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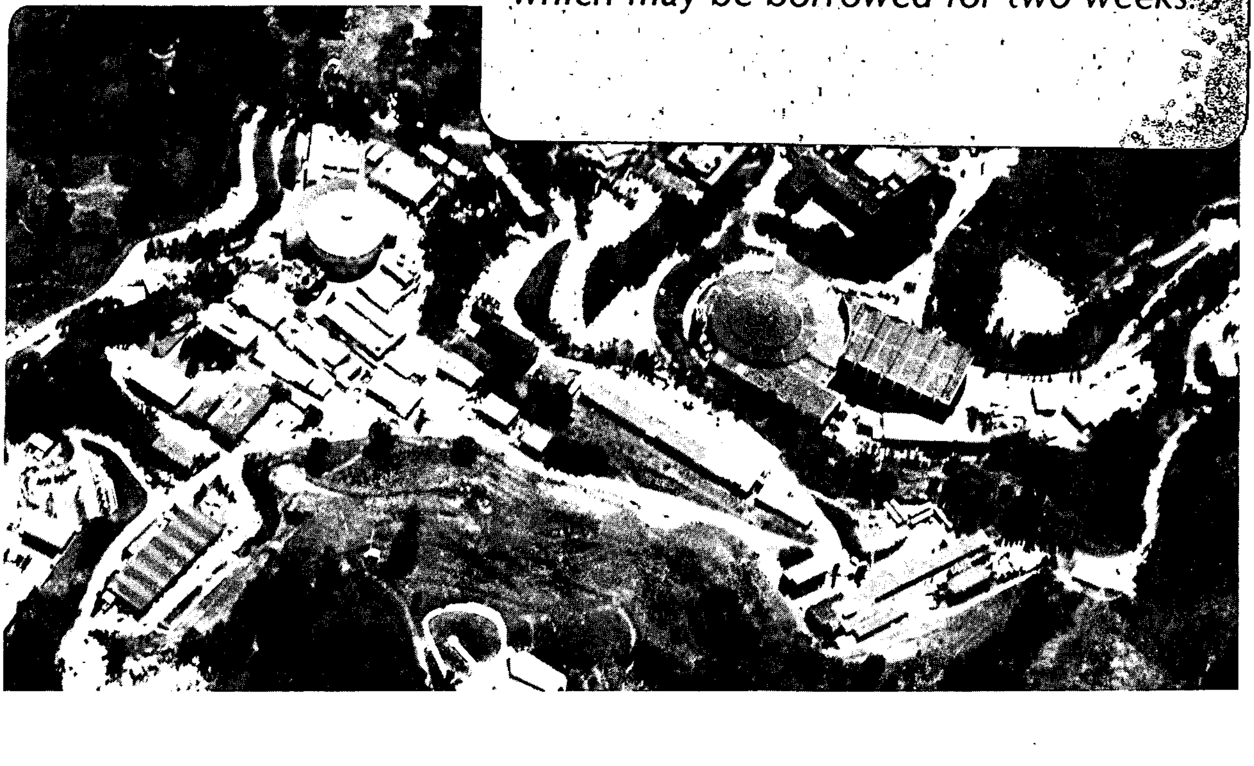

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Signal, Recombination Effects and Noise
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Amorphous Silicon Detectors

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Abstract

Some properties of hydrogenated amorphous silicon diodes are described. Back biased diodes of the Schottky, p-i-n type, in thicknesses ranging from 5-15 microns have been tested with 6 MeV alpha particles and with 1- and 2- MeV protons. Large signal saturation, due to electron-hole recombination, occurs for high L.E.T. particles. Diodes have been exposed to fast neutron fluences up to 10^{13}cm^{-2} and shown to have better radiation resistance than similarly exposed crystalline silicon detectors. From our measurements we extrapolate that minimum ionizing particles can be detected with stacked layers 100-120 microns thick, with adequate signal/noise levels.

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Introduction

Hydrogenated amorphous silicon is a material whose useful electrical properties were first reported by Spear and LeComber in 1976 [1].This material is usually made by the decomposition of silane (SiH_4) in a glow discharge machine, and the subsequent deposition onto a heated glass, ceramic or metal substrate. p and n properties can be induced by the addition of diborane (B_2H_6) and phosphine (PH_3) in the reaction chamber [2]. Since the preparation method is from gases, the area of a-Si:H can be made as large as the substrate holder. For solar cells it is often made in areas 50x50 cm or larger, or on continuous rolls of stainless steel. The favored type of deposit is p-i-n with the intrinsic layer, i, being the thickest for reasons given below. Given the possibility of making thick depletion layers in back biased a-Si:H diodes, it follows that charged particles can be detected in such devices. In a previous paper [3], we have shown the response of Hydrogenated Amorphous Silicon layers (a-Si:H) 2, 5, 10 microns thick to alpha particles of different energies. Some of these layers were reverse biased p-i-n diodes and others were Cr-(a-Si)-Cr Schottky diodes. The main characteristics that were found were:

a) There was a clear α-particle signal, well above the system noise. Signal size increased with bias voltage.

b) There appeared to be a saturation effect on the signal produced with α particles. Evidence for this was that alpha particles depositing different amounts of energy in the depleted region of the detectors produced the same amplitude signal. Furthermore, on the basis of signal size, this depletion region appeared to be confined to a $\sim$ 2-μm-thick zone adjacent to the negative contact, where the electric field was in excess of 10^5 V/cm.

In this paper we discuss various measurements that we have done subsequently in order to interpret these characteristics. We also present here other properties of a-Si:H in order to enable a more comprehensive understanding of the various configurations possible for such detectors in order to enable the future detection of minimum ionizing particles with good position resolution.

I. Amorphous Silicon Diode Characteristics

Crystalline semi-conductor detectors are basically back biased diodes of the Schottky, p-n, or p-i-n (e.g. Lithium drifted Si) junction type. Hydrogenated amorphous devices use similar configurations. The mobilities and lifetimes of electrons and holes are considerably larger in the non- doped intrinsic a-Si:H than in the doped material. Hence, the diode configurations that we used are (1) metal-i-metal (Schottky) (2) metal-n-i-p-metal barrier diodes with thin n and p layers (30-to-50 nm, which is sufficient to make a good barrier), and with the bulk of the material being intrinsic. In this p-i-n geometry the i layers have been made as thick as 30 μm, to date. In Fig. 1 we show forward and back biased voltage-current characteristics for a number of p-i-n and Schottky detectors. There is an asymmetry between the two metal-a-Si interfaces: the barrier characteristics are in general poorer at the substrate boundary, which may be due to the high temperature at which it is formed [4-5].

II. Electron–Hole Collection and Charge Recombination in a–Si:H

The mobilities, μ, and lifetimes, t, of the charge carriers depend on the density of dangling bond states in a-Si:H. For material estimated to have $\sim$ 3x10^{15} dangling bond states per cm^3, the following numbers have been measured [6].

Electrons: $\mu = 2\text{cm}^2/\text{Vsec}$ $\quad \mu t = 1\text{x}10^{-6}\text{cm}^2/\text{V}$
Holes: $\mu \sim 10^{-2}\text{cm}^2/\text{Vsec}$ $\quad \mu t = 2\text{x}10^{-7}\text{cm}^2/\text{V}$.

Electric fields in a-Si:H as a function of dangling bond density calculated from a solution of the Poisson equation [7] are shown below in Fig. 2. When we applied the maximum bias, before the material noise increased appreciably, maximum average electric field in our 5-, 10-, and 15-μm-thick detectors is $\sim$ 3x10^5 V/cm. If μ remains constant for electric fields of this magnitude, the mean free paths for the carriers, L_e and L_h, would be 3x10^3 μm and 600 μm respectively. This means that with peaking times in a charge sensitive preamplifiers of 1 μsec., we should be able to collect both holes and electrons with high efficiency for detectors up to 100-μm thick.

Our early results were not consistent with this picture. Charge collection efficiencies as a function of peaking time for an older detector 5-μm thick are shown in Fig. 3. In addition, measurements using alpha particles incident on p-i-n or Schottky a-Si:H detectors 2-15 μm thick, gave the apparent result that the signal was (a) independent of energy ΔE deposited in the detector, (b) that the apparent sensitive region was only about 2-μm thick [7]. Both of these results are now explainable as due to a large degree of charge recombination produced in the high density of electron-hole pairs of the alpha track. The large signal-saturation effect was first confirmed when a detector was rotated through 60° with respect to the direction of the incident alphas (Fig. 4a). Instead of a 2-fold increase in signal size due to the geometric increase in path length, there was an almost 4-fold increase in signal size. Fig. 5 shows a comparison of signal sizes as functions of applied voltage and relative path length (expressed as $1/\cos\theta$). Not only did signal size increase more rapidly than $1/\cos\theta$, but the fractional excess increased with applied voltage. This behavior suggested very strongly, not only signal saturation, but that the source of the saturation was direct recombination within the ionization column produced by the particle transit [8]. That is, that electrons and holes were recombining with each other along the beam track, which was also the field axis. When the beam axis is rotated with respect to the field, it becomes much easier for electrons and holes to escape this column [9] (Fig. 4b). Fig. 6 shows the signal amplitudes obtained from 5- and 10-μm detectors, expressed as electrons/(keV/μm), for various α energies, and for 1- and 2-MeV protons from a Van de Graaf accelerator. These data were taken at 0° and 60° angles relative to the perpendicular direction. If there were no variation in charge-collection efficiency the signal amplitude would be equal for all these cases. Fig. 7 shows these data plotted as a function of dE/dx of the various particles. These data show that for $\frac{dE}{dx} = 28$ keV/μm (2-MeV protons) at 60°, we collect at least 70% of the full electron-hole signal. We expect these results to extrapolate to $\sim$ 100% collection efficiency for minimum ionization particles. This extrapolation is consistent with laser induced ionization data on a-Si:H, which show full charge collection from diodes 4- to 7-μm thick, and with E fields as low as $5\text{x}10^2$ V/cm [5].

III. Signal/Noise

The ability to detect small signals is limited by the irreducible noise of the overall system -- detector and charge sensitive amplifiers. The irreducible signal/noise of the charge sensitive amplifier is limited by the input F.E.T. loaded by the capacity of the detector. The detector generates some noise in the material itself as well as from the leakage currents: reverse current + surface leakage current. In Figure 8 we show noise from 15-μm and 5-μm detectors as a function of leakage current. The detectors were also simulated by a 20-megohm resistor in parallel with 47-pf and 150-pf capacitors respectively. From this figure we see (a) that the leakage current is only a minor contributor to noise under normal operating detector currents ($<10^{-7}$A), and (b) above normal operating biases excess detector noise is generated. Sources and mechanisms for this noise are currently under investigation.

IV. Radiation Damage

Semiconductor detectors, in applications at high-energy-physics particle accelerators are presently, and will be even more in the future, subjected to high radiation doses. Such doses can seriously degrade crystalline-silicon detector performance after limited-time exposures [10].

We have made some measurements on the relative radiation resistance of crystalline and a-Si:H detectors exposed to fast neutrons. Two detectors were exposed to fast neutron fluences at the Berkeley Research Reactor, a 5-μm a-Si:H detector and a 255-μm diffused-junction crystalline detector. For these first tests we were reluctant to sacrifice one of our better a-Si:H detectors or a good crystalline detector. Therefore the a-Si:H detector held lower bias than our better detectors, and the crystalline detector was initially noisy. Fig. 9 shows the changes in leakage current and noise in these detectors initially, and after exposure to 10^{12} and 10^{13} 1-MeV-equivalent neutrons/cm^2 [11]. After exposure to 10^{13}n/cm^2 an alpha-particle signal could no longer be observed from the the crystalline Si detector. For the a-Si:H detector, test pulser and alpha signals were clearly seen after 10^{13}n/cm^2, but with a factor of 2 decrease in resolution (Fig. 10). We plan to repeat these measurements with initially better detectors, and to extend them to larger neutron fluences.

V. Summary and Conclusions

The electrical and mechanical properties of Hydrogenated Amorphous Silicon have improved steadily since its discovery in 1976 by LeComber and Spear. Present technology can make material of dangling bond densities $\sim$ few x 10^{15} and with deposits that can be made in good quality to thicknesses of 40 μm or more [12]. To date, we have detected particles with dE/dx down to 28 keV/μm in 10-μm-thick layers. By stacking layers up to a total thickness of 100-120 μm, we expect to be able to detect minimum ionizing particles with signal/noise $>$ 6 [13]. This assumes 20-μm-thick layers, each with a capacity of 50--60 pf, and with the signal recorded by a low-noise high-gain FET with a comparable input capacity. In the configuration, each layer would be connected to a separate charge-sensitive amplifier. For n layers the total signal would be proportional to n, whereas the noise would be proportional to $\sqrt{n}$.

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[13] Blair Jarrett (LBL) - private communication

Figure Captions:

Fig. 1 Forward and reverse currents as function of voltage in a-Si:H diodes.

Fig. 2 Calculated electric field across a 10-μm a-Si:H diode assuming various densities, N(cm^{-3}), of ionized dangling bonds, and a D.C. bias of 100 V.

Fig. 3 Output signal as function of peaking time from a charge sensitive amplifier attached to 2μm (120 p.f.) detector.

Fig. 4 Schematic diagram of factors affected by detector rotation: a) path length in depleted region, and b) electron- hole recombination in α-track "tube".

Fig. 5 Signal from 5-μm diode detector as function of 1/cosθ, where θ is the α-particle angle of incidence. The signal is normalized to unity for normal incidence. The dotted line (labeled 1/cosθ) corresponds to the increase in path length with angle of incidence.

Fig. 6 Signal output (electrons/keV/μm) from p-i-n 5μm thick detector for α particles, 1, and 2 MeV protons at 0° and 60° incidence. Saturation effect is shown clearly.

Fig. 7 Charge-collection efficiency vs. dE/dx for a 5-μm p-i-n diode.

Fig. 8 Equivalent amplifier input noise from 5-μm (150 pf) and from 15-μm (47 pf) detectors as a function of surface-leakage and reverse current, compared to noise from a 20-megohm resistor in parallel with capacitors having the same capacity as the detectors.

Fig. 9 Detector noise (FWHM) before and after exposure to fast neutron fluences, for a) a crystalline Si detector, and b) an a-Si:H detector.

Fig. 10 Pulse-height resolution of a 5-μm a-Si:H detector a) before, and b) after exposure to a fast-neutron fluence of 10^{13}n/cm^2. The alpha pulse width, measured in units of equivalent input-charge, increased by almost a factor of 2. For the measurements, the detector was rotated ~60°g to the α-particle direction of incidence, and the 20% difference in α-signal size between the two measurements is probably due to uncertainty in this angular orientation.

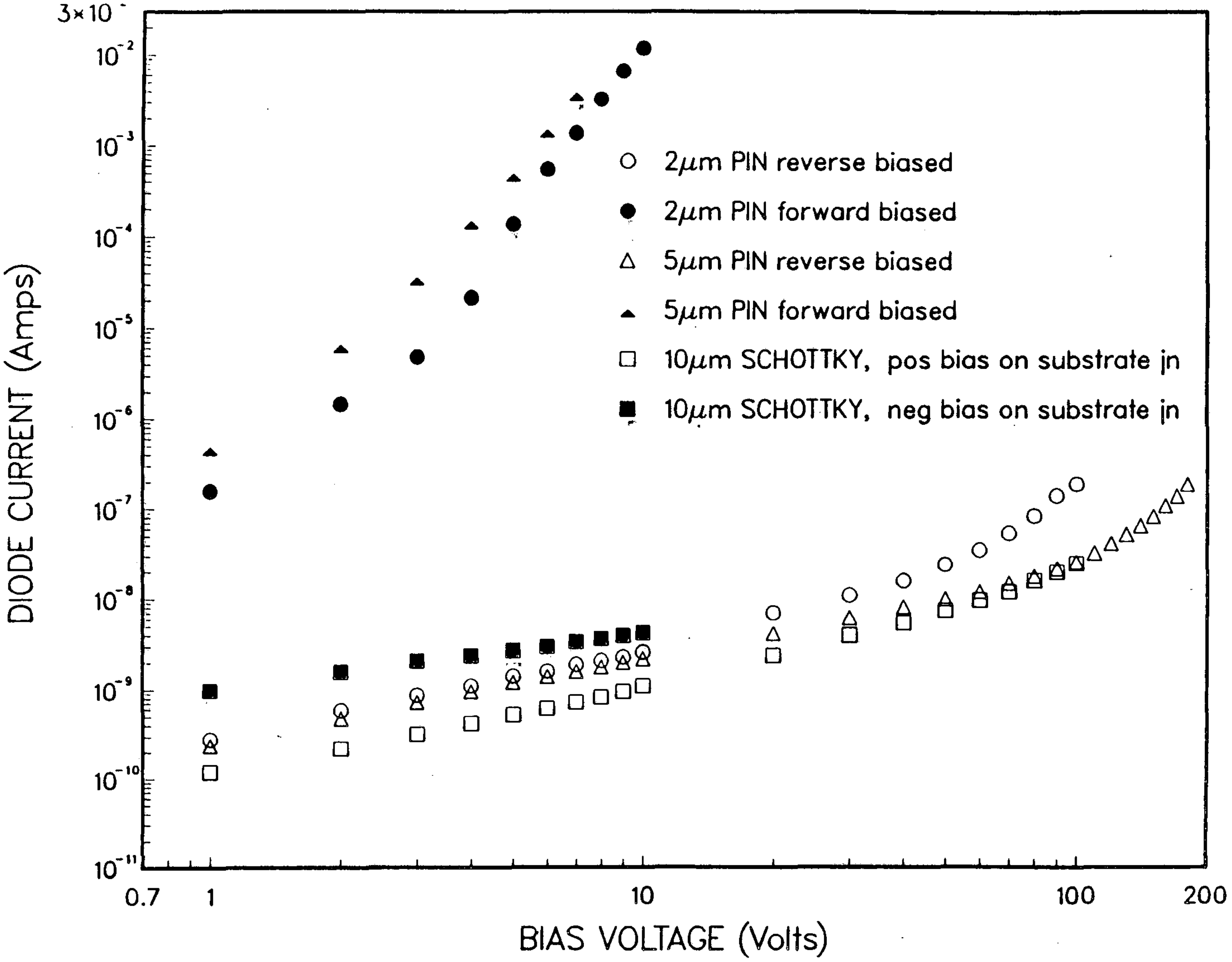

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Fig. 1

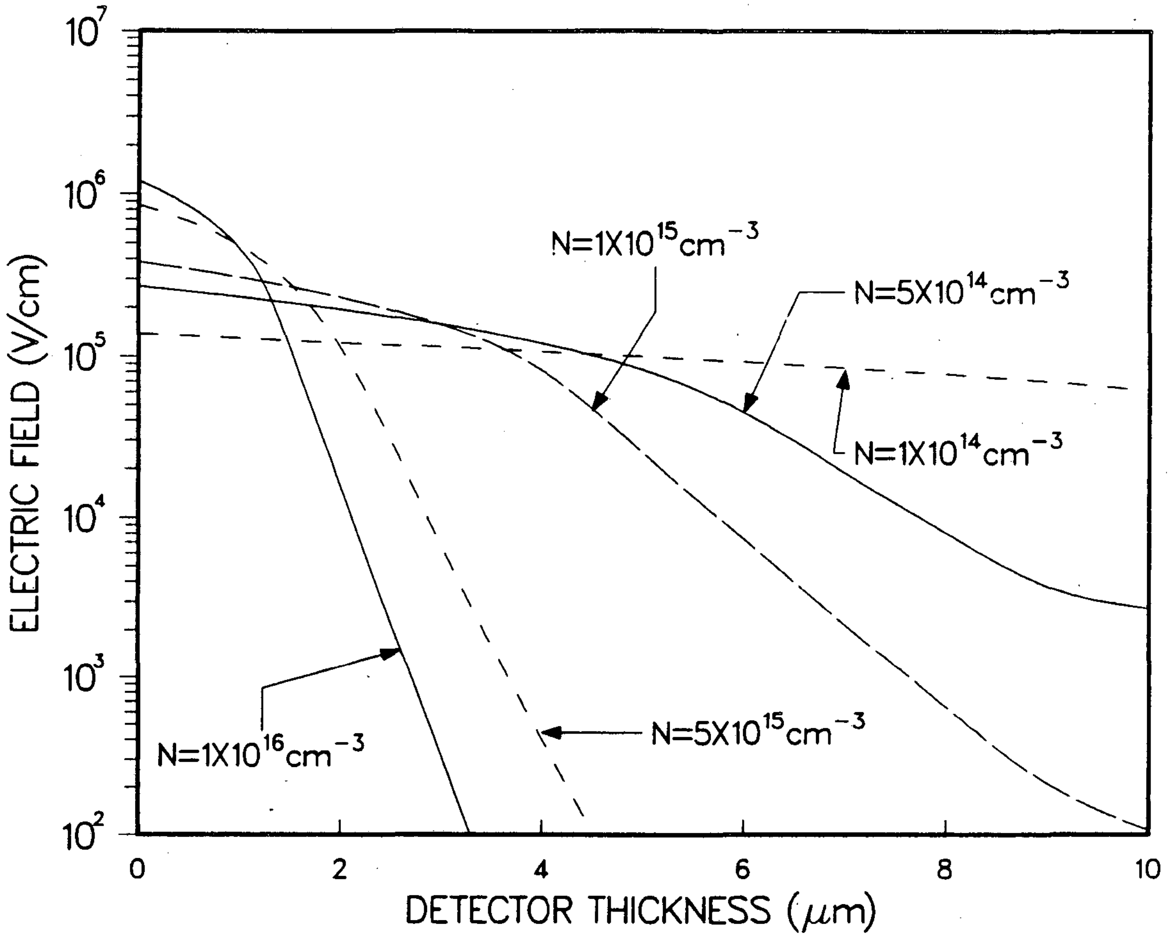

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Fig. 2

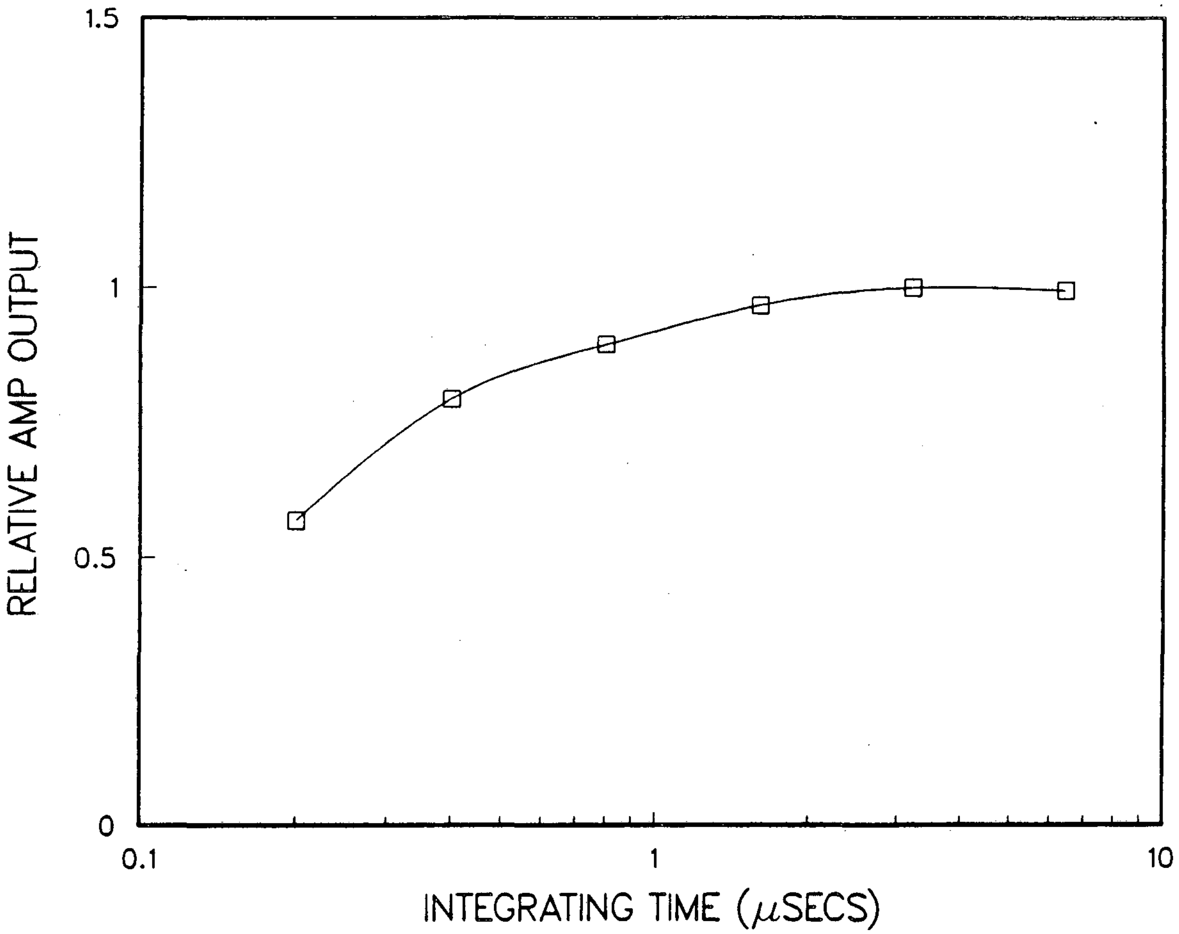

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Fig. 3

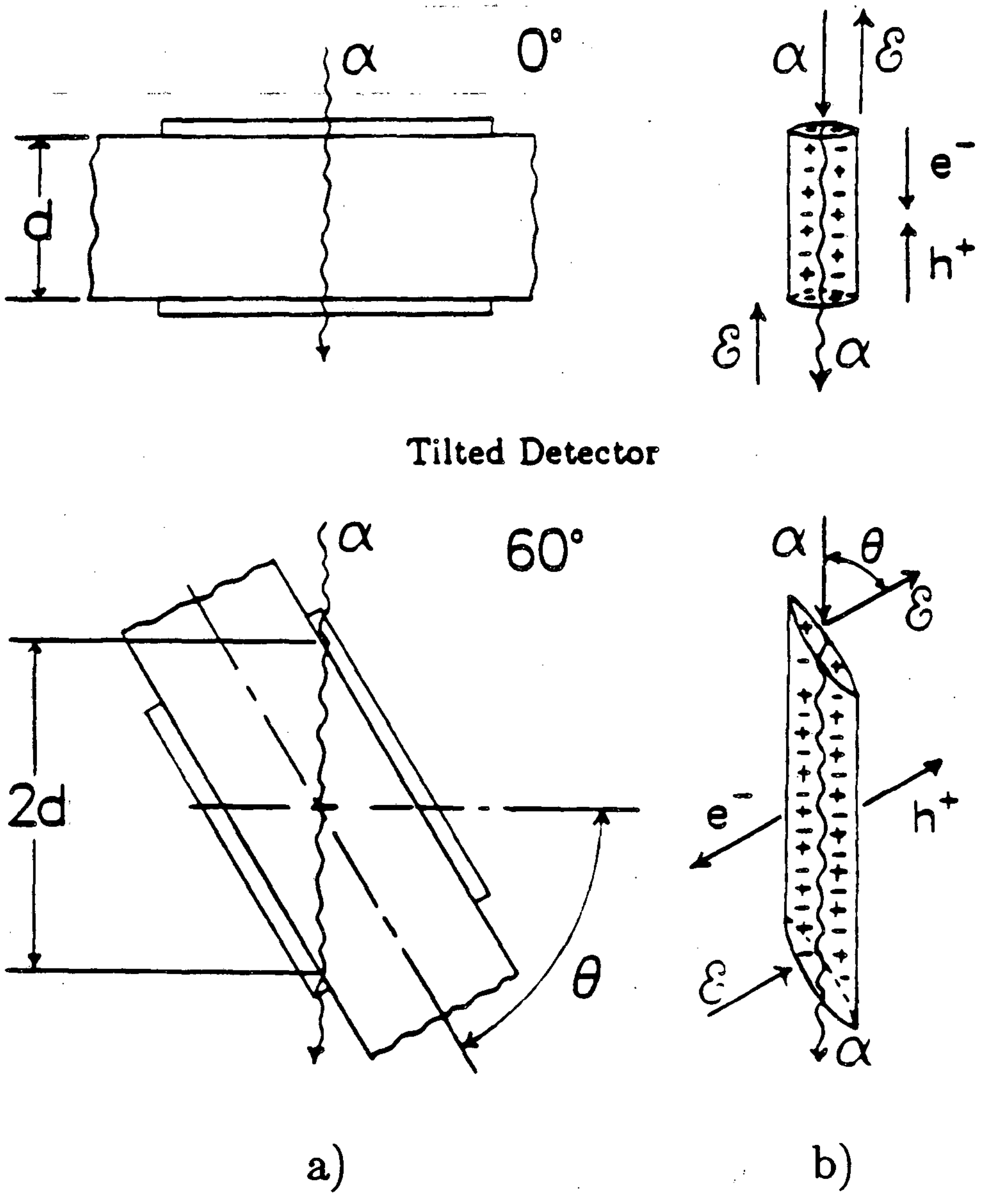

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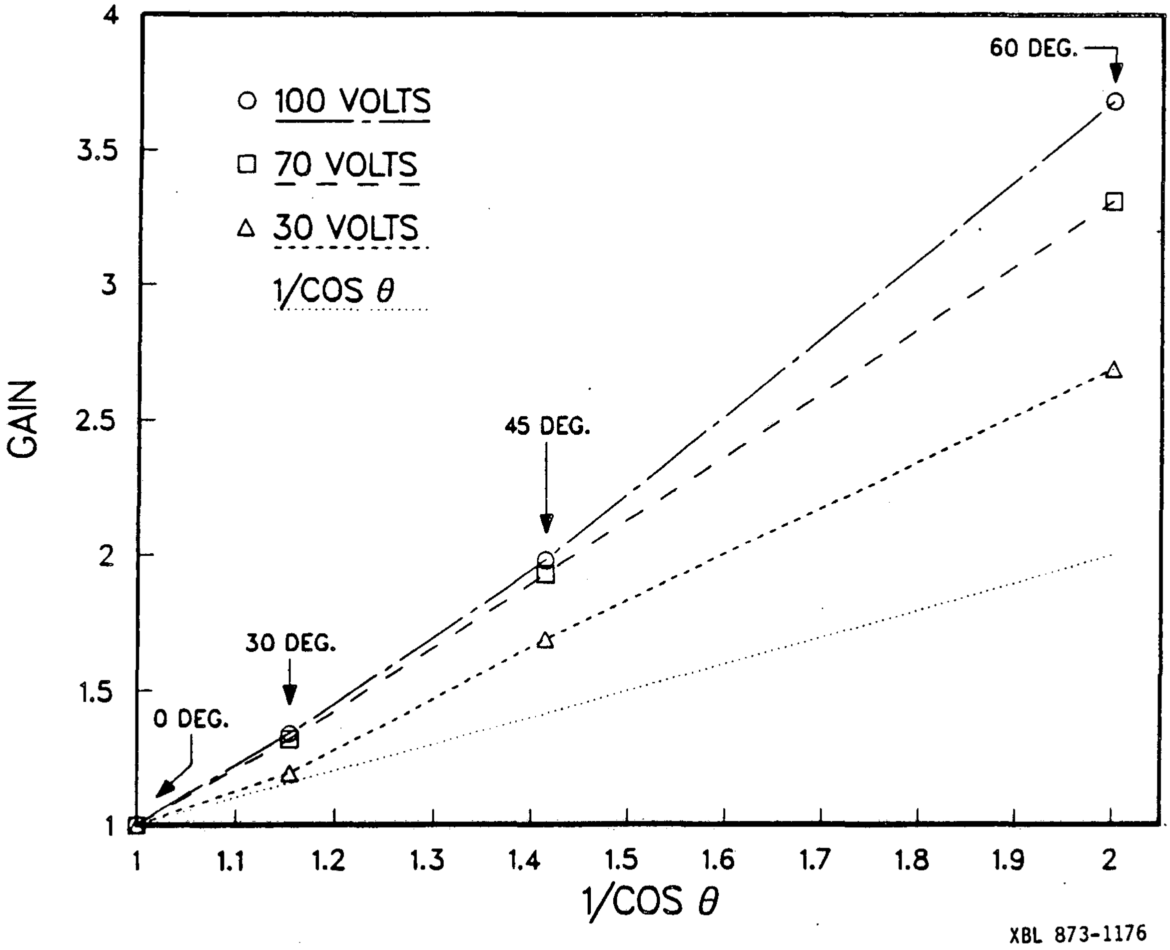
Fig. 4



GAIN
1/COS θ
○ 100 VOLTS
□ 70 VOLTS
△ 30 VOLTS
1/COS θ
0 DEG.
30 DEG.
45 DEG.
60 DEG.
1
1.5
2
2.5
3
3.5
4
1
1.1
1.2
1.3
1.4
1.5
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1.7
1.8
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2
XBL 873-1176

Fig. 5

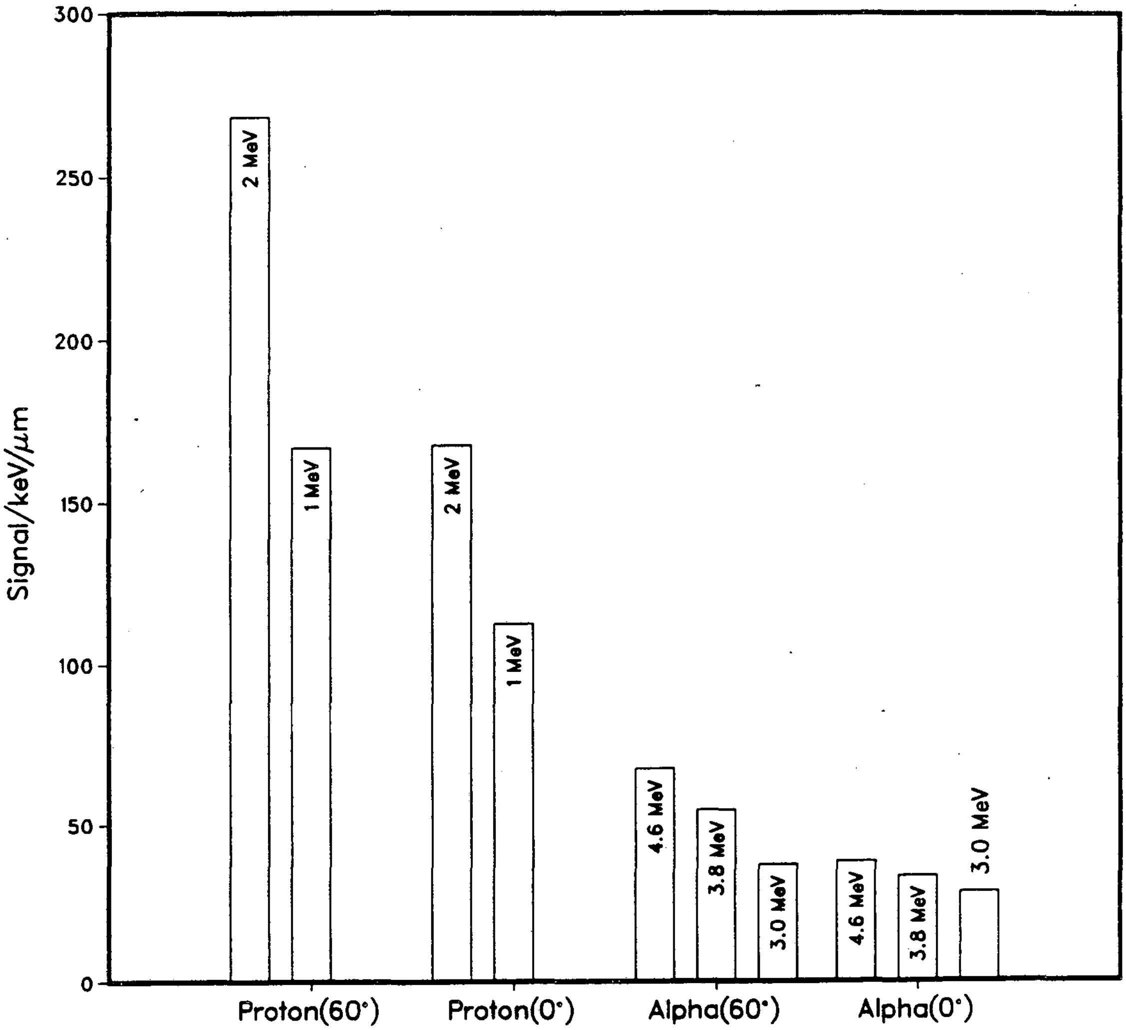

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Fig. 6

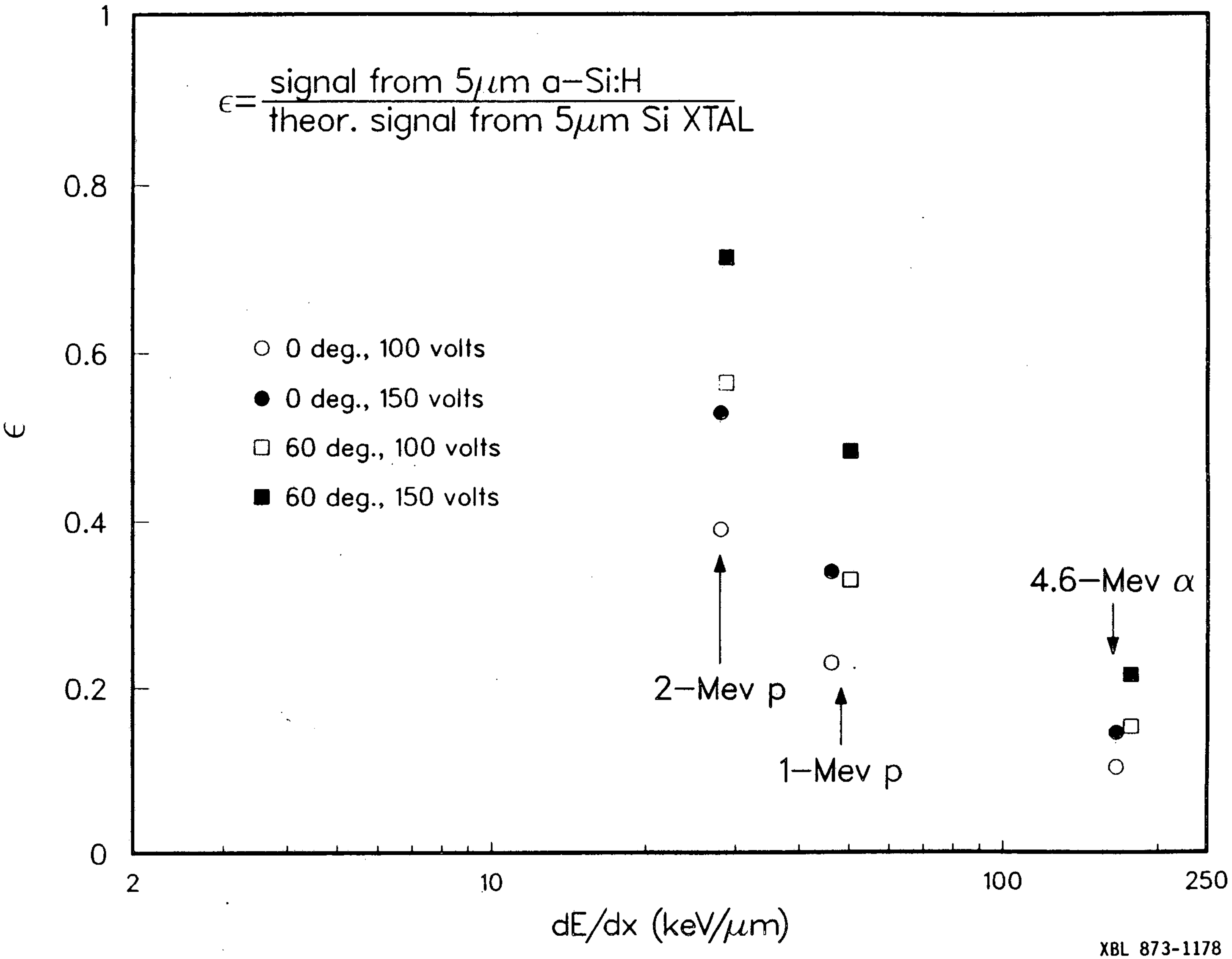

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Fig. 7

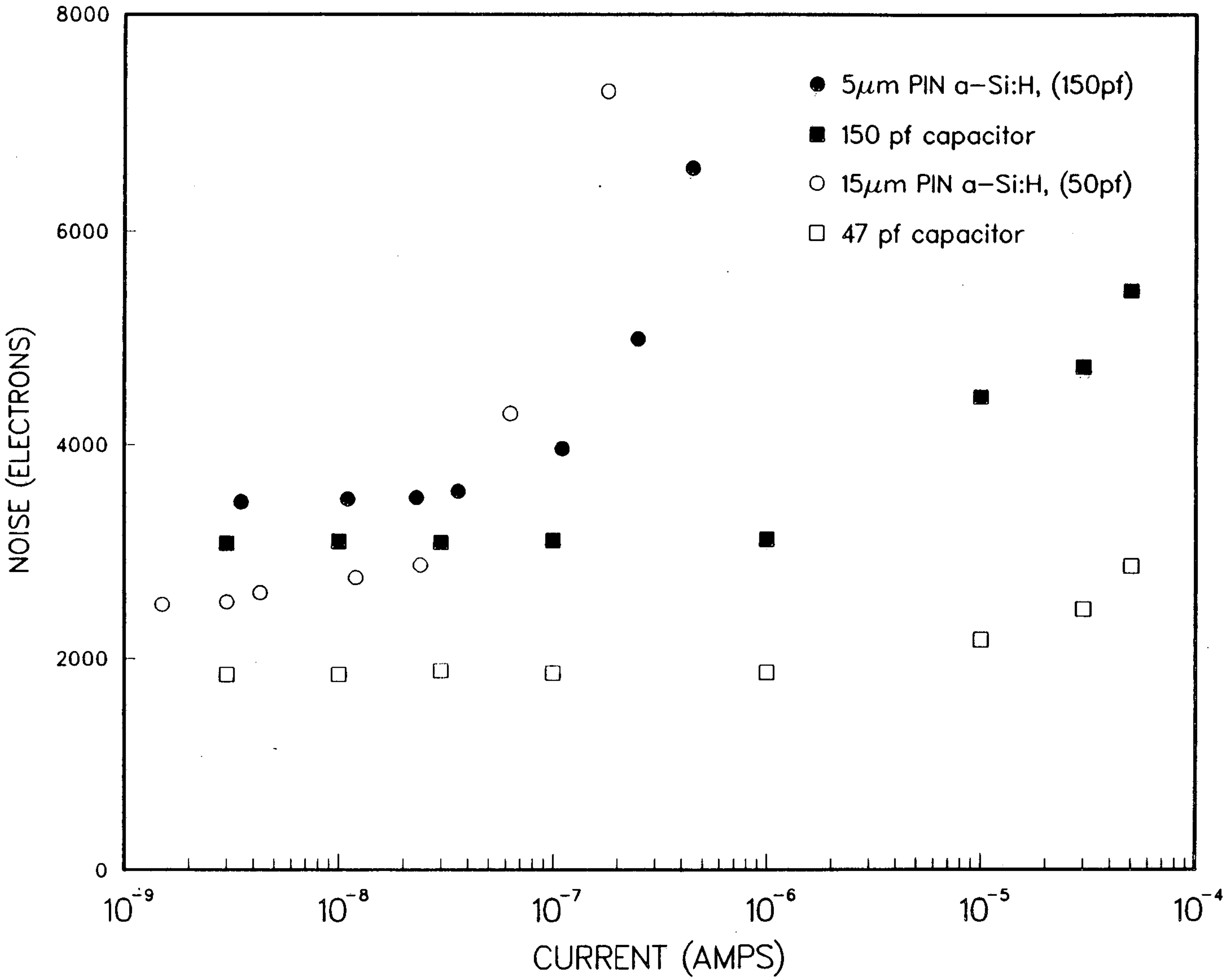

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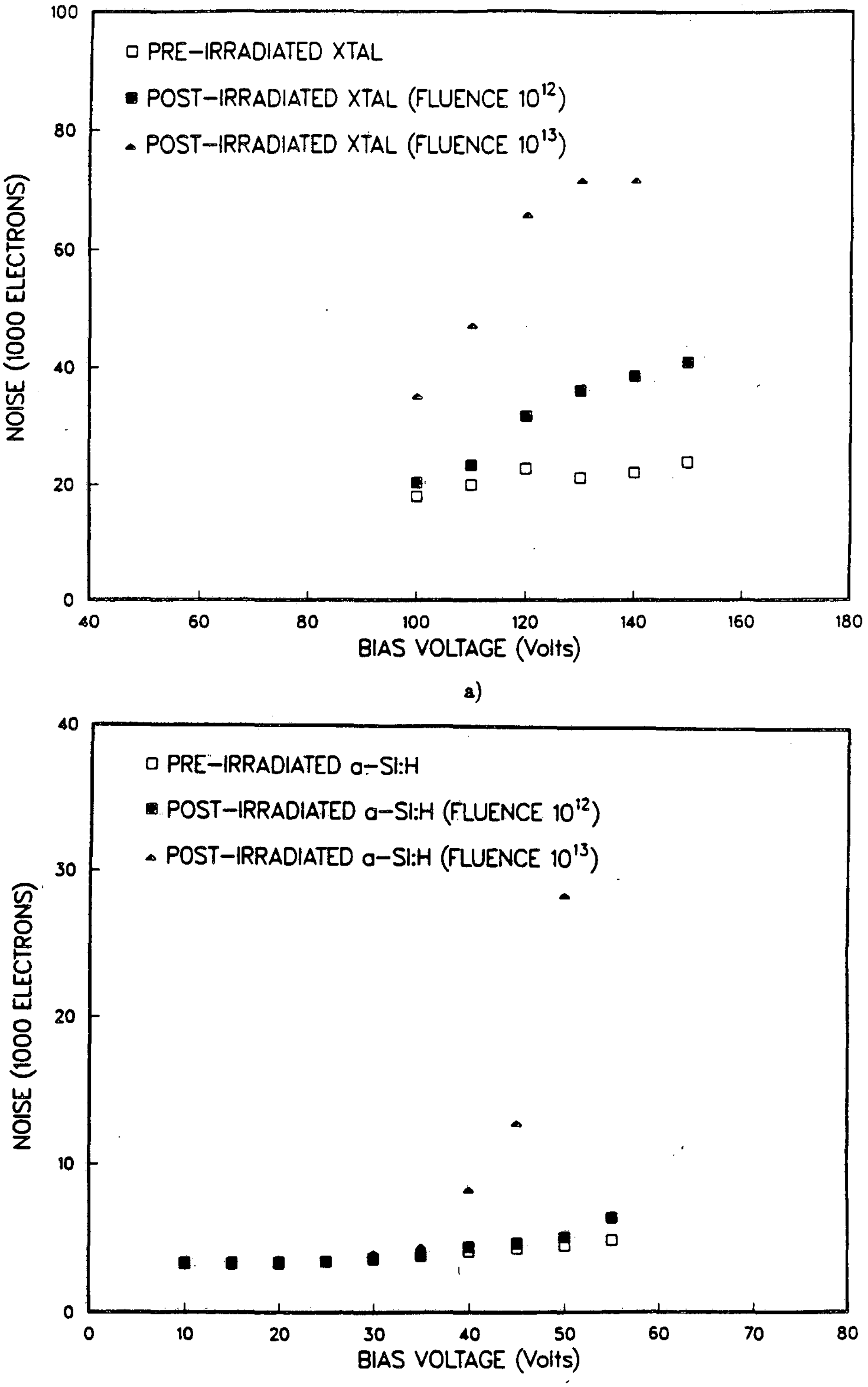
Fig. 8



a)

b)

XBL 873-1180

Fig. 9

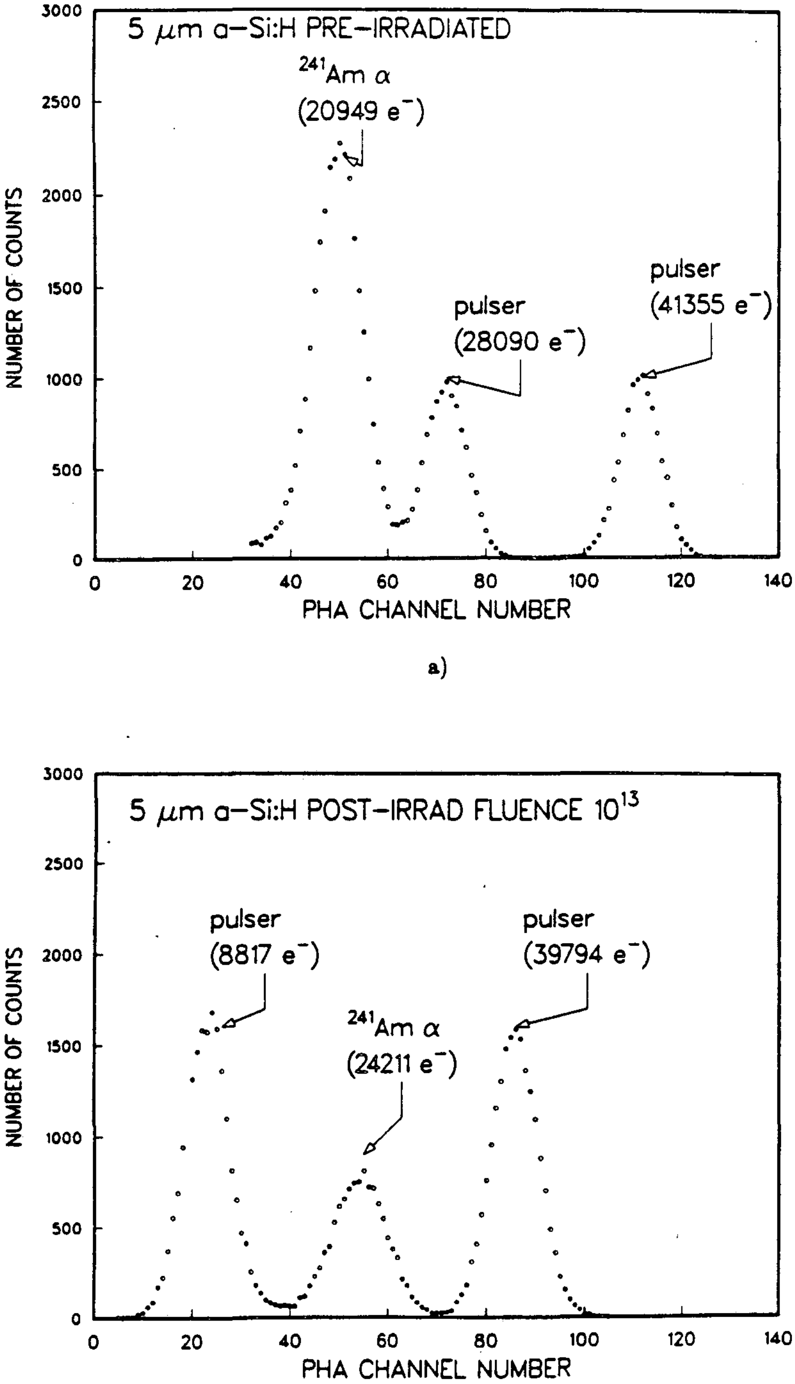


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Fig. 10

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