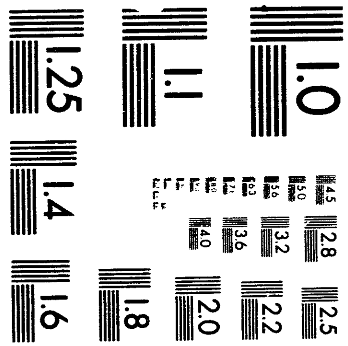

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HIGH EFFICIENCY NEUTRON SENSITIVE AMORPHOUS SILICON PIXEL DETECTORS

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High Efficiency Neutron Sensitive Amorphous Silicon Pixel Detectors

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abstract

A multi-layer a-Si:H based thermal neutron detector was designed, fabricated and simulated by Monte Carlo method. The detector consists of two PECVD deposited a-Si:H pin detectors interfaced with coated layers of Gd, as a thermal neutron converter. Simulation results indicate that a detector consisting of 2 Gd films with thicknesses of 2 and 4 μm, sandwiched properly with two layers of sufficiently thick (~30μm) amorphous silicon diodes, has the optimum parameters. The detectors have an intrinsic efficiency of about 42% at a threshold setting of 7000 electrons, with an expected average signal size of ~12000 electrons which is well above the noise. This efficiency will be further increased to nearly 63%, if we use Gd with 50% enrichment in ^{157}Gd. We can fabricate position sensitive detectors with spatial resolution of 300 μm with gamma sensitivity of ~1×10^{-5}. These detectors are highly radiation resistant and are good candidates for use in various application, where high efficiency, high resolution, gamma insensitive position sensitive neutron detectors are needed.

I. INTRODUCTION

Two dimensional pixel arrays of thermal neutron detectors, especially with high sensitivity and small pixel size are desirable for a wide range of application, from industrial real time imaging systems to powerful research tools for probing material properties which are not possible through other means such as X-rays and electrons. In real time neutron imaging different kinds of neutron cameras have been used, some with image intensifier tubes having internal neutron sensitive screens, and some with external scintillating screens coupled to video cameras [1,2].

Position sensitive neutron detectors such as: BF_3 proportional-counters, microchannel-plates, and Anger cameras [3] are in use in many neutron scattering facilities. These detectors offer spatial resolutions in the range of 500 μm to a few mm. In general neutron scattering experiments require position sensitive detectors with good fast neutron and gamma rejection. There are some special experiments which require high spatial resolution. For instance, diffraction experiments with biological crystals, small angle neutron scattering (SANS) experiments which use well focused neutron beams to achieve high momentum resolution [4], near surface studies with neutron reflection, and cold neutron microscopy [5]. The position sensitive neutron detectors which have been considered for these high resolution experiments consist of ^{6}Li glass scintillators coupled to Hamamatsu position sensitive photomultiplier (PM) tubes (R 2487). The problem with these 55x45 mm^2 PM tubes is that they have a fairly large gamma sensitivity and their gain is also position dependent. M. Kanyo *etal* [6] have introduced a new discrimination method which is said to reduce the gamma background drastically while not affecting neutron efficiency.

In our pervious work [7] we proposed a low cost, high resolution, large area position sensitive neutron detector based on hydrogenated amorphous silicon (a-Si:H). Despite its poorer electronic characteristics compared to crystalline silicon, a-Si:H offers strong advantages of availability in large area and much higher radiation resistance [8]. This material has been successfully used as detector for X-rays, gamma rays, charged particles and neutrons [9,7]. For neutron detection we interfaced amorphous silicon n-i-p diodes with Gd converters. Gadolinium even in its natural composition has a large thermal neutron absorption cross section (~46000 barns) and facilitates achievement of much higher neutron detection efficiencies than possible with other converters such as: ^{10}B and ^{6}Li[7]. It is more suitably used in its metallic form rather than its scintillator compounds i.e. gadolinium oxisulfate (Gd_2O_2S), because, a) it is not gamma sensitive, and b) the signal size produced by neutron capture in the Gd_2O_2S scintillator is about 2000 electrons, which is far less than the average signal size from Gd metal on a-Si:H diode [7].

In the present design the maximum neutron efficiency is boosted to 53% from the previous value of 25% which was achieved by using a single layer Gd converter. In this new design we have integrated two back-to-back- connected amorphous silicon diodes with two layers of Gd coatings in a sandwiched configuration, so that, not only the probability of neutron absorption is considerably increased, but the chance of

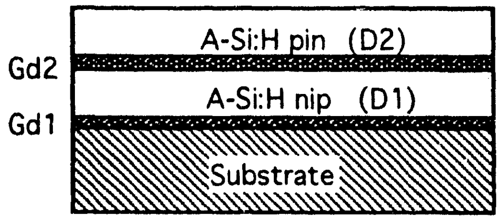

Fig.1 Schematic diagram of the multilayer neutron detector

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detecting internal conversion electrons produced by neutron capture is also enhanced appreciably. The detection efficiency is shown to increase to a level of 73%, by using Gd layers enriched to 50% in ^{157}Gd isotope which has the highest neutron absorption cross section (2.55x 10^5).

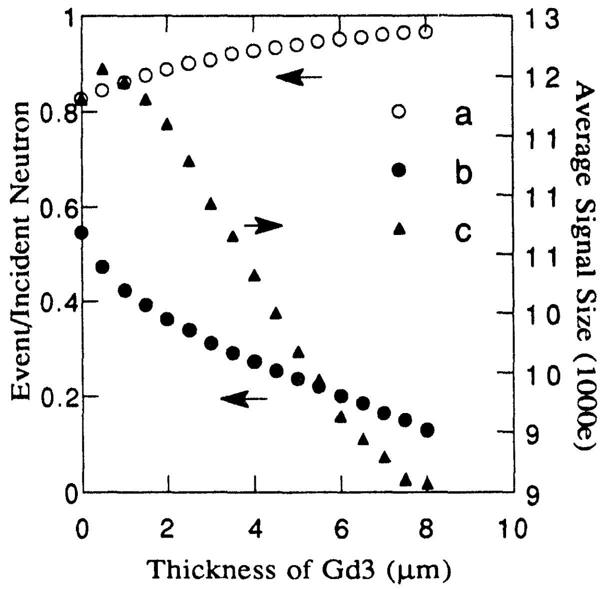

Fig.2 The effect of thickness of Gd3 on (a) neutron stopping efficiency (b) electron event efficiency, and (c) average signal size; for a 2 μm Gd2 layer.

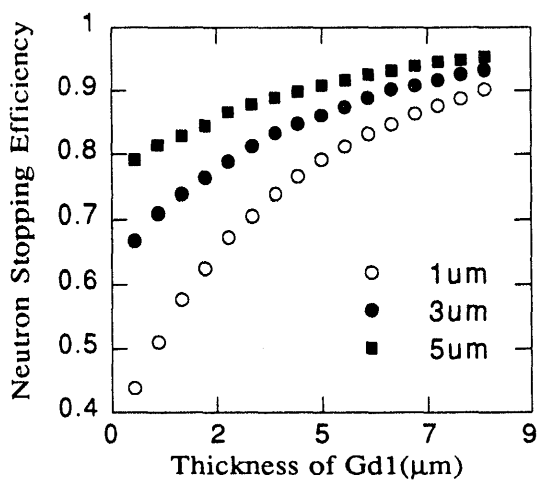

Fig. 3 Neutron stopping efficiency vs. thickness of Gd1 for various values of thicknesses of Gd2.

II. DEVICE MODELING

In order to find the optimum design parameters before fabrication of the detector, we performed a Monte Carlo simulation of the device, using an improved version of our previously developed computer program. This new version can simulate multilayer Gd-interfaced detectors. The detector has to be planar and is assumed to be thick enough to stop all conversion electrons, otherwise an electron stopping efficiency should also be incorporated in the final charge collection efficiency and signal size prediction. Our Monte Carlo program takes into account neutron interaction in two most prominent absorbing isotopes of gadolinium i.e. ^{155}Gd and ^{157}Gd with 14.8% and 15.7% natural abundance, respectively. The conversion electron energies and transition probabilities for these isotopes are separately computed and used as input to the simulation program. The program registers stopping of an incident neutron in the detector, locates its point of absorption in either of the Gd layers and follows the path of conversion electrons produced by neutron capture in Gd isotopes, and determine their energies, emission angles, their path lengths in the Gd converter, and finally their remaining energy upon arrival into either of the a-Si:H diodes. The values of these remaining energies are saved as the stored energies in the amorphous silicon diodes and then converted to signal sizes based on the following assumption: a) the average energy required to produce an e-h pair (w) for a-Si:H diode is 4.8 eV [10]. b) charges produced in a-Si:H diodes can be fully collected.

A. Simulation Results:

The first device configuration that we simulated had three converter layers, but the Monte Carlo simulation results proved that using a top Gd layer on the structure of Fig.1 would increase neutron stopping efficiency, but drastically decreases both average signal size and the electron event efficiency. Electron events are defined to be : "those neutron captures involving internal conversion electron emission (rather than gamma emission), from which at least one of the electrons would be able to escape the Gd films into one of amorphous silicon diodes." Since only such events would contribute as a count, the electron event efficiency is in fact the real neutron detection efficiency, as long as the signal size is above the noise level. The effects of variation of thickness of the top Gd layer (Gd3) on: (a) neutron stopping efficiency, (b) electron event efficiency, and (c) average signal size ; are shown in Fig. 2. Similar results were obtained when several other values were used for thicknesses of the remaining two Gd layers. As a result of this investigation we decided to use only two Gd layers.

The remaining task for the Monte Carlo simulation was to study the electron event efficiency and average signal size as a function of thicknesses of Gd1 and Gd2 layers, in order to find an optimum configuration. In Fig. 3 we show the exponential behavior of the simulated neutron stopping efficiency with converter thickness, just as a confirmation of the consistency of the Monte Carlo program. Variation of electron event efficiency as a function of Gd layer thickness is shown in Fig.4. It is seen that the optimum value for middle Gd layer thickness (t_{Gd2})varies with t_{Gd1}, and also the increase in t_{Gd1} from 4 μm does not result in a significant change in the electron event efficiency. The maxima in these curves is in fact the result of a compromise between increasing neutron stopping efficiency (Fig.3) and declining number of electrons exiting the Gd layer with thickness increase of the Gd2 layer.

Similar result from our previous work (see SL curve in Fig.4) for a one layer Gd detector shows the same behavior, except that the maximum efficiency is improved by more than a factor of two in our present design.

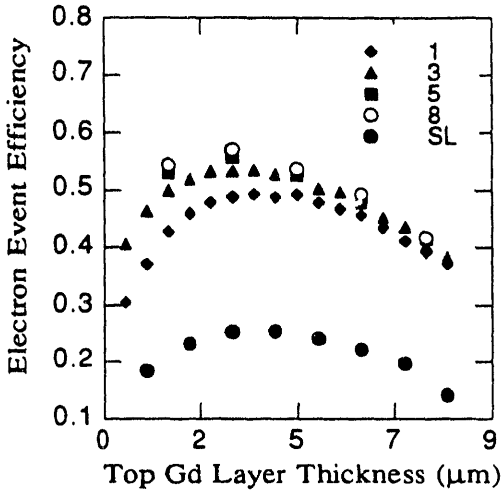

Fig. 4 variation of electron event efficiency vs. thickness of Gd2, for various thickness values of Gd1 layer; the SL curve is for single layer detector (previous design).

The expected average signal size (Fig.5), on the other hand is larger with thinner Gd1 layer and declines with increasing t_{Gd2}. This quantity is calculated based on the energy of the conversion electrons upon their arrivals in a-Si:H diode, therefore it is sensitive to the Gd thickness as the electrons will lose more of their energy in thicker Gd layers. Considering these two results, one can see that the optimum choice proves to be a thickness of 4 µm for Gd1 and 2 µm for Gd2 layers. For such a detector, our simulation predicts an electron event efficiency of ~ 53% and an average signal size of about 12000 e-. This efficiency would translate into a real neutron detection efficiency provided that the amorphous

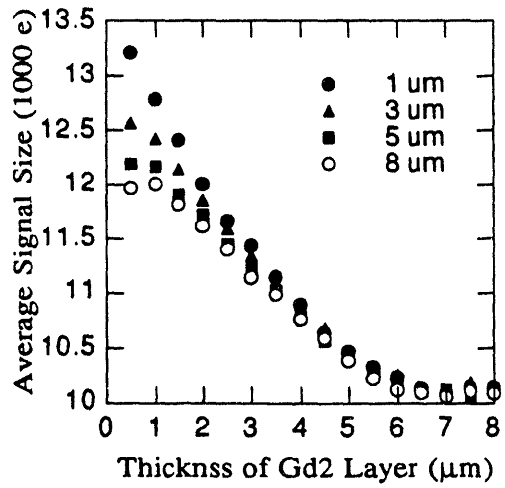

Fig.5 Variation of average signal size vs. Gd2 layer thickness for various values of Gd1 thickness.

silicon diodes are thick enough to stop all conversion electrons emitted by Gd converters into them and the noise level is low enough to allow detection of low energy conversion electrons. The detector efficiency can be further increased by using an

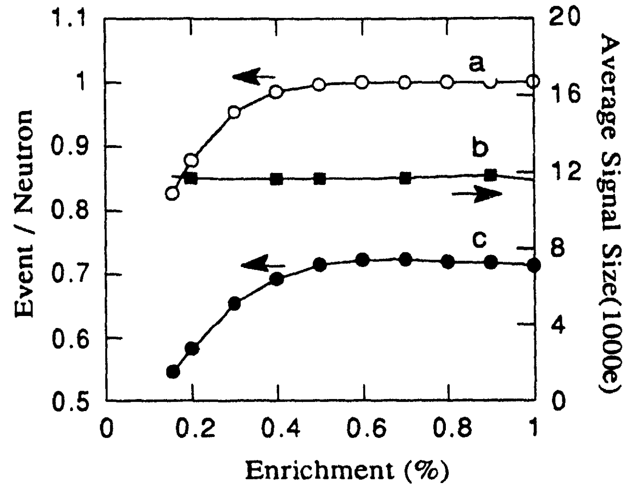

Fig. 6 The effect of ^{157}Gd enrichment on (a) neutron stopping efficiency, (b) average signal size, (c) electron event efficiency.

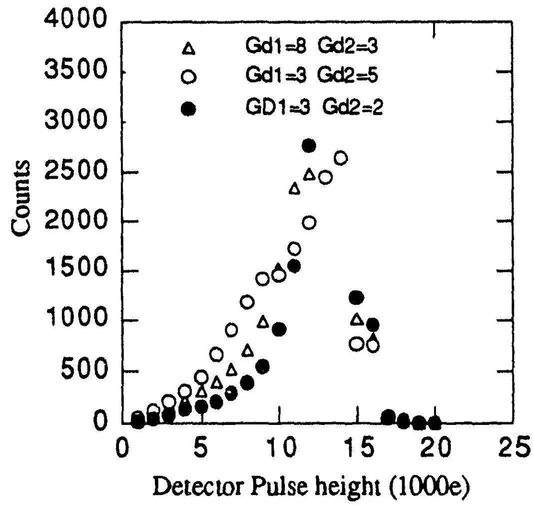

Fig. 7 Detector pulse height spectrum for various combinations of values for Gd1 and G2 layer thicknesses.

enriched Gd converter. The ^{157}Gd isotope with the highest neutron absorption cross section($2.55x10^5$) has only 15.7% natural abundance. We have studied the effect of using higher enrichment Gd converters by our Monte Carlo program. The results of this study shown in Fig.6 indicate that : a) detector efficiency can be raised to about 73% by using a 50% enriched gadolinium; b) increasing enrichment beyond 50% has no positive effect; c) gadolinium enrichment does not increase average signal size.

B. Charge Collection and Signal Size

The average signal size predicted by the Monte Carlo calculation assumes that all IC electrons sent to the a-Si:H diodes are stopped there and all charges produced by ionization within the diodes are totally collected. In order to prevent the escape of internal conversion electrons from the sensitive volume of the diode, the intrinsic layer should be thicker than, or approximately the mean range of average-energy electrons entering the diodes, i.e. about 30 μm. If the diodes are thinner, then the higher energy IC electrons can escape and they will not deposit all of their energies in the diodes and therefore, the average signal size would be less than expected. In Fig.7, the simulated spectrum of the signals are shown. as we can see most of the pulse height will be above 6000 electrons. So,

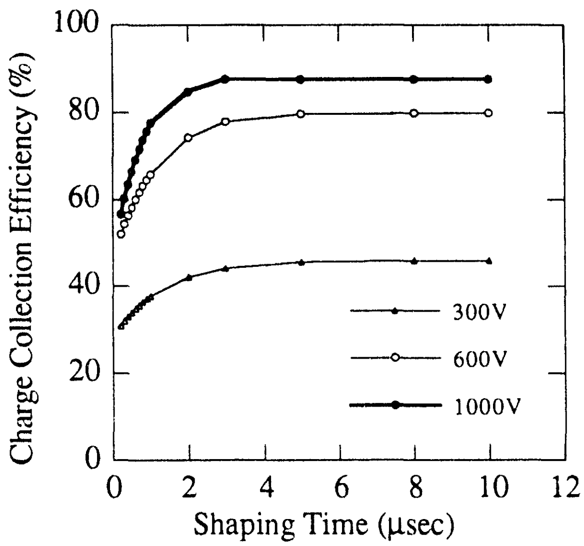

Fig. 8 Charge collection efficiency of a 30 μm a-Si:H diode vs. shaping time for three values of the reverse bias voltage.

with sufficiently thick detectors, we can tolerate noise of up to this level and raising discriminator threshold to eliminate such noise would not appreciably affect the neutron pulse count. For thin diodes the spectrum would shift towards lower pulse heights and therefore, the elimination of noise can reduce

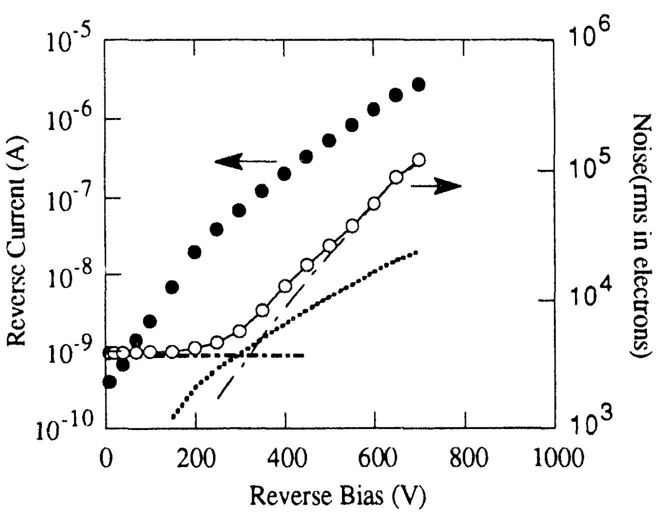

Fig. 9 Reverse current and noise in a typical a-Si:H diode (26μm) with a shaping time of 2.5 μsec, the solid line is the sum of three noise components.

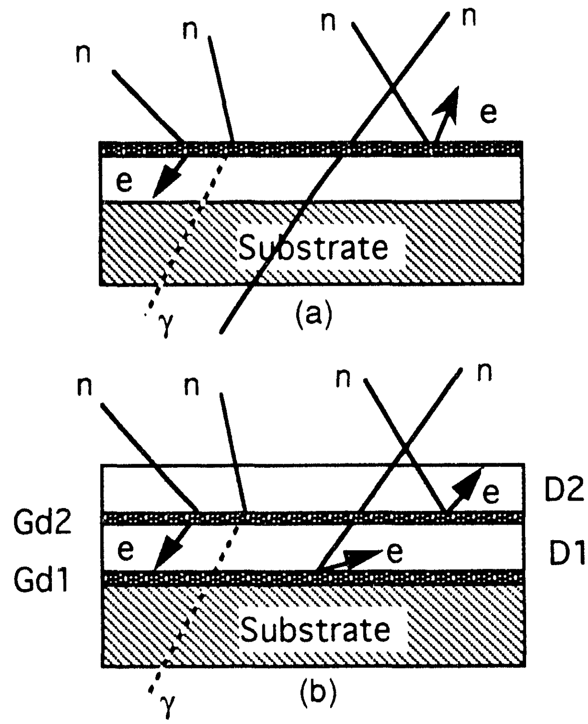

Fig. 10 Schematic diagram showing various interactions of incident neutrons, it shows how the probability of producing electrons in the diodes is increased in the new design.

the counting efficiency. Another factor that reduces the signal size is the charge collection efficiency of the a-Si:H diode. For complete charge collection, the diode should be fully depleted by the external field and the shaping time of the amplifier should be long enough to allow for transit time of electrons and holes. Fig. 8 shows the variation of charge collection efficiency as a function of shaping time at various bias levels for a 30 μm thick a-Si:H diode , assuming a dangling bond density of 0.7×10^{15} cm^{-3}. The dots are calculated points and the curves are just connecting the points. It is seen that using shaping times longer than 2 μsec would not increase the charge collection efficiency. It means that for choice of a proper value for the shaping time, one has to consider other parameters such as amplifier noise and the noise of the a-Si:H diode. While the former noise would normally be reduced by selecting longer shaping times, the latter may or may not, depending on which noise component is dominating. The detector 1/f and shot noise, are proportional to τ^2 and τ, respectively [11], where τ is the shaping time. The only noise component that favors larger τ is the series contact resistance noise which is proportional to $1/\tau$. So for the case where the leakage current is not very low, the 1/f and shot noises are dominant and thus, it would be better to use shorter shaping times, and $\tau \sim 2$ μsec would be a reasonable choice. In Fig.9 reverse current and noise for a typical a-Si:H diode (26 μm) long with contributions from various components are shown.

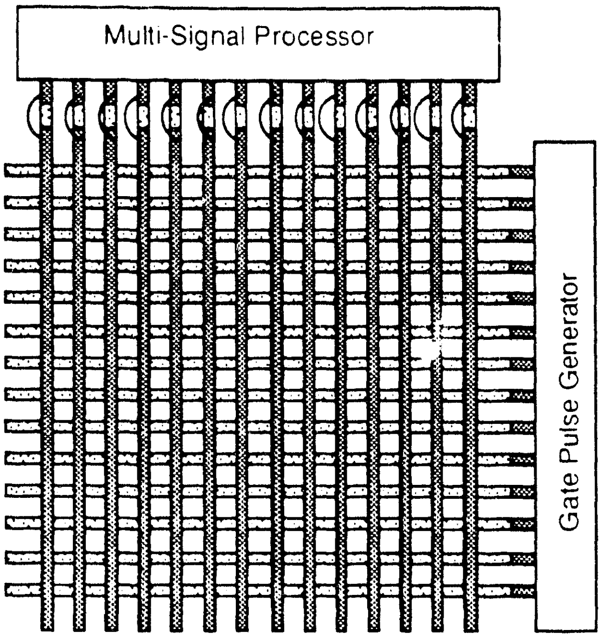

Fig. 11 Schematic drawing of the position sensitive neutron detector, the curved lines show the wire-bonding between the bottom and top Cr contacts.

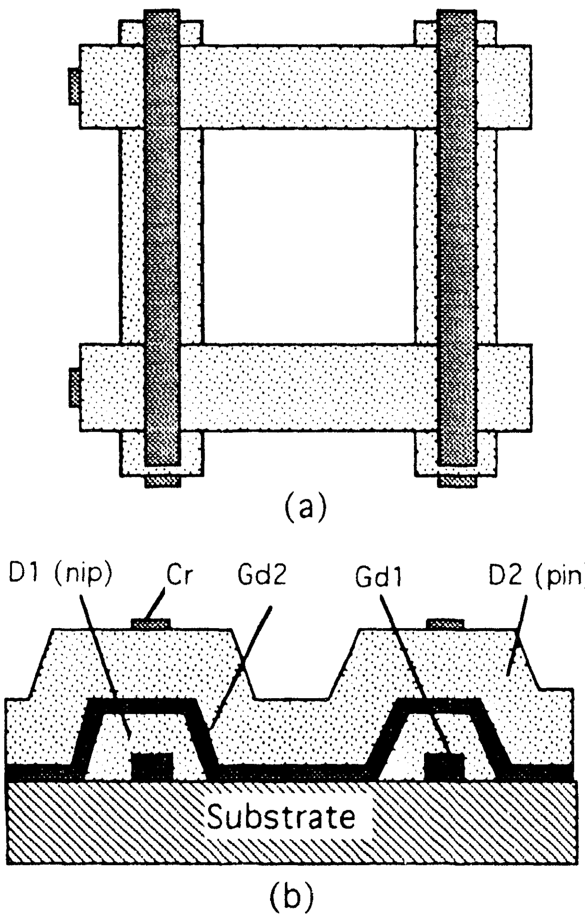

Fig. 12 The top view (a), and the cross sectional view of two adjacent pixels(b), in fig (b) the Cr coatings before and after Gd depositions are not shown.

III. DETECTOR STRUCTURE

Our previous detector [7]consisted of a single amorphous silicon n-i-p diode with one layer of Gd converter on the top. The cost of simplicity in this design was two short-comings: a) since the angular distribution of conversion electrons at the point of neutron interaction is isotropic, 50% of the produced electrons escaped without reaching the n-i-p diode; b) the thickness of the Gd layer had to be less than the neutron mean free path in order to prevent stopping of electrons in the converter. In the current design, we have eliminated these deficiencies by considering a more elaborate structure consisting of two back-to-back connected n-i-p diodes, one converter layer (Gd1) coated on the substrate before deposition of the first n-i-p diode(D1), and another one (Gd2) sandwiched between the top and bottom diodes. The top diode is a p-i-n diode, so that the middle p layers are electrically connected through the Gd2 layer. This structure has two advantages. First, for most of the stopped neutrons the absorption occurs in the middle Gd2 layer and therefore, the electrons they produce will certainly be detected by one of the diodes. Secondly, those neutrons which escape absorption in Gd2 will have to pass through the thicker Gd1 layer and therefore, find very little probability of escaping that layer. Neutron interaction has a higher probability to occur near the top of Gd1 layer. This means the resulting conversion electrons reaching the first diode (D1) will deposit most of their energy in that diode. Various interaction possibilities for incident neutrons are shown schematically in Fig. 10 .

The a-Si:H diodes are made in our PECVD machine under the standard deposition conditions. A 30 nm chromium layer is coated before and after any Gd deposition to provide good ohmic contact with a-Si:H doped layers. Both Cr and Gd are vacuum coated while the substrate temperature is kept below 200 ^{o}C· Although all patterning can be performed by photolithography when small dimensions (< 250 μm) are involved, for our test samples we just used metallic masks to pattern various layers. Two masks were made, one for coating metallic layers, and the other one with sharp edges for depositing a-Si:H diodes. The substrate was a silicon wafer coated with 1 μm polyimide. The device is designed in the form of crossing strips, so that it provides for position sensitivity (Fig. 11). The top and bottom Cr contacts are wire bonded together and are connected to bias voltage, and the middle Cr strips extend out as output signal leads. Fig.12a shows the blown up of the encircled part in Fig. 11. The cross section of the two adjacent pixels are shown in Fig. 12.b.

Pixel array readout

There are two ways that our neutron detectors can be put into two dimensional position sensitive configuration. one is to make crossing horizontal and vertical strips and connect the horizontal leads (top and bottom Cr contacts) through an array of switches to an appropriate bias line and derive the output signal from the vertical leads, which are connected to Cr contacts of the middle p-layers, by means of an external multi-signal processor. The pixels in successive rows are selected by applying proper gate pulses to the line switches and the pixels

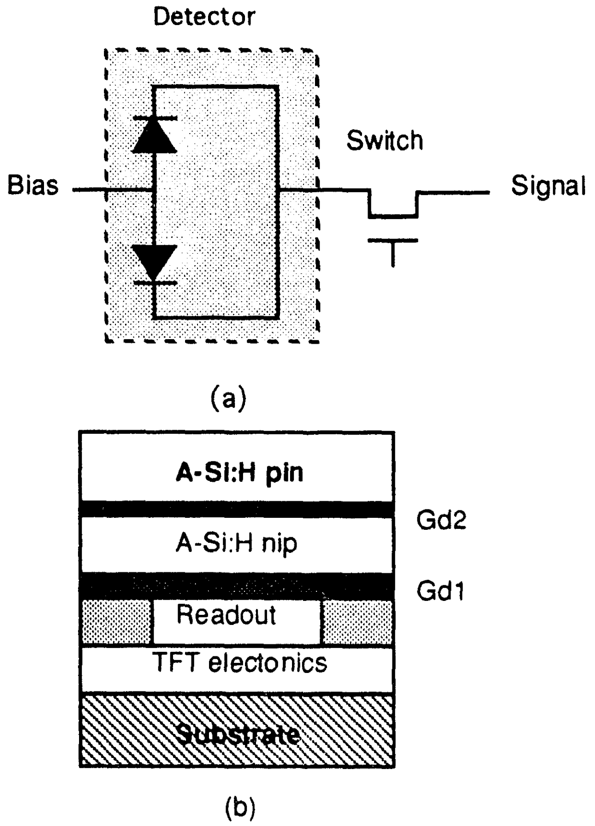

Fig. 13 The Schematic diagram of (a) a detector pixel and its associated TFT switches, (b) realization of the integrated detector with TFT electronics and readout on a single substrate.

in a selected row are then scanned by the multi-signal processor unit to read their stored information. The switches used in two dimensional arrays of photodiodes for X-ray imaging are conventionally a-Si:H TFTs. The other method for using our neutron detector in a two dimensional array is to integrate each pixel with its associated TFT and readout electronics on a single substrate, as shown in Fig. 13.

IV. Measurement

Our experimental set up for measuring neutron detection efficiency is described elsewhere [7]. The neutron source is a 70 Ci Pu-Be which is used in a water tank to produce thermal neutrons. The detector gamma sensitivity is measured by exposure to a 10^5 mCi Ra source.

Results and discussion

Our single Gd layer detector measurement results were in good agreement with predictions of the Monte Carlo simulation [7]. In that experiment, due to excessive noise of our measurement system, we had to raise the discriminator level to ~10000 e-. For the new design the pulse height spectrum shows a rather narrow peak at ~13500 e- and with only about 10% of counts below 10000 e- level (see Fig. 7). The measured spectrum, depending on the shaping time and the bias voltage would shift towards lower pulse heights. At a reverse bias of 20 V/μm and with a shaping time of 2 μsec, a 30 μm diode has a charge collection efficiency of ~75% (Fig. 8). As a result, in the measured results the peak in pulse height distribution would shift to ~10000 electrons. This means in a better noise situation, even by setting the discriminator level to ~7000 e-, we would only loose 11% of the counts and thus, the measured neutron detection efficiency should not be less than 42% which is close to twice the efficiency of the previous design. The gamma sensitivity is not expected to be affected by addition of a 30 μm a-Si:H diode and our multilayer detector should have the gamma sensitivity of ~1×10^{-5}, as measured by the Ra source for the single Gd layer prototype.

V. Conclusion

we have presented a new high efficiency neutron pixel detector with a detection efficiency of ~42% at the sensitivity level of 7000 e-. This efficiency would further increase to nearly 63%, if we used enriched Gd layers. The pixel size can practically go as low as 200 μm thus providing a high spatial resolution as needed in some neutron scattering experiments. At this high spatial resolution in a typical flux of 1×10^7 cm^2/sec a neutron count rate of ~1700 sec^{-1} is expected. The radiation hardness of a-Si:H assures a very high radiation resistance for this detector up to neutron fluxes of ~5×10^{14} cm^2/sec.

V. References

[1] S. Fujine, K. Kanda, G. Matsumoto, J.B. Barton, *Proc. 3rd World Conf. on Neutron Radiography,* Osaka, Japan, May 1989, Kluwer Academic 1990.

[2] V. Orphan, D. Kedem, F. Johansen, "Mobile neutron radiography system for aircraft inspection," *Proc. 2nd World Conf. on Neutron Radiography*, Paris, France, June 1986, Kluuwer Academic, 1987, pp.447-454.

[3] R.K. Crawford, J.R. Haumann, J.E. Epperson, P. Thiyagarajan, A.J. Schultz, G.P. Felcher, D. G. Montague and R.J. Dejus, "Experience with position sensitive neutron detectors at the intense pulsed neutron source," *Nucl. Instr. and Meth.* A299, pp. 17-24, 1990.

[4] B. Alefeld, D. Schwan and T. Springer, *Nucl. Instr. and methods*, A274 (1989) 210.

[5] A. Steyerl, W. Drexel, T. Ebrsawa, E. Gustsmiedl, K.A. Steinhauser, R. Gahler, W. Mampe and P. Ageron, *Rev. Phys. Appl.* 23(1988) 171.

[6] M. kanyo, R. Reinartz, J. Schelten and K.D. Muller, *IEEE Trans. of Nucl. Sci.* Vol. 40, No.4, pp. 438-442.

[7] A. Mireshghi, G. Cho, J. Drewery, T. Jing, S.N. Kaplan, V. Perez-Mendez, D. Wildermuth, "Hydrogenated Amorphous Silicon Position Sensitive Neutron Detector ," *IEEE Trans. Nuc. Sci.*, Vol. 39, No. 4, 1992, pp. 635-640.

[8] V. Perez-Mendez, S.N. Kaplan, G. Cho, I. Fujieda, S. Qureshi, W. Ward, and R.A. Street, "Hydrogenated Amorphous Silicon Pixel Detectors for Minimum Ionizing Particles," *Nucl. Instr. and meth.*, A273, 1988,pp.127-134.

[9] V. Perez-Mendez, J. Morel, S.N. Kaplan and R.A. Street, " Detection of Charged Particles in Amorphous Silicon Layers," *Nucl. Instr. and meth.*, A252, pp.478-482 (1987). To be publishied in MRS Symp. Proc.,1993.

[10] V.Prez-Mendez, chapter 8 in "Physics and applications of amorphous and microcrystalline semiconductor devices," J. Kanicki, ed., Boston,MA., Artech House Pub., 1991, pp. 297-330.

[11] G. Cho, S. Qureshi, J.S. Drewery, T. Jing, S.N. Kaplan, H. Lee, A. Mireshghi, V. Perez-Mendez and D. Wildermuth, "Noise in A-Si:H p-i-n Detector Diodes," IEEE Trans. of Nucl. Sci., NS-40, No.4, 1992, pp. 641-644.

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