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Amorphous Silicon Position Sensitive Neutron Detector

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Amorphous Silicon Position Sensitive Neutron Detector

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Abstract

In this work,we present an investigation of the possibility of using a-Si:H diode coated with an appropriate converter, as a position sensitive neutron detector. Our Monte Carlo simulation predicts that using a Gd film ~2μm thick, coated on a sufficiently thick amorphous silicon n-i-p diode, we can achieve a neutron detection efficiency of 25 percent. The experimental results presented give an average signal size of about 12000 e^- per neutron interaction, which is well above the noise and is in good agreement with the expected values. We can also fabricate pixel detectors with element size as small as 300 μm and still register a count rate of 2200 events/sec in a typical neutron flux situation of about 10^7 n/cm^2.sec. The fact that these detectors are not sensitive to gamma rays, and show excellent radiation hardness, make them good candidates for being used in applications such as neutron imaging, neutron crystallography and neutron scattering.

I. INTRODUCTION

The application of a-Si:H diodes as charged particle and X-ray detectors has been previously reported [1]. Moreover, some important characteristics such as, charge collection, signal generation and noise have been studied [2]. In fact, the possibility of laying out a substantial number of small size diode pixels on a large substrate makes a-Si:H an appropriate choice as a Position Sensitive Detector (PSD). By interfacing such arrays with suitable neutron converters, it is possible to develop neutron-sensitive PSD's with desirable spatial resolution and efficiency. An obvious and important application for neutron PSD would be neutron crystallography, and neutron imaging or real-time neutron radiography, a NDT method which has been a typical utilization of research reactors for several decades. The World Conferences in Neutron Radiography, specially the recent ones [3,4,5] have contained many papers on neutron imaging systems. The image capturing part of all neutron imaging systems is a so called neutron camera .Some neutron cameras are just a Thomson tube, an image intensifier tube with an internal neutron sensitive scintillator screen [6]. Others use a combination of an external scintillating screen optically coupled to a TV camera through a front surface mirror and some lens system, refered to as LTV [7]. A matrix of neutron-sensitive a-Si:H pixels in conjunction with an array of TFT amplifiers and readout electronics (Fig. 1) may be considered as an alternative to neutron cameras with better or comparable spatial resolution and at a much lower cost. In Fig. 1 the pixel readout uses thin film transistors made of a-Si:H. TFT readout fabricated from poly-crystalline silicon can give a faster readout time. Another important area of application of position sensitive neutron detectors is neutron scattering. For this application, various kinds of PSD's with spatial resolution ranging from

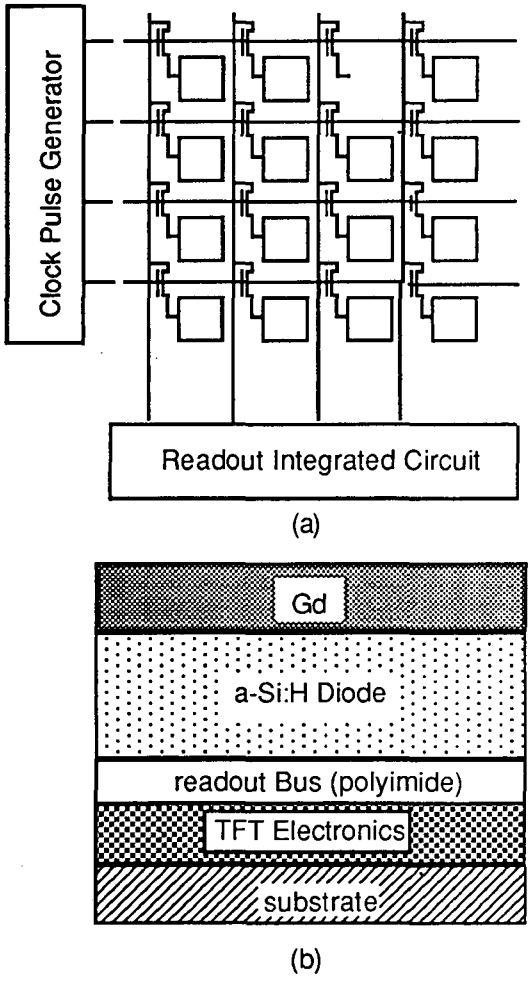

Fig.1 (a) Schematic diagram of a-Si:H pixel detector, (b) Structure of a single pixel

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0.5 to a few mm, such as: proportional-counters, Microchannel-plates, and Anger cameras have been used [8]. For this specific application, in which good fast neutron and gamma rejection is a desirable requirement, the a-Si:H based PSD offers advantages over the currently used detector configurations. The radiation hardness property of a-si:H neutron detectors together with the possibility of being fabricated in small sizes, make them suitable for direct beam measurements as well.

In the following we will review different kinds of available neutron converters, and give the results of our Monte Carlo simulation of a Gd neutron converter. This analysis suggest that using a Gd film ~2 μm on a fairly thick amorphous Si diode (30μm), we can detect thermal neutrons with an efficiency of 25 percent. Our experimental results are presented and their agreement with the Monte Carlo analysis is discused.

II. DETECTOR

A. Neutron Converter

The neutron converter material used with a-Si:H diodes arrays should be either provided in the form of a screen in close proximity to it, or coated as a thin layer on the top contact of the planar device. Commonly used neutron converter materials are Boron (^{10}B), Lithium (^{6}Li), and Gadolinium (Gd) . The first two produce alpha particles with energies close to 2 MeV, but the range of these alpha particles in the convertor itself are much less than the mean free path of thermal neutrons, resulting in low detection efficiency. A simple calculation shows that for pure ^{10}B and ^{6}Li films the converter efficiencies (escaping α particle per neutron) are limited to 5 and 2 percent, respectively. However, for Gd even in the natural isotopic mixture, our Monte Carlo simulation (see next section) predicts an efficiency as high as 25 percent. Gd foils have a history of being used in neutron radiography in conjunction with X-ray films, but not in real time applications lsuch as neutron imaging. Gd has a very high cross section for thermal neutron capture, which yields short range conversion electrons of about 70 KeV energy. These have a mean range of about 25 μm in silicon; the energy deposition of these low energy electrons will be very localized and therefore , a high spatial resolution can be achieved. All these advantages plus the fact that we are able to coat fairly thick films of this metal on a-Si:H samples, make the Gd the best conveter. There are several commercial neutron sensitive scintillators commonly used in real time neutron radiography. The one frequently used is a composite screen of ZnS(Ag), ^{6}LiF called NE426. The other one named Trimax2 is a Gd2O2S:Tb compound used in Thomson tubes. The spatial resolution of the commercially available Gd2O2S is appreciably higher than NE426. Hitachi co. has also produced a ceramic scintillator made of Gd2O2S:Pr,Ce,F... compacked by hot isostatic processing [9], which has been shown to have good properties for X-ray detection. All of these neutron sensitive scintillators have the drawback of containing high Z elements and therefore being gamma sensitive. This is of course, an undesirable feature for applications where neutron beams contain appreciable gamma fluxes. We have considered using Hitachi Gadolinium Oxysulfate scintillators for our purpose. The result of our calculation, based on a semi Monte-Carlo analysis of point spread function (Fig. 2), indicates that with layers as thick as 0.3 mm, a FWHM resolution of 0.5 mm is achievable. This figure shows an improvement over the microchannel plates, currently used as high resolution devices in neutron scattering [8]. Meanwhile we have measured the light producing efficiency of several 1.1 mm Hitachi samples to be about 28000 to 30000 electron-hole pairs per 1 MeV of deposited energy. This number suggests a signal size of about 2000 e^- from the 70 KeV electron, produced by neutron capture on Gd content of the scintillator, which is not much above the expected noise. On the other hand, in our effort to detect the thermalized neutrons from a 70 Ci Pu-Be source, by a p-i-n diode covered with one of these samples, we found that the Gd_2O_2S scintillator is quite sensitive to source gamma rays. From this finding and also by considering the small signal predicted, we concluded that the use of this scintillator could not serve our purpose.

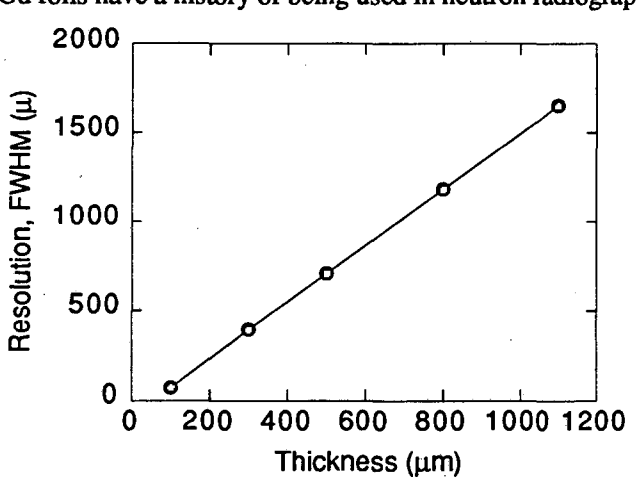


Fig. 2 Variation of Gd2o2s spatial resolution with thickness

B. Monte Carlo Simulation

Monte Carlo Analysis was used to simulate the interaction of incident thermal neutrons with a Gd converter and subsequent energy loss of the resulting conversion electrons. Due to the large neutron capture cross sections of the predominant Gd isotopes (^{155}Gd and ^{157}Gd), other reactions were assumed to have negligible effect. An investigation of all possible conversion electron lines for both isotopes, provided in detail, the energies and emission probabilities of all electrons. Because of the relatively low energies of the conversion electrons (average energy ~ 70 KeV), calculation of their energy loss was done by using the

range-energy relation to find the residual range, and from that the energies of electrons escaping the Gd film and entering the a-Si:H detector were found. The angular distribution of electrons at their points of creation were assumed to be isotropic. Neutron stopping and conversion electron efficiencies as a function of Gd film thickness are shown in Fig. 3.a . Electron events are defined to be: "those neutron captures involving internal conversion electron emission (rather than γ emission), from which at least one of the electrons would be able to escape the Gd film into the amorphous silicon diodes". The neutron stopping efficiency increases and saturates at about three times the mean free path. But the electron event efficiency passes through a maximum of 25 percent at film thickness of about 4 μm. The decline afterwards is due to the fact that, for a given film thickness, most of the neutrons are stopped in lower depths and therefore, the chance of electrons escaping the film will decrease as the thickness increases. In Fig. 3.b we show the simulated pulse height distribution for two different film thicknesses. The signal size is calculated from the escaping energy of the conversion electrons, assuming: a) the p-i-n diode is sufficiency thick to stop all electrons; b) the average energy required to produce an e-h pair (w) for a-Si:H diode is 4.8 eV [10]. As we can see, for thick Gd films a larger number of conversion electrons, especially the lower energy ones are lost by stopping in the foil. It is also interesting to study the effect of film thickness on the average signal size (Fig. 3.c). For an ideal charge collection by the a-Si:H diode, the minimum occurs at the mean range corresponding to the average energy electrons (~ 6 μm). For thinner films, the number of escaping electrons does not change as much but their energies increase. While for thicker films, only higher energy electrons can escape, resulting in a rise of the average signal size. However, this rise can not continue for very thick films that are able to stop all produced electrons. Our simulation results suggest that a foil thickness of 2 μm, while not being far from optimum event efficiency, would produce the largest average signal in the detector.

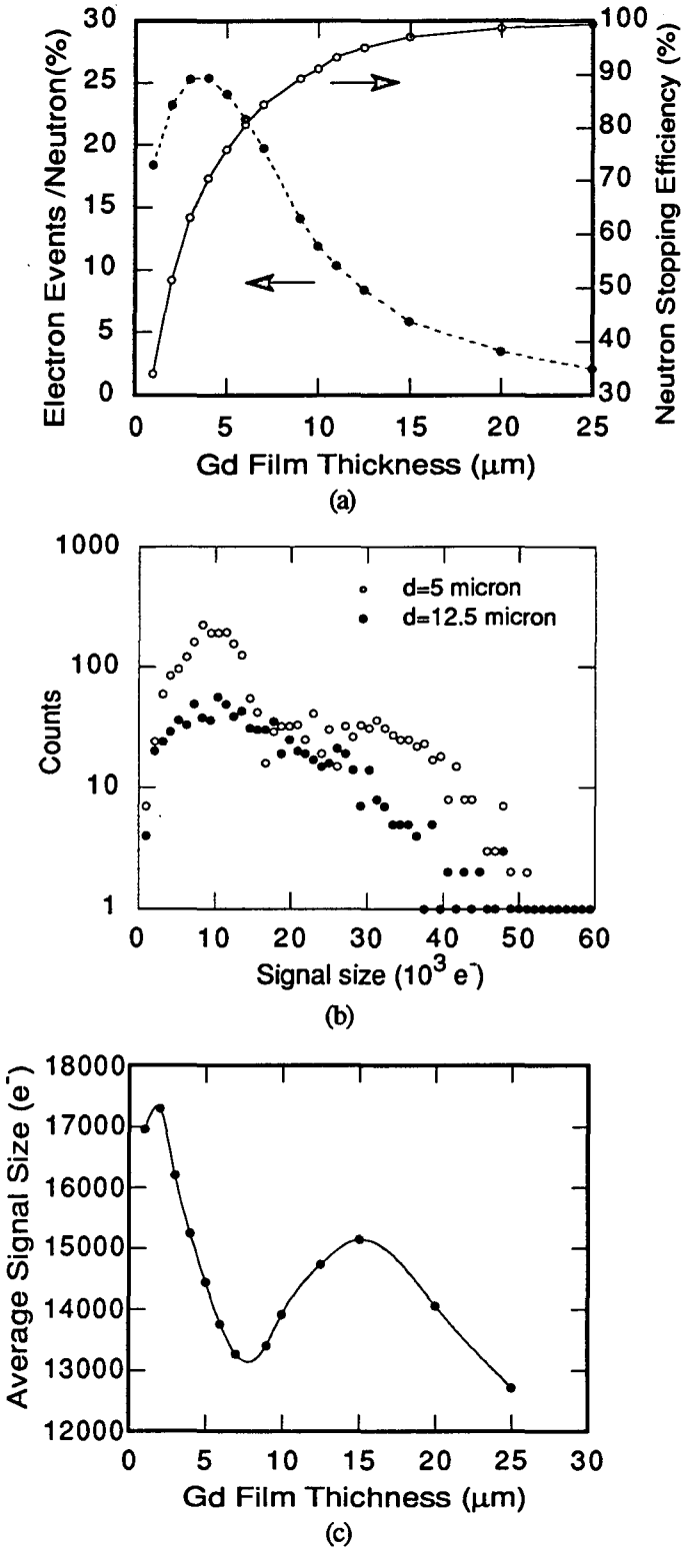


Fig. 3 Monte Carlo simulation results; (a) neutron stopping and event efficiency, (b) simulated pulse height distribution for two different Gd film thicknesses, (c) variation of average signal size with Gd film thickness

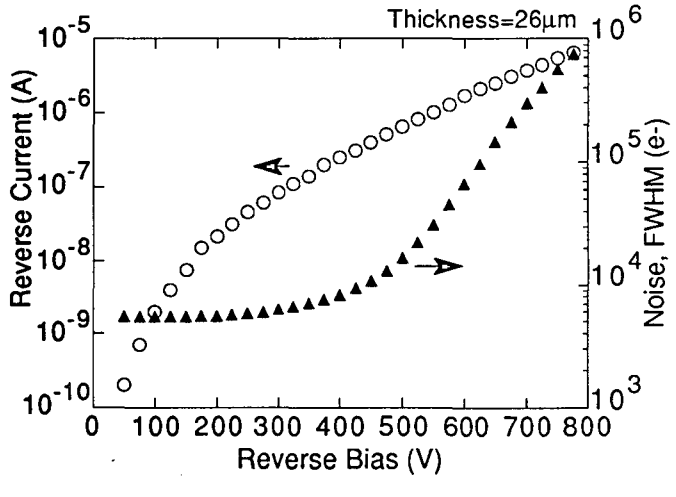


Fig. 4 Nosie and I-V characteristics of an a-Si:H diode

C. Amorphous Silicon Diode

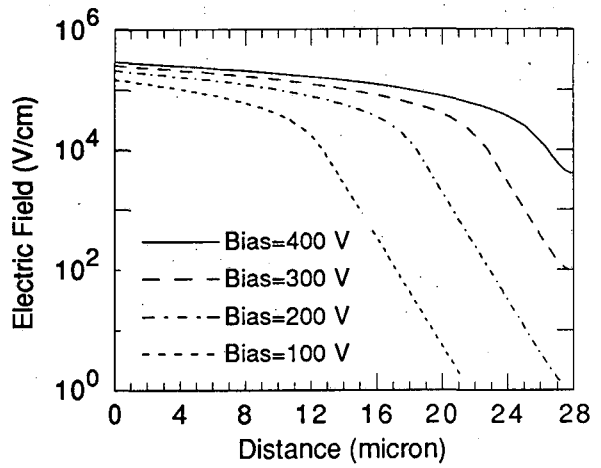
The internal conversion electrons escaping the Gd layer are detected by an amorphous silicon n-i-p diode. The incoming electrons produce electron-hole pairs by direct interaction in the depleted region of the reversed bias diode. In order for a complete energy deposition, the intrinsic layer should have a thickness larger or, at least comparable to the mean range of the conversion electrons. Therefore, in our experiments we have used diodes with thickness within the range of 25-30 μm, with capacitance values between 50-80 pf. The I-V and noise characteristics of a reversed biased, 27 μm thick n-i-p diode are shown in Fig. 4. The flat portion of the noise at lower voltages comes from the preamplifier loaded with detector capacitance, and to some extent is due to contact and p-layer resistance (Nyquist noise). At higher bias voltages, the shot noise and 1/f contribution show up. The overall noise is proportional to the contact area [11]. With DC bias, the electric field distribution through the intrinsic layer is dependent both on dangling bond density (N_d) and the external bias. In Fig. 5.a we show the bias dependence of the field distribution in a 28μm thick p-i-n diode. The full depletion is expected to occur at about 500 V. This bias voltage is necessary if a complete collection of produced electron-hole pairs is to take place. However, the extent of charge collection also depends on the shaping time of the amplifier. Fig. 5.b shows that for detector bias that we have used, maximum charge collection efficiency is not possible, for timings faster than 3.5 μsec. In Fig. 5.c we show the charge collection efficiency versus bias voltage for a fixed 3.5 μsec shaping time.

One interesting aspect of a-Si:H pertinent to high dose applications is considered to be its radiation hardness. Radiation damage induced by ~1 MeV neutrons up to fluences of ~5×10^{14} neutron/cm^2, measured by the increase in leakage current and in shot noise, were minimal and almost completely disappeared after annealing for 2 hours at ~ 200°C [1] . In another study [12] photodiode a-Si:H sensors were shown to suffer less than 3 percent change in output signal, over the course of irradiation with a ^{60}Co source to a total dose of ~10^6 rad.

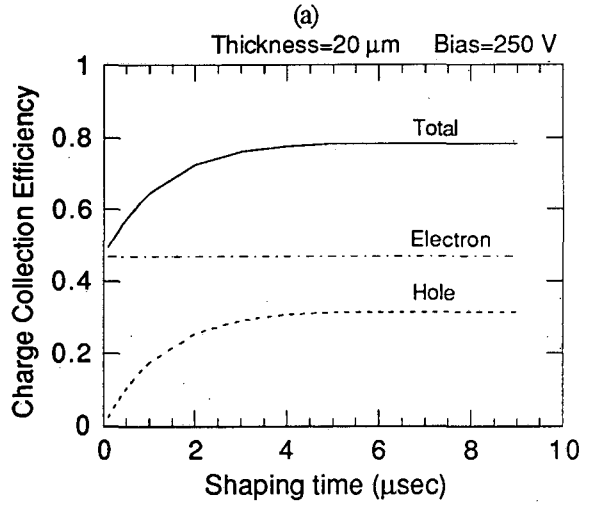
III. EXPERIMENT

A. Setup

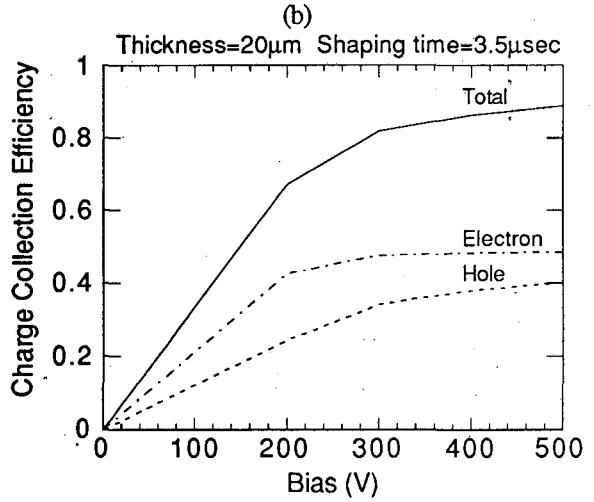
The setup of our experiment is shown in Fig. 6. The peaking time of the CR-(RC)^2 shaping amplifier used was about 3.5 μsec. The PHA spectra were received by and processed on a microcomputer. The samples were amorphous silicon n-i-p diodes with 4-6 mm diameter metallic top contacts, later covered with 12.5 μm Gd foil or plated with Gd.The Gd coating procedure developed can successfully make uniform and stable films of up to 7 μm thick, over the desired area, while maintaining the required low temperature for prevention of any damage to the sample. Using photo-lithographic technique to make patterns, and etching Gd with Hydrochloric Acid, we can produce arrays of numerous small



(a)



(b)



(c)

Fig.5 (a) Bias dependance of of the internal electric field in 28 μm a-Si:H diode, (b) variation of charge collection efficiency with shaping time, (c) bias dependance ot the charge collection efficiency

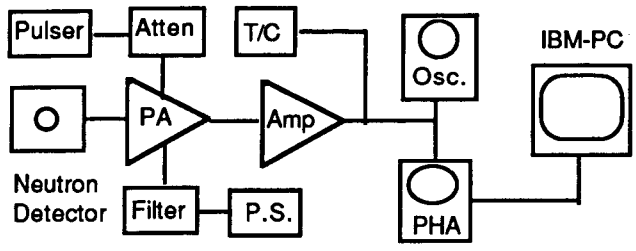


Fig. 6 Bloch diagram of the experimental setup

size detectors for our future imaging tests.

Thermal neutrons were produced by moderating neutrons from a 70 Ci Pu-Be source in a special water hole arranged in a concrete floor. At the detector location the thermal flux was about 400 n/cm^2.sec, a value which is extremely low compared to the minimum neutron flux ~ 10^4 n/cm^2/sec, used in any neutron radiography application.

B. Results and Discussion

The spectrum of events related to neutrons detected by a 20 μm thick n-i-p diode, coated with 5 μm Gd with an effective area of ~0.1 cm^2 is shown in Fig. 7.a. A reverse bias of 250V was applied, and a net count rate of ~9 events/sec was recorded. Due to a high noise level in our system electronics, signals below 10000 e$^-$, overwhelmed by noise, were eliminated by raising the PHA threshold. The mean signal size is ~11900 e-, which considering an approximately 77 % charge collection efficiency of the diode for the applied bias and shaping time (Fig. 5.c), is only 7% higher than the estimated value by the Monte Carlo simulation results of Fig. 3.c This difference would have been removed if the smaller size signal had not been lost by the hreshold setting. The background subtracted spectra for two amorphous silicon n-i-p diodes covered with 5 and 12.5 μm Gd films are shown in Fig. 7.b The spectrum for the detector with the thinner converter, has about 2 times more counts compared to the other one. This is consistent with the expected event efficiencies calculated by our Monte Carlo analysis (Fig. 3.a). The data related to the mean signal

Table-I
Comparison of expected and measured average signal size

Characteristics	Diode #1 (28 μm)	Diode #2 (20μm)
Convertor thickness (μm)	12.5	5
Diode charge collection efficiency	%43	%77
Expected signal size (e$^-$)	6320	11200
Average measured signal size (e$^-$)	7350	11890

size for both detectors ispresented in Table-I. In the table the expected signal size is taken from Fig. 3.c, and then multiplied by the respective charge collection efficiencies of the diodes. The reason for the discrepancy between the measured and expected average signal size is again the missing contribution of the lower part of the spectra. For the 20 μm diode, which is thinner than the mean range of the average energy conversion electron, some signal loss due to this effect might have compensated for the greater cut in the low level signals resulting in an smaller difference.

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We have also measured the gamma sensitivity of the 28 μm sample with the 12.5 μm Gd foil, by a 10 minute exposure to a 105 mCi Ra source. The net number of count was 440, giving a near zero sensitivity of .001 percent.

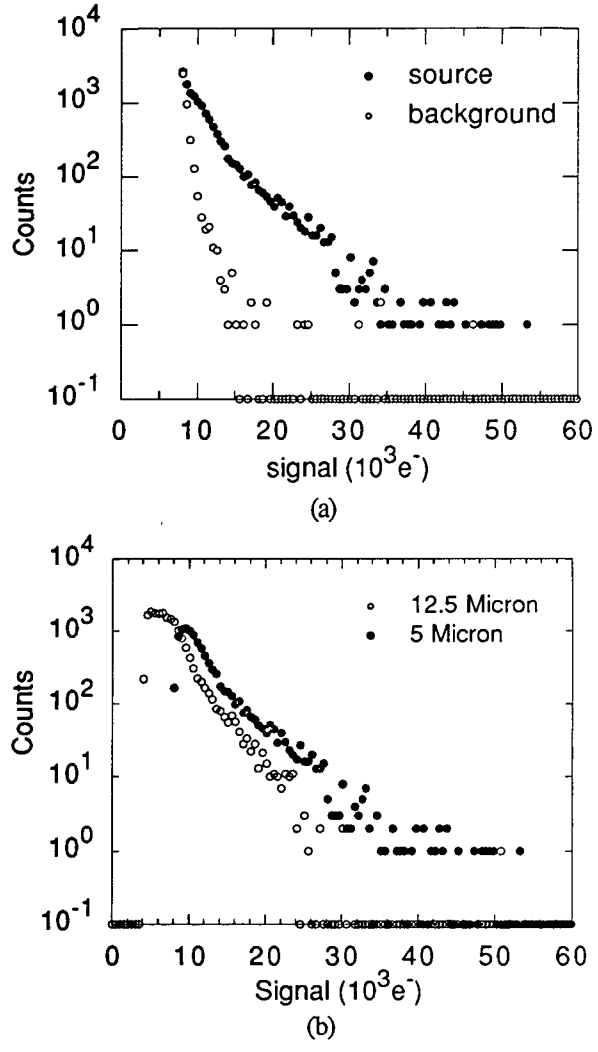

Fig. 7 Experimental results; (a) pulse height distribution of 25 μm diode covered with 5 μm Gd, (b) comparision of results for two differnt thicknesses of Gd film used

IV. CONCLUSION

In our investigation of th use of a-Si:H diodes for neutron detection, we found that with adequately thick n-i-p diodes coated with ~2 μm Gd film, one can detect thermal neutrons

with an efficiency of about 25%. This means that a pixel size of 0.3x0.3 mm^2, in a flux of $10^7 n/cm^2$.sec which is a typical flux used in most applications, including neutron imaging, will register more than 2200 events/sec. Considering the other favorable properties of these detectors, such as radiation hardness and insensitivity to gamma rays, that we have shown, the a-Si:H seems to be an excellent candidate for a neutron position sensitive detector.

Acknowedgement

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