Title
DETECTION OF MINIMUM-IONIZING PARTICLES IN HYDROGENATED AMORPHOUS SILICON

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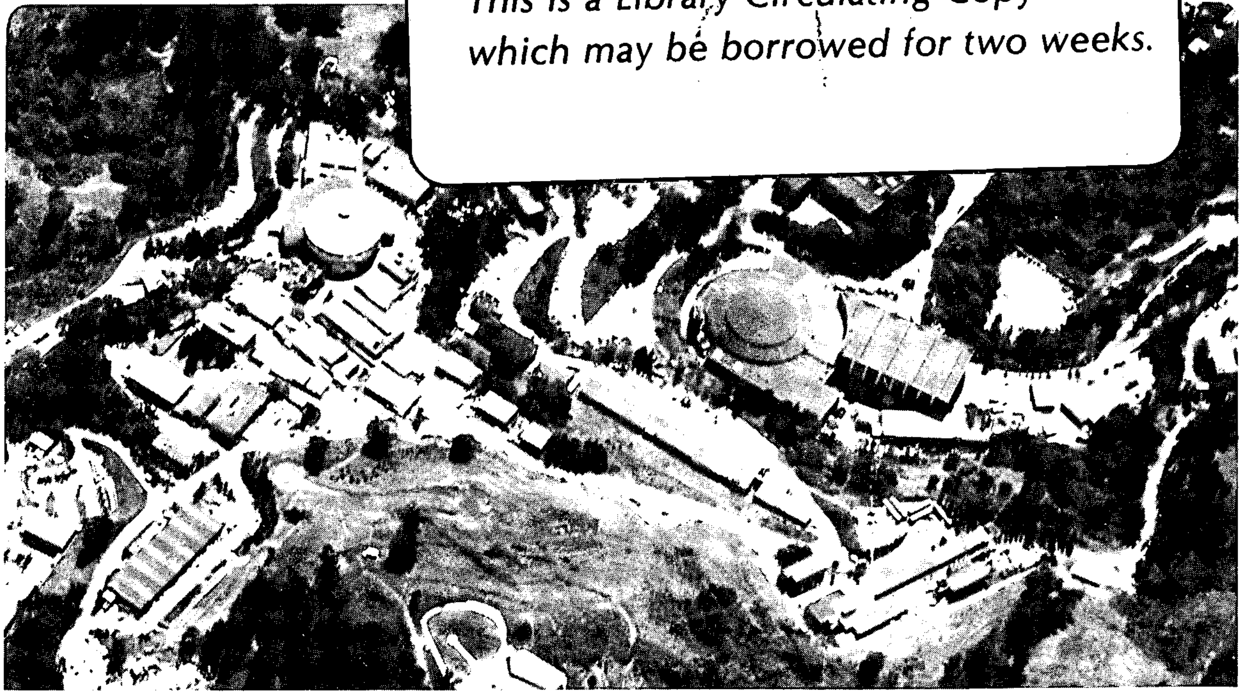

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ABSTRACT

Based on previously-reported results of the successful detection of alpha particles and 1- and 2-Mev protons with hydrogenated amorphous silicon (a-Si:H) diodes, detection of a single minimum-ionizing particle will require a total sensitive thickness of approximately 100-150 μm, either in the form of a single thick diode, or as a stack of several thinner diodes. Signal saturation at high dE/dx makes it necessary to simulate minimum ionization in order to evaluate present detectors. Two techniques, using pulsed infrared light, and pulsed x-rays, give single-pulse signals large enough for direct measurements. A third, using beta rays, requires multiple-transit signal averaging to produce signals measurable above noise. Signal amplitudes from the a-Si:H limit at 60% of the signal size from Si crystals extrapolated to the same thickness. This is consistent with an a-Si:H radiation ionization energy, $W = 6$ eV/electron-hole pair. Beta-ray signals are observed at the expected amplitude.

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Introduction

In the ten years since Spear and LeComber demonstrated that practical semiconductor diodes can be produced on a suitable substrate by the decomposition of silane gas in a low-temperature glow discharge[1], this amorphous semiconductor material, now known to be hydrogenated amorphous silicon (a-Si:H), has been the subject of considerable study, and has found important applications as a substitute for crystalline silicon semiconductors in a variety of applications. Because this material can be produced relatively cheaply in large-area depositions it offers exciting possibilities for applications in large-area position-sensitive radiation detection. Presently available a-Si:H has significantly greater trap density, and much lower electron and hole mobilities and lifetimes than the crystalline silicon used for radiation detectors. In addition the largest junction thicknesses achievable are considerably smaller than for corresponding crystalline silicon. Quality of diode material has continued to improve, and the potential rewards of successful detector development have been sufficient motivation to stimulate our active study of this material for radiation detection.

We have previously reported the successful detection of α particles[2], and 1- and 2-MeV protons[3] in small prototype detectors. A schematic diagram of an early position-sensitive configuration is shown in Figure 1. Although the prototype junctions were quite thin, on the order of 5 μm, we demonstrated that diode stacks could be made, that would give correspondingly larger signals. We observed, however, that for heavily ionizing particles, α's, signal size did not indicate the true junction thickness. Collected current was limited by electron-hole recombination along the charged-particle track[3]. This signal loss diminished markedly for the more lightly ionizing 1- and 2-MeV protons.

Present detectors are not sufficiently sensitive to give detectable signals from the transit of a single minimum-ionizing particle, due to their small thickness. However we are employing three techniques for producing low ionization density through the full junction thickness in order to evaluate the operating characteristics of the diodes under conditions similar to minimum ionization. Two of the techniques, employing pulsed infrared light, or x-ray, ionization sources, produce single-pulse signals large enough to be measured directly. A third method, using single transits of β rays, requires, for present detectors, digital analysis and signal-averaging techniques to produce a signal observable above background.

I Pulsed Infrared Light and X–Rays

The first of these methods, Fig. 2, employs a Gallium Aluminum Arsenide infrared-emitting diode (GE F5E1), with an emission spectrum centered at, λ = 880 nm. The light of this wavelength has a mean-free-path in a-Si:H of 1 cm[4], and therefore uniformly illuminates the junction, producing ionization throughout its depth. The diode is pulsed by a capacitor discharge, and produces an infrared light pulse with a width of 2.8 μs. This width is governed by the 1.5-μs rise and fall times of the diode. The output signals from 5.5-μm and 10-μm p-i-n a-Si:H detectors are shown in Figure 3 as a function of applied bias. The 5.5-μm shows a marked flattening of the signal at the higher voltages, suggesting both full depletion of the junction, and efficient charge collection. The 10-μm appears also to be at, or near, its plateau. The relative sizes of the signals are not significant. No corrections were made for differences in light loss in the metal contact or from reflection at the surface.

The second method employs a pulsed x-ray source (Fig. 4). This more closely simulates the passage of high-energy ionizing particles. For the x-ray measurements, a narrow-beam, 2-μs-wide pulse of x-rays from a pulsed source is directed at the detector. The x-rays are produced by a 22-kVP electron beam incident on a molybdenum target. To calibrate detector response as a function of energy deposition the beam was first filtered by a 500-μm-thick Al filter, and then, with thin Si absorbers and a crystalline-Si detector, the effective Si attenuation coefficient for the x-rays, as a function of absorber thickness was measured. From this Si-crystal calibration, the expected detector signal as a function of depletion depth was calculated. The observed signal amplitude from a plateaued 5-μm p-i-n is plotted in Fig. 5 as a fraction of the charge signal that would be expected from a crystalline Si detector with a junction thickness of 5 μm. The peak signal reached was only 60% of that expected from a fully-depleted crystal detector of the same thickness. A likely explanation of this yield difference is not a reduced electron collection efficiency from the amorphous material, but a reduced electron-hole production efficiency. Figure 6, due to Klein[4], shows, for a number of semiconductors, the average energy needed to produce one electron-hole pair, W, as a function of band gap. The effective band gap for our a-Si:H is approximately 1.9 eV[6], shown as a vertical shaded line. It intersects Klein's line at W = 6.0 eV, compared to the accepted value of 3.62 eV for crystalline Si. This corresponds to an a-Si:H electron-hole yield from a-Si:H that is only 60% that of xtal-Si, consistent with the observed signals (Fig. 5).

II. Beta Rays

Direct detection of β's is achieved with the setup illustrated in Figure 7. The source of β rays is a 4-mCi ^{90}Sr—^{90}Y gun source with its beam directed through an additional collimator onto an a-Si:H detector sample followed by a thin c-Si detector. Each β detected by the crystal detector initiates an acquisition cycle in a Tektronix 2430 digital oscilloscope. This causes the signal output from the a-Si:H detector to be accepted by the oscilloscope, and averaged into the composite trace already stored. The scope will signal average up to 256 successive traces and digitally store the result. The resultant average trace is read into a desktop microcomputer that emulates a PHA by determining the net height of the signal-averaged a-Si:H pulse, and then incrementing the pulse count at the corresponding address in a "PHA" array. For the results described below, the 256-trace averages gave a PHA sensitivity, referred back to single-β-transit equivalent, of 6.9 electrons per PHA channel (4-channel sums are shown in Figs. 8 and 9.), and a noise FWHM of 275 electron. The noise value was consistent with the actual noise of individual traces combined in quadrature over the 256-trace average.

Figure 8 shows the amplitude distribution from single oscilloscope traces when the a-Si:H diode is replaced by a thin c-Si detector -- 95% of the triggers produced by the lower detector show a coincident β-ray-transit pulse in the upper detector.

Figure 9 shows the first results of a β measurement for a nominal 5-μm Schottky-barrier a-Si:H detector. While the distribution of the 256-trace-averaged β signal is clearly distinguishable from the source-out background distribution, the resolution is not adequate to distinguish individual 256-trace averages with both high confidence and high efficiency. The centroid of the β amplitude distribution corresponds to the collection of 160 electron-hole pairs per electron transit. With no improvement in noise, the same result could have been achieved with a single β transit through a detector 16 x thicker (because the noise adds in quadrature for the 256-trace average). A thicker detector, having lower capacity, would, however, be expected to give lower noise.

III. Summary and Conclusions

While further study and development is still required before a position sensitive detector for minimum ionizing particles can be easily produced, we have considerable cause for optimism. The infrared and x-ray measurements give evidence that the thickest samples we have tested can be fully depleted. The x-ray results suggest that we are extracting charge with high efficiency, differences in signal size between a-Si:H and c-Si being due to a difference in W for the two materials. The first β measurements, using a multiple-event signal averaging technique have succeeded in pulling β-ray signals from the noise. The signals were approximately at the projected amplitude level, showing that there is no intrinsic inhibition, or threshold, for the detection of minimum ionization in a-Si:H.

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References

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[6] R. Street, to be published.

Figure Captions

Fig. 1 Schematic of a single-layer p-i-n detector configured for position-sensitive detection. The top and bottom conducting contacts were deposited in the orientation illustrated, as 1-mm-wide strips separated by 2 mm. A similar, position-sensitive 2-diode stack was also made by a successive deposition process, and successfully tested (from Ref. 2).

Fig. 2 Schematic of experimental setup for pulsed infrared light measurements.

Fig. 3 Amplifier output from 880-nm infrared light pulses incident on 5.5-μm and 10-μm a-Si:H detectors, as a function of detector bias.

Fig. 4 Schematic of experimental setup for pulsed x-ray measurements.

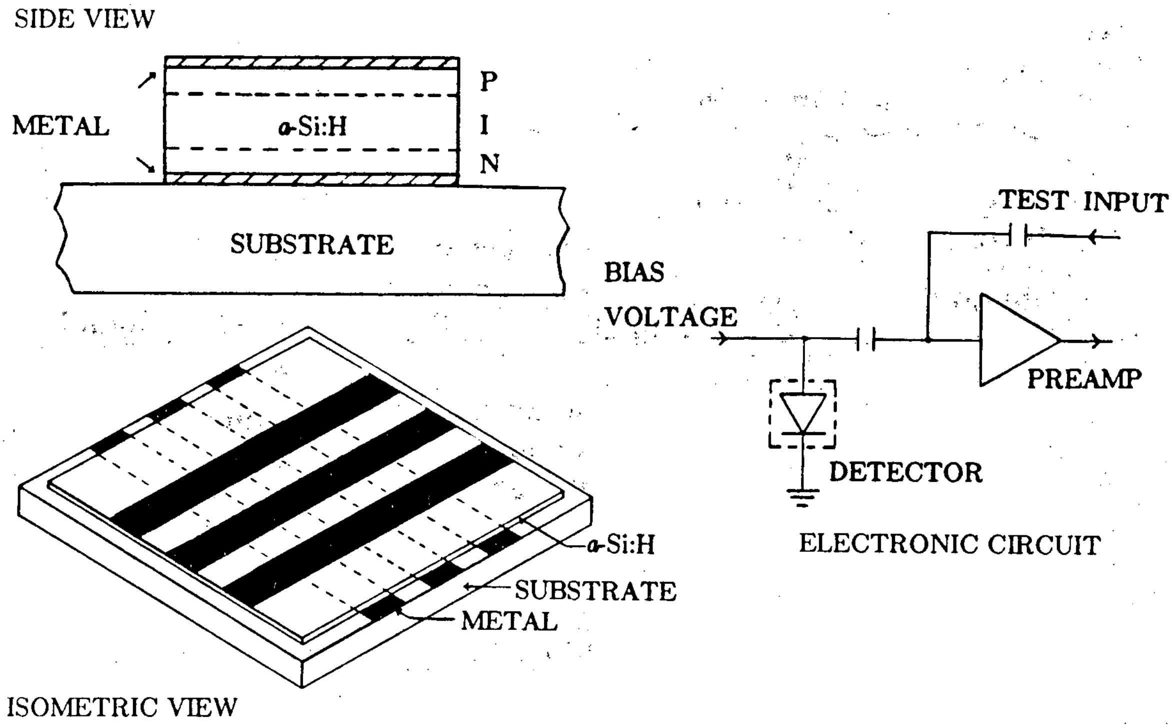
Fig. 5 Amplifier output from x-ray pulses incident on a voltage-plateaued 5-μm a-Si:H detector. The signal amplitude (S_a) is normalized to the signal expected from a 5-μm crystalline silicon detector (S_c) in the same beam. W_a and W_c are the respective radiation ionization energies for the two materials.

Fig. 6 Radiation ionization energy, W (in eV/ion-pair), vs band-gap energy for a number of semiconductor materials (from Ref. 4). The average band gap for a-Si:H is indicated by the vertical shaded line.

Fig. 7 Schematic of experimental setup for digital signal-averaging measurements of β-ray pulses.

Fig. 8 Pulse-height spectrum from upper (c-Si) detector in coincidence with β trigger (●), and with pulser trigger (○) from lower (c-Si) detector.

Fig. 9 Pulse-height spectrum from upper (a-Si:H) detector in coincidence with β trigger (●), and with pulser trigger (○) from lower (c-Si) detector. (Each pulse is derived from a 256-event signal average.)



SINGLE LAYER DETECTOR

XBL 863-801

Fig. 1

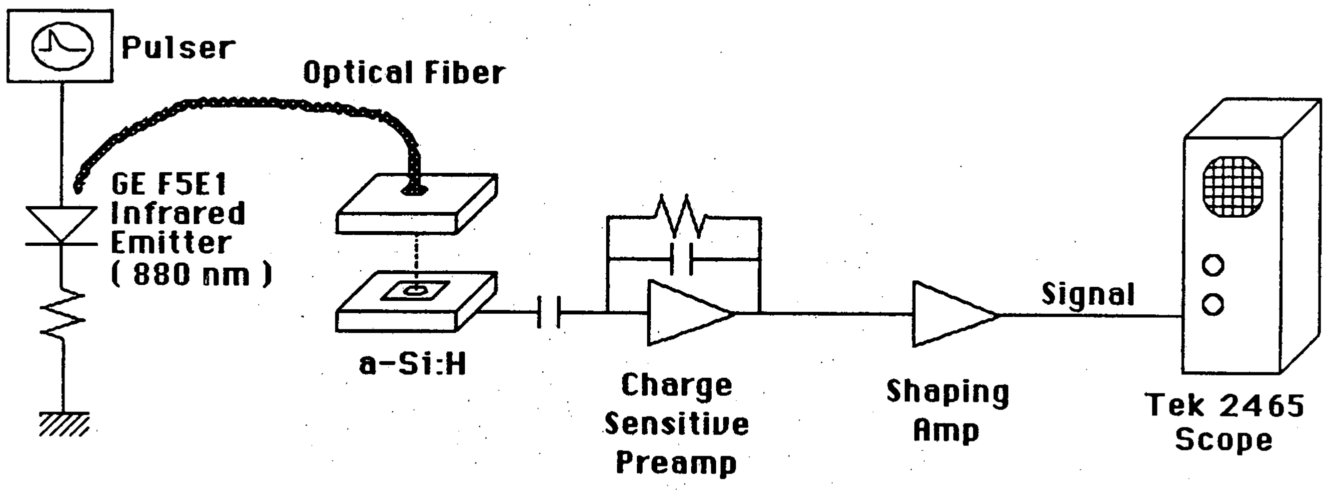

Pulser
Optical Fiber
GE F5E1
Infrared
Emitter
(880 nm)
a-Si:H
Charge
Sensitive
Preamp
Shaping
Amp
Signal
Tek 2465
Scope

Fig. 2

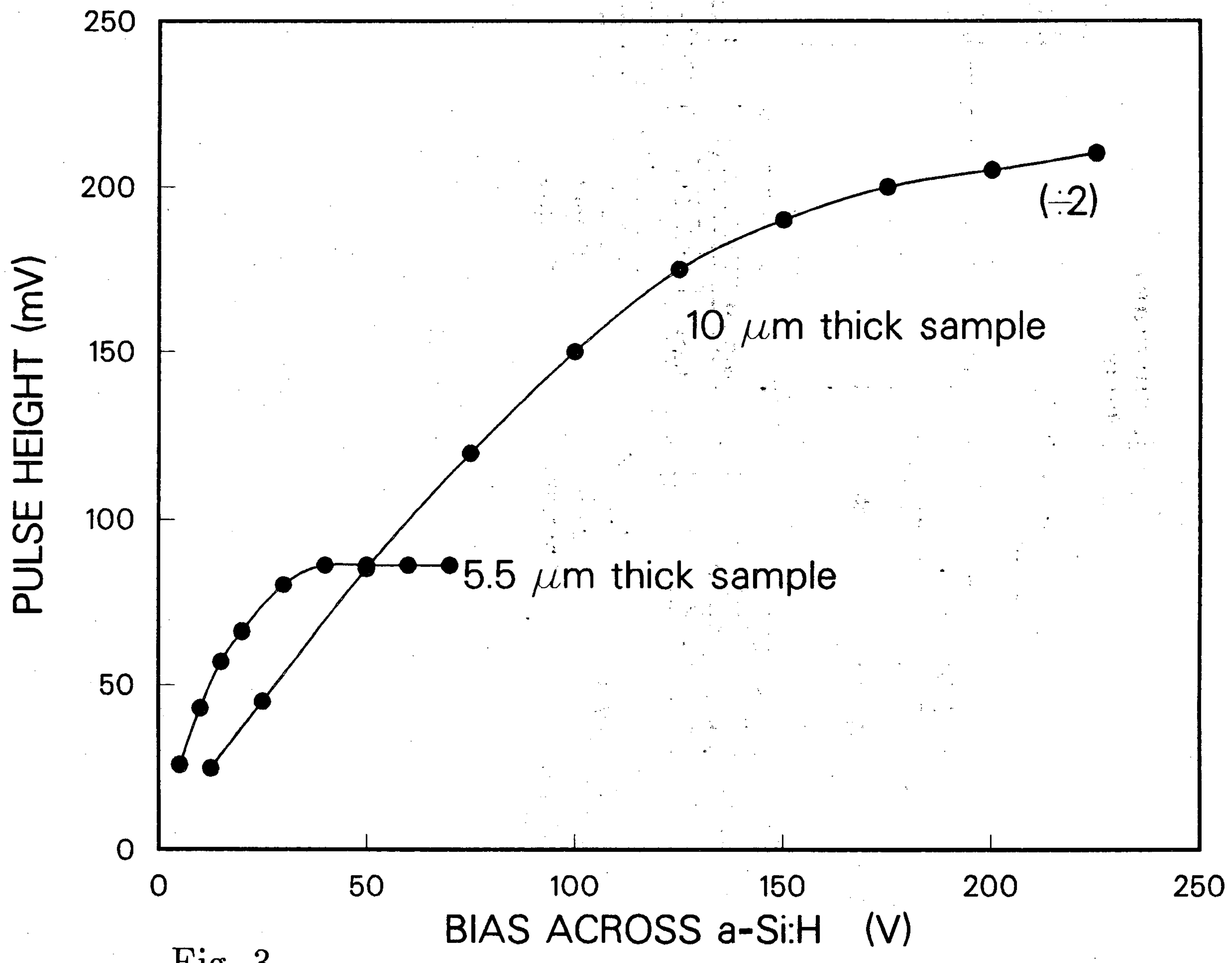

PULSE HEIGHT (mV)
0
50
100
150
200
250
0
50
100
150
200
250
BIAS ACROSS a-Si:H (V)
10 μm thick sample
(÷2)
5.5 μm thick sample

Fig. 3

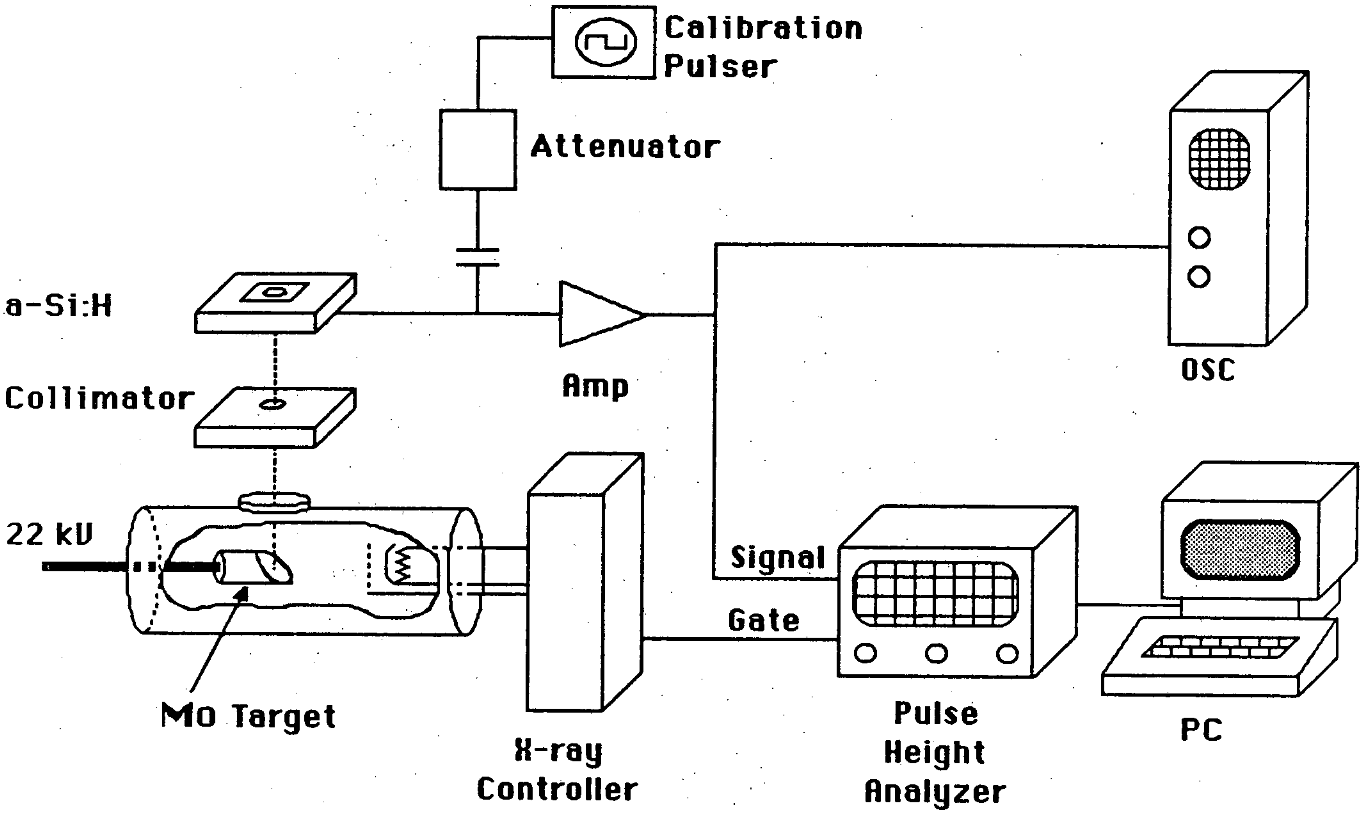

Calibration
Pulser
Attenuator
a-Si:H
Collimator
Amp
OSC
22 kV
Signal
Gate
Mo Target
X-ray
Controller
Pulse
Height
Analyzer
PC

Fig. 4

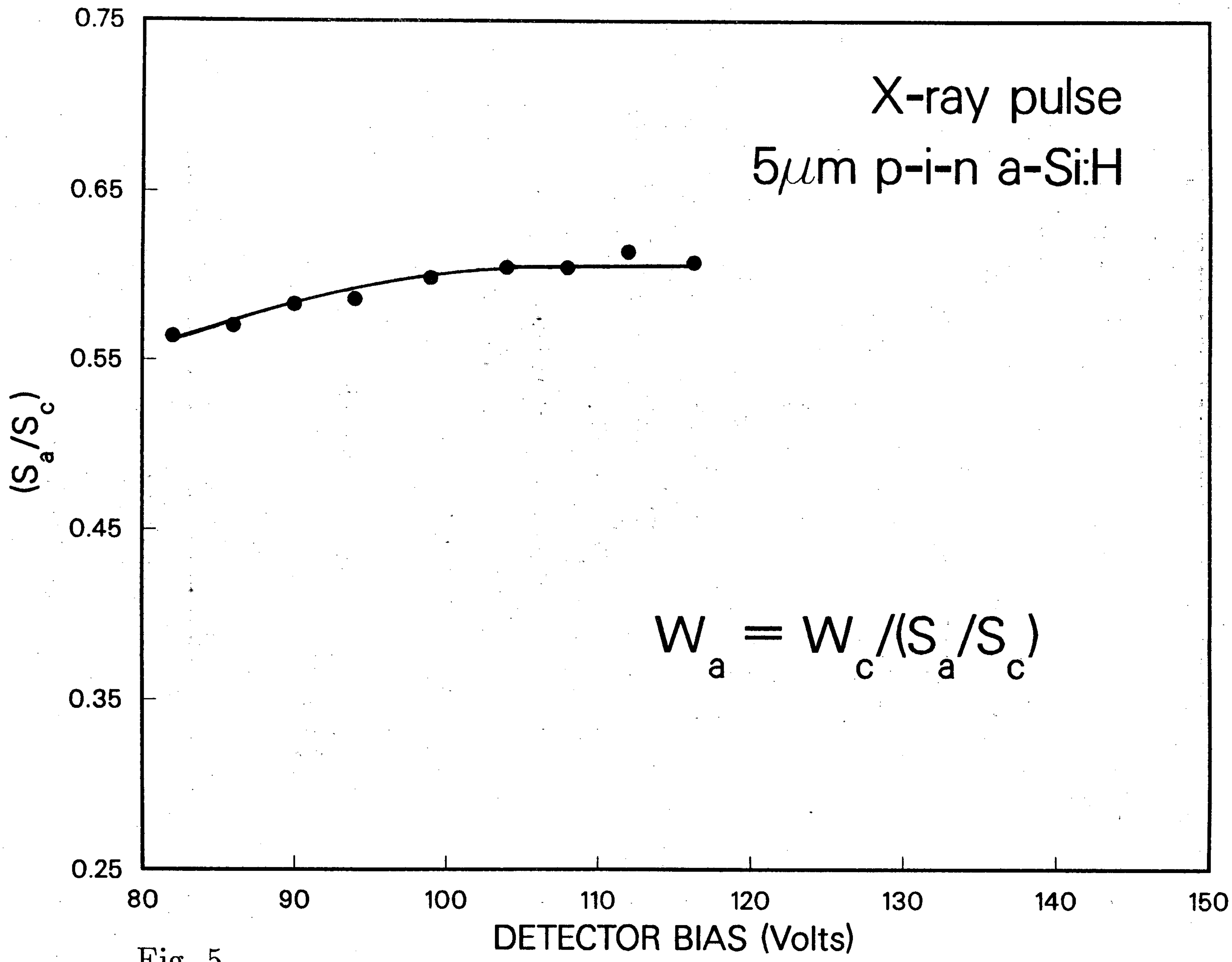
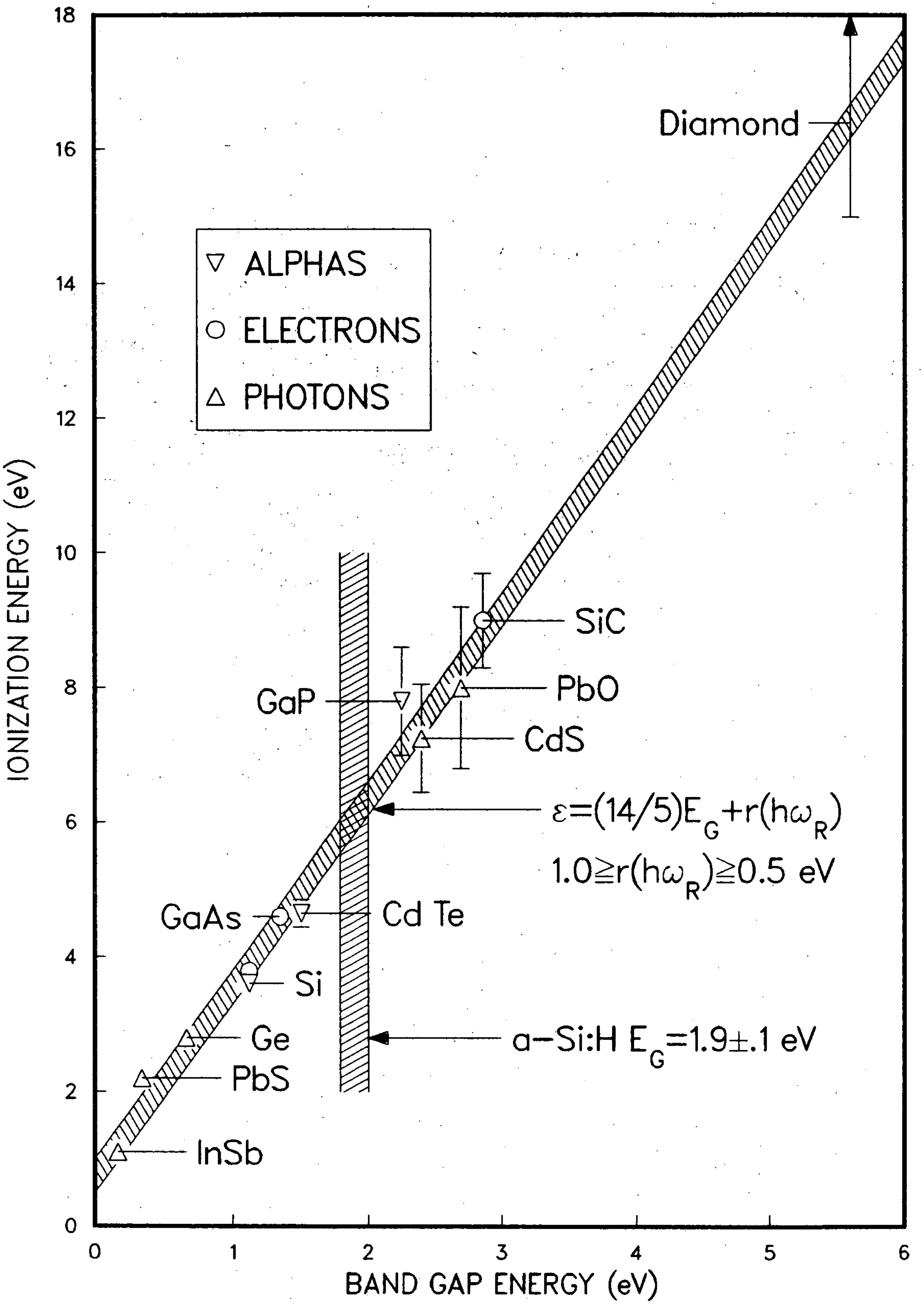

X-ray pulse
5μm p-i-n a-Si:H
$W_a = W_c/(S_a/S_c)$
(S_a/S_c)
0.75
0.65
0.55
0.45
0.35
0.25
80
90
100
110
120
130
140
150
DETECTOR BIAS (Volts)

Fig. 5



IONIZATION ENERGY (eV)
BAND GAP ENERGY (eV)
0
2
4
6
8
10
12
14
16
18
0
1
2
3
4
5
6
▽ ALPHAS
○ ELECTRONS
△ PHOTONS
Diamond
SiC
PbO
GaP
CdS
ε=(14/5)E_G+r(hω_R)
1.0≧r(hω_R)≧0.5 eV
GaAs
Cd Te
Si
Ge
PbS
InSb
a–Si:H E_G=1.9±.1 eV

Fig. 6

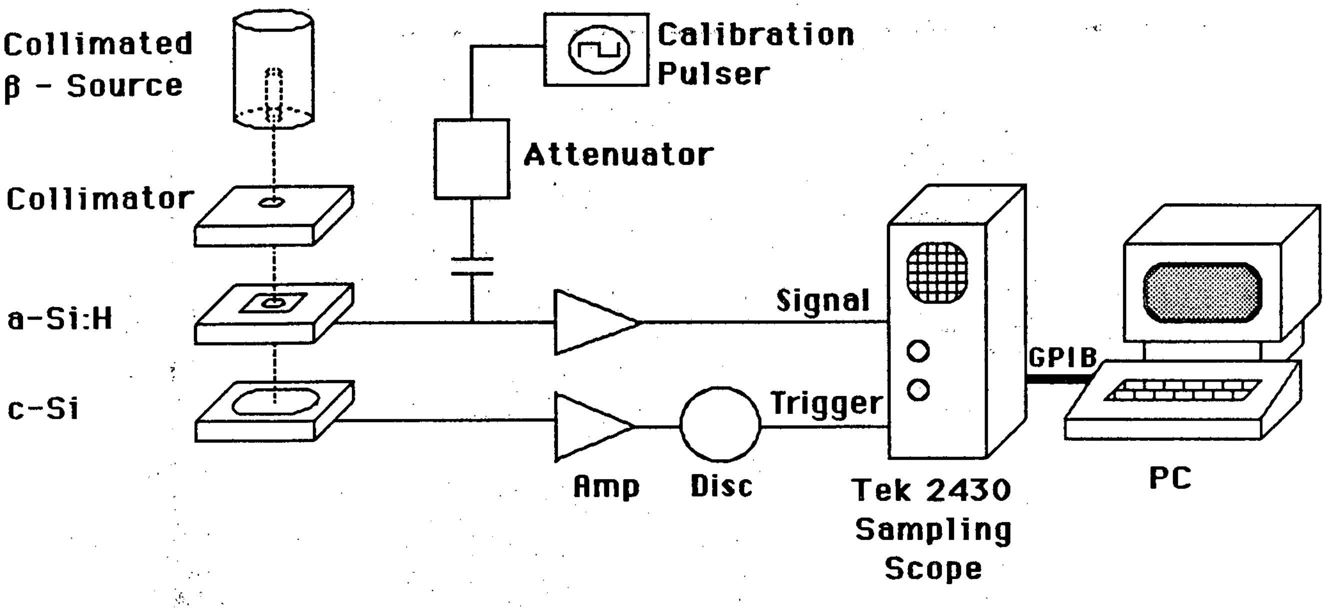

Collimated
β - Source
Collimator
a-Si:H
c-Si
Calibration
Pulser
Attenuator
Signal
Trigger
Amp
Disc
Tek 2430
Sampling
Scope
GPIB
PC

Fig. 7

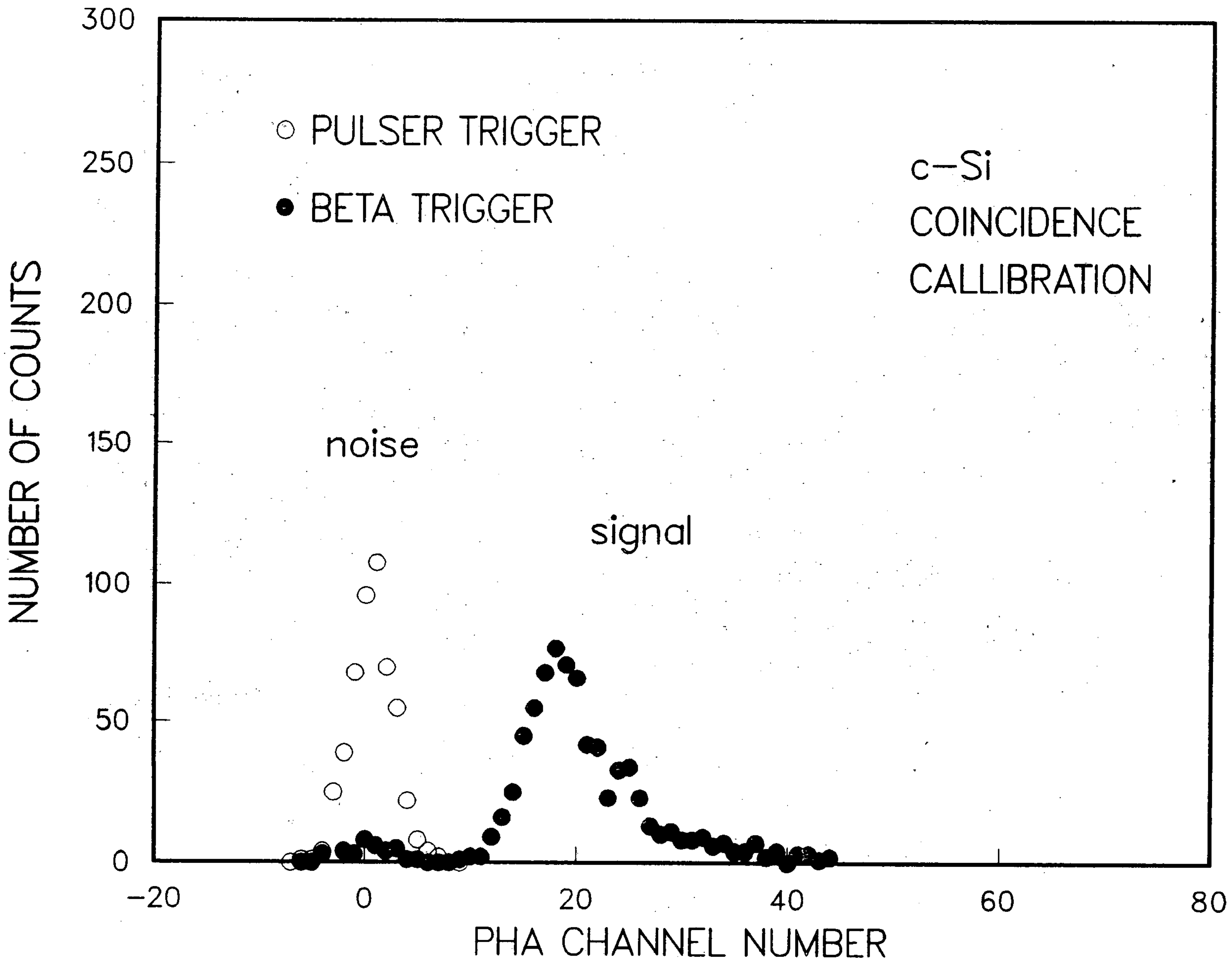

PULSER TRIGGER
BETA TRIGGER
c–Si
COINCIDENCE
CALLIBRATION
noise
signal
NUMBER OF COUNTS
300
250
200
150
100
50
0
−20
0
20
40
60
80
PHA CHANNEL NUMBER

Fig. 8

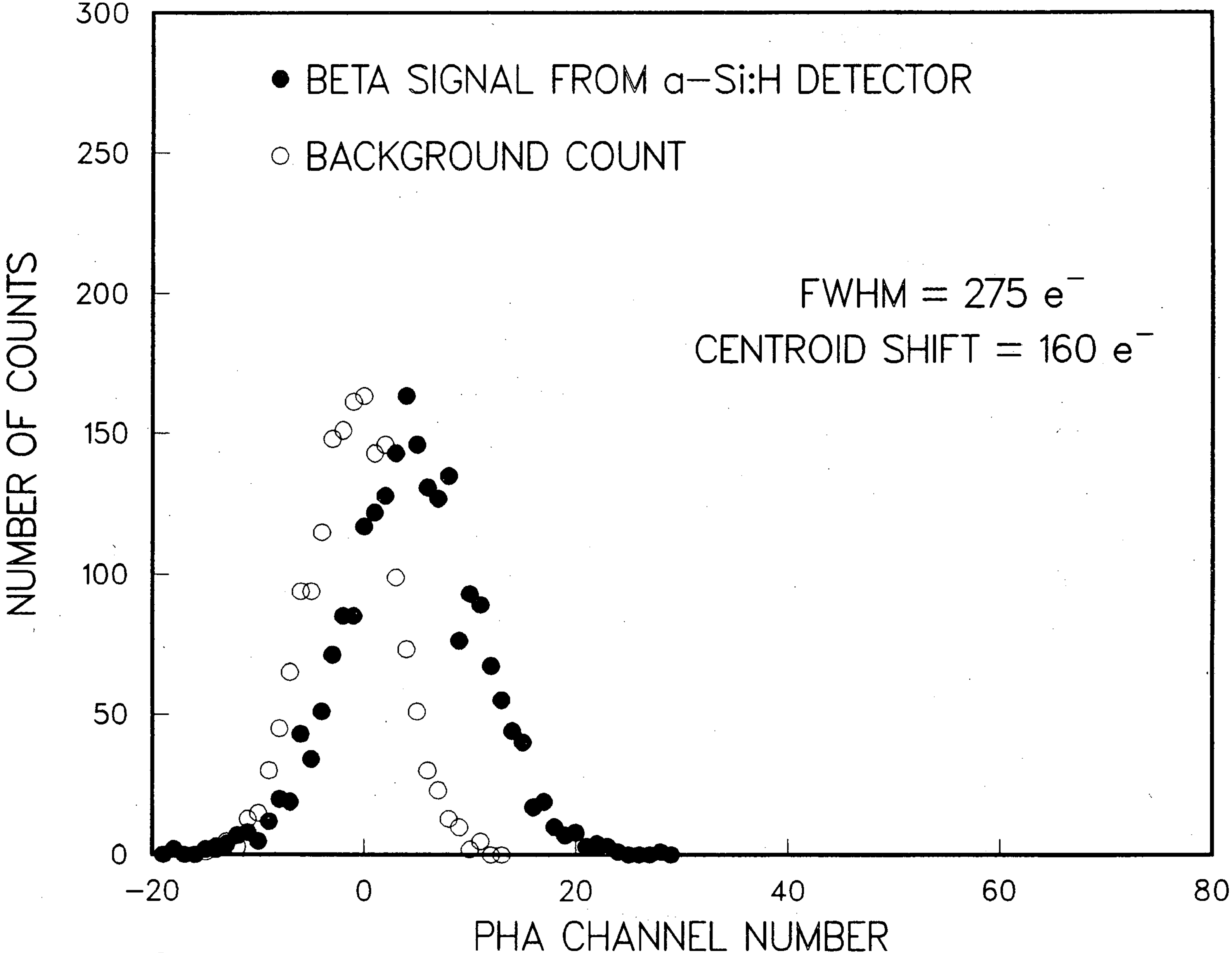

● BETA SIGNAL FROM a–Si:H DETECTOR
○ BACKGROUND COUNT
FWHM = 275 e⁻
CENTROID SHIFT = 160 e⁻
NUMBER OF COUNTS
300
250
200
150
100
50
0
–20
0
20
40
60
80
PHA CHANNEL NUMBER

Fig. 9

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