the Hubble Space Telescope (HST) which would allow direct observational data gathering to test predictions that electron impact excitation of water vapor plumes explains the auroral observations at Europa's polar regions in 2012 [9]. Although electron spectroscopy can also be realized with scintillators [10,11], semiconductor detectors are of a great advantage in many electron detection applications Poorer energy resolution is achieved using scintillators than using semiconductor detectors [10,12]. The lower energy needed to produce an electron–hole pair in a semiconductor (eg., 4.184 eV for GaAs [1]) than the energy needed to produce a photoelectron ejection in a scintillation/photomultiplier tube (≥ 100 eV) results in better statistics (production of more charge

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carriers from the primary ionization effect) and hence in energy resolution improvement of semiconductor detectors compared to scintillators [13]. Electron spectrometers have also been realized using microchannel plate (MCP) detectors, which have been proven to be useful devices in space applications (e.g. the Electron Spectrometer in the Cassini Plasma Spectrometer for the exploration of the Saturn system [14]). An alternative to MCP detectors is charge coupled devices (CCD) for the direct detection of electrons without the need of high voltages and high vacuums required in MCP detectors [15]. Langmuir probes are also used for electron detection (e.g. in measuring the electron energy distribution functions in plasmas [16]).

Results characterizing GaAs planar p^+-i-n^+ diodes with Schottky contacts and guard rings in a 5 × 5 array structure with low dark current densities (< 6 nA/cm^{-2} at room temperature) coupled to ultra low noise front end electronics was reported in Ref. [17]. The best energy resolution achieved with these devices was 266 eV at 5.9 keV at room temperature and has not yet been replicated. Similar structure and thicker devices in a 32 × 32 pixel array form were reported in Ref. [18] with an energy resolution of 300 eV at 5.9 keV at room temperature. GaAs p^+-i-n^+ mesa X-ray photodiodes have been characterized for X-ray (2 μm [19], 3 μm [20] and 7 μm [21,22] i layer thickness) and β^- particle spectroscopy (2 μm i layer thickness [23]). Research has also been conducted on the use of GaAs p^+-i-n^+ mesa X-ray photodiodes as X-ray photovoltaic batteries [24].

In this paper, results from randomly selected fully etched GaAs p^+-i-n^+ mesa X-ray photodiodes with 10 μm thick i layers are presented. These are the thickest GaAs p^+-i-n^+ mesa X-ray photodiodes reported in the literature to date. 22 devices of two different diameters (200 μm and 400 μm) are electrically characterized and reported. Following this, one representative device of each diameter is characterized as an X-ray photon counting spectroscopic detector. Accumulated ^{55}Fe spectra are presented and the noise of the system is analyzed. Finally, results are reported using one 200 μm diameter device for ^{63}Ni β^- spectroscopy and its suitability in β^- particle and electron detection is discussed.

2. Device structure

The GaAs p^+-i-n^+ mesa photodiodes were grown and fabricated to the Authors' specifications at the EPSRC National Centre for III-V Technologies, Sheffield, UK. GaAs epilayers were grown on a commercial GaAs n^+ substrate by metalorganic vapor phase epitaxy. The unintentionally doped i layer had a thickness of 10 μm. The resulting wafer structure is summarized in Table 1. Mesa diodes with diameters of 200 μm and 400 μm were chemically etched using a 1:1:1 H_3PO_4:H_2O_2:H_2O solution followed by 10 s in a 1:8:80 H_2SO_4:H_2O_2:H_2O solution. The top Ohmic contact consisted of 20 nm of Ti and 200 nm of Au. It covered 45% of the surface of the 200 μm diameter devices and the 33% of the 400 μm diameter devices. The rear Ohmic contact consisted of 20 nm of InGe and 200 nm of Au. The GaAs devices were unpassivated.

Table 1
GaAs p^+-i-n^+ mesa photodiodes layer structure.

Material	Type	Thickness (nm)	Doping density (cm^{-3})
Ti		20	
Au		200	
GaAs	p^+	500	2×10^{18}
GaAs	i	10,000	Undoped
GaAs	n^+	1000	2×10^{18}
GaAs	n^+ substrate		
Au		200	
InGe		20	

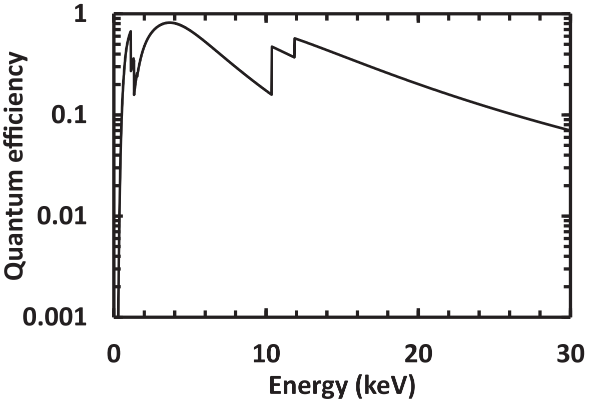

Fig. 1. Calculated X-ray quantum efficiency of the GaAs p^+-i-n^+ mesa photodiodes as a function of X-ray photon energy.

The quantum efficiency of the devices for X-ray photons up to 30 keV was calculated and can be seen in Fig. 1. As a cautious assumption, to prevent over estimation of the quantum efficiency, the whole of the p^+ layer was assumed to be a dead region and only the i layer was assumed to be the active region of the devices.

3. Electrical characterization

Electrical characterization of 22 GaAs mesa p^+-i-n^+ photodiodes was performed under dark conditions at room temperature. There were 14 diodes with 200 μm diameter and 8 diodes with 400 μm diameter.

3.1. Current–voltage measurements

Dark current measurements as functions of both forward and reverse applied voltage (*I-V* characteristics) were performed using a Keithley 6487 Picoammeter/Voltage Source. The dark current was measured as a function of forward bias from 0 V to 1 V and as a function of reverse bias from 0 V to 50 V at room temperature. Fig. 2 shows the measured currents, I_F, as a function of applied forward bias, V_F, of representative 200 μm and 400 μm diameter devices.

The saturation current, I_0, and the ideality factor, n, were extracted for each device based on the linear region of their semilogarithm dark current as a function of forward bias [22]. The saturation current, I_0, was found to vary from 3×10^{-13} A to

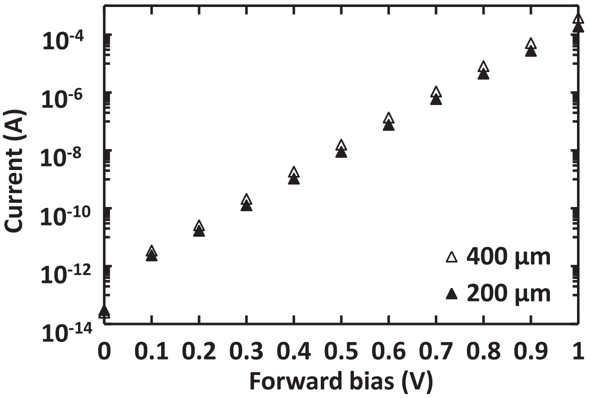

Fig. 2. Dark current as a function of applied forward bias for a 200 μm (filled triangles) and 400 μm (open triangles) diameter GaAs p^+-i-n^+ photodiode at room temperature.