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Chromium compensated gallium arsenide detectors for X-ray and γ-ray spectroscopic imaging

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ABSTRACT

Semi-insulating GaAs material of 500 μm thickness grown using the Liquid Encapsulated Czochralski (LEC) method has been compensated with chromium to produce high resistivity single crystals suitable for spectroscopic imaging applications. Results are presented for the performance of three small pixel detectors each with 80 × 80 pixels on a 250 μm pitch, fabricated with metal contacts and bonded to a spectroscopic imaging ASIC. Current–voltage measurements demonstrated a material resistivity of 2.5×10^9 Ω cm at room temperature. At an optimised bias voltage, the average energy resolution at 60 keV (FWHM) was in the range 2.8–3.3 keV per pixel. An analysis of the voltage dependent X-ray spectroscopy suggests that the electron mobility lifetime ($\mu\tau_e$) for each detector is in the range 2.1–4.5×10^{-5} cm^2 V^{-1}. The spectroscopic imaging capability of the detectors is also demonstrated in X-ray absorption spectroscopy measurements.

1. Introduction

Semiconductor based X-ray imaging detectors have been under development for many years. Ideally these detectors should have high spatial resolution, excellent energy resolution and, in many cases, be capable of stable operation under high radiation fluxes at room temperature. Substantial time and resource have led to the development of silicon based detectors capable of meeting these requirements for X-ray energies <20 keV [1,2]. At higher X-ray energies the poor mass attenuation coefficient of Si leads to a drastic reduction in detector efficiency. Alternative technologies, such as hyper-pure germanium detectors (HPGe), are capable of providing excellent energy resolution at these higher energies but are difficult to finely segment and require large cryogenic cooling systems [3].

The properties of compound semiconductors such as cadmium telluride (CdTe), mercuric iodide (HgI_2), thallium bromide (TlBr) and gallium arsenide (GaAs) are desirable for the production of high energy X-ray detectors [4]. The wide band gaps of these compounds mean that they have high resistivity ($>10^9$ Ω cm) and are capable of room temperature operation, removing the need for cooling systems. Small pixel imaging detectors fabricated from cadmium telluride have demonstrated sub-keV energy resolution at hard X-ray energies [5,6] but are prone to polarisation under high flux irradiation. Mercuric iodide and thallium bromide, while having very high resistivity ($>10^{12}$ Ω cm), still suffer from relatively poor spectroscopic performance and their toxicity and structural stability represent challenges for some applications [7,8].

Semi-insulating GaAs has a wide band gap of 1.43 eV and a resistivity of $>10^7$ Ω cm at room temperature. The material also has excellent charge carrier mobilities of the order $\mu_e = 10^3$ cm^2 V^{-1} s^{-1} and $\mu_h = 10^2$ cm^2 V^{-1} s^{-1} for electrons and holes respectively [9]. The density of GaAs is low compared with some of the other compound semiconductors (5.32 g cm^{-3} compared with 7.56 g cm^{-3} for TlBr) but still offers an advantage over traditional semiconductors such as Si at X-ray energies >10 keV. GaAs has also demonstrated excellent radiation hardness compared with other semiconductor detectors, making it suitable for use in extreme environments [10]. Despite the advantageous properties of GaAs it is yet to be adopted as a material of choice for X-ray detection due to the high concentration of traps in the material that have until now limited its spectroscopic resolution.

2. GaAs:Cr compensation scheme

The EL2 deep donor defect in melt-grown GaAs material has been the focus of intense research for many years [11–13]. The trap

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is responsible for the poor charge transport properties of semi-insulating GaAs material as well as instabilities in the detector electric field which have limited the usefulness of the material in the field of X-ray imaging.

The EL2 trap is a complex of an arsenic antisite (As_{Ga}) and an interstitial arsenic atom, as established by electron spin resonance (ESR) and electron–nuclear double resonance. The defect complex sits $\sim$0.65 eV below the conduction band and has a typical concentration of the order 10^{16} cm^{-3}. The presence of EL2 centres defines the electric field distribution within the detector and limits the sensitive volume for radiation detection. The ionised EL2 defects ($EL2^{+}$) are efficient centres for recombination due to their large electron trapping cross-section of $>10^{-13}$ cm^2. This large cross-section limits the electron lifetime to values on the order of 10^{-9} s, reducing the drift length of electrons and leading to detectors with poor charge collection efficiency and spectroscopic performance.

Two methods exist for decreasing the concentration of $EL2^{+}$ centres within GaAs material. The first method is to reduce the growth temperature through the use of epitaxial growth techniques. While epitaxial grown GaAs material has been shown to have good properties [14] the thicknesses of the grown layers are limited to the order of 100 μm, making them unsuitable for the detection of higher energy X-rays. An alternative method of reducing the concentration of $EL2^{+}$ centres is through chromium compensation of bulk material.

The GaAs material used in this study was grown using the Liquid Encapsulated Czochralski (LEC) method [15]. The initial material was grown with an excess of shallow donors (N_d) producing n-type material with an electron concentration of the order 10^{17} cm^{-3}. Post-growth, chromium dopant (N_{Cr}) is evaporated onto wafers of material and diffused into the bulk through annealing such that

$$N_{Cr} > N_d > N_{EL2^+}$$

The diffused chromium produces interstitials in the crystal lattice (Cr_i) before becoming fixed at gallium vacancies (V_{Ga}), producing a deep acceptor trap (Cr_{Ga}.) with an energy of 0.78 eV above the valance band. Excess shallow donors present in the initial material fill the ionised $EL2^{+}$ states, producing the neutral $EL2^{0}$ and partially compensate the Cr_{Ga} traps. The resulting highly compensated p-type material has high resistivity ($\rho \sim 1 \times 10^9$ Ω cm) and good charge carrier transport properties ($\mu_n \sim 4000$ cm^2 V^{-1} s^{-1} and $\mu_p \sim 300$ cm^2 V^{-1} s^{-1}), allowing the production of active layers of up to 1 mm thickness [9].

3. Simulation of the small pixel effect in GaAs detectors

Charge induction in small pixel detectors can be described by the Shockley–Ramo theorem [16]. The theorem introduces the concept of the weighting potential which describes how charge carriers drifting in a detector induce a signal on an electrode. If the size of the detector pixel is small relative to the thickness of the detector, then the weighting potential is concentrated close to the pixel electrodes and this is known as the small pixel effect. Electrons and holes drifting in such a weighting potential induce a significant amount of charge only when close to the pixel. If the anode is pixelated and radiation interactions occur close to the cathode, then the drift of holes will occur far away from the anode pixel and will not induce a significant charge.

The expected weighting potentials in GaAs devices were simulated using a Sentaurus Technology Computer-Aided Design (TCAD) simulation package [17] which is commonly used to develop and optimise semiconductor processing technologies and devices. Fig. 1 (Top) shows a TCAD simulation of a 500 μm thick GaAs substrate

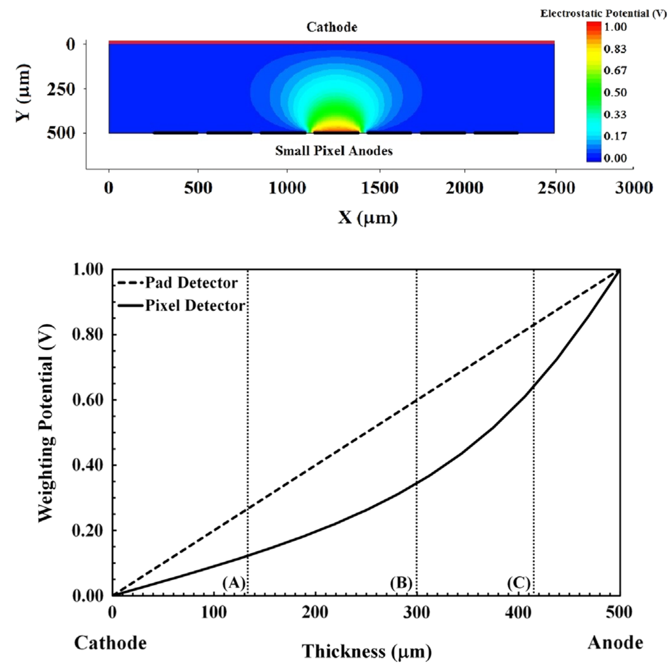

Fig. 1. (Top) A TCAD simulation of the weighting potential of a single pixel in a 500 μm thick GaAs detector with 7 pixels on a 250 μm pitch. (Bottom) A comparison of the weighting potential for a pad and pixel detector. Indicated on the plot are the mean free paths of 30 keV (A), 40 keV (B) and 45 keV (C) photons within the detector.

with 7 anode pixels of pad size 200 μm and spacing of 50 μm. To calculate a typical weighting potential the pixel of interest was set to a voltage of 1 V and all other electrodes were set to 0 V.

With a ratio of the pixel pitch to device thickness of 0.5, a modest small pixel effect is observed. The energy of the X-rays interacting within the detector will determine the contribution of electrons and holes to the detector signal. The mean free path of X-rays in the GaAs detector was calculated using the NIST XCOM: Photon Cross-sections Database for energies of 30, 40 and 45 keV. Fig. 1 (Bottom) shows how the magnitude of the weighting potential varies across the detector as well as the mean free path of different X-ray energies.

An X-ray with energy 30 keV will have a mean free path in the GaAs detector of 135 μm corresponding to a weighting potential magnitude of 13%. In this instance, the contribution of the electrons and holes to the induced charge on the pixel will be 87% and 13% respectively. For the higher X-ray energy of 45 keV the mean free path is 417 μm, corresponding to a weighting potential of 65%. The relative contribution of the electrons and holes at this higher energy is 35% and 65% respectively.

Differences in the transport properties of electrons and holes in the GaAs:Cr material imply that for higher energy events the large contribution of holes to the induced charge may lead to a degradation of the detector signal. The simulations suggest that 500 μm thick detectors are suitable for the detection of X-ray energies <40 keV but to operate efficiently at higher energies thicker detectors may be required [9].

4. Experimental method

Wafers of n-type GaAs were grown using the Liquid Encapsulated Czochralski (LEC) method. Post-growth annealing to compensate crystals with chromium to produce high resistivity, single crystal, and material was performed by Tomsk State University,