Semi-Insulating Bulk GaAs Thermal Neutron Imaging Arrays

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Abstract

Prototype thermal neutron imaging arrays have been fabricated from semi-insulating (SI) bulk GaAs. The arrays are 1 mm square Schottky diodes arranged in a 5 x 5 matrix. GaAs Schottky barrier radiation detectors are relatively radiation hard and can withstand higher neutron and gamma ray exposure fields than MOS-based Si diode imaging arrays. The devices use ^{10}B to convert incident thermal neutrons to energetic Li ions and alpha particles. The truncated field effect observed with SI bulk GaAs detectors produces high and low field regions in the device. Electron-hole pairs produced in the active (or high field) region of the device contribute to the observed induced charge, whereas electron-hole pairs produced in the low field region contribute very little to the induced charge. The effect is manipulated to reduce the background gamma ray interaction rate in the devices. Preliminary results show no indication of device degradation after exposure to a total thermal neutron fluence of 1.73×10^{13} n/cm^2. Images have been formed of 1, 1.5, and 2 mm holes and crosses from 2 mm thick Cd templates.

I. Introduction

Thermal neutron radiography is a powerful interrogation tool used for industry and manufacturing [1,2]. The technique allows for the investigation and interrogation of light elements and compounds encased in heavy element containers. High resolution images can be formed if the neutron detecting device (or medium) is capable of high spatial resolution. An ideal device for such an application would be a semiconductor imaging device, such as a charge coupled device (CCD), that is sensitive to thermal neutrons. However, MOS-based Si CCD devices can undergo catastrophic failure when exposed to a harsh radiation environment. Hence, the imaging device should be radiation hard in order to withstand the radiation fields that usually accompany thermalized neutron beams. Additionally, the charge capacity of a CCD potential well is generally much lower than the charge generated by converter film reaction products, which indicates that the total charge measured would no longer correlate to the number of reaction products generated by thermal neutrons entering the device.

GaAs Schottky barrier devices have shown considerable radiation hardness to gamma rays and neutrons [3,4]. Schottky barrier devices operated in a pulse mode have been demonstrated as charged particle and gamma ray detectors [5], and such devices would preserve information pertaining to the thermal neutron intensity since they can operate as simple particle counters. Fabrication procedures for pixelated bulk GaAs devices are relatively inexpensive and straightforward. Such devices can be used for real time thermal neutron radiography, small angle scattering measurements, reactor control, and treaty verification.

II. Theoretical Considerations

A. GaAs Schottky Barrier Detectors

Semi-insulating (SI) bulk GaAs Schottky barrier detectors have demonstrated energy resolution better than 2.5% and charge collection efficiency above 80% for 5.5 MeV alpha particles [6-8], indicating the ability of such devices to discern between high energy charged particle interactions and background gamma ray events. Schottky barrier and *p-i-n* detectors fabricated from SI bulk GaAs have truncated electric field distributions presently attributed to the presence of high concentrations of native deep level compensation centers [5-7, 9-11].

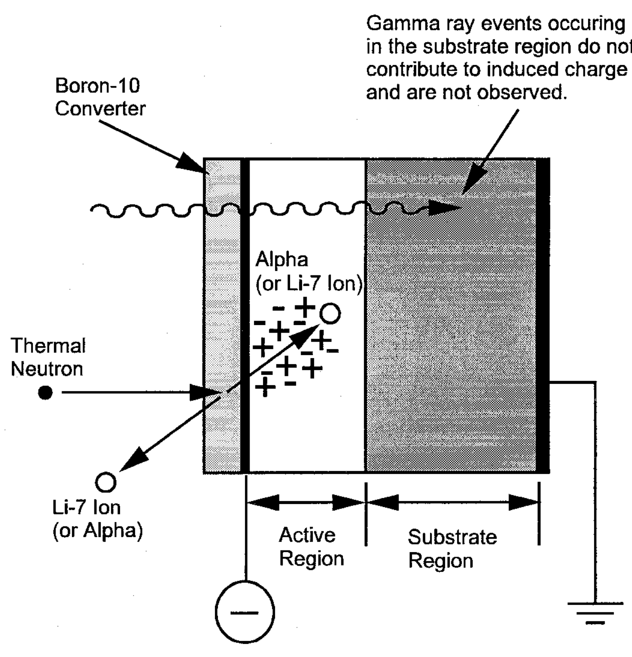

Fig. 1. The basic construction of a ^{10}B thin film GaAs Schottky barrier detector. Neutrons interact in the ^{10}B and release an alpha particle and a Li ion in opposite directions. As a result, only one of the particles can enter the detector.

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The truncated electric field effect produces a high field region and a low field region in the devices. The high field region averages near 10^4 V/cm and increases in width linearly with applied voltage, requiring approximately one volt per micron of high field active region. Under operation, ionizing events occurring in the high field active region produce induced charge and are measured, however ionizing events occurring in the low field substrate region are not observed. Hence, the applied voltage need only be enough to extend the active region beyond the maximum range of the charged particle under observation, which is only a few tens of microns for most naturally emitted alpha particles. Additionally, the semi-insulating nature of the material ensures that the high frequency capacitance is determined by the total detector bulk thickness and not the thin active region thickness [5, 6].

The surface Fermi level for Schottky barrier contacts for a well prepared SI bulk GaAs substrate is pinned due to the high density of surface states. The effect allows for easily reproducible and reliable Schottky contact diodes. Additionally, the Schottky contacts are radiation hard and demonstrate only minor changes in device performance when exposed to high fluences of ionizing radiation [3,4]. Reverse bias leakage currents have been observed to increase from fast neutron damage at fluences greater than 3.6 $\times 10^{14}$ n/cm^2 [12]. However, the low bias voltages necessary to operate SI bulk GaAs charged particle detectors are not expected to produce significant leakage currents. Thermal neutron beams for radiography applications are generally well thermalized and have reduced fast neutron components. Hence, radiation damage from fast neutrons is not expected to be a significant issue.

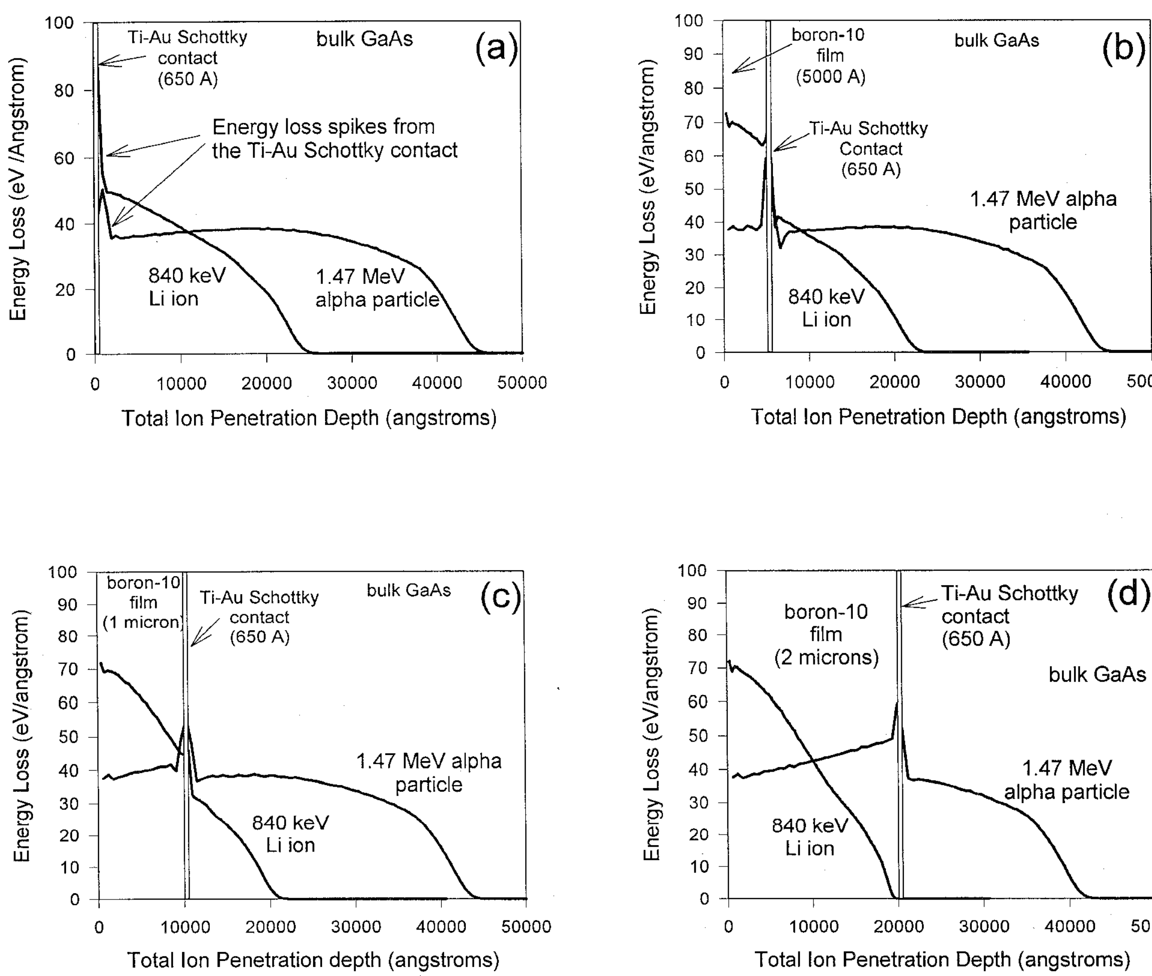

Fig. 2. Shown are the average ranges and average energy loss distributions for several different thicknesses of ^{10}B films, those being (a) no boron (Schottky contact only), (b) 0.5 microns of ^{10}B, (c) 1.0 micron of ^{10}B, and (d) 2.0 microns of ^{10}B [14]. The calculations were performed with an ion entrance angle of 90°, which yields the maximum range a particle can have when attenuated by the described absorber thicknesses.

B. Detector Sensitivity

Thermal neutrons absorbed by ^{10}B produce energetic Li ions and alpha particles which are released in opposite directions. After absorption, 94% of the reactions result in the release of a 840 keV Li ion in an excited state and a 1.47 MeV alpha particle [13]. The Li ion rapidly de-excites (10^{-13} s) to the ground state by releasing a 480 keV gamma ray. The remaining 6% of the reactions release a 1.015 MeV Li ion and a 1.777 MeV alpha particle. Since the particles are emitted in opposite directions, only one particle (Li ion or alpha particle) will enter the detector active volume (see Fig. 1). As shown in Fig. 2a, the average range of a 1.47 MeV alpha particle in GaAs is 4.2 microns and the average range of a 840 keV Li ion is 2.1 microns [14].

Reactions that take place in the ^{10}B absorber next to the detector contact undergo minimal energy loss in the metal contact, hence most of the particle energy is deposited in the active region of the detector (Fig. 2a). Reactions in the ^{10}B converter taking place further from the detector entrance contact result in energy self absorption before the particles enter the detector. As shown in Fig. 2b-d, energy self absorption ultimately limits the useful thickness of the converter film. The total charge deposited in the detector by a Li ion is significantly reduced for interactions occurring only 1 micron deep in the ^{10}B film, and Li ions do not reach the detector contact beyond a depth of 2 microns.

The calculated particle range for Li ions and alpha particles in a GaAs detector as a function of interaction depth in the ^{10}B film is shown in Fig. 3. Interactions occurring in the ^{10}B film 1.5 microns from the Schottky contact result in no penetration of 840 keV Li ions into the detector. The same is true for 1.47 MeV alpha particles released at a distance of 3.5 microns in the ^{10}B film from the detector contact. The energy deposition as a function of distance (*dE/dx*) is non-linear in both the ^{10}B film and the GaAs detector. The particle energy deposited in the detector as a function of interaction depth is shown in Fig. 4. It becomes apparent that only 100 keV of energy is deposited in the GaAs detector for 840 keV Li ions originating at 1.25 microns from the contact. The same is true for 1.47 MeV alpha particles released at 3 microns from the contact.

Films thicker than the optimum absorber width decrease the total detector sensitivity to neutrons (as illustrated in Fig. 5). The microscopic thermal neutron absorption cross section (σ) for ^{10}B is 3840 barns and the atomic density is 1.3 x 10^{23} atoms/cm^3. The resulting macroscopic absorption cross section (Σ) is 500/cm. Assuming front side irradiation, the thermal neutron beam intensity as a function of distance from the detector contact is described by

$$I(x) = I_0 e^{-\Sigma(D-x)} \quad (1)$$

where I_o is the initial beam intensity before entering the ^{10}B film, *D* is the film thickness, and *x* is the interaction depth from the contact. In the case where *L* represents the maximum allowable interaction distance from the detector contact, further increase in the film thickness (*D*) beyond *L* serves only to decrease the neutron flux, thus reducing the overall neutron sensitivity of the detector system.

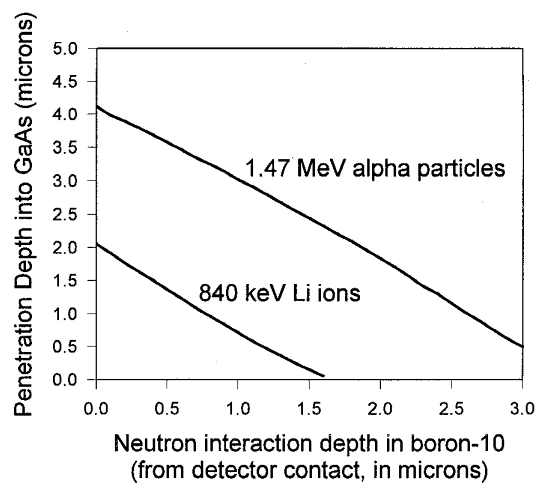

Fig. 3. Particle range in GaAs as a function of interaction distance in the ^{10}B absorber from the detector front contact. Attenuation from the Schottky contact has been included in the calculation. The calculation was performed for an entrance angle of 90°.

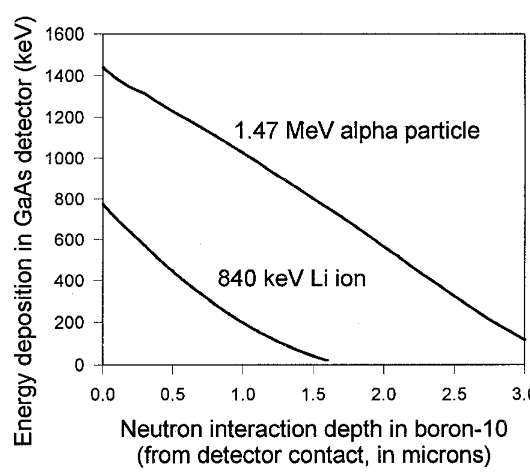

Fig. 4. Total particle energy deposition in GaAs as a function of interaction distance in the ^{10}B absorber from the detector front contact. Attenuation from the Schottky contact has been included in the calculation. The calculation was performed for an entrance angle of 90°.

The angular contribution to self attenuation must also be addressed. Referring to Fig. 6, a neutron interaction occurring at a distance *x* in the ^{10}B film has a probability of entering the detector as described by the fractional solid angle subtending the GaAs detector surface. The solid angle is described by

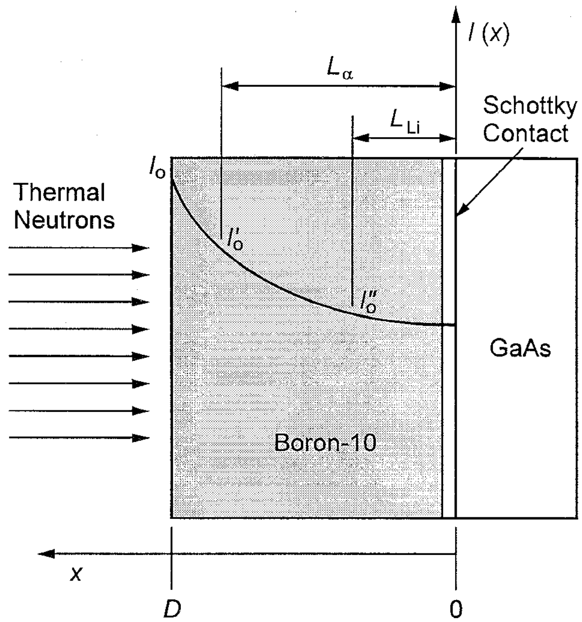

Fig. 5. The initial thermal neutron intensity (I_o) is reduced by absorption in the ^{10}B converter. If the ^{10}B film thickness is greater than the maximum allowable attenuation range (L) of either or both particles, the initial beam I_o will be reduced before reaching the sensitive region. Depicted is the case in which the film is greater than both the alpha particle attenuation range (L_α) and the Li ion attenuation range (L_{Li}). Hence the beam intensity is reduced to I_o' at L_α and I_o'' at L_{Li}.

$$\Omega(x) = 2\pi(1 - \frac{x}{L}) \quad (2)$$

where L is the maximum allowable attenuation range for the particle of interest in the ^{10}B absorber. The solid angle decreases as the neutron interaction distance from the contact increases. Fig. 7 demonstrates the effect on the detection sensitivity as a function of neutron interaction depth. Interactions occurring at the detector contact surface result in a particle (either Li or alpha) entering the detector with a probability above 95%. The solid angle for the Li ion decreases rapidly as the interaction distance from the contact increases, however the initial effect on the alpha particle is less pronounced. The result is an overall rapid decrease in sensitivity to half of the reaction products (Li ions). At a further distance, the sensitivity to alpha particles diminishes to zero.

The detector sensitivity to thermal neutron produced reaction products can be determined by collectively considering the previously mentioned effects. The neutron absorption probability per unit distance is described by

$$P(x) = \Sigma e^{-\Sigma(D - x)} dx. \quad (3)$$

Referring to Figs. 4, 5, 6, and 7, the sensitivity to a particular reaction product (Li ion or alpha particle) as a function of film thickness is found by integrating over the product of the interaction probability and the fractional solid angle through thickness D where

$$S(D) = \frac{1}{4\pi I_O} \int_0^D I_O 2\pi\Sigma e^{-\Sigma(D - x)} (1 - \frac{x}{L}) dx \quad (4)$$

$$= 0.5\left\{(1 + \frac{1}{\Sigma L})(1 - e^{-\Sigma D}) - \frac{D}{L}\right\} \quad (5)$$

for $D \leq L$, and

$$S(D) = \frac{I_O e^{-\Sigma(D - L)}}{4\pi I_O} \int_0^L 2\pi\Sigma e^{-\Sigma(D - x)} (1 - \frac{x}{L}) dx \quad (6)$$

$$= 0.5 e^{-\Sigma(D - L)}\left\{(1 + \frac{1}{\Sigma L})(1 - e^{-\Sigma L}) - 1\right\} \quad (7)$$

for $D > L$.

The detectors operate as thermal neutron counters and require only the ability to discriminate between gamma ray and thermal neutron events. The truncated fields observed in SI bulk GaAs Schottky barrier detectors provide a natural discrimination feature. From Fig. 2a, the maximum range of a reaction product will not exceed 5 microns into the GaAs detector, hence the active region need only extend slightly beyond 5 microns.

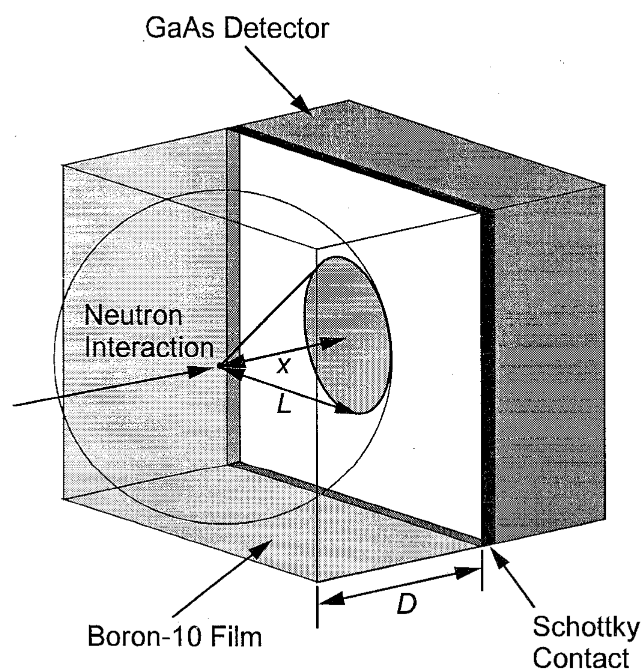

Fig. 6. The probability of the reaction products entering the detector is a function of the solid angle and the maximum allowable range (L).

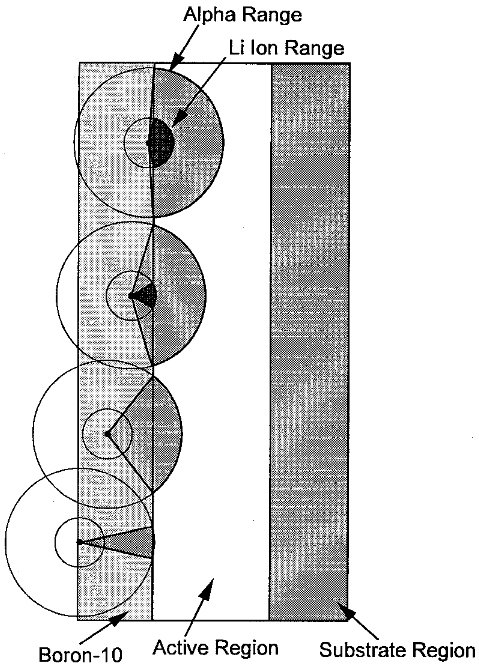

Fig. 7. Events occurring near the contact have a very high probability that one of the reaction products (alpha particle or Li ion) will enter the detector. The probability diminishes as the reactions take place further from the contact.

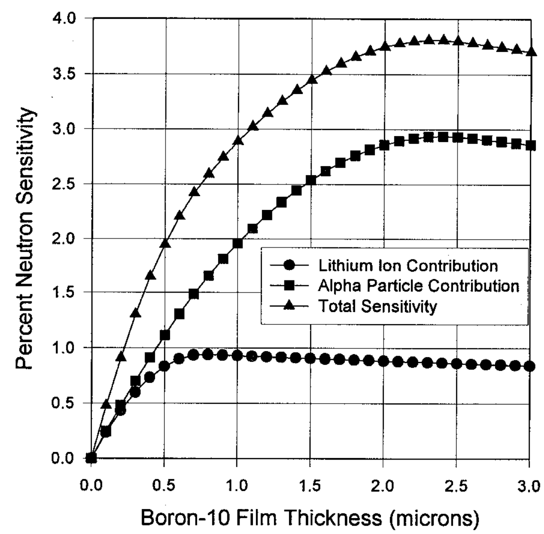

Fig. 8. Calculated sensitivity of ^{10}B coated GaAs Schottky barrier detectors to thermal neutrons as a function of film thickness. Shown are the sensitivity contributions from the Li ions and alpha particles as well as the resulting total sensitivity. The analysis was performed for front side irradiation and a particle minimum energy requirement of 300 keV.

The application of only a few volts to the detector increases the active region beyond the maximum particle range. The gamma ray photoelectric linear attenuation coefficient for GaAs is small beyond 150 keV (< 0.7/cm), hence the probability of absorbing high energy gamma rays in the thin high field active region (for instance, a 10 micron thick active region) is extremely small. Gamma rays absorbed in the low field substrate region do not contribute to the observed induced charge. A conservative discriminator setting of 300 keV would significantly decrease the probability of mistaking a gamma ray interaction for a thermal neutron reaction product interaction.

The requirement that the particles entering the detector have at least 300 keV of energy results in $L = 0.7725$ microns for 840 keV Li ions and $L = 2.456$ microns for the 1.47 MeV alpha particles (see Fig. 4). Since L is different for the alpha particles and the Li ions, the analysis is treated separately for each particle. The total thermal neutron sensitivity is determined by simply adding the calculated Li ion and alpha particle sensitivities. Using a discriminator criteria of 300 keV, the expected total thermal neutron sensitivity of a ^{10}B converter on a GaAs Schottky diode detector as a function of film thickness is shown in Fig. 8. As can be seen, the sensitivity is maximized at a film thickness of 2.4 microns. The sensitivity increases only slightly from 3.75% at $D = 2.0$ microns to 3.81% at $D = 2.4$ microns, indicating that films greater than 2.0 microns thick do not significantly increase the thermal neutron sensitivity for the criteria set in the present case.

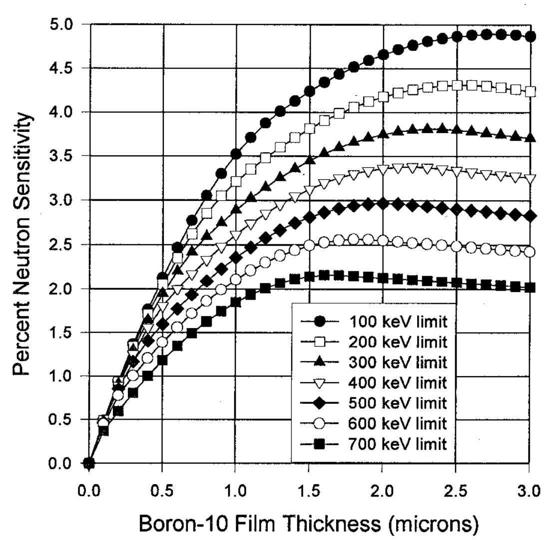

Fig. 9. Calculated total thermal neutron sensitivity of ^{10}B coated GaAs Schottky barrier detectors as a function of film thickness and lower level energy discriminator (LLD) setting. Lower LLD settings allow for increased sensitivity with the risk of including more background noise in the measurement. The calculation is performed for front side irradiation.

Fig. 9 shows the total thermal neutron sensitivity as a function of the ^{10}B film thickness and the lower level discriminator (LLD) setting. The total thermal neutron sensitivity can be increased to 4.9% by increasing the film thickness to 2.75 microns and decreasing the LLD setting to only 100 keV. However, lowering the LLD setting increases the risk of including noise with the measurement. Ultimately a compromise must be met with any given radiation environment (neutrons and gamma rays) between sensitivity and noise discrimination. In the present work, measurements were taken with the LLD set at approximately 600 keV, 300 keV, and 100 keV.

III. Detector Fabrication

Commercial SI bulk GaAs wafers were thinned using 3 micron alumina followed by a preliminary polish with 0.3 micron alumina suspended in a sodium hypochlorite solution. The final polish was performed using a 0.25% bromine/methanol solution. The pieces were subsequently cleaned in a series of solvents (trichloroethylene, acetone, propanol, methanol). The polished surfaces were lightly etched in a solution of 1:1:320 H_2SO_4:H_2O_2:DI followed by an oxide removal etch with 1:1 HCl:DI. The pieces were thoroughly washed in DI water afterwards.

After the polishing and cleaning procedure, the wafers were patterned and full area square layers of Au/Ge/Ni [15] were patterned and lifted off. The metal layers were annealed for 1 minute in pure H_2 at 410°C to make ohmic contact to the bulk GaAs material. The opposite side of the wafers were then polished as previously described to reduce the overall thickness to 300 microns. Using photolithography liftoff, the array of Ti/Au (150 angstroms/500 angstroms) Schottky contacts were patterned and evaporated onto the surface. Protective photoresist was patterned over the Schottky contact array pads and pin-outs, and 6 micron deep isolation grooves were etched around the metal patterns using reactive ion etching (RIE).

Two methods were used to pattern the ^{10}B converter onto the Schottky contact arrays; which will be referred to as type "A" and type "B" detectors. The ^{10}B converter was patterned onto type A detectors by first defining the square regions directly over each of the pixels with thick photoresist. The ^{10}B was then evaporated and lifted off, leaving behind a 4000 angstrom film of ^{10}B covering only the 1 mm square pixels. To prevent shorts between the pixels, the Schottky contacts on type B detectors were coated with a very thin layer of PECVD Si_3N_4 before depositing the ^{10}B. Afterwards, a large square area exposing the entire Schottky contact array was patterned with thick photoresist. The ^{10}B was then evaporated and lifted off. Photoresist was patterned around the ^{10}B area and the excess Si_3N_4 was removed by RIE in order to expose the pin-outs. The ohmic contact back planes of the devices were bonded to standard die packages with Ag epoxy, followed by wire bonding to the pin-outs. The sensitive Schottky contact region size is 1 mm square for both detector types. Fig. 10 shows the basic 25 pixel array layout for a type A detector. At present, only type A detectors have been tested.

IV. Experimental Results

Type A GaAs Schottky barrier arrays were tested at a beam port from a thermal nuclear reactor with a calibrated thermal neutron flux of 2 x 10^6 n/cm^2-s. The pixels were reverse biased with only 10 volts and the measured reverse bias leakage current was negligible. Neutron induced particle counts were distinguished from background gamma ray counts by taking measurements with and without a sheet of gadolinium between the beam port and the detector array. The signals produced by the gamma rays were easily discernible from the alpha particle and Li ion signals, and were easily discriminated by setting the LLD appropriately high. However, discrimination tests indicate that the background noise signals were created primarily from scattered and albedo neutrons and not gamma rays. The low operating voltages ensured that the device active regions were only a few microns thick. As a result, the bulk of the 300 micron thick GaAs devices were insensitive to ionizing gamma ray events. The thermal neutron signal to noise ratio of the detector array was greater than 24:1. Dead time during operation was minimal at only a few percent.

With the LLD set at approximately 600 keV, the thermal neutron sensitivity was measured to be 1.19%. Reducing the LLD to approximately 300 keV yielded a thermal neutron sensitivity of 1.67%, and further reducing the LLD to the electronic noise limit yielded a maximum sensitivity of 1.8%. The sensitivity measurements match well with the predicted results indicated in Fig. 9.

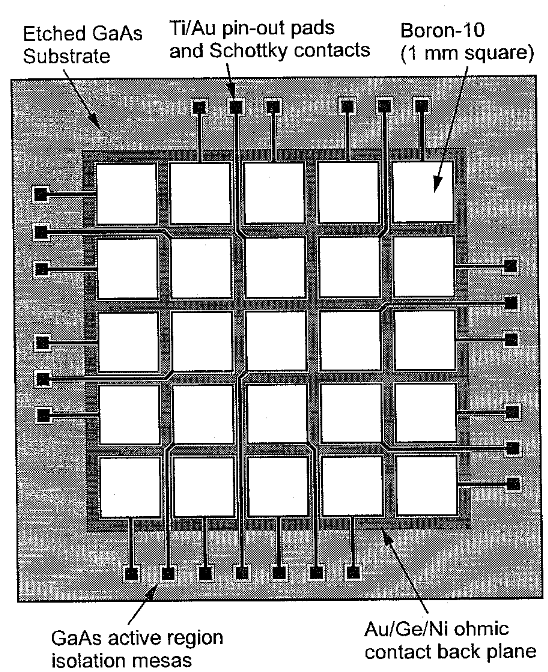

Fig. 10. Front view of a type A 25 pixel SI bulk GaAs Schottky diode array. The area of each ^{10}B pad is 1 mm square.

One type A device was irradiated for a period of over 100 full irradiation days in the neutron beam, corresponding to a total neutron fluence greater than 1.73 x 10^{13} n/cm^2. With all electronic processing equipment held constant, the device did not demonstrate a reduction in count rate (Fig. 11), and the maximum fluctuation in count rate was within statistical limits (slightly exceeding one standard deviation). The pulse height and shape remained fairly constant, indicating no apparent reduction in charge collection efficiency. Hence, the device appears to be radiation hard to thermal neutrons and the accompanying gamma rays.

The LLD was set at approximately 600 keV for image accumulation. Templates made from 2 mm thick Cd sheet were used to test the imaging capability of the devices. Crosses with dimensions of 1 mm, 1.5 mm, and 2 mm bars are clearly imaged. Holes 1 mm, 1.5 mm, and 2 mm in diameter were also cut into a 2 mm thick Cd sheet, in which the holes were easily recognizable. Opaque regions totaled 600 counts/minute background to the open area 14,500 counts/minute. Fig. 12 shows the resulting images of the tests from a type A detector.

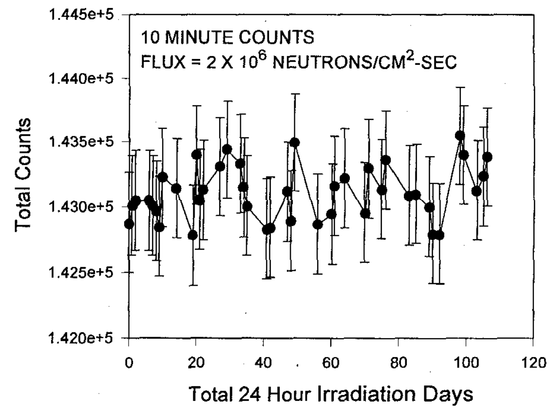

Fig. 11. Detector count rate response as a function of beam port irradiation time. Measurements were taken over a 10 minute period. The count rate did not noticeably depreciate after over 100 full irradiation days in a thermal neutron beam.

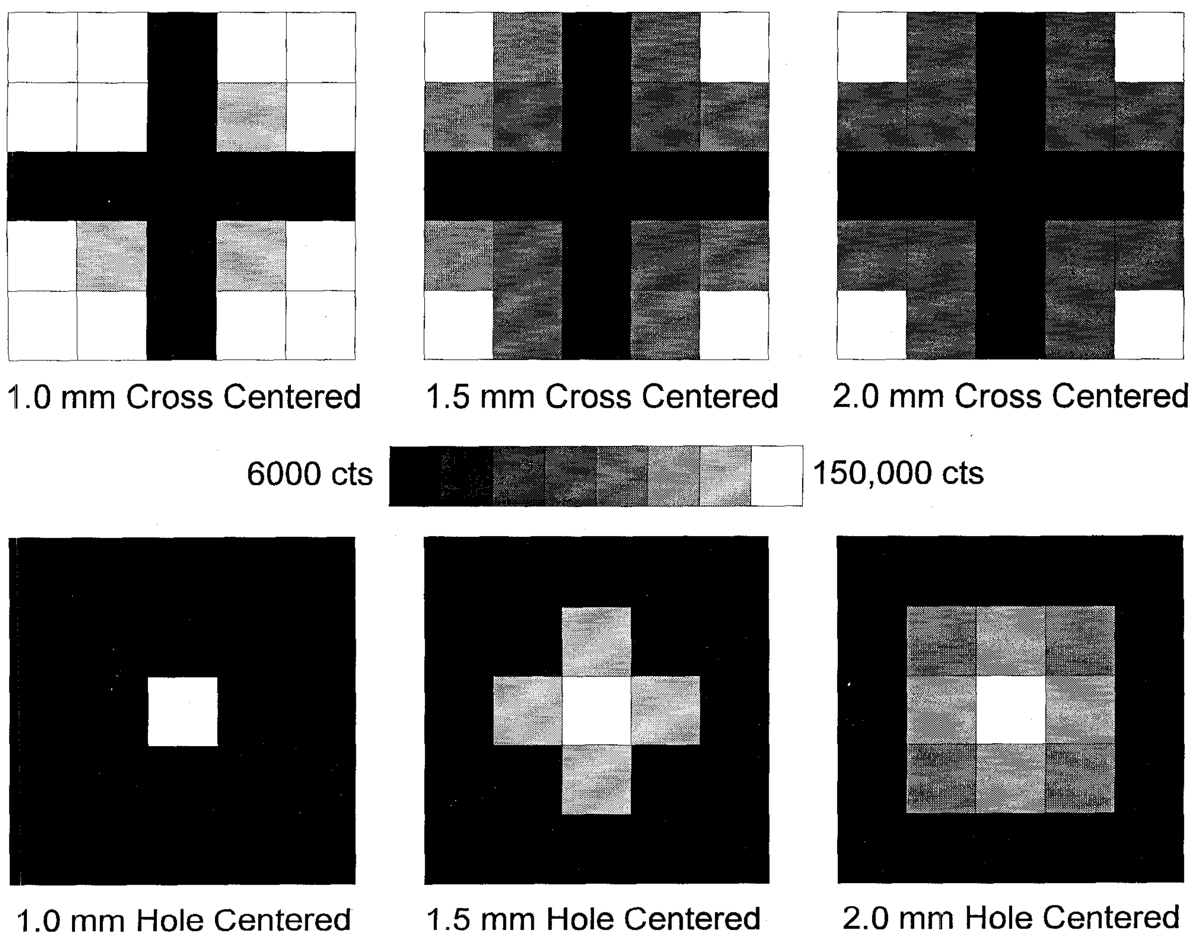

Fig. 12. Thermal neutron images produced with 10 minute long transmission measurements of Cd templates. The scale is linearly divided, ranging from 6000 counts to 150,000 counts. The Cd sheet was 2 mm thick and the crosses were 1 mm, 1.5 mm, and 2 mm wide. The holes in the Cd sheet were 1 mm, 1.5 mm, and 2 mm in diameter.

V. CONCLUSIONS

Prototype Schottky barrier imaging arrays have been fabricated from SI bulk GaAs and tested. The devices need only low bias voltages to operate, in the present case being only 10 volts. The devices are radiation hard and have withstood a fluence of 1.73 x 10^{13} n/cm^2 without noticeable degradation in performance.The signal to noise ratio (or signal neutron to albedo neutron ratio) is presently better than 24:1. Alterations in the detector's environmental geometry can increase the signal to noise ratio to greater values. The maximum total thermal neutron sensitivity for the prototype devices (type A) averaged 1.8% with the LLD set below 100 keV. Images of Cd crosses 1-2 mm wide and holes in Cd sheet 1-2 mm in diameter have been successfully imaged.

Theory indicates that the total thermal neutron sensitivity can be increased to 4.9% by lowering the LLD to approximately 100 keV and increasing the ^{10}B film thickness to 2.75 microns. In mixed radiation fields where the gamma ray background is significantly high, the LLD setting should be increased to reduce the background gamma ray interaction probability. A conservative LLD setting of 300 keV allows for a maximum thermal neutron sensitivity of 3.8% at a ^{10}B film thickness of 2.4 microns. Future generation devices are now being designed with thicker ^{10}B films to increase sensitivity, and with higher pixel densities to increase spatial resolution.

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