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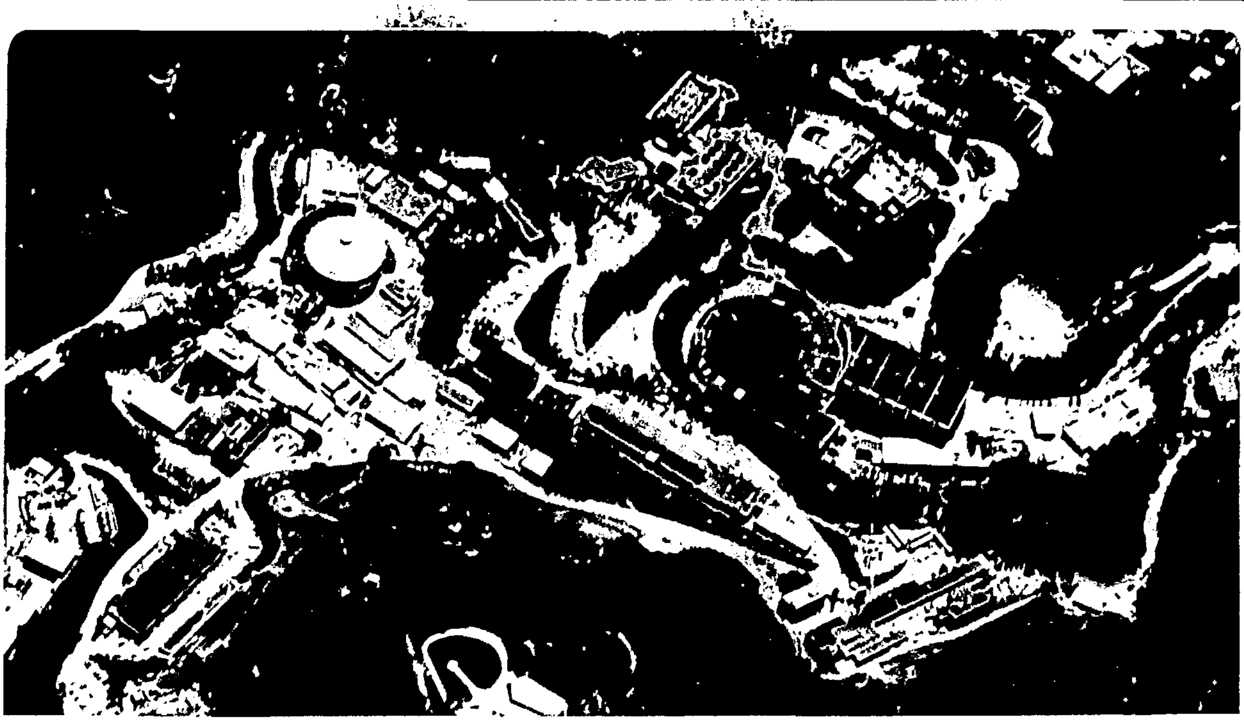

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DETECTION OF CHARGED PARTICLES IN AMORPHOUS SILICON LAYERS

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Abstract

The successful development of radiation detectors made from amorphous silicon could offer the possibility for relatively easy construction of large area position-sensitive detectors. We have conducted a series of measurements with prototype detectors, on signals derived from alpha particles. The measurement results are compared with simple model calculations, and projections are made of potential applications in high-energy and nuclear physics.

Introduction

Single-crystal solid-state detectors, especially those fabricated from silicon and germanium, have enjoyed a long and productive history as radiation detectors. The single-crystal restriction, unfortunately, results in high cost and limited sensitive area. If non-crystalline semiconductors could be made sufficiently sensitive to low levels of radiation, they would, for certain applications, circumvent the need for single crystals, and allow the easy manufacture of large area position-sensitive sensors. Moreover, because they are already in a state of greater disorder, they could be expected to be considerably less sensitive to radiation damage than their single-crystal counterparts. Recent advances in the fabrication of amorphous silicon devices, particularly in deposition techniques that produce layers with low trap densities, have encouraged us to investigate amorphous silicon as a radiation detector.

Detector Material

The detector samples studied were all hydrogenated amorphous silicon (a-Si:H) devices that ranged in thickness from 2 to 15 μm. These devices were fabricated by plasma decomposition of silane gas, at the Xerox Palo Alto Research Center.[1] Depositions were made over a thin conducting bottom contact of chromium on a glass substrate. During the deposition of the a-Si:H, parameters such as gas pressure, gas mixture (diborane for p doping and Phosphine for n doping), gas flow rates, R.F. power, and sample temperature, were controlled in a manner that can produce dangling bond densities ranging from 10^{17}cm^{-3} down to 10^{15}cm^{-3}.[2] These devices have electron mobility of the order of 2 cm^2/Vsec and hole mobility of the order of 5 x 10^{-3}cm^2/Vsec at room temperature, for dangling bond densities $\sim 10^{15}$/cm^3.[3] Depositions can be made in a continuous operation at a rate of about 0.5 μm per hour.

Initially the devices that we used were fabricated without any doping, and with Cr contacts on top and bottom. This configuration formed two back-to-back Schottky barriers.

Later we used p-i-n junctions fabricated by introducing the appropriate doping gases for short periods of time at the beginning, and the end of the a-Si:H deposition. Most recently we have made measurements on two-layer n-i-p-p-i-n stacks, and plan to extend these measurement to thicker, multilayer stacks.

Experimental Procedure

The experimental setup is shown in figure 1. Because we anticipated the need to cool the detector as well as to provide a vacuum for alpha-particle detection, the detector and source were mounted in an old Ge(Li) detector housing. An ^{241}Am alpha source was mounted in the cap of the housing, upstream of an eccentric disk that contained thin aluminized-mylar absorber windows of 1, 2, and 3 layer thickness, one open window, and a windowless region that would block the alphas completely. The active window could be changed by rotating the disk using a magnet mounted on the outside of the cap. A single layer of the aluminized mylar material consisted nominally of 0.05 μm Al and 8 μm mylar. A four layer thickness was sufficient to stop the alphas. The energies of the alphas emerging from each of the windows were measured with a Si-crystal detector.

The detector and amplifier (Amptek A225) were mounted on an aluminum block that was attached to the cold finger of the recycled Ge(Li) detector chamber. (Preliminary reduced-temperature measurements showed no net improvement in signal/noise. The results reported here are all at room temperature.)

The samples we used were approximately 1.5 x 1.5 cm in area, deposited on a chromium plated thin glass substrate. The top Cr contact of the detector was connected electrically to the coupling capacitor and the bias supply by a tiny tiny spring-loaded gold-plated finger. The Amptek amplifier, while self contained, with an output shaping circuit, did not produce a large enough output signal for our available pulse-height analyzer, so additional external amplification was required.

Test calibration pulses were used to determine the input charge equivalent of the detector pulses. The test pulses originated as long voltage steps from a calibrated Datapulse 101 pulse generator. This calibration voltage was then attenuated, as required, terminated in 50 ohms at the amplifier, and coupled into the amplifier input through a 2.5 $\pm$ 0.2 pf test capacitor. An example PHA display, with both pulser and α-particle signals, is shown in Figure 2. The equivalent energy of the pulser signal, E_t was taken to be,

$$E_t = V_t C_t W_{Si}/e$$

Where V_t is the attenuated test-pulse voltage, C_t is the test capacitance, W_{Si} is 3.62 eV/electron-hole pair, and e is the electron charge. An absolute calibration check against a full -energy alpha peak with a normal crystalline Si detector, in a different setup, agreed, to within 5%, with test-pulse values.

The first detectors tested were back-to-back Schottky diodes, that had a uniformly deposited bottom metal contact, and top metal contacts in the shape of 2- and 3-mm-diameter circles. All of our detectors used chromium as the contact metal. The Cr and the a-Si:H form Schottky barriers at both contacts. We found that there was consistently a very significant difference in leakage and noise between the two barriers, and successful measurements could only be made by back biasing the upper barrier. This first group of detectors ranged in thickness from 1- to 15-μm.

Later detectors tested had the bottom metal contacts deposited as 1 mm-wide metal strips, that were separated by 2 mm. The top contacts were deposited in the same pattern, but with the lines perpendicular to the bottom lines (Figure 3). The intention of this patterning was to simulate the geometry of a position-sensitive-detector configuration, where the signal origin could be localized to the intersection of two perpendicular electrodes. The samples that were 10-μm thick were also of the Schottky type, but the 2- and 5-μm samples were of the p-i-n type described earlier.

Measurements have also been made on a two-layer "stacked" detector. Here the detector was made as an n-i-p diode deposited on top of a p-i-n diode. The second deposition was masked in such a way that we could make signal contact with the middle set of metal strips (Figure 4).

For the detectors tested, Alpha-particle-signal size and noise were measured as a function of applied bias. Typically two different test-pulse amplitudes were superimposed on each experimental measurement to give the input-signal calibration.

Experimental Results

We detected alpha-particle signals from nearly all of the detectors tested. Signals were first found with the Schottky diodes with the circular contact patterns. From this group, the thinnest diodes to produce detectable signals were 5-μm thick, and these also had some p doping. Signals were also detected with the 7.5 and 15μm samples. With the exception of the 15μm sample, which was biased as high as 150 V, the detectors would hold no more than 40 V. Observations from these detectors showed that all of the segments (defined by the circular contact areas) on a single detector performed consistently with regard to signal size, noise, and efficiency. In all cases the signal continued to rise with increasing high voltage, however the signal size did not increase with detector thickness.

The p-i-n detectors had much better high-voltage characteristics. The 2-μm had a low noise signal up to 100V of bias, so it was possible to do a direct comparison of three detectors, of thickness 2, 5, and 10 μm respectively, over the same range of bias voltage (Figure 5). Within cross-calibration uncertainties the signal size appears to be the same for all detectors, independent of physical thickness. The noise (taken to be the FWHM of the calibration pulse), also plotted on the curve, does not appear to be significantly different for the three detectors, nor does it increase with applied voltage.

Figure 6 shows a direct comparison between a single 5-μm and a stack of two back-to-back 5-μm detectors (Figure 4). The signal from the stacked detector is twice as large as that from the single detector, and the noise is not significantly different.

Analysis of Results

In a-Si diodes similar to ours with density of trapping states $\approx 5 \times 10^{15}/\mathrm{cm}^3/\mathrm{eV}$ direct measurements have shown [3] that the electrons and holes have the following properties:

	Mobility	Lifetime
	$\mathrm{cm}^2/\mathrm{sec\ V}$	sec
Electrons	0.5	6.4×10^{-8}
Holes	3×10^{-3}	3×10^{-7}

In the measurements described in this paper, we have used a charge sensitive amplifier with an integrating time $< 1\ \mu$sec. This is short compared to the hole collection time, hence the signal we get is mostly from electron collection. In order to estimate the expected signal size and its behaviors as a function of the applied potential, the space dependence of the electrical field within the a-Si has to be known.

At low biases (2-5 volts/micron), the electric field has been shown [3] to drop off exponentially with distance. In our case where we apply a bias higher (10-20 volts/micron), the band gap, density of depleted states and Fermi level, is expected to behave as shown below in Fig. 7. In region I it is assumed that all the donor states are completely ionized, hence the charge density $\rho = ne$ where n is the density of gap states. Poisson's equation for this case is:

$$\frac{d^2V}{dZ^2} = \frac{-\rho}{\epsilon\epsilon_0} = \frac{-ne}{\epsilon\epsilon_0} \qquad (1)$$

with solutions which give a parabolic dependence of V on Z and a corresponding electric field E which is linear in Z.

In region II, the gap states are only partially ionized and it is assumed that $\rho(Z) = n'eV(Z)$ with a corresponding Poisson equation:

$$\frac{d^2V}{dZ^2} = \frac{-n'eV(Z)}{\epsilon\epsilon_0} \qquad (2)$$

Solutions of (2) give an exponential dependence for V and E with Z. At the boundary between regions I and II (at a distance t_c from one surface), the solutions of equation (1) and (2) are required to be continuous with continuous derivatives. The potential at this boundary, V_c is the ratio of n to n′ . The parameter t_c was selected by the computer program to give the best fit to the voltage dependence of the signal amplitude in our various diodes.

In Fig. 8 we show the Z dependence of the potential and electric field for a 5 μm p-i-n sample at a bias of 100V. The solid line shown in Fig. 6 is the best fit to the signal through the diodes assuming electron collection only and a uniform deposition of energy/unit distance by the alpha particles traversing our samples. For the 2 micron thick p-i-n detectors, integration of the signal over the electric field gives the result that we collect only 0.3 of the maximum of the combined electron and hole signal.

Discussion and Conclusions

The trap densities and electron mobilities of presently producible amorphous silicon diodes are already at a level that permits detection of α particles passing through them. While measurements show that the effective sensitive thickness of these diodes is less than 2 μm, they have also shown that a back-to-back pair of diodes can be made, and will give twice the signal of a single diode.

Simple model calculations can explain the effective sensitive thickness of the detector and the increase in signal size with applied voltage in a way that is consistent with the measured electric-field profiles of reference 4. The log slope of the electric field, and the ionized trap density, that best fit our data are comparable to, but somewhat greater than those obtained by direct measurement on similar material. At the high voltages and peak fields of these measurements, and with no account being taken of other effects such as the kinetics of trapping and release of carriers, the precise meaning of the fitted values is not completely clear. They nevertheless appear to describe the behavior of the material and provide a basis for prediction and comparison.

The fitted data was based on signals from alphas passing through a windowless hole in the absorber wheel. On the basis of the simple model we would have expected to see a larger signal from alphas that had first passed through three thicknesses of mylar absorber. Instead we saw a slightly smaller signal. This is still an unresolved issue, but could imply signal saturation. A consequence of such saturation would be that less heavily ionizing particles would give relatively larger signals than would be inferred from linear extrapolation.

Even without further significant improvement in the quality of the amorphous material itself, we expect to make sufficiently large stacks from present material to produce useful position-sensitive detectors for minimum-ionizing particles. Detection of minimum-ionizing particles would require stacks of 15, or more, of the diodes described. The present measurements are being extended to thicker stacks.

Acknowledgments

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Figure Captions

Fig. 1. Block electronic diagram of the test setup with the Amptek A225 amplifier. The components inside the dashed box were mounted inside the vacuum chamber.

Fig. 2. PHA spectrum, showing alpha peak and two pulser calibration peaks. The data is from a 2-μm p-i-n diode, of the type illustrated in Figure 3, biased at -90 V. The energy-equivalence of the pulser calibration peaks was determined both by direct comparison with a full-energy alpha pulse in a Si-crystal detector, and by calculation, from the measured value of the test capacitor. The two results were consistent to within 5%.

Fig. 3. Single-layer p-i-n detector with striped conductor contacts at top and bottom.

Fig. 4. Back-to-back detector.

Fig. 5. A comparison of signal and noise from three thicknesses of p-i-n detectors. Within measurement uncertainty both signal and noise were identical, independent of detector thickness.

Fig. 6. Comparison of signal and noise from a single 5-μm p-i-n detector and a stacked 10μm (5+5) n-i-p-p-i-n detector. Within measurement uncertainties the signal was double, and the noise unchanged, for the stacked detector.

Fig. 7. Valence, band, conduction band and Fermi level in p-i-n sample. The deep depletion; region I is completely ionized at high biases. Region II at a lower bias potential is partially ionized.

Fig. 8. Calculated values of potential and electric field from solutions of the corresponding Poisson equations in regions I, II.

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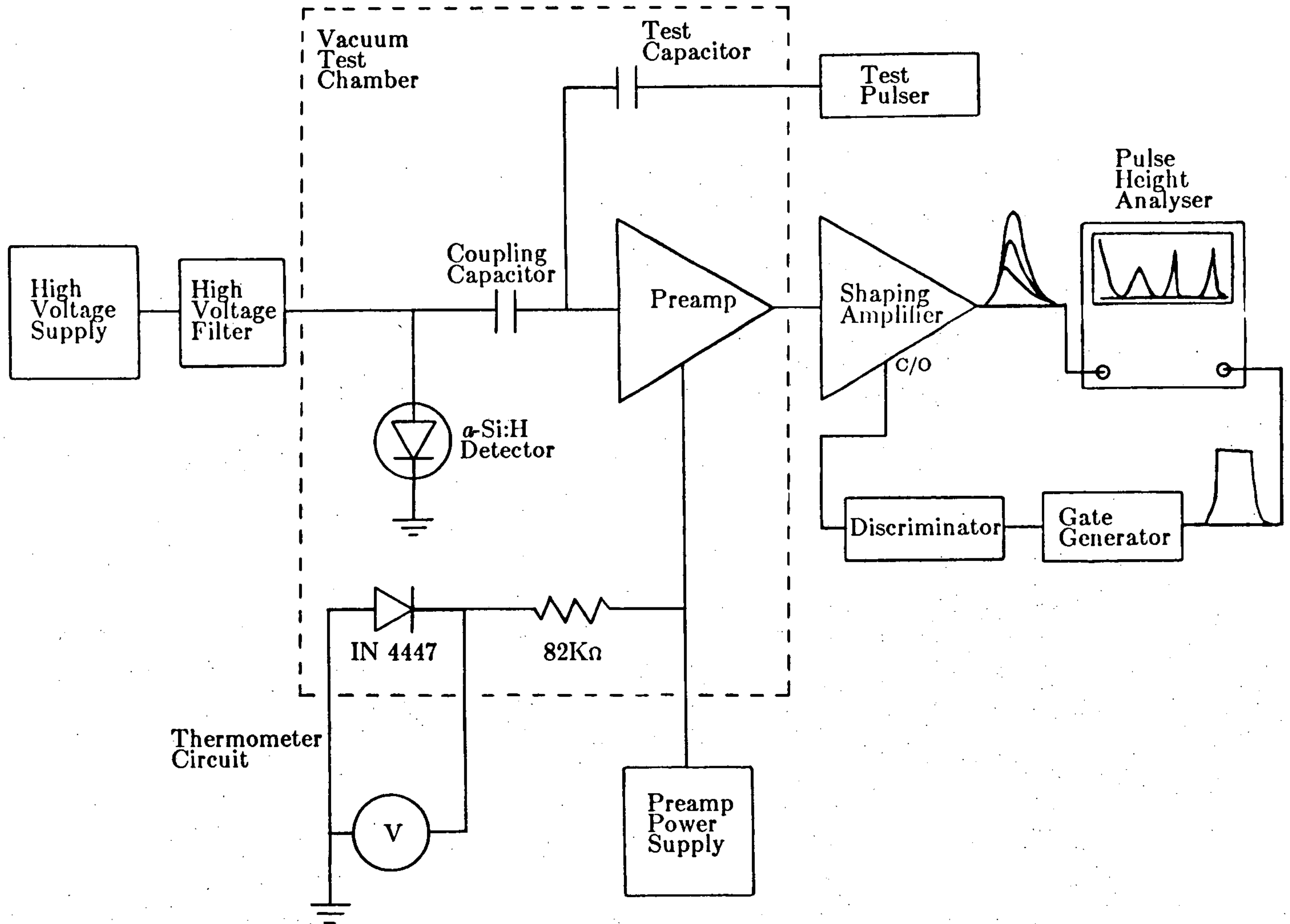

CIRCUIT BLOCK DIAGRAM

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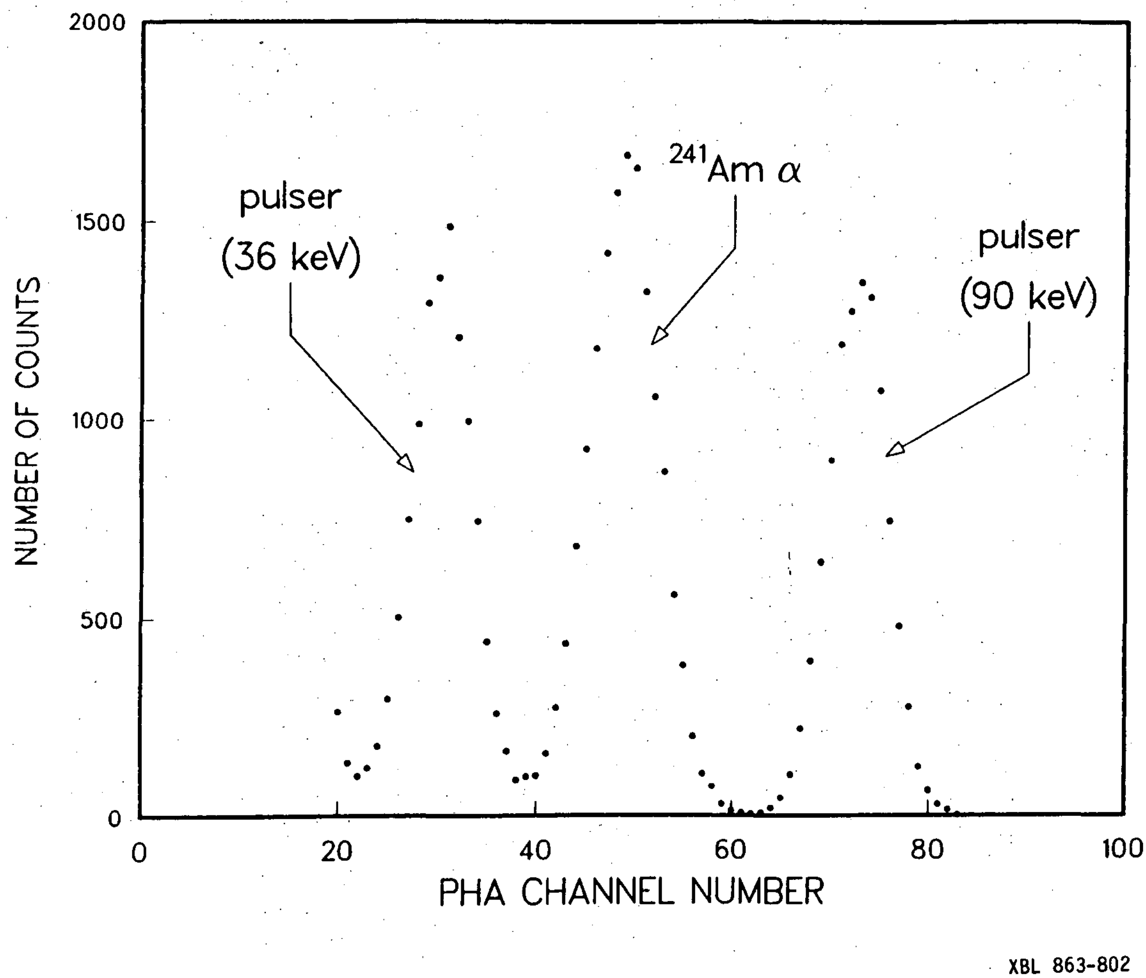
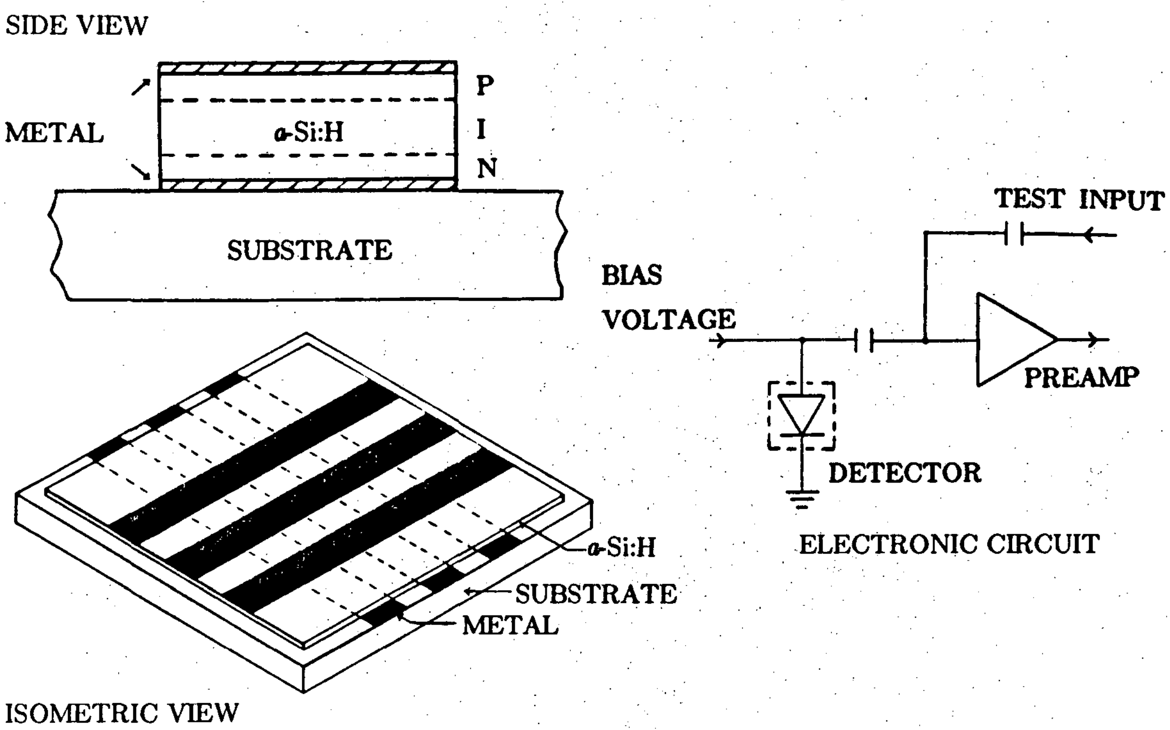
Fig. 1



2000
1500
1000
500
0
NUMBER OF COUNTS
0
20
40
60
80
100
PHA CHANNEL NUMBER
pulser
(36 keV)
241Am α
pulser
(90 keV)
XBL 863-802

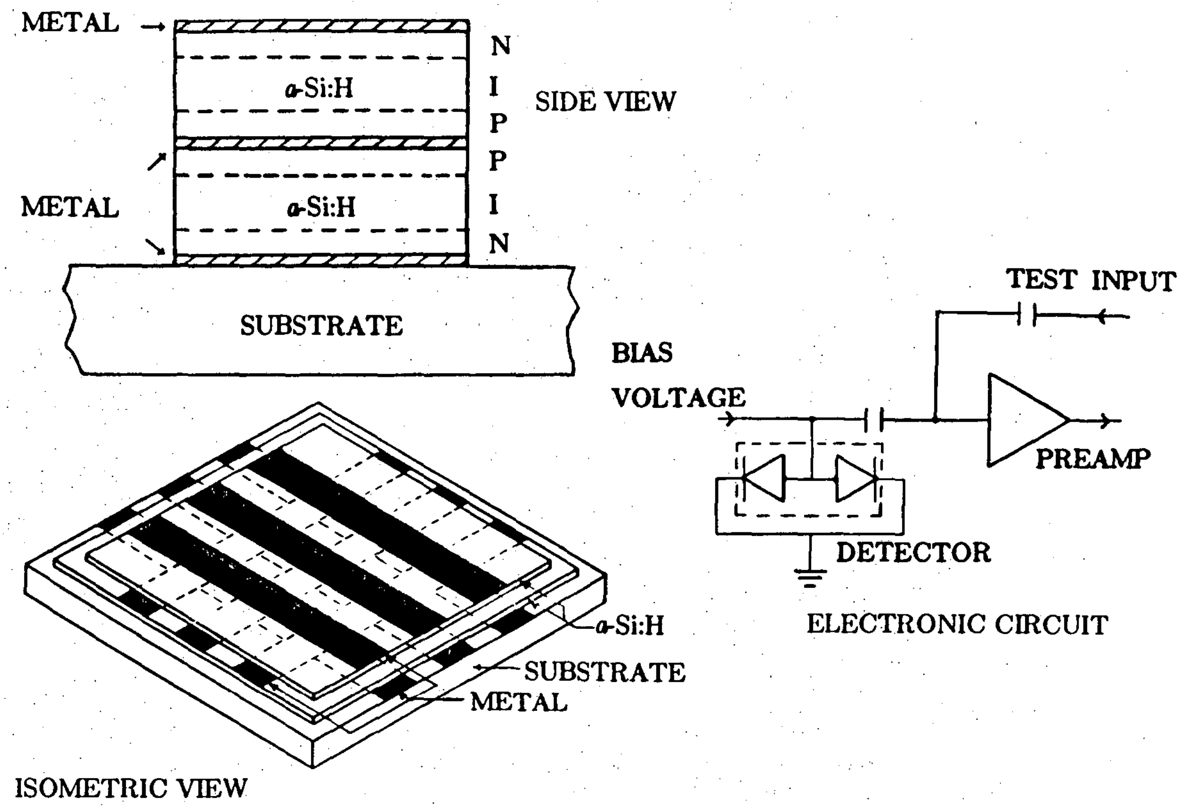
Fig. 2



SINGLE LAYER DETECTOR

XBL 863-801

Fig. 3



DOUBLE LAYER DETECTOR

XBL 863-800

Fig. 4

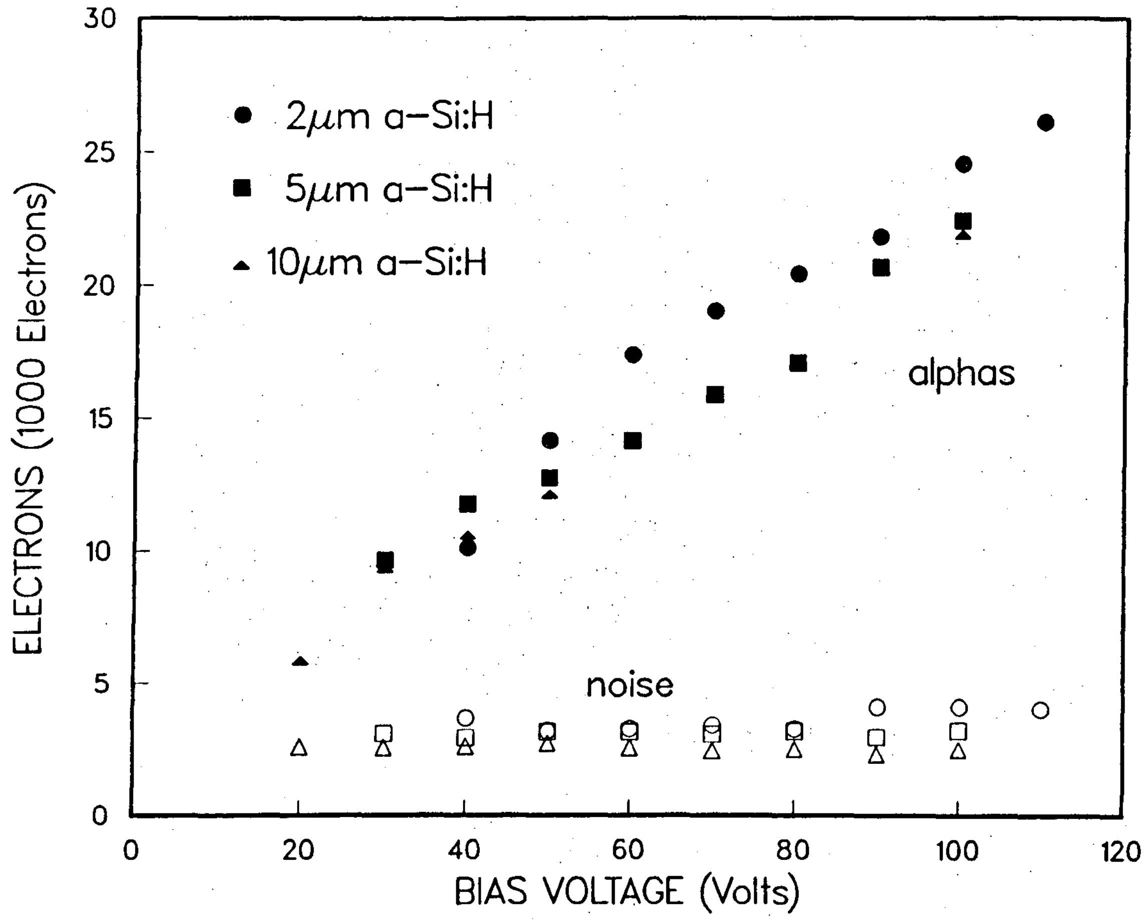


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Fig. 5

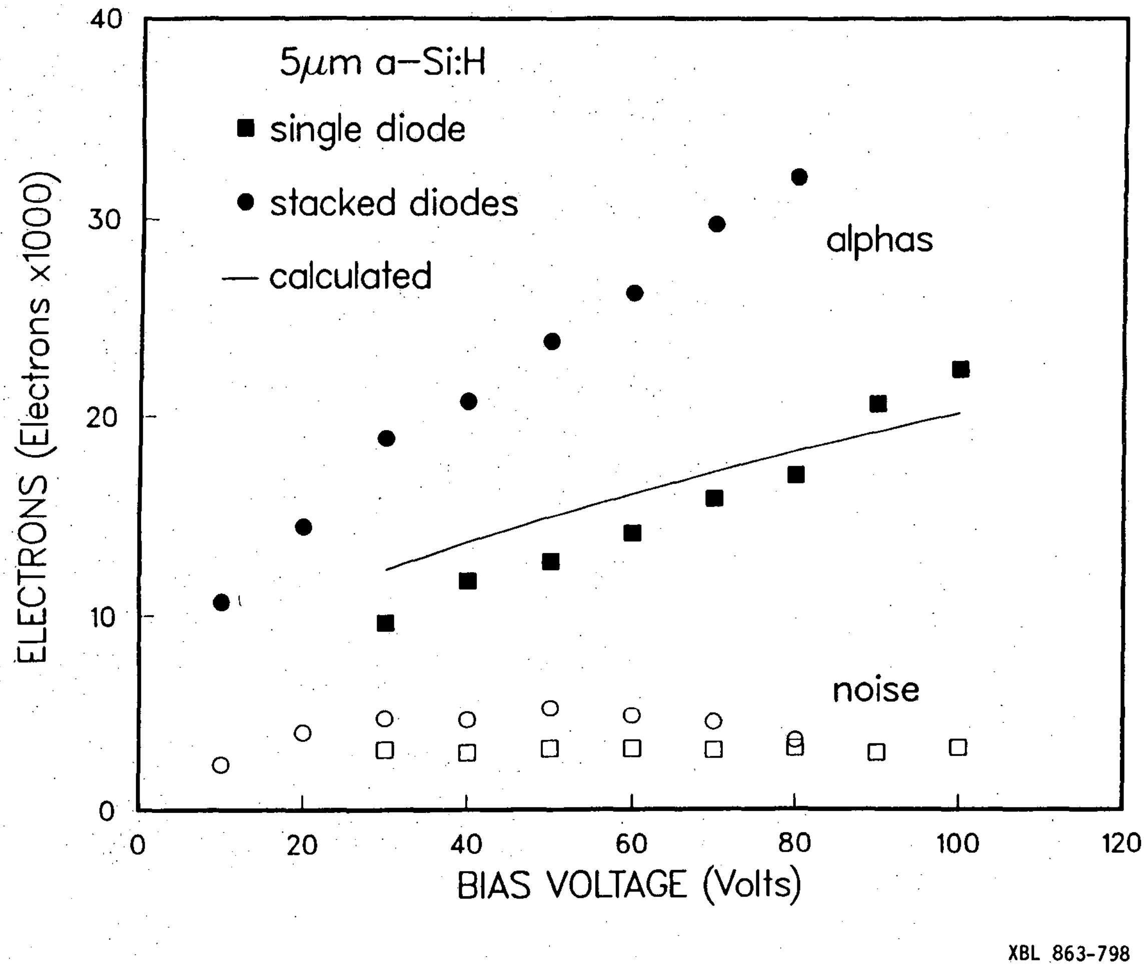
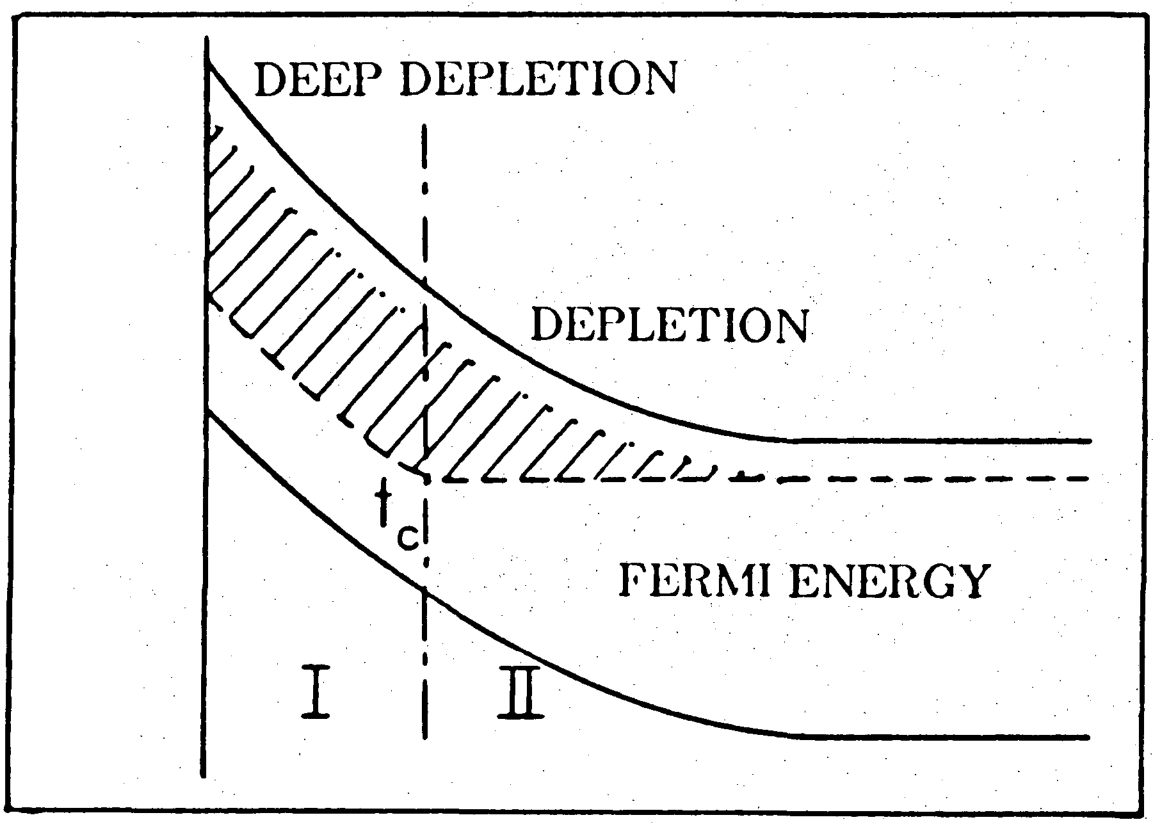
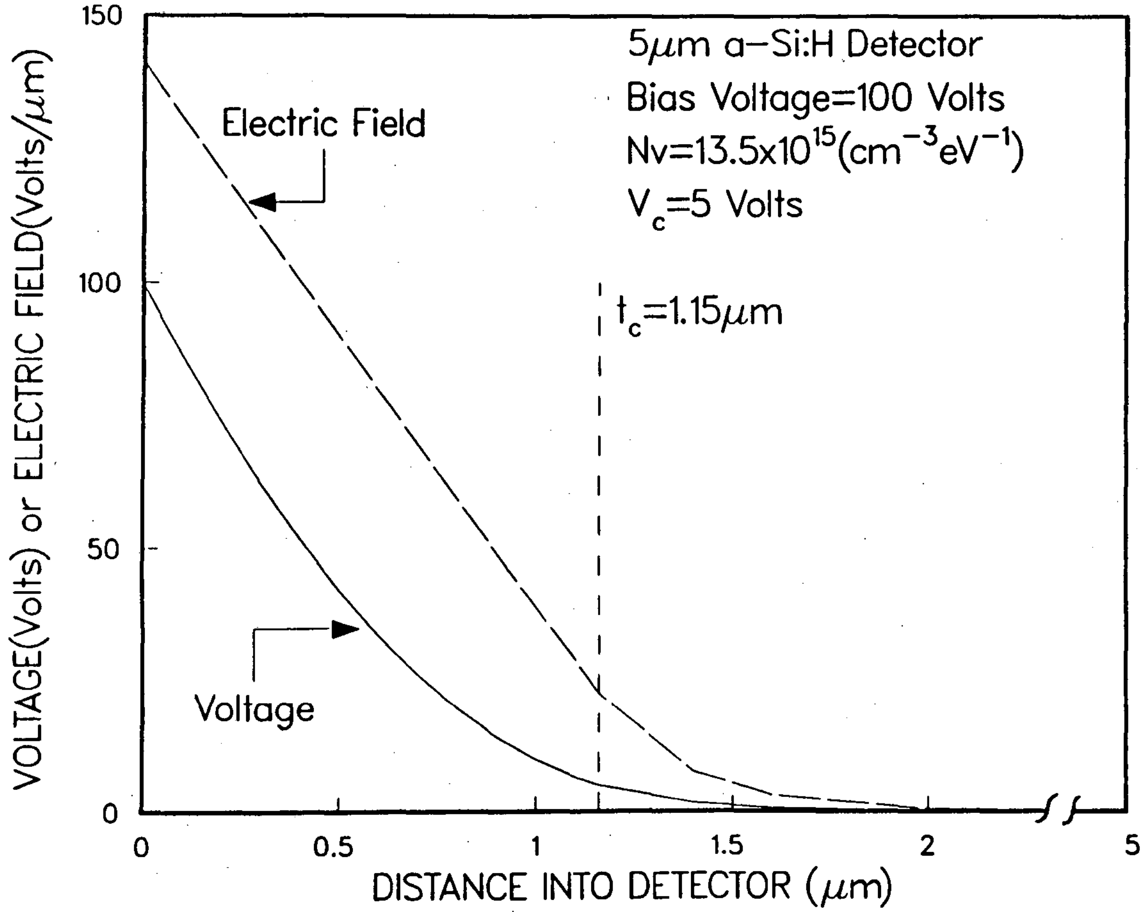

5µm a-Si:H
single diode
stacked diodes
— calculated
alphas
noise
ELECTRONS (Electrons x1000)
BIAS VOLTAGE (Volts)
0
10
20
30
40
0
20
40
60
80
100
120
XBL 863-798

Fig. 6



XBL 863-804

Fig. 7



XBL 863-797

Fig. 8

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