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Semi-insulating bulk GaAs as a semiconductor thermal-neutron imaging device

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Abstract

Thermal-neutron Schottky barrier detector arrays fabricated from semi-insulating bulk GaAs are presently being tested. The devices use a film of ^{10}B to convert the incident thermal-neutron field into α particles and lithium ions, either of which interact in the detector. Bulk GaAs Schottky barrier detectors are relatively radiation hard to thermal neutrons and γ rays and have shown reasonably good energy resolution for α particles. Additionally, reverse biased radiation detectors fabricated from semi-insulating bulk GaAs have been shown to have truncated electric field distributions, resulting in the formation of a high field active region and a considerably lower field dead region. The device is sensitive only to electron–hole pairs excited in the high field region, thus the truncated field effect is advantageous as an inherent γ-ray discrimination feature for neutron detectors. Preliminary results show no indication of device degradation after over 2400 hr in a thermal-neutron beam from a reactor. Images have been formed of 1, 1.5, and 2 mm holes and crosses from 2 mm thick Cd templates.

1. Introduction

Thermal-neutron radiography is a powerful interrogation tool for industry and manufacturing needs [1,2]. Such technology relies on the ability to accurately measure thermal-neutron spatial intensity variations after passing through the medium under investigation. An ideal high resolution device for use with thermal-neutron imaging would be a highly neutron sensitive charge coupled device (CCD). Unfortunately, Si based CCDs are rapidly destroyed by the high neutron (and γ-ray) fluxes commonly used for neutron radiography. Devices and radiation detectors fabricated from GaAs have demonstrated radiation hardness to neutrons and γ-rays [3,4]. A radiation hard thermal-neutron imaging device fabricated from bulk GaAs could be utilized in a number of different applications, including radiography, small angle scattering measurements, reactor control, and treaty verification. Reported are preliminary results from a simple 25 pixel array of 1 mm^2 Schottky barrier diodes fabricated on SI bulk GaAs.

2. Background

The thermal-neutron absorption cross section of ^{10}B is 3840 b, and upon neutron absorption, the ^{10}B nucleus splits into an α-particle and a Li ion which are emitted in opposite directions [5]. The Li ion is left in the excited state after 94% of the reactions, yielding a 1.47 MeV α-particle and a 840 keV Li ion. The Li ion rapidly returns to its ground state ($t_{1/2} \approx 10^{-13}$ s) and emits a 480 keV γ-ray. As shown in Fig. 1, the average range of 1.47 MeV α-particles in GaAs is 4.2 μm, and the average range for 840 keV Li ions is 2.1 μm [6]. Also, 6% of the reactions leave the Li ion in the ground state, producing a 1.015 MeV Li ion and a 1.777 MeV α-particle. The high energies of the reaction products are easily detectable in thin solid state detectors, making the ^{10}B reaction an attractive mechanism for thermal-neutron detection.

Schottky barrier detectors fabricated from SI bulk GaAs have been demonstrated as good α-particle spectrometers, often yielding resolution better than 2.5% at FWHM for

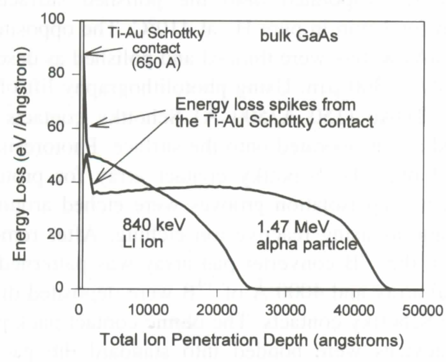

Fig. 1. Expected range and ionization produced in GaAs from a 1.47 MeV α-particle and a 840 keV Li ion [6].

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5.5 MeV α-particles [7–9]. Such resolution is much better than needed to discriminate between thermal-neutron interactions and background γ-ray events. Additionally, reverse biased radiation detectors fabricated from SI bulk GaAs have been shown to have truncated electric field distributions [10]. Under bias, the electric field in the devices is split into a high field region and a low field region [7,8,11]. The high field region averages near 10^4 V/cm and grows linearly with applied voltage, requiring approximately one volt per μm of active high field region. Hence, only a few volts are necessary to increase the active region in a SI bulk GaAs device beyond the maximum range of the α-particle or Li ion (see Fig. 1).

The surface Fermi level for Schottky barrier contacts on properly cleaned and polished GaAs surfaces is pinned from the high density of surface states. Hence, Schottky barrier contacts are easily reproduced on GaAs with reliable results. The contacts are relatively radiation hard, demonstrating only minor changes in device parameters when exposed to ionizing radiation [3]. Increases in reverse leakage current as a result of fast neutron damage have been reportedly observed after a total fast neutron fluence of 3.6×10^{14} n/cm^2 [12]. Degradation from fast neutron damage is not expected in typical thermal-neutron radiography environments since the neutron beams are generally well thermalized and the Cd ratio is on the order of 10–200 (depending on the type of irradiation facility and or filtering). In any case, the low bias voltage required for a small depletion mode bulk GaAs device ensures that the reverse leakage current is low.

3. Detector fabrication and operation

The SI bulk GaAs Schottky barrier arrays were fabricated in the following sequence. Bulk GaAs wafers were thinned using 3 μm alumina followed by a preliminary polish with 0.3 μm alumina suspended in sodium hypochlorite solution. The final polish was performed using a 0.25% bromine/methanol solution. Full area Au/Ge/Ni layers were evaporated onto the polished surface and annealed for 1 min in pure H_2 at 410°C. The opposite side of the GaAs wafers were thinned and polished as described previously to 300 μm. Using photolithography lift-off, the array of Ti/Au (150 Å/500 Å) Schottky contacts were patterned and evaporated onto the surface. Photoresist was patterned over the Schottky contact array for protection and 6 μm deep isolation grooves were etched around the metal patterns using reactive ion etching. After removing the resist, the ^{10}B converter pad array was patterned over the metal array and 4000 Å of ^{10}B were deposited directly onto the Schottky contacts. The ohmic contact back planes of the devices were bonded into standard die packages with Ag epoxy, followed by wire bonding to the pin outs. Fig. 2 shows a diagram of the 25 pixel array layout, in which a single ^{10}B converter pad pixel size is 1 mm^2.

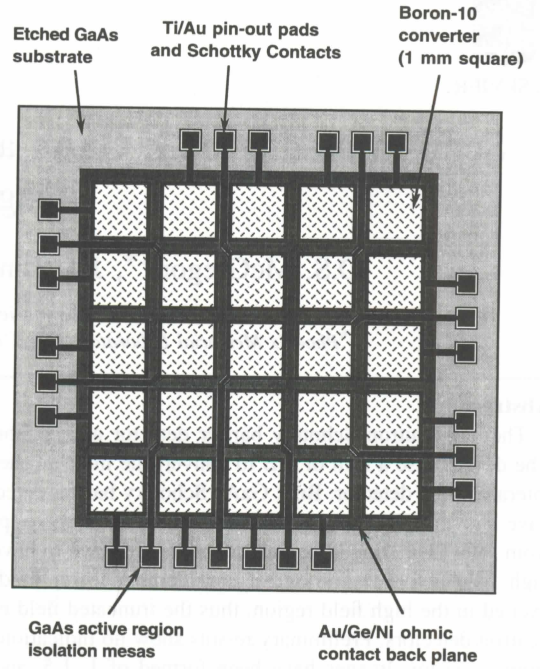

Fig. 2. Diagram of the prototype 25 pixel SI bulk GaAs Schottky diode array. The pixel areas of the ^{10}B pads are 1 mm^2.

Fig. 3 shows the basic operation of one pixel. A thermal neutron interacts with the ^{10}B converter film, in which either an α-particle or Li ion enter the detector. The ^{10}B film thickness is tailored such that both (or only one)

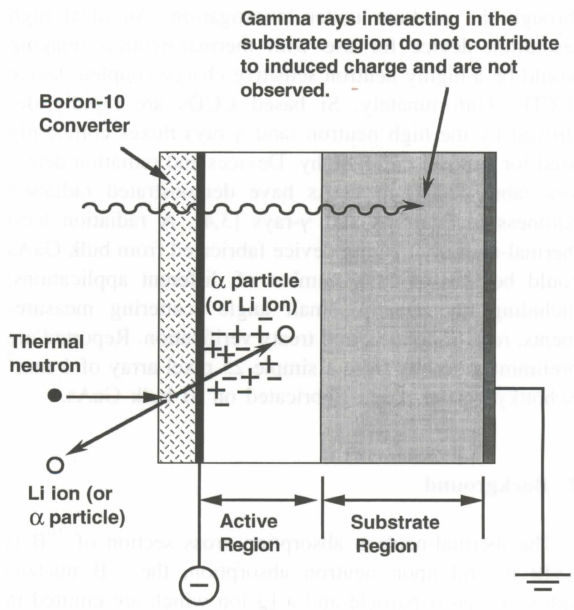

Fig. 3. An α-particle or Li ion enters into the detector after a thermal-neutron reaction with the ^{10}B converter. The detector is biased such that the active region extends slightly beyond the particle range, which allows for self discrimination of γ-rays.

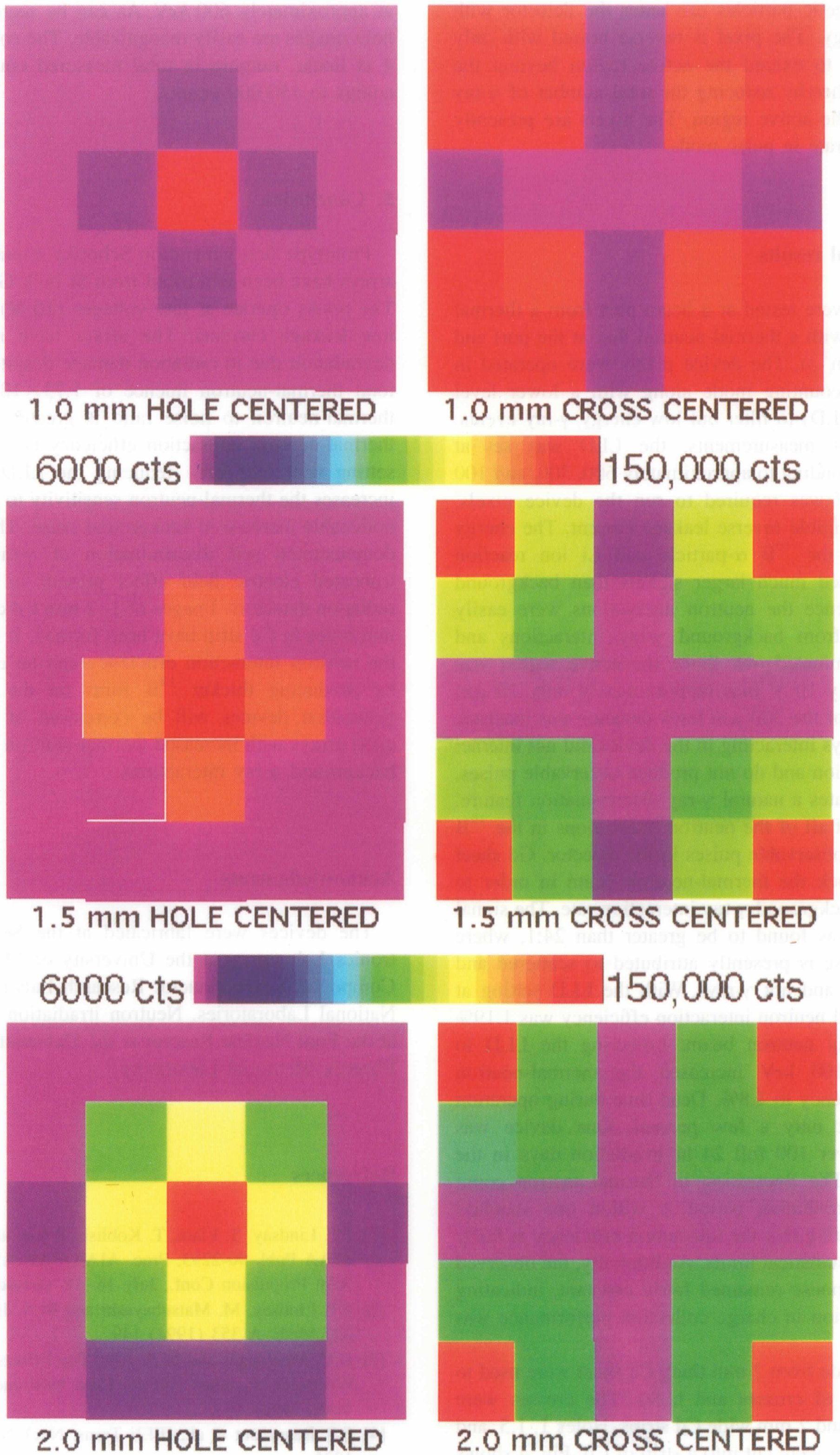

Fig. 4. Thermal-neutron images produced by transmission measurements through 2 mm thick Cd templates. The color range is linearly divided, ranging from 6000 accumulated counts (light purple) to 150 000 accumulated counts (deep red). Shown are images of a 1 mm hole, 1.5 mm hole, and a 2 mm hole through Cd sheet, and a 1 mm cross, 1.5 mm cross, and a 2 mm cross of Cd sheet.

species of energetic particles can enter the detector with substantial energy. The pixel is reverse biased with only enough voltage to extend the active region beyond the particle range, thereby reducing the total number of γ-ray interactions in the active region. The pixels are presently designed to operate in pulse mode.

4. Experimental results

The devices were tested at a beam port from a thermal nuclear reactor with a thermal-neutron flux at the port end of 2×10^6 n/(cm^2 s). The device pixels were operated in quantum pulse counting mode along with a lower level discriminator (LLD) to filter out low energy γ-ray events. During different measurements, the LLD was set at energies corresponding to approximately 600, 300, and 100 keV. Only 10 V was required to run the device pixels, resulting in negligible reverse leakage current. The energy deposited from the ^{10}B α-particle and Li ion reaction products produced much larger signals than background γ-ray events, hence the neutron interactions were easily distinguishable from background γ-ray interactions and could be discriminated out. Since the active region was narrow with only 10 V bias (approximately only 10 μm wide), the bulk of the 300 μm thick detector was inactive. Most of the γ-rays interacting in the device did not interact in the active region and do not produce observable pulses, which demonstrates a natural γ-ray discrimination feature. However, almost all of the neutron interactions in the ^{10}B film resulted in observable pulses in the detector. Gd sheet was used to block the thermal-neutron beam in order to determine the background γ-ray interaction rate. The signal to noise ratio was found to be greater than 24:1, where most of the noise is presently attributed to scattered and albedo neutrons and not γ-rays. With the LLD setting at 600 keV, the total neutron interaction efficiency was 1.19% of the impinging neutron beam. Lowering the LLD to approximately 100 keV increased the thermal-neutron interaction efficiency to 1.8%. Dead time during operation was minimal at only a few percent. One device was irradiated for over 100 full 24 hr irradiation days in the neutron beam. The fluctuation in thermal-neutron count rate over the irradiation period is within one standard deviation, indicating that the interaction efficiency is fairly constant within statistical limits. Additionally, the observed pulse height response remained fairly constant, indicating that no degradation in charge collection performance was observed.

Templates made from 2 mm thick Cd sheet were used to produce images of crosses and holes. The crosses were made of 1, 1.5, and 2 mm wide Cd strips. Holes 1, 1.5, and 2 mm in diameter were cut into a strip of Cd. Fig. 4 shows thermal-neutron transmission images of the templates obtained over a 10 min collection period with the LLD set at approximately 600 keV. As can be seen, the cross and hole images are easily recognizable. The color scale in Fig. 4 is linear, ranging in total measured counts from 6000 counts to 150 000 counts.

5. Conclusion

Prototype first generation Schottky contact square pixel arrays have been fabricated from SI bulk GaAs and tested. The pixels operate at low voltages (10 V) and have very low leakage currents. The arrays have not shown any degradation due to radiation damage despite exposure to a total thermal-neutron fluence of 1.73×10^{13} n/cm^2. The thermal-neutron to noise ratio is greater than 24:1. The thermal-neutron interaction efficiency is 1.19% at a LLD setting near 600 keV. Reducing the LLD near 100 keV increases the thermal-neutron sensitivity to 1.8% without a noticeable increase in background noise. The devices have demonstrated self discrimination of γ-rays due to the truncated electric field effect present in SI bulk GaAs radiation detectors. Images of 1–2 mm Cd crosses and 1–2 mm holes in Cd strip have been formed. It is expected that the neutron interaction efficiency can be easily increased by producing thicker ^{10}B films on the pixels. Future generation devices will be composed of higher density pixel arrays with increased thermal-neutron sensitivity over background γ-ray interactions.

Acknowledgments

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