LA-UR -76-2291

CONF-761006--12

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SUBMITTED TO: 1976 Nuclear Science Symposium in New Orleans, LA, October 20-22, 1976, to be published in the IEEE Proceedings.

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ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

THIN EPITAXIAL SILICON FOR dE/dx DETECTORS†

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Abstract

The techniques for fabricating thin self-supporting epitaxial films for dE/dx detectors have been studied. Detectors having thicknesses between 1 and 4 μm with areas of 12.5 mm^2 have been fabricated and tested. The response of the detectors has been studied with alpha particles, oxygen ions, and fission fragments.

I. Introduction

The use of epitaxial material to produce thin (4.6 μm) epitaxial silicon Schottky barrier (ESSB) detectors has been demonstrated in the works of J. P. Ponpon, P. Siffert, and F. Vazeille[1] and A. Tetefort.[2] The technique for producing the thin silicon used in these works was first introduced by R. L. Meek.[3] This paper reports our experience in the use of this technique to produce dE/dx detectors as thin as 1 μm. The thinning technique has been generalized to allow the simultaneous fabrication of 9 films per wafer. The response of detectors made from these films has been studied using alpha particles, oxygen ions, and fission fragments. The results indicate that these thin dE/dx detectors will find considerable value in the detection of heavy ions. Thinner detectors will make lower threshold detector systems possible. For example, a 1 μm silicon detector will just stop 120 keV alpha particles, 512 keV oxygen ions, 2.1 MeV Pd ions, 2.7 MeV La ions, and 4.1 MeV Fm ions. The radiation lifetime is expected to be at least 10 to 100 times longer than conventional detectors because the charge transport occurs in a shorter time (thinner detectors) and the lower resistivity (greater impurity density, $\sim 10^{16}/cm^3$) has a higher threshold to radiation effects.

The electroetch technique of Meek[3] relies on the large difference in etch rate between low resistivity (~.01 Ω-cm) and high resistivity (>1 Ω-cm) n-type silicon. The production of a thin film is achieved by etching away the lower resistivity substrate leaving the higher resistivity epitaxial layer. Thickness uniformity is determined by the epitaxial process which can be ± 10% across a 5 cm wafer. Epitaxial layers can be grown as thin as 1 μm. The fabrication process and its generalization to mass production is discussed in Sec. II.

The response of 1, 3, and 4 μm detectors is discussed in Sec. III. The uniformity was studied using alpha particles.

II. Fabrication

A schematic design of the ESSB detector is shown in Fig. 1. The uniformly thin epitaxial film is supported on its perimeter by the thick (~200 μm) substrate. A Schottky barrier is formed on the thin silicon film, and the signal is taken from the Schottky barrier using a strip contact that terminates on a wax pad (Apiezon W). The detectors were fabricated from n-type silicon epitaxially grown on 5 cm n^+-type substrates. The properties of the starting material are shown in Table I.

†Work performed under the auspices of the USERDA.
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TABLE I

Characteristics of Starting Material

Detector	Resistivity ρ (Ω-cm) ±10%	Thickness t (μm) ±10%	Substrate ρ (Ω-cm)	Substrate t (μm) ±25%
26-4	9	4.4	.005-.015	300
40-1	9	3.0	.005-.015	250
28-2	1	1.0	.005-.020	200

Using the selective electrochemical etch technique of R. L. Meek, the wafer is etched with a multiple electrode apparatus to produce a pattern of nine epitaxial films on a single wafer. After mounting to the sapphire plate and before etching, the substrate is completely coated with wax (Apiezon W) and 5 mm diameter regions removed where the self-supporting films are to be produced. This mask is easy to apply, stands up well to the long etching times, and is easily removed.

The main problem encountered with multiple etching of the wafer is that the individual patterns etch at different rates. The problem appears to be related to the detailed probe-wafer geometry. A number of different probe geometries were tried; the most uniform and consistent results were obtained with 3 mm platinum probes with either a flat or hemispherical end. The probes were 1 mm from the wafer. A magnetic stirrer and nitrogen bubbler were used during the etch. The etch in 5% HF solution required 1-2 hours at ~8 V bias. As indicated by Meek, termination of the etch is critical to prevent etch-through around the edge of the film. The films were monitored visually and as the size approached 5 mm, etching of individual films was terminated by masking with wax. The etch was performed in the dark. There were no problems associated with possible crosstalk between electrodes and adjacent films.

After etching the entire wafer was removed from the sapphire plate and cleaned. The wafer was diced into separate self-supporting films using a diamond scriber. The films were mounted in transmission holders and the gold (50 μgm/cm^2) and aluminum (40 μgm/cm^2) contacts evaporated. A typical I-V characteristic of a finished detector is shown in Fig. 2.

The yield of suitable films varied depending on the thickness of the epitaxial layer and care in handling. In general yields were ~50% for the 1 μm material and >80% for the 3 and 4 μm films. The production of self-supporting films from epitaxial material is straightforward but requires care to prevent breakage after etching. Five mm diameter films were the largest obtained with 3 μm material, but films up to 2.5 cm in diameter have been produced with 50 μm material.

III. Results

The finished detectors were scanned for uniformity of thickness and response with a micro-coordinate table and an alpha thickness gauge. The differential energy loss of the 5.48 MeV alpha particle from ^{241}Am passing through the ESSB detector was measured with a standard 250 μm surface barrier detector. The alpha source was collimated to a spot 0.5 mm in diameter and measurements were taken in a matrix with 0.5 mm spacing. The electronics consisted of an Ortec 125 preamplifier and a Tennelec TC205A amplifier with symmetric baseline restoration. The response of the 4 μm detector to alpha particles is shown in Fig. 3. The results on the uniformity measurements are shown in Table II. No alpha response for the 1 μm detector could be measured because the signal was less than the electronic noise of the system. This was primarily due to the Nyquist contribution to the noise and the high capacitance of the detector. A pulser was used to measure the total electronic noise of the system (122 keV FWHM).

TABLE II

Uniformity Measurements

Detector	Total Thickness[a] (μm of Si)	Thickness Minus[b] Electrodes (μm)	Observed[c] Thickness (μm)
26-4	4.39±.15	4.13±.16	4.18±.06
40-1	2.88±.13	2.62±.13	2.52±.04
28-2	.97±.08	.71±.10	

[a] The thickness determined by the standard surface barrier detector.

[b] The total thickness minus the thickness due to the front and back contacts as measured at the time of evaporation.

[c] Thickness measured by the alpha response of the ESSB detector itself.

The alpha thickness measurements indicate that the electroetch technique is able to produce films uniform to ≤0.16 μm over areas of 12.5 mm^2.

Our particular electrode geometry makes the detector sensitive not only in the thinned region but also in the region over the substrate under the evaporated connecting gold contact. Figure 4 shows the alpha response of detector 40-1 in this region. The signal is 3.9 times larger than in the thinned region indicating that charge is being collected from the substrate.

The detectors were also checked with 45 MeV ^{16}O ions scattered from a self-supporting gold target (40 μgm/cm^2) using the Van de Graaff accelerator at Los Alamos Scientific Laboratory. Figure 5 shows the spectrum observed with detector 26-4. The broad tail on the low energy side of the peak and the sharp cutoff at 2.5 MeV are due to channeling. In support of this interpretation, Fig. 6 is the spectrum obtained when the same detector was tilted ~10° from the normal. Absolute charge measurements indicate that the effective thickness of detector 26-4 is 4.31±0.1 μm and detector 40-1 is 2.71±0.1 μm. These results are in good agreement with the alpha particle data.

Figure 7 is the spectrum obtained with an uncollimated 1 μm detector and 52 MeV ^{16}O ions. This response is due primarily to the large area sensitive region over the substrate and not the much smaller area of the thinned detector. The peak is 2.8 times larger than that expected for a 1 μm thick sensitive region. This type of measurement provides an added control on the quality of the epitaxial material and the fabrication process since the region over the substrate has a different processing history.

The detectors were also tested with fission fragments from a ^{252}Cf source. The 4.18 and 2.52 μm detectors both exhibited anomalous and irregular high energy tailing in the spectra. This is probably due to tunneling injection[4] at the front or rear contact or both. In the fabrication of these detectors no special precautions were taken to avoid this problem.

Figure 8 is the fission fragment spectrum observed with the 0.71 μm detector. The absolute charge collected for the fission fragments as a function of the total voltage across the detector is shown in Fig. 9. The shape is consistent with nonuniform resistivity profile of the epitaxial material and a short recombination lifetime, T_R. The predicted charge indicated is for a detector 0.71 μm thick assuming the energy loss calculations of Northcliffe and Schilling.[5] If you assume (1) ρ is uniform and equal to 1 Ω-cm, (2) only the calculated depletion region contributes to the charge collection, and (3) the range-energy calculations are correct, then our results imply a bias dependent insensitive layer of ≤0.2 μm for the 0.71 μm detector. This is less than that observed with fission fragments for the thicker ESSB detectors making similar assumptions.

Figure 10 is the resistivity depth profile for the 1 μm material indicating that the epitaxial material is not of uniform resistivity over its thickness. The ambiguities in our knowledge of the charge transport and the uncertainty in the energy loss calculations for fission fragments makes it difficult to determine a thickness of the insensitive region. Table III lists the observed energy loss for the average low energy fission fragment peak in each detector and a predicted energy loss for the detectors based on the alpha thickness measurements.

TABLE III

Fission Fragment
Energy Loss for the Low Energy Peak

Detector	E(observed) (Mev)	E(predicted) (MeV)
26-4	37 ±3	43.7±2.4
40-1	20 ±3	27.5±2.0
28-2	4.7±.2	7.2±1.5

IV. Conclusions

We have investigated the problems associated with the fabrication of thin dE/dx detectors from epitaxial silicon. Detectors 12.5 mm^2 in area, 1-4 μm thick, and having resistivities as low as 1 Ω-cm have been fabricated. Absolute charge measurements indicate that the detectors behave as expected for a silicon Schottky barrier detector when exposed to alpha particles and ^{16}O ions. The response of the detectors to fission fragments provides a diagnostic tool for investigating problems with these detectors. This is because of the higher density of ionization associated with these particles.

The use of epitaxial material offers a viable alternative to conventional processing techniques for the production of uniform ultra thin dE/dx silicon detectors. This is because: lower resistivities are accessible in the epitaxial material, the epitaxial material is of lower cost, larger areas are possible with the epitaxial material, and longer radiation lifetime designs are possible.

Acknowledgments

The authors wish to thank P. Siffert, F. Vazeille, and M. Querrou for their stimulating discussions concerning these detectors. We also wish to thank Judy Gursky for help in evaporating the contacts on the detectors and the Tandem Van de Graaff staff.

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3. R. L. Meek, W. M. Gibson, and R. H. Braun, 'Preparation of Supported, Large-Area, Uniformly Thin Silicon Films for Particle-Channeling Studies," Nucl. Instrum. Methods, 94, 435-442 (1971).

4. F. J. Walter, "Multiplication in the Fission Fragment Pulse Height Response of Silicon Surface Barriers," IEEE Trans. Nucl. Sci., NS11, No. 3, 232-236 (June 1964).

5. L. C. Northcliffe and R. F. Schilling, Nucl. Data Tables, A7, 233-463 (1970).

Figure Captions

Fig. 1. Schematic diagram of epitaxial silicon Schottky barrier (ESSB) detector.

Fig. 2. Typical I-V characteristics of an ESSB detector.

Fig. 3. Response of a 4.18 μm detector to 5.48 MeV alpha particles from ^{241}Am. The detector is tilted ~10° from normal to eliminate channeling.

Fig. 4. Normal response of a 2.52 μm detector to alpha particles from ^{241}Am and the enhanced signal due to charge collection from the substrate.

Fig. 5. Response of a 4.18 μm detector to ^{16}O ions.

Fig. 6. Response of the same detector as in Fig. 5 but tilted ~10° from normal to eliminate channeling.

Fig. 7. Response of an uncollimated 1 μm detector to 52 MeV ^{16}O ions.

Fig. 8. Response of a 0.71 μm ESSB detector to fission fragments from ^{252}Cf source.

Fig. 9. Bias dependence of the fission fragment response of the 0.71 μm detector.

Fig. 10. Resistivity depth profile of the 1 μm epitaxial material.

EPITAXIAL SILICON SURFACE BARRIER (ESSB) DESIGN

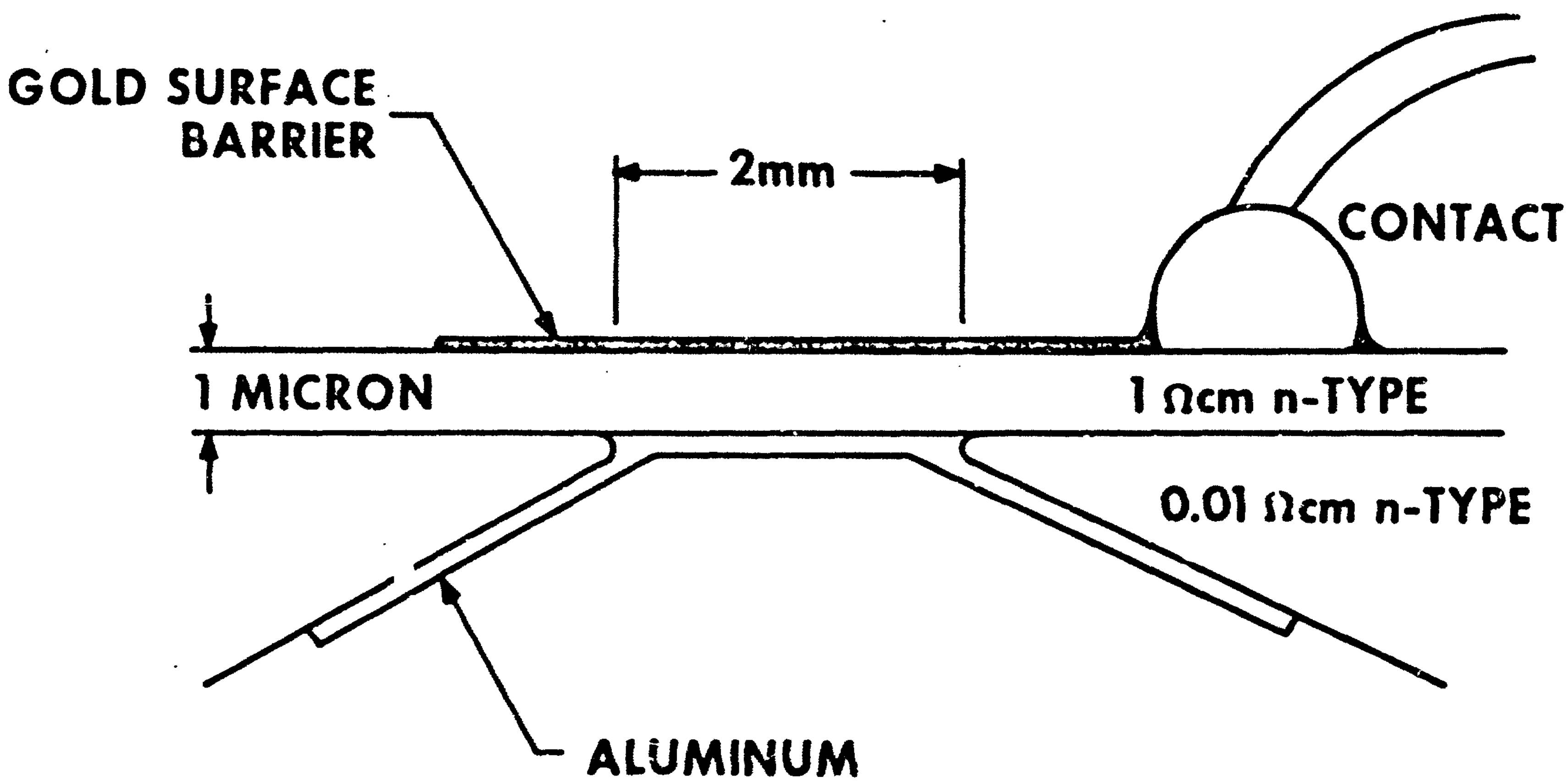


Fig. 1

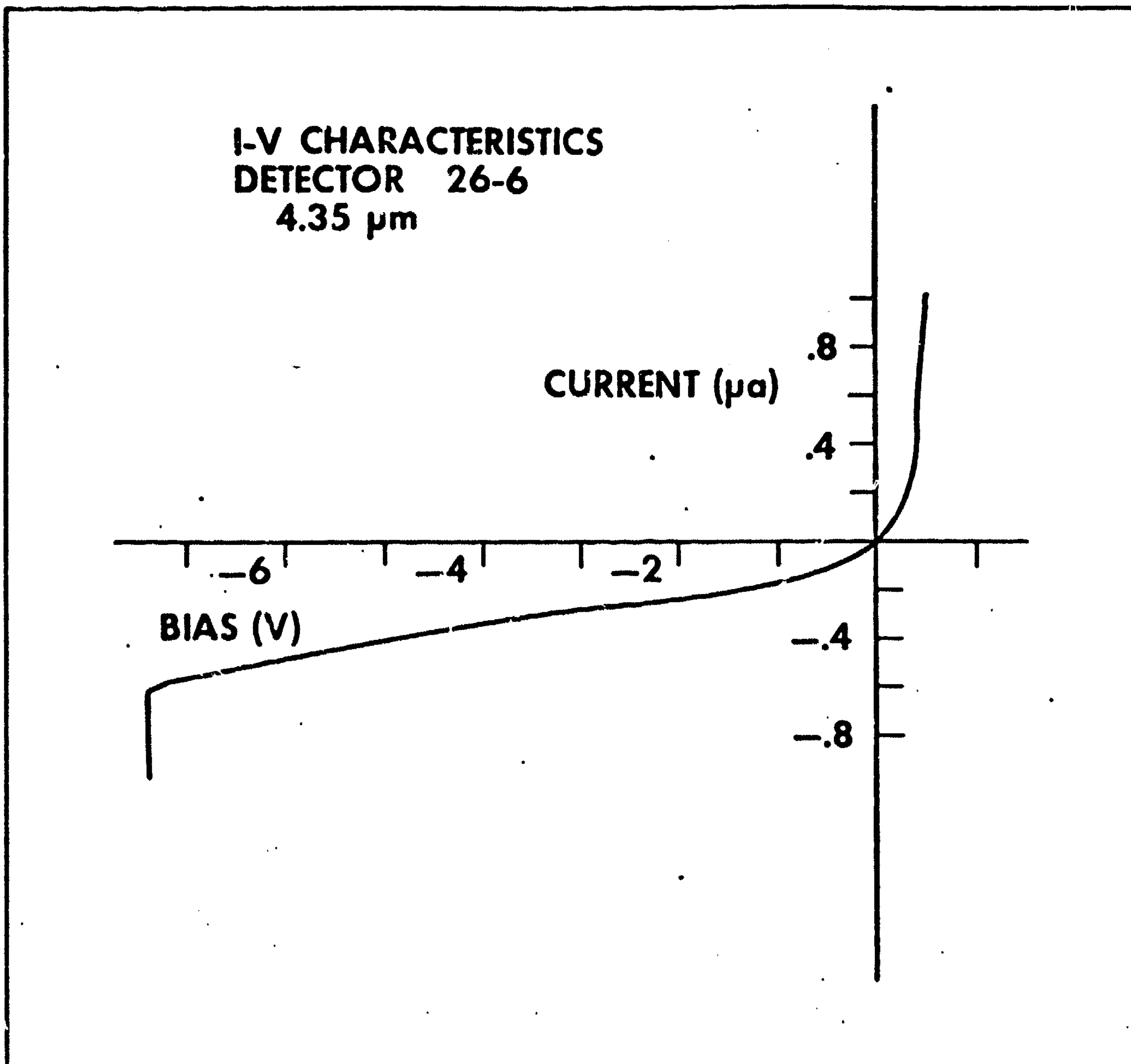
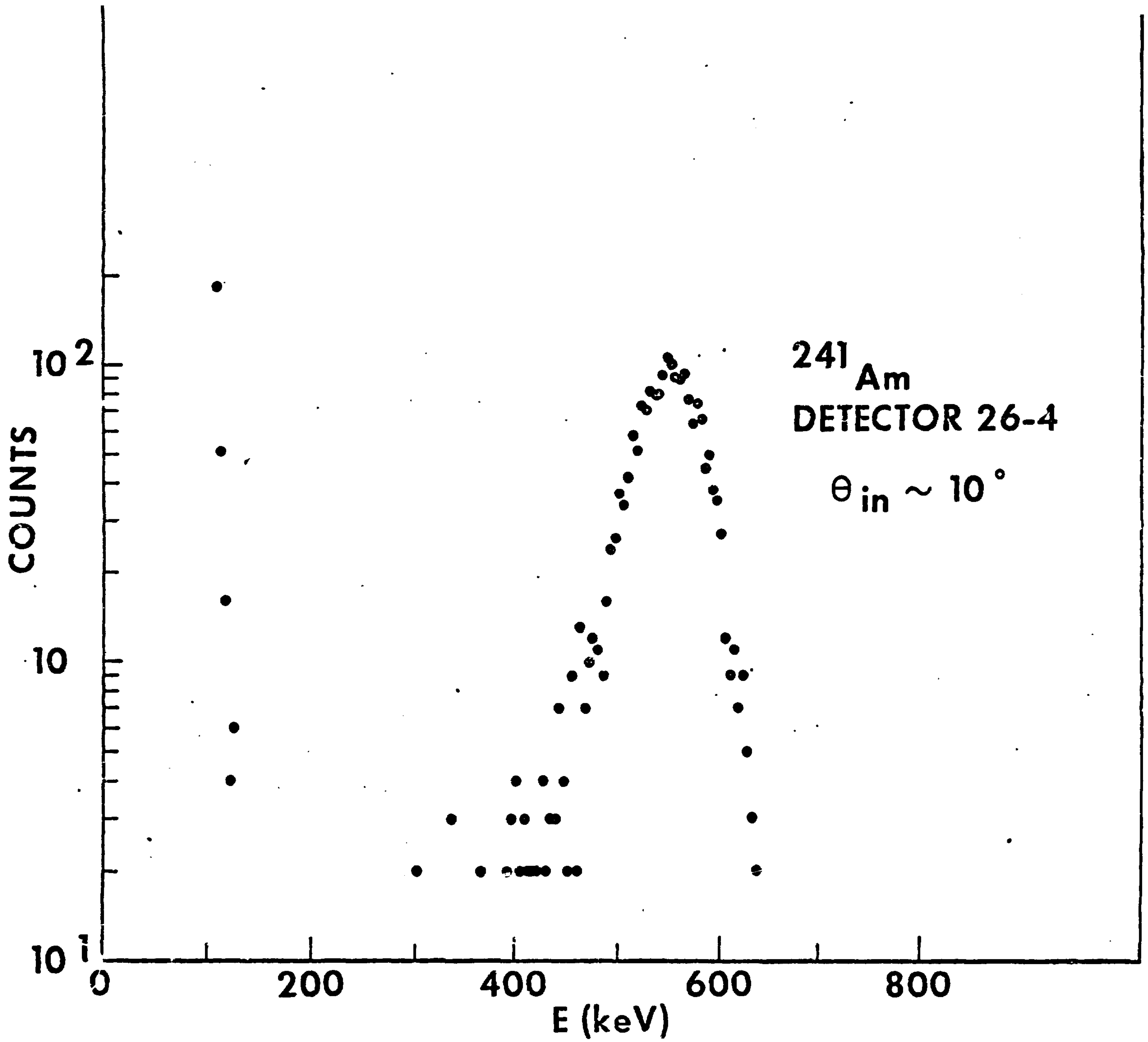
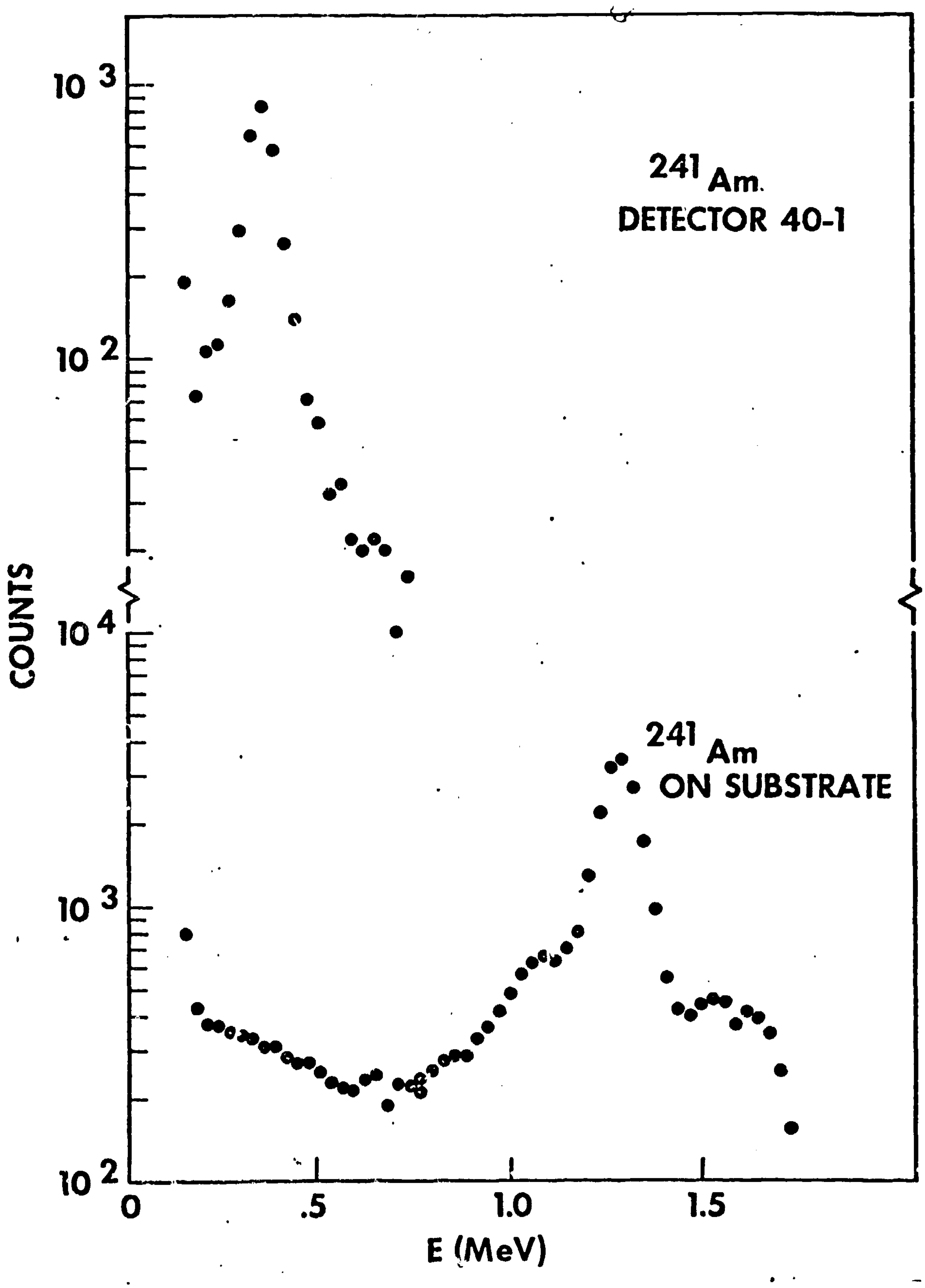

I-V CHARACTERISTICS
DETECTOR 26-6
4.35 μm
CURRENT (μa)
.8
.4
−.4
−.8
−6
−4
−2
BIAS (V)

Fig. 2



COUNTS
10^2
10
10^1
0
200
400
600
800
E (keV)
^{241}Am
DETECTOR 26-4
$\theta_{in} \sim 10°$

Fig. 3



COUNTS
10^3
10^2
10^4
10^3
10^2
241 Am
DETECTOR 40-1
241 Am
ON SUBSTRATE
0
.5
1.0
1.5
E (MeV)

Fig. 4

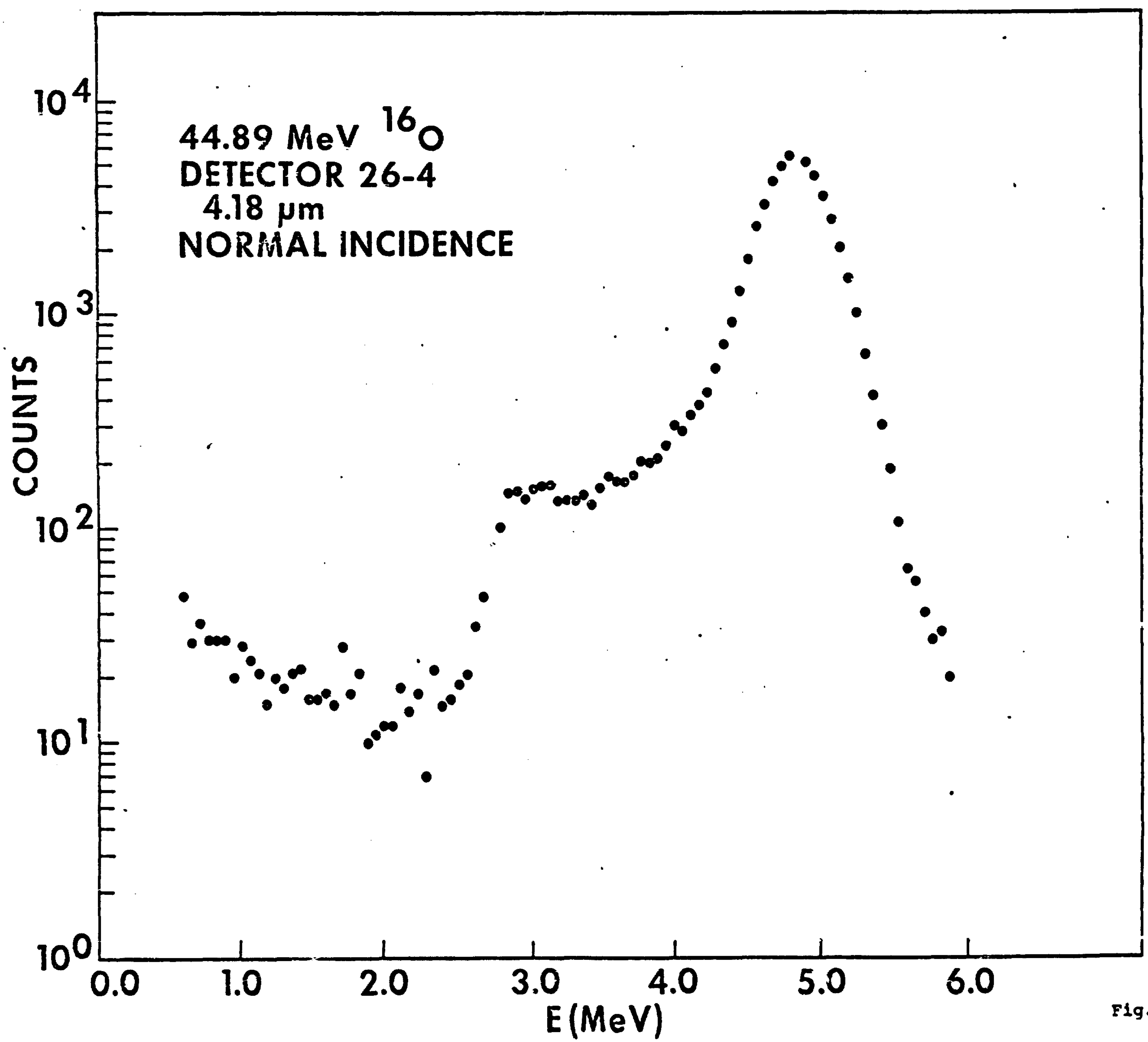
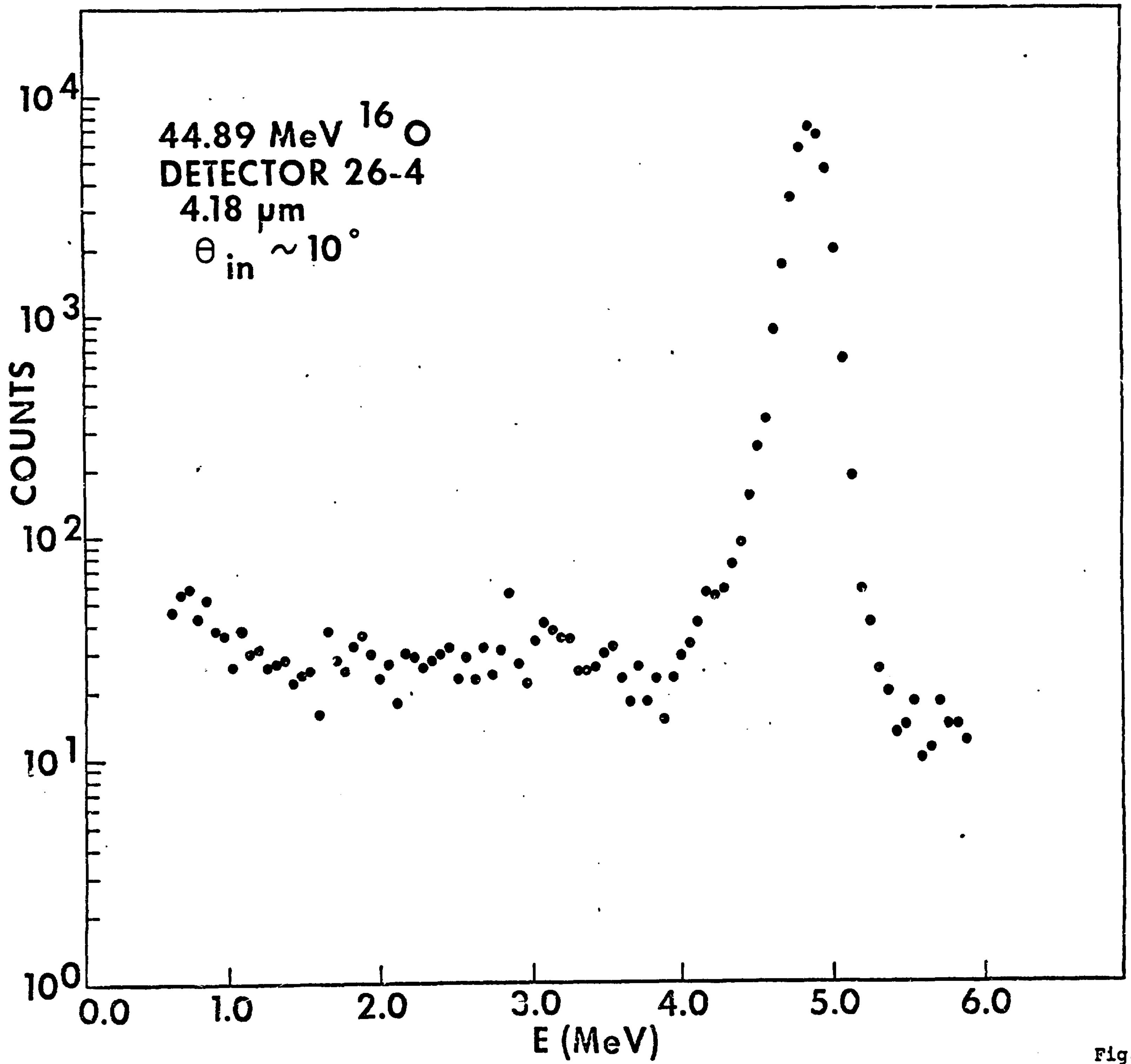

44.89 MeV ^{16}O
DETECTOR 26-4
4.18 μm
NORMAL INCIDENCE
COUNTS
10^4
10^3
10^2
10^1
10^0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
E (MeV)

Fig. 5



44.89 MeV ^{16}O
DETECTOR 26-4
4.18 μm
$\theta_{in} \sim 10°$
COUNTS
10^4
10^3
10^2
10^1
10^0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
E (MeV)

Fig. 6

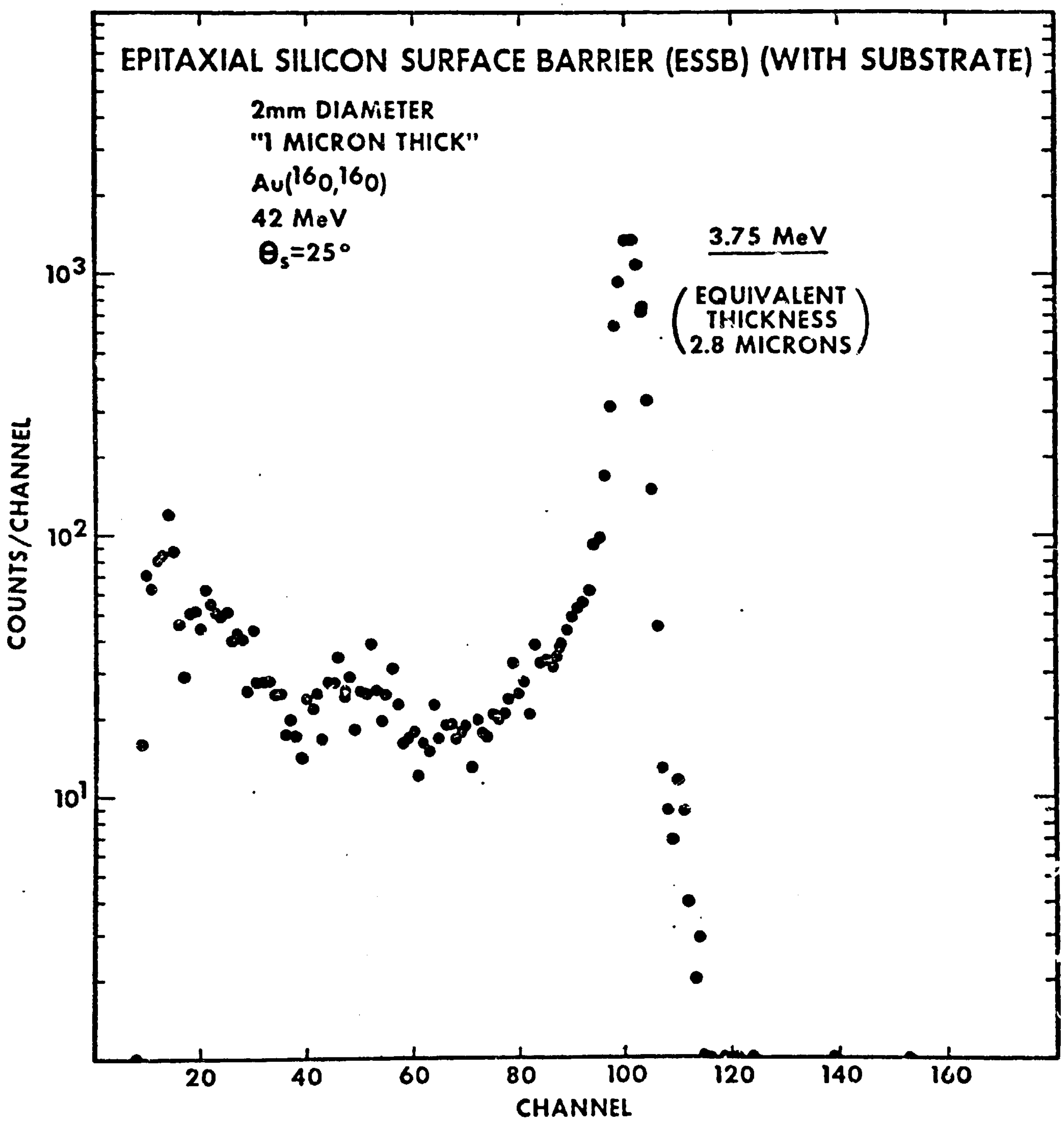
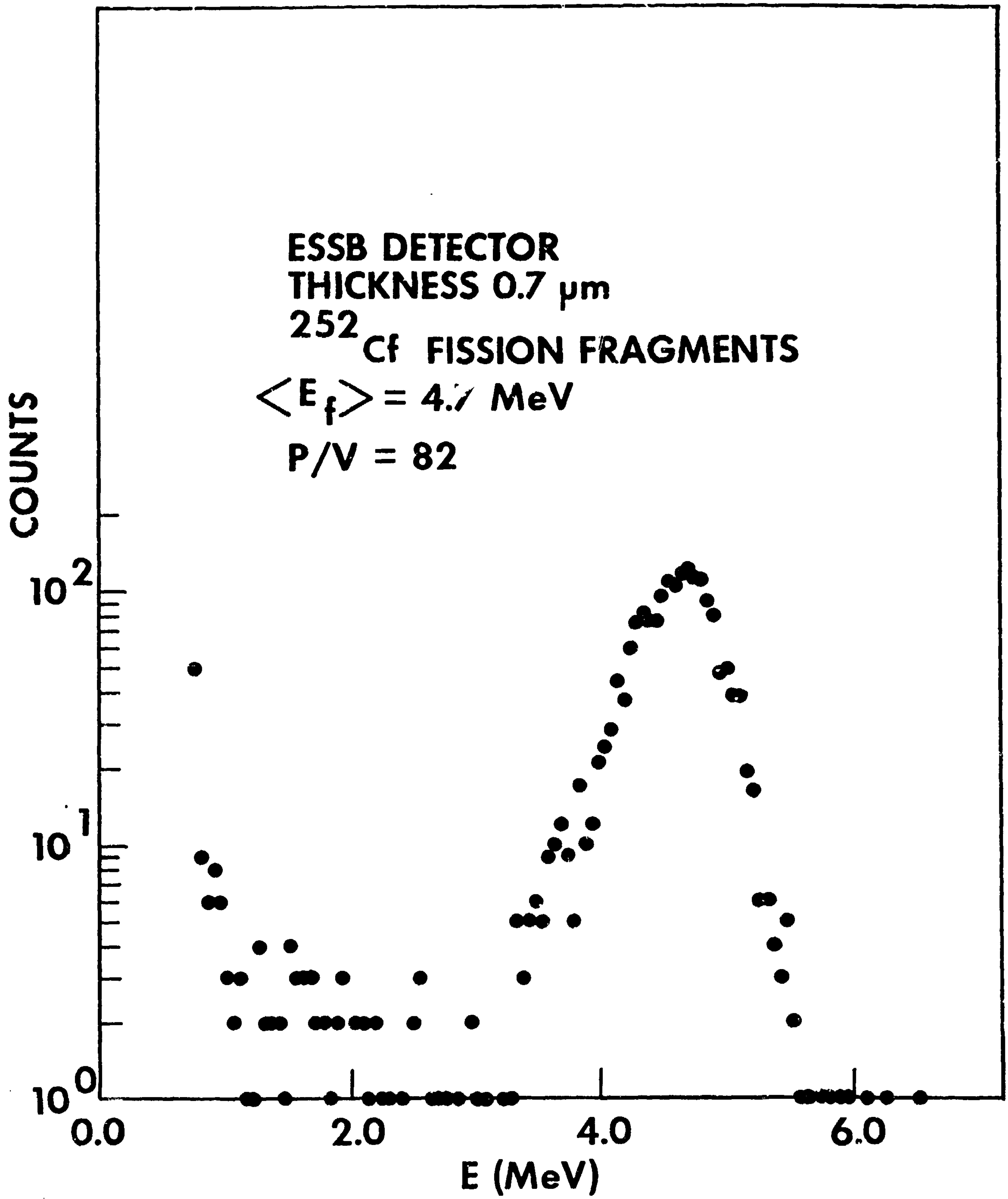
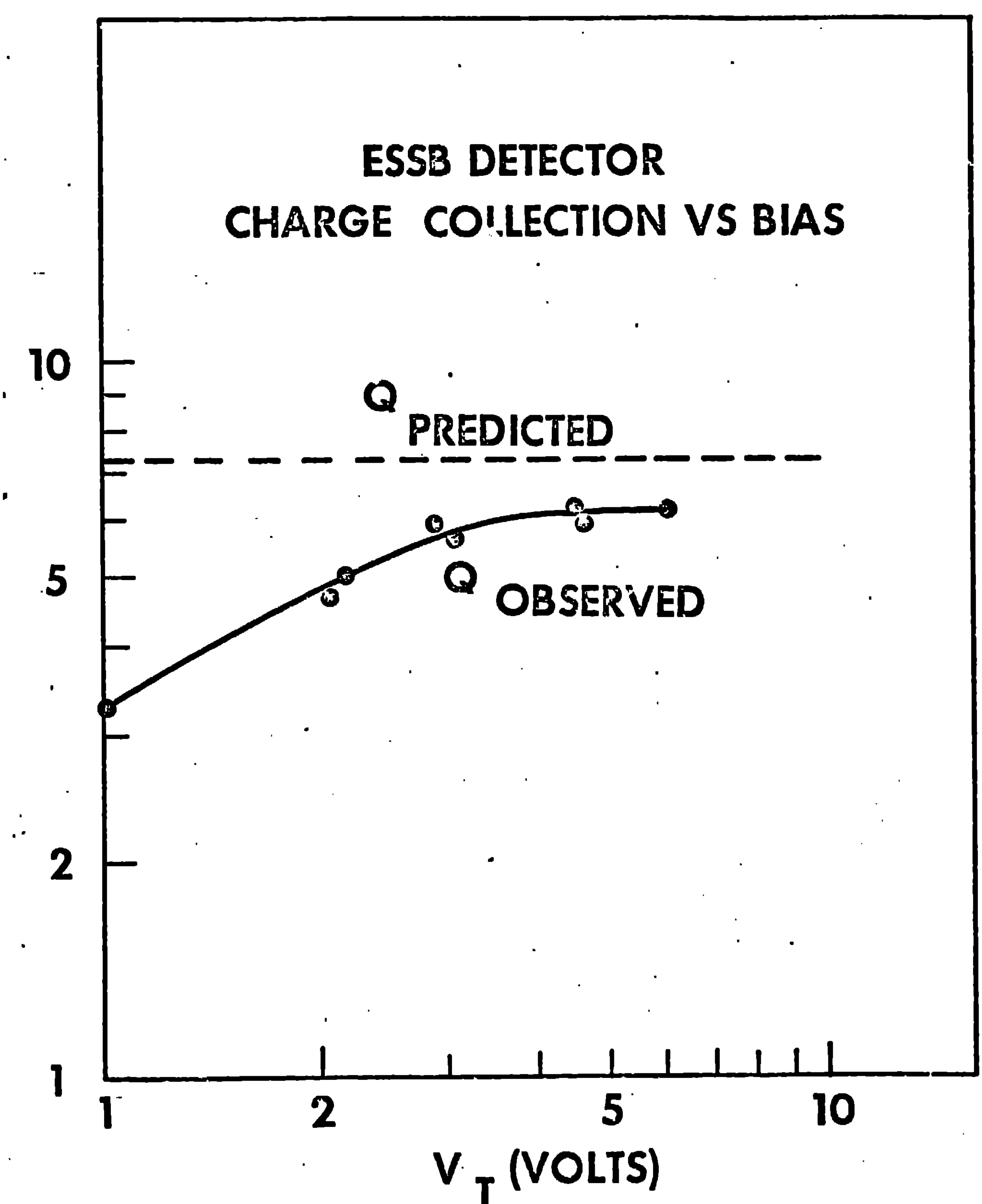

EPITAXIAL SILICON SURFACE BARRIER (ESSB) (WITH SUBSTRATE)
2mm DIAMETER
"1 MICRON THICK"
Au(16O,16O)
42 MeV
θs=25°
3.75 MeV
(EQUIVALENT THICKNESS 2.8 MICRONS)
COUNTS/CHANNEL
10^3
10^2
10^1
20
40
60
80
100
120
140
160
CHANNEL

Fig. 7



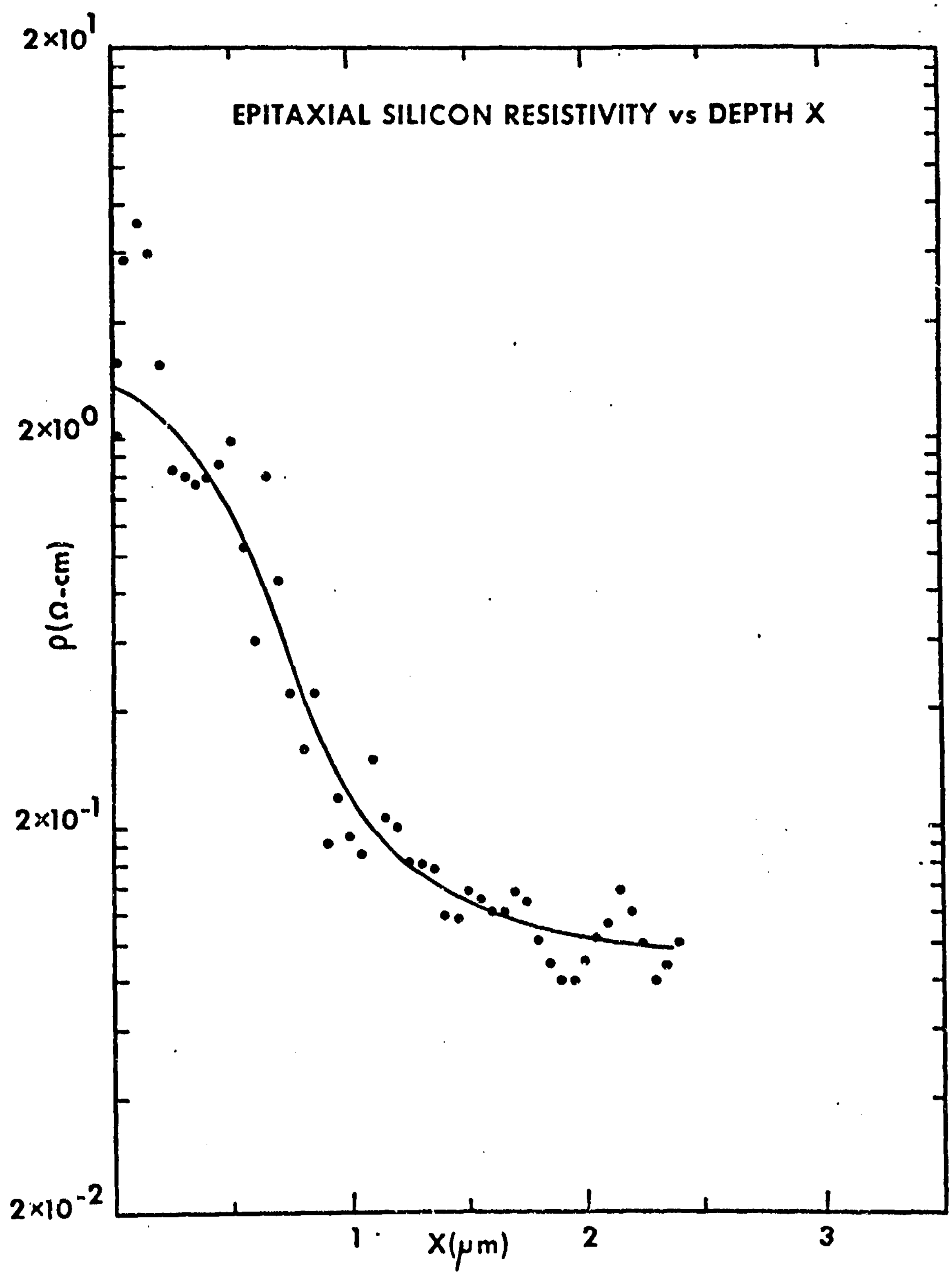
ESSB DETECTOR
THICKNESS 0.7 μm
252Cf FISSION FRAGMENTS
⟨Ef⟩ = 4.7 MeV
P/V = 82
COUNTS
10^2
10^1
10^0
0.0
2.0
4.0
6.0
E (MeV)

Fig. 8



ESSB DETECTOR
CHARGE COLLECTION VS BIAS
10
5
2
1
Q PREDICTED
Q OBSERVED
1
2
5
10
V T (VOLTS)

Fig. 9



EPITAXIAL SILICON RESISTIVITY vs DEPTH X
2×10^1
2×10^0
2×10^-1
2×10^-2
ρ(Ω-cm)
1
2
3
X(μm)