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Authors

Perez-Mendez, V.
Cho, G.
Fujieda, I.
et al.

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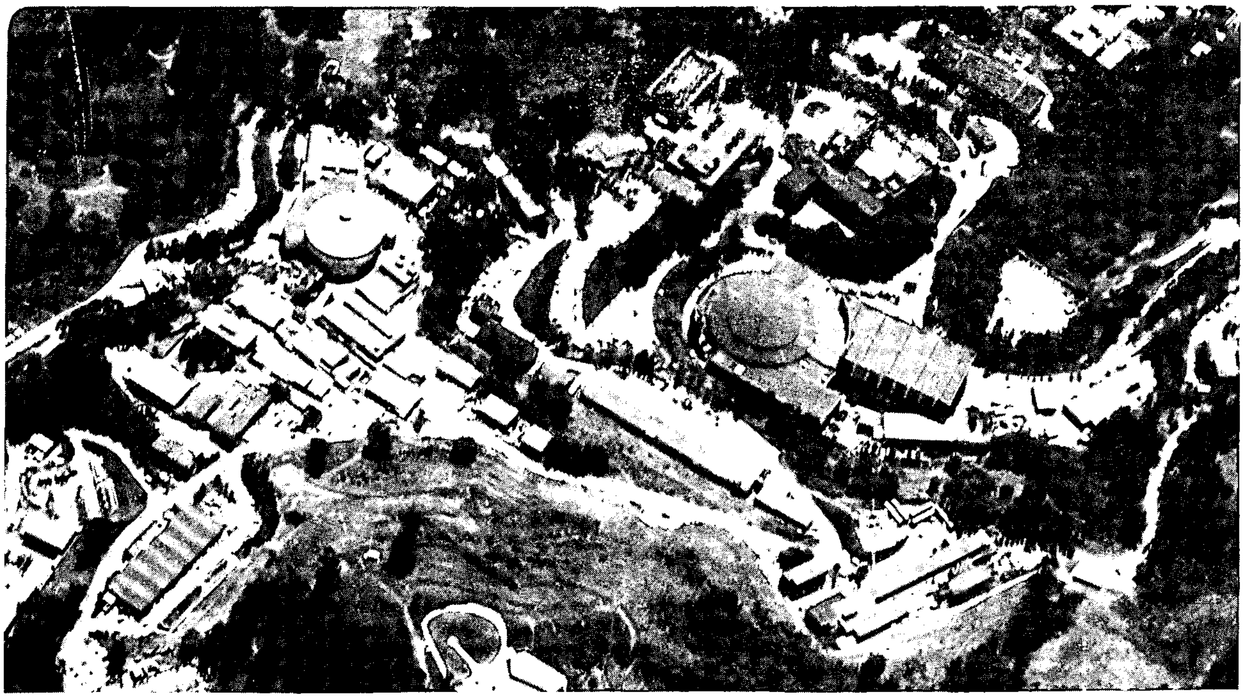
April 1989



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THE APPLICATION OF THICK HYDROGENATED AMORPHOUS SILICON LAYERS TO CHARGED PARTICLE AND X-RAY DETECTION*

April 10, 1989

V. PEREZ-MENDEZ, G. CHO, I. FUJIEDA, S.N. KAPLAN, S. QURESHI,
Lawrence Berkeley Laboratory, University of California,
Berkeley, California 94720

R.A. STREET, Xerox P.A.R.C., Palo Alto, California 94304

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ABSTRACT

We outline the characteristics of thick hydrogdenated amorphous silicon layers which are optimized for the detection of charged particles, x-rays and γ-rays. Signal amplitude as a function of the linear energy transfer of various particles are given. Noise sources generated by the detector material and by the thin film electronics - a-Si:H or polysilicon proposed for pixel position sensitive detectors readout are described, and their relative amplitudes are calculated. Temperature and neutron radiation effects on leakage currents and the corresponding noise changes are presented.

I. INTRODUCTION

Thin layers of hydrogenated amorphous silicon (a-Si:H) of thickness ~1 µm have found extensive application in solar cells and in thin film transistors (T.F.T.). A well known application of thick ~40 µm layers of a-Si:H is to electrophotography devices. In these devices the usual configuration is a p-i-n diode with thin p and n doped layers, and the bulk consisting of intrinsic a-Si:H. We have studied the possibility of using a-Si:H reverse biased diode arrays for charged particle, x-ray and γ-ray detectors. These would find use in particle physics research, in biological, and in medical imaging applications.

In particle physics a common requirement is to locate the trajectory of relativistic and slower particles by determining their passage through a number of layers of position sensitive detectors. These detector layers have consisted in the past of gas filled multiwire proportional chambers, scintillation counters and of crysal silicon diode arrays. The potential usefulness of a-Si:H detectors lies in the ease of making large area devices by PECVD techniques, defining the shape and size of the detector element by lithography, and by being able to couple thin film readout electronics — a-Si:H or polysilicon directly to the detector "pixels" or "strips" as shown schematically in Fig. 1. In the following sections we describe the results of our measurements using alpha particles, low energy 1-2 MeV protons, 1 MeV minimum ionizing electrons, x-rays and γ-rays.

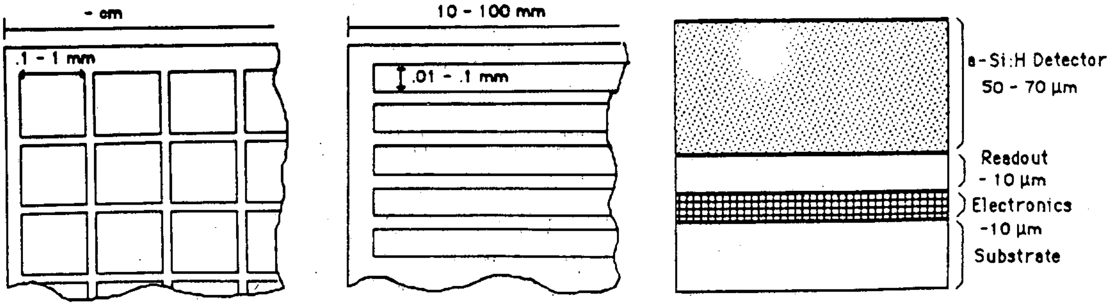

Fig. 1 Schematic coupling of a-Si:H detector pixels or strips to thin film electronics. Each metal pad is coupled to an individual charge sensitive amplifier below.

II. DETECTION OF CHARGED PARTICLES

For the detection of charged particles traversing a sensitive layer of a-Si:H suitably doped to form a p-i-n diode we have the following requirements:

a. The sensitive layer has to be thick enough to ensure that the charged particle produces a sufficient number of electron-hole pairs that will result in a signal appreciably larger than noise. For the detection of minimum ionizing particles, which are of interest in high energy particle physics, we have shown that layers 50-70 μm thick could be sufficient for this purpose. This conclusion stems from our measurement (given below) of the average energy $w = 6.0 \pm 0.2$ eV required to produce 1 e-h pair in a-Si:H, which results in a yield of 60 e-h pairs/μm of detector layer.

b. The i layer of the thick p-i-n diodes has to be fully depleted in order to collect the bulk of the e-h pairs produced by the transit of a charged particle. This implies that the E field should be ≥ 10^2 V/cm throughout the layer in order to ensure that a large fraction of both electrons and holes are collected. The electric field drops off as a function of distance due to the residual (+ve) charges left in the ionized dangling bond states of the i layer. Figure 2 shows the electric field versus distance for various bias voltages for an assumed value of ionized dangling bond states $N_D{}^* = 7 \times 10^{14}/\mathrm{cm}^3$ [1]. Recent measurements - presented at this meeting [2], show that only a small fraction ~30-35% of the dangling bonds as measured by E.S.R. are ionized. Hence with the present quality of material available to us from Xerox PARC (Palo Alto, CA), Glasstech-Solar (Wheatridge, CO), Plasma Physics (Locust Valley, NY) and others, with dangling bond densities of $1\text{-}2 \times 10^{15}/\mathrm{cm}^3$ we are assured of full depletion for our proposed thick detectors for elementary particle physics experiments.

We confirm these projections by our measurements on p-i-n diodes 38 μm thick. Figure 3 shows the signal produced by light pulses of $\lambda = 665$ nm, whose mean free path for absorption in a-Si:H is ~ 1μm, and from 880 nm light with an absorption mean free path > 100 μm. The signal collection threshold from the 665 nm light incident on the n surface shows the minimum bias needed for the electric field to extend across the layer thickness. This allows us to calculate the density of ionized dangling bonds and to confirm the onset of full depletion[3]. The 880 nm light simulates the e, h production, by the transit of a minimum ionizing particle.

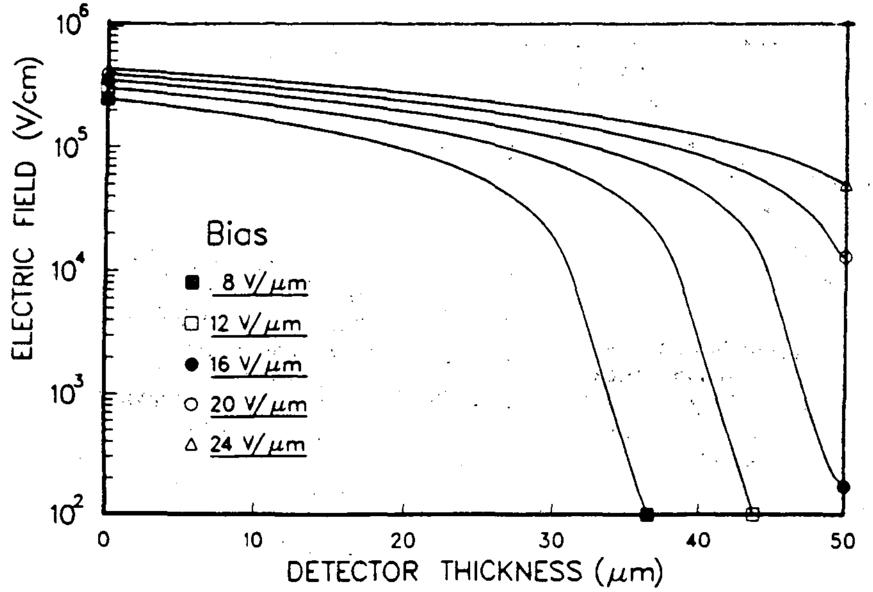

Fig. 2 Electric field shape in 50 μm thick i layer of p-i-n diode for various bias voltages.

c. The detector material itself generates noise, primarily due to the fluctuations in the capture and release of the e,h traversing the detector material. Figure 4 shows the noise and reverse bias current produced in a 38 μm p-i-n layer. As is conventional in particle physics both signal and noise are recorded by charge sensitive amplifiers followed by a shaping network; in this case we used 3 μ sec RC-(CR)^3 shaping.

Noise calculations indicate that the rapid increase of the noise amplitude above some bias level as seen in Fig. 4 is not the shot noise from the leakage current but is probably due to some incipient breakdown mechanism associated with defects in the sample layer. Microscope pictures (Fig. 5) taken of the surface of a typical metal coated p-i-n diode show bubbles and other aberrations which could explain this partial breakdown effect.

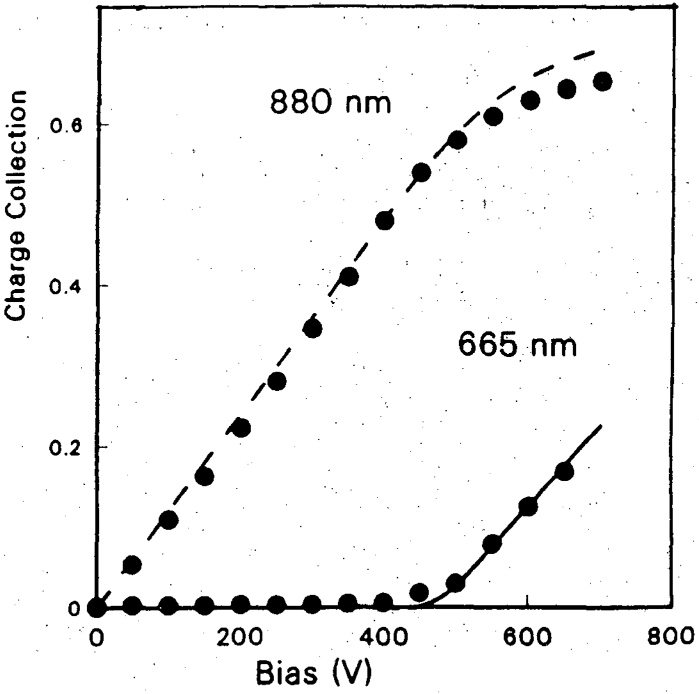

Fig. 3 Signal output versus bias for laser light incident on p-i-n diode solid, dashed lines calculated using $\mu_e = 1.2$; $\mu_h = 0.004$ cm^2/Vs· $(\mu\tau)_e = 1.0 \times 10^{-7}$; $\mu\tau_h = 1.2 \times 10^{-8}$ shaping time = 3 μ sec.

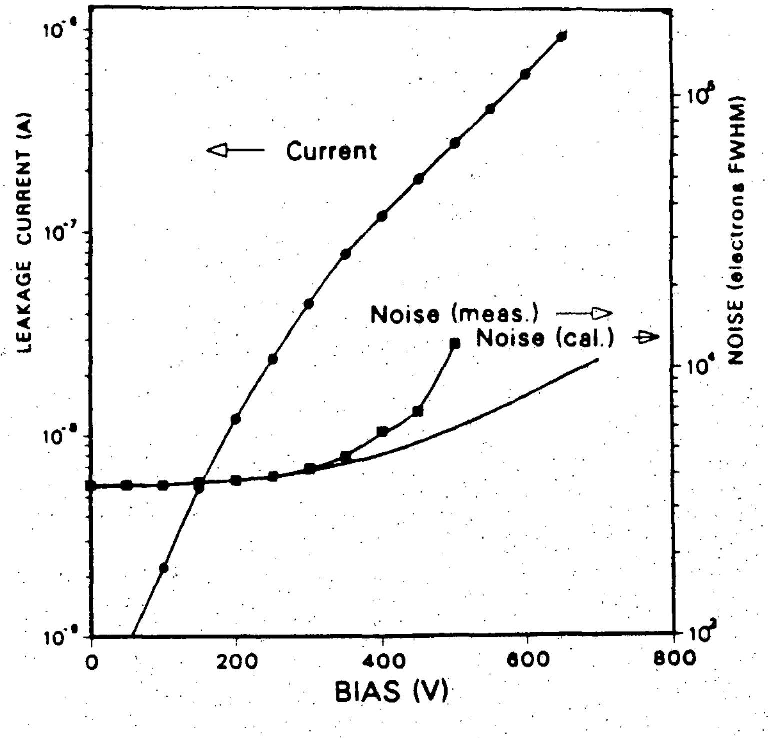

Fig. 4 Reverse current and noise of a 38 μm thick p-i-n detector diode. The initial increase of noise follows the calculated shot noise due to the current. The extra noise at higher biases may be due to incipient breakdown.

III. MEASUREMENTS WITH ALPHA PARTICLES, LOW ENERGY PROTONS AND MINIMUM IONIZING ELECTRONS.

We started this research using relatively thin p-i-n diodes and exposed them to 5-6 MeV alpha particles from Americium sources. We found, [4] and other groups also confirmed this[5] that the alpha particle signals were quite small relative to what would be expected from such a high energy deposition. As shown in Fig. 6 the observed signals were due to collection of 20,000-30,000 electrons. This effect is probably due to the large recombination rate of e, h in the highly dense ionization channel produced by the alpha tracks. Such charge recombination is also seen in xtal Si detectors when exposed to very highly ionizing particles such as fission fragments. The signals produced by 1 and 2 MeV protons with linear energy (LET) transfers of 46 and 28 KeV/micron respectively show less signal loss due to recombination effects, than the alpha particle. Minimum ionizing (~ 1 MeV electrons produce signal levels (Fig. 6) consistent with W = 6 eV. The signals produced by ~1 MeV electrons in 12, 29 and 38 µm thick detectors are shown in Fig. 7. The fact that the signal amplitude is proportional to the detector thickness and is consistent with our measured value of w indicates that there is little or no charge recombination. These measurements were done by summing signals and noise over a number of pulses [6] in order to overcome the large noise threshold of the charge sensitive amplifiers that we used.

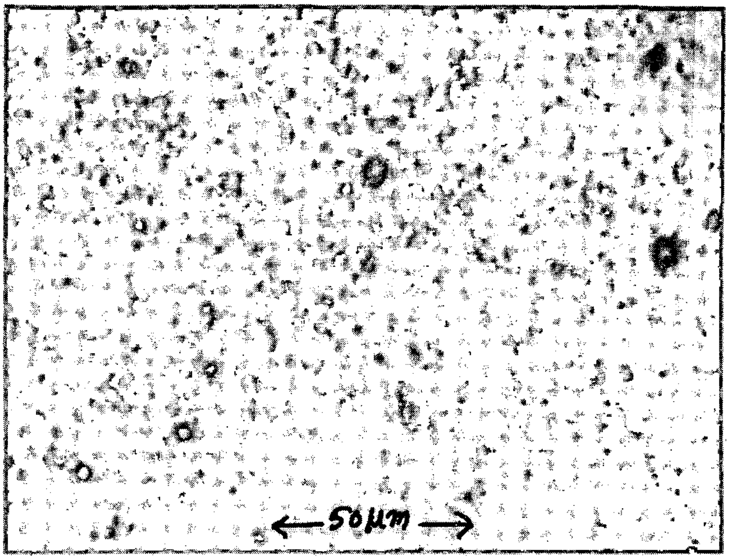

Fig. 5 Photograph of 38 µm p-i-n diode surface showing bubbles or dust imperfections.

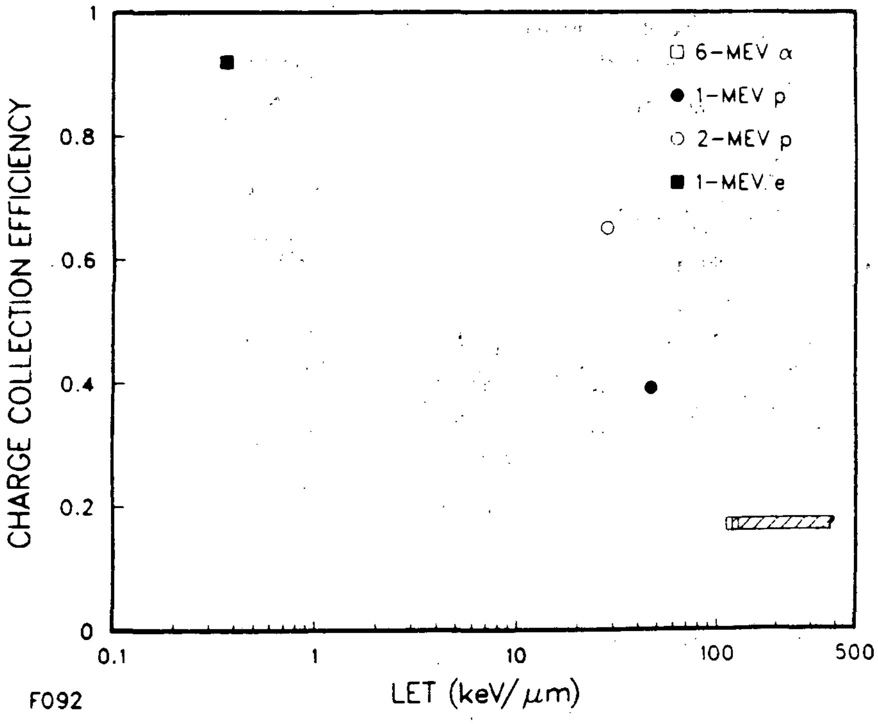

Fig. 6 Signal levels produced by alpha particles, 1, 2, MeV protons and by minimum ionizing 1 MeV electrons. Expected signal calculated from W = 6 eV to produce e, h pair. Charge recombination seen for alphas and low energy proton.

IV. DETECTION OF X-RAYS IN a-Si:H

The signals produced by x-ray pulses were detected in the set up shown in Fig. 8. One to three µsec long pulses of x-rays produced in a 20 kv molybdenum anode x-ray tube were incident on 5 and 10 µm n-i-p a-Si:H diodes, as well as on 180 µm thick xtal silicon detectors. By comparing the signal amplitudes and energy deposited in the a-Si:H and xtal silicon and using the known value of w(xtal S_i) = 3.62 eV, we obtain the result w(a-Si:H) = 6.0 ± 0.2 eV pairs.[7] The value of w depends on the width of the band gap of the semiconductor diode and is consistent with the interpolated value obtained from measurements on various semiconductors [8].

We, and others [9] have also detected signals produced by 130 KeV γ-rays on the thicker a-Si:H detectors where the γ-rays eject electrons of a few tens of KeV energy by the Compton effect.

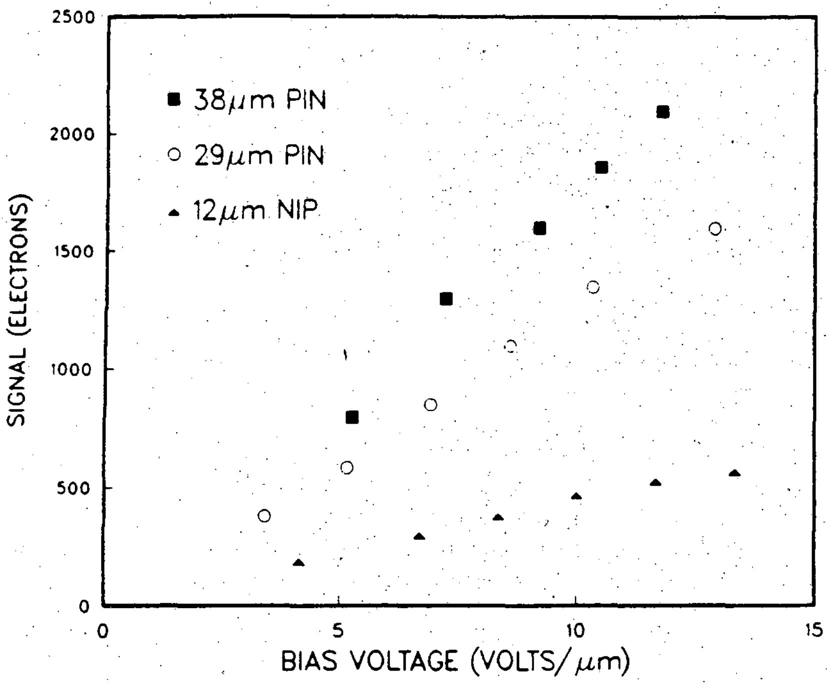

Fig. 7 Signals produced by minimum ionization electrons ~1 MeV as function of bias voltage on 12, 19, 38 µm thick p-i-n diodes.

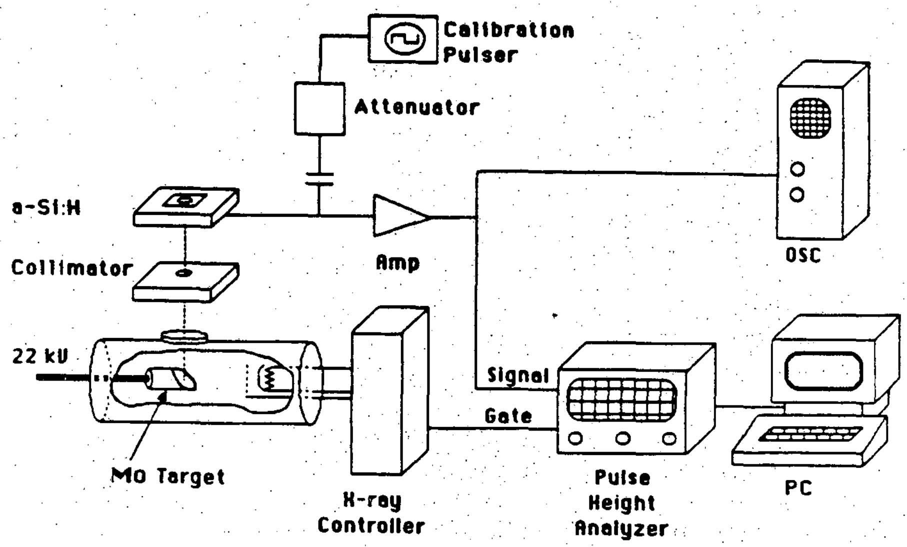

Fig. 8 Schematic of pulsed x-ray set up used for measuring W in a-Si:H p-i-n diodes.

A more sensitive method for detecting x-ray fluences, single high energy (E_γ 100 KeV) γ-rays and individual minimum ionizing charged particles is shown in Fig. 9. A C_sI [Thallium or Sodium doped] scintillation layer, deposited on top of the a-Si:H p-i-n layer converts the energy of the incident radiation into light in the visible range which in turn produces e-h pairs in the a-Si:H with effective detection efficiency >70% for 350 nm $< \lambda <$ 750 nm. [10] The light emission efficiency of doped C_sI ranges from 30,000- 50,000 visible light photons per MeV of deposited energy [11], with decay times between 0.6 - 1.1 µsec. For high spatial resolution detection with pixel sizes $\leq$ 50 µm, the sideways spread of the light can be prevented by suitable heat treatment of the evaporated C_sI layers which produces columnar structures in the phosphor.[12] For alpha particle detection, layers 15-20 µm are sufficient. For x-rays, γ-rays and minimum ionizing particles, layers 300-400 µm thick would be adequate for the detection of single particles.

V. NOISE DEPENDENCE ON ENVIRONMENT: TEMPERATURE AND RADIATION EFFECTS

For single particle detection it is desirable to maintain a signal/noise ratio ≥ 10. Since the signal is fixed by the detector thickness it is necessary to keep the noise at a sufficiently low level. In a physics detector the ambient temperature could rise due to power dissipation in the readout electronics for the pixel arrays. Figure 10 shows the reverse current and noise increase as a function of temperature. Since the overall noise is the sum in quadrature of the Nyquist, shot,and flicker noise,the shot noise produced by the thermal increase in reverse current becomes a major contribution at higher temperatures. The appropriate threshold in noise increase around 60° C is satisfactory for most applications, and can be increased by shortening the shaping time and or decreasing the reverse current by enhancing the p layer barrier which can be done by adding carbon [13].

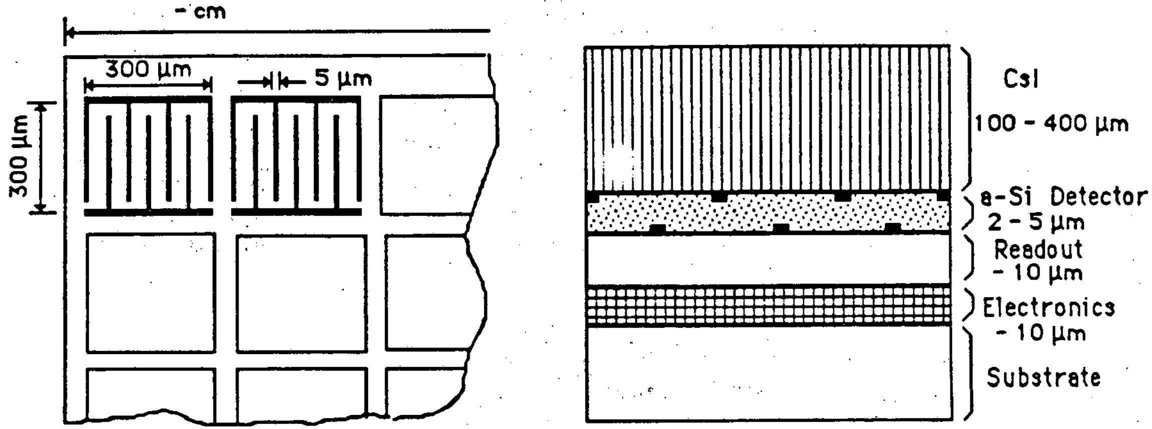

Fig. 9 Projected pixel device using C_sI evaporated layer as detector. The C_sI layer converts the incident radiation to visible light which is detected by thin a-Si:H diodes with interdigitated electrodes to reduce capacitance.

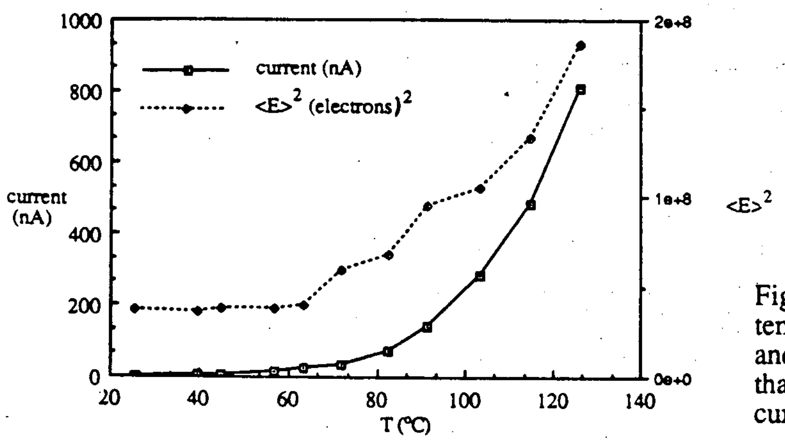

Fig. 10. Effect of ambient temperature on leakage current and noise. The curves show that the noise yield tracks the current increase.

In Fig. 11 we show the increase in leakage current and in shot noise produced by radiation damage induced by ~ 1 MeV neutrons.[7] The noise and leakage current increases were minimal up to the largest fluxes ~ 5 x 10^{14} neutrons/cm^2, that we used. These increases are almost completely annealable by heating the samples at ~ 200° C for 2 hours. Data using proton exposures up to 10^{15} protons/cm^2 show similar results [14].

The relative insensitivity of a-Si:H detectors to these environmental effects as compared to xtal Si detectors enhances their usefulness for large area pixel arrays in particle physics research.

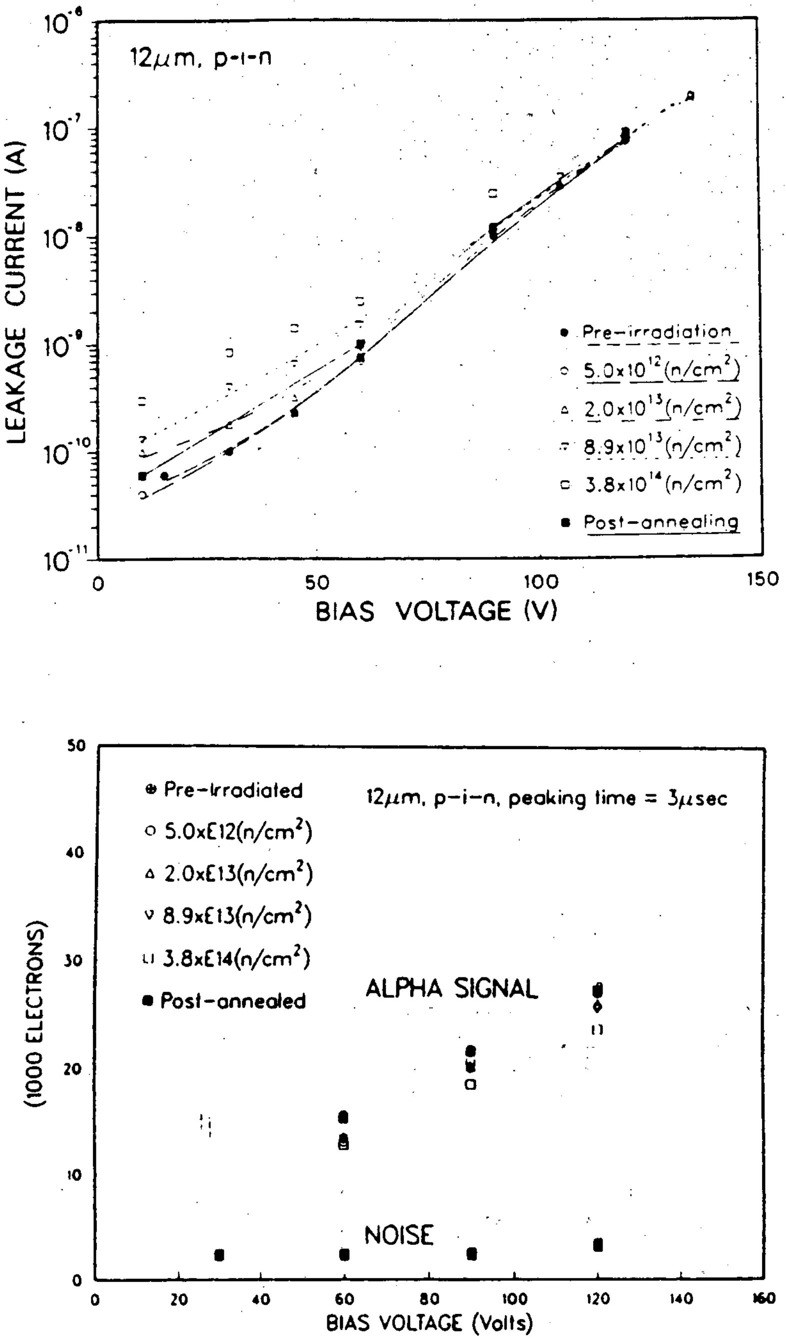

Fig. 11 Radiation damage induced by ~1 MeV neutrons and subsequent annealing (a) leakage current increase (b) change alpha particle signal and noise increase.

VI. THIN FILM TRANSISTOR READOUT ELECTRONICS

The capability of making thin film distributed electronics amplifiers and of coupling them to the pixel detector arrays as shown in Fig. 1 provides very attractive prospects for this technology. At present we are engaged in making various measurements of a-Si:H and polysilicon T.F.T. in order to assess their usefulness for the detector field.[15] In Table I below we show estimates of the characteristics of various T.F.T. technologies. A major unknown has been the noise level that a-Si:H or polysilicon input amplifier stage would contribute to the noise of a pixel detector. Our preliminary measurements, shown here, indicate that this noise -- while larger than that of xtal silicon MOSFETS is low enough to be acceptable.

Table I

Type of T.F.T.	Electron Mobility ($cm^2/Vsec$)	W/L	g_m ($\mu A/V$)	Frequency Limit (3db) (MHz)	Noise * (1 μsec) (electrons)	Radiation Resistasnce
a-Si:H 10μm Tech.	0.3 - 0.8	2-20	2 - 4	1-3	∼ 350	Excellent
a-Si:H 4 μm Tech.	0.3 - 0.8	2-50	2 - 5	3-10	∼ 350	Excellent
a-Si:H Vertical	0.3 - 0.8	100-1000	30-300	5-10	≥ 1000	Unknown
Polysilicon 400°Anneal	10-20	2-20	3-30	10-20	≥ 500 (expected)	Unknown
Polysilicon 900°Anneal	50-100	2-20	15-150	50-100	∼300 (PMOS) ∼480 (NMOS)	Unknown
c-Si on Insulator (SOI)	1000-1500	2-20	1000-2000	› 100	Same as c-Si FET	Excellent

* Noise values are given for a typical size of each TFT with 1 μsec CR-RC shaping amplifiers. However these measurements are preliminary because we have not measured enough samples.

The noise of a MOSFET in the frequency domain is given by the following formula[16].

$$\overline{V_i^2} = 4KT\frac{2}{3}\frac{1}{gm} + \frac{K_f}{C_i f}$$

The first term is the Nyquist noise and the second is the 1/f (flicker) noise. In the equations below, the detector noise sources, Nyquist, shot, 1/f are combined together with the input stage amplifier noise and given as number of electrons N detected in a RC-CR shaping interval τ_0 as given below [17].

$$\overline{N_\Delta^2} = 6.0 \times 10^5 \frac{(C_D + C_i)^2}{\tau_o g_m}$$ Nyquist noise

C_D, C_i, are the detector and FET input capacities in pF, τ_0 - shaping time constant in μsec and g_m = transconductance of the FET in μA/v.

The shot noise of the reverse bias current assumes the form

$$\overline{N_s^2} = 1.15 \times 10^7 I \cdot \tau_o$$ where I is in μA

The 1/f noise is given as

$$\overline{N_f^2} = 1.44 \times 10^{26} \frac{(C_D + C_i)^2}{C_i} \cdot K_f$$

The Δ and 1/f noise expressions show the need to keep the combined detector and FET input capacity low. Figure 12 shows measurements of the frequency dependence of noise from a-Si:H and from a 900°C anneal polysilicon TFT. In Table II below we give the expected noise numbers for a detector [300 x 300 μm x 50 μm thick] TFT combination.

The 1/f noise from various types of TFT's is the largest noise component and indicates that continuing research to decrease this would be a useful avenue for continued development.

Table II

Noise (e)		a-Si:H TFT	Poly-NMOS	Poly-PMOS
N_{LD}	(Thermal noise of R_L)	77	77	77
N_{SD}	(Shot noise of detector)	72	72	72
N_{FD}	(1/f noise of detector)	7	7	7
N_{LT}	(Thermal noise of R_D)	24	5	5
N_{TT}	(Thermal noise of TFT)	107	27	33
N_{FT}	(1/f noise of TFT)	340	480	280
S_{SIG}	(Signal from detector)	3000	3000	3000
N_{TOT}	(Total noise)	370	490	300
S/N		8.1	6.1	10.

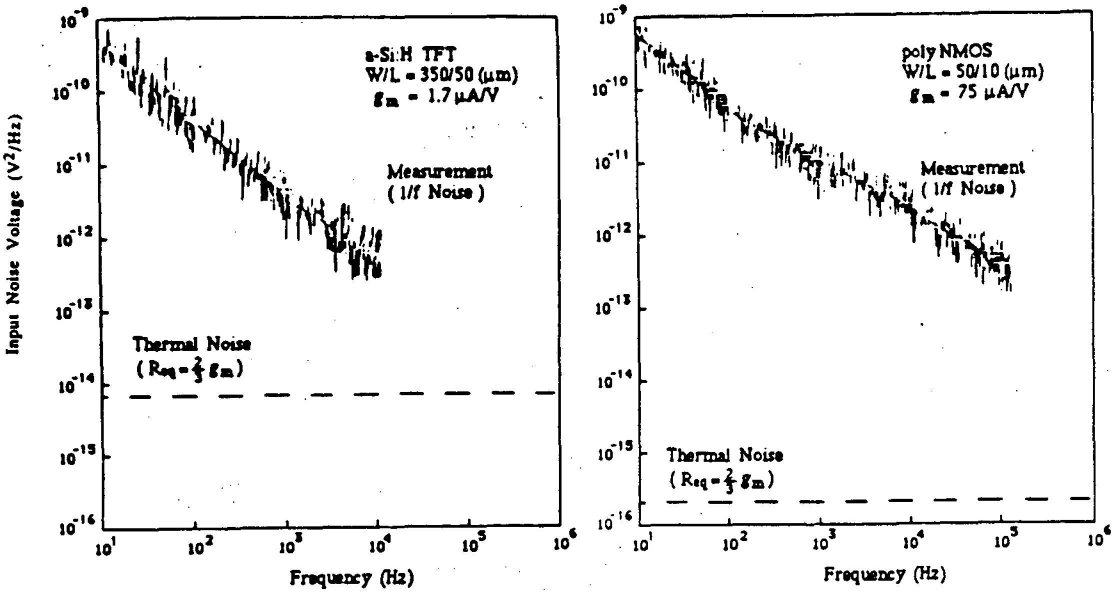

Fig. 12 Flicker (1/f) and Nyquist noise in a-Si:H and poly silicon T.F.T.

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