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THE BEHAVIOUR OF HIGH PURITY SEMICONDUCTOR SURFACE-BARRIER NUCLEAR RADIATION DETECTORS AT LOW TEMPERATURES

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ABSTRACT

The characteristics of a germanium and a silicon surface barrier detector have been examined at low temperatures (78 to 5 K). Preliminary results have also been obtained from a gallium arsenide detector. All detectors were fabricated from high purity material.

Below some critical temperature (10 K in germanium and 32 K in silicon) the spectral response to γ-rays deteriorated markedly, particularly for low bias. Near liquid helium temperature best resolutions of 10.0 keV at 662 keV and 3.0 keV at 122 keV were obtained with the germanium and silicon detectors respectively. Relative efficiency measurements found no change in the sensitive depth with temperature in contrast to the indications of the capacitance.

A model based on field-assisted detrapping is proposed to account for the fact that sensitive depth is independent of temperature. The behaviour of the capacitance and the existence of slow components in the pulse risetime are explained in terms of the equivalent circuit of the detector.

The energy resolution of the gallium arsenide detector did not change on cooling to 7 K where a resolution of 3.9 keV at 60 keV was measured.

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(0) CRITICAL TEMPERATURE; GAMMA RADIATION; GAMMA SPECTRA; GOLD; JUNCTION DETECTORS; JUNCTION DIODES; SURFACE BARRIER DETECTORS; TEMPERATURE DEPENDENCE;
(1) GERMANIUM; KEV RANGE 100–1000; LOW TEMPERATURE; SILICON;
(2) ARSENIDES; GALLIUM COMPOUNDS; KEV RANGE 10–100

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1. INTRODUCTION

While the behaviour of Ge(Li) and Si(Li) γ- and X-ray radiation detectors at low temperatures has been studied in some detail the situation with respect to step-junction detectors is not so clear. Carrier trapping and detrapping at the primary shallow dopants has been identified as causing a marked deterioration in the resolution of Ge(Li) and Si(Li) detectors. The lower limit of high resolution operation seems to be about 30 K in Ge(Li) and 40–50 K in Si(Li) detectors. Martini, McMath and Fowler (1970) have reviewed much of the available data at low temperatures.

This paper describes the operation of a germanium and a silicon step-junction detector near liquid helium temperature. Examinations were made of leakage current and capacitance as well as spectral response and efficiency at temperatures between 78 and 5 K. Preliminary results with a gallium arsenide detector at liquid helium are also presented. All three were fabricated from high purity material.

2. EXPERIMENTAL DETAILS

The measurements were made using a cryostat designed especially for liquid helium work. The detector, in a polished aluminium holder, was mounted on the outer surface of a copper flange sealing the lower end of the helium container. An outer container of liquid nitrogen reduced the helium boil off rate. The detector was surrounded by two radiation shields, the inner at liquid helium temperature and the outer at liquid nitrogen. During the examination of the germanium detector the temperature was measured using a gold (0.03 atomic per cent iron) chromel thermocouple which has a high sensitivity at liquid helium temperature ($\sim$ 15 μV/K). The reference junction was maintained at the boiling point of liquid nitrogen. This was replaced for the silicon and gallium arsenide measurements by a germanium resistor which is more robust and more sensitive at the low temperatures. With liquid helium in the inner vessel the two thermometers gave agreement within 1 K.

All the detectors were gold barrier step-junction diodes. The gold was evaporated in vacuum onto a freshly etched surface to a thickness of $\sim$ 200 Å. The germanium and silicon detectors both had ohmic contacts produced by diffusion in vacuum of lithium from a metallic source. An ohmic contact was prepared on the gallium arsenide substrate by alloying with a eutectic mixture of gallium and indium.

Measurements of leakage current and capacitance were made in addition to spectral examinations of resolution and efficiency. The capacitance measurements were made at 1 kHz using a conventional RC bridge and at 130 kHz with a Tektronix Type 130 LC meter. The spectral analysis system consisted of a charge sensitive preamplifier with a first stage FET at room temperature (Ortec 118A), an active filter amplifier (Ortec 440) and a 1024 channel analyser (Nuclear Data 1024). Relative efficiency measurements were made by choosing a source of penetrating γ-rays and adopting a fixed source-detector geometry.

3. MEASUREMENTS

3.1 Germanium Detector

The behavior of this detector at low temperatures has already been reported by Lawson and Tavendale (1971), but a brief description is included here for continuity.

The germanium detector was made from a high purity n-type single crystal grown by the Czochralski method in the < 100 > direction*. A 2 mm thick slice was cut from the crystal and lapped into the form of a disc with a diameter of 19 mm. The gold diameter was 16 mm. The net donor density of the slice was determined from measurements of the capacitance at 78 K, to be 3×10^{11} cm^{-3}.

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* Supplied by R. N. Hall, G. E. Co. Schenectady, N.Y., U.S.A.

On cooling from 78 to 5 K the marked temperature dependence of the leakage current (at a fixed bias) that is usually found above 78 K soon became less obvious and by 25 K the current had saturated for low bias at a value only 10 times down on that at 78 K (see Lawson and Tavendale (1971), Figure 1). An abrupt change in the 130 kHz capacitance was observed between 10 and 5 K (see Lawson and Tavendale (1971), Figure 5). The capacitance characteristic was found to be less dependent on the applied bias at 5 K than 78 K. This effect was more noticeable at 130 than at 1 kHz (see Lawson and Tavendale (1971), Figures 3 and 4).

Spectra from ^{137}Cs were examined at 78 and 5 K for several values of reverse bias and at temperatures between 78 and 5 K for a fixed bias of 200 V (see Lawson and Tavendale (1971), Figures 6, 7, 8 and 9). A marked deterioration in resolution was observed on cooling below 10 K. By increasing the bias the spectral response was improved. No change in efficiency was observed under partial depletion conditions (fixed bias of 200 V) in the temperature range 78 to 5 K (see Lawson and Tavendale (1971), Figure 10).

Two components in the rise time of the preamplifier output pulse were observed below 10 K with an oscilloscope. There was an initial fast component, system-limited to $\sim$ 70 nsec, which had the same slope as the pulses at higher temperatures, and a slow component whose slope was $\sim$ 100 times less. As was expected the resolution improved with longer amplifier time constants.

3.2 Silicon Detector

Float-zoned, phosphorus-doped n-type silicon with a nominal resistivity of 90 kΩcm (purchased from Wacker-Chemie) was used to make this detector. The orientation was $< 111 >$. The device was about 2.5 mm total thickness and had a gold diameter of 14.5 mm. The lithium diffused n^+ contact was $\sim$ 0.2 mm thick. The net donor density was determined to be 1.2×10^{11} cm^{-3} from examination of the capacitance characteristic at liquid nitrogen temperature.

On cooling from 78 to 6 K very little change was observed in the leakage current at 1000 V and the dependence on bias was similar to that at 78 K. With a bias (150 V) producing only partial depletion at 78 K an abrupt change in the 130 kHz capacitance occurred between 24 and 30 K. This change can be seen in Figure 1. The capacitance measured at 6 K was practically independent of bias at both 130 and 1 kHz. Figure 2 shows the bias dependence of the capacitance at 78 and 6 K.

Spectra from a ^{57}Co source were recorded on cooling from 78 to 6 K with a bias (1000 V) sufficient to give full depletion. These are shown in Figure 3. A deterioration in the resolution was observed with decreasing temperature commencing at $\sim$ 32 K.

At 6 K the spectral response was poorer than at 78 K for all bias values. Figure 4 shows the effect of bias on the spectra at 6 K. The performance was very poor at low bias values but improved with increased bias. It was noted that significant improvement in resolution with bias could still be obtained for bias values beyond that for full depletion.

Figure 5 shows ^{57}Co spectra taken at a fixed bias of 150 V for temperatures between nitrogen and helium boiling points. An abrupt worsening of resolution was again noted at $\sim$ 32 K. As can be seen from Figure 2, a bias of 150 V produces only partial depletion (at least at 78 K). However, no change in efficiency with temperature was observed at this bias as can be seen from Table 1. The limits of integration are shown by the small arrows in Figure 5. Two lower integration limits are given for the spectrum at 6 K, one located by inspection of the spectral shape, and the other chosen to give good agreement with the efficiency at the highest temperature (72 K). There is a difference of only six channels or $\sim$ 3% in the efficiency. While the integration becomes less accurate for lower temperatures and bias values we feel the data indicate no change in depletion depth with temperature.

Examination of preamplifier pulse shapes with the detector only partially depleted showed a system-limited rise time at various temperatures between 78 and 6 K – 70, 40, 30, 25, 18, 13, 10 and 6 K. No slow component was observed at these temperatures. The pulse amplitude was seen to decrease with decreasing temperature below 30 K.

3.3 Gallium Arsenide Detector

The measurements on gallium arsenide were far less comprehensive than those on germanium and silicon and are to be regarded as very preliminary. A detector was made from high purity n-type gallium arsenide grown by liquid phase epitaxy. The epitaxial layer was 60 to 80 μm thick and oriented in the $< 100 >$ direction. The doping density was $\sim 6 \times 10^{13}$ cm^{-3}. The gold diameter was 1.5 mm. For a full description of material properties and detector fabrication see Eberhardt, Ryan and Tavendale (1971).

The detector was cooled to liquid helium and found to count efficiently and with energy resolutions similar to those obtained at higher temperatures. The piezo-electric effect in gallium arsenide is so significant that measurements could not be made with boiling liquid helium in the inner vessel. A γ-ray spectrum (shown in Figure 6) from ^{241}Am was obtained at 7 K; the 60 keV line and the escape peak about 10 keV lower are resolved clearly. The resolution at 60 keV γ-ray energy was 3.9 keV (FWHM).

4. DISCUSSION

4.1 Germanium Detector

In a previous publication (Lawson and Tavendale 1971) we reported the examination of a germanium detector at low temperatures. The parameters measured were capacitance, leakage current, pulse shape, energy resolution and efficiency for γ-radiation.

The rapid change in the measured detector capacitance is explained in terms of an equivalent circuit (EC) model. At some critical temperature carrier freezeout on the primary shallow doping impurities begins (Wang 1966), and the resistivity increases rapidly. Assuming no compensation we calculate these critical temperatures to be 13, 37 and 24 K in the germanium, silicon and gallium arsenide used by us. At some temperature close to but below this critical temperature the resistance of the undepleted region becomes so large that it no longer shorts the capacitance of this region and a capacitance corresponding to the geometrical dimensions of the detector is measured. The detector equivalent circuit is such that at a fixed temperature the effect of carrier freezeout will be sensed first at higher frequencies.

The efficiency measurements with ^{137}Cs indicate no change in depletion depth on cooling to 5 K. It is proposed that this observation can be explained by a model based on field-assisted detrapping (FAD) of primary shallow doping impurities. Such a mechanism has been found in work with Ge(Li) detectors (Martini and McMath 1970). Application of bias allows ionisation of the shallow dopants thus restoring the depletion depth and field distribution obtained at higher temperatures. The efficiency therefore remains constant.

The existence of a slow component in the pulse rise time below 10 K can be explained in two ways. Firstly as has been already suggested trapping and detrapping occur in the depletion depth. This would give a two component pulse rise time. Secondly, consideration of the equivalent circuit indicates that two components will be produced when the resistivity of the undepleted material becomes high. In a previous publication (Lawson and Tavendale 1971) we favoured the first explanation, but concluded that more experimental work was necessary to resolve the ambiguity. It was hoped that the experiment with the silicon detector would show similar results and allow the selection of the correct mechanism.

Recent similar results from high purity p^+n step-junction germanium detectors have been reported by Stuck et al. (1971, 1972). Their observations are explained on the basis of the EC model. Although an increase in efficiency with decreasing temperature was noted (for fixed bias) this increase is slight ($\sim$ 6 per cent). We feel that this small change cannot be explained by the EC model and that the FAD model is more applicable. A slight increase in efficiency may be present in our germanium and silicon results but the spectral response at low temperatures and low bias values is too poor to allow its estimation with accuracy.

4.2 Silicon Detector

Basically we find that silicon and germanium detectors behave in a similar manner at low temperatures. The critical temperature for silicon is higher than that for germanium primarily because of the larger ionisation energies of the normal doping impurities. One immediate result of this is that, as observed, the abrupt change in capacitance to the geometrical value takes place at a higher temperature in silicon. Since no change with temperature was observed in the efficiency of the silicon detector to ^{57}Co γ-rays we conclude the FAD model for the maintenance of constant depletion depth at a given bias is applicable to silicon also.

If this conclusion is correct this work provides the first experimental indication of field-assisted detrapping in silicon. Martini and McMath (1970) using Si(Li) detectors found no evidence for field-assisted detrapping, at least for fields up to 2 kV cm^{-1}. Our fields are comparable — 1.4 kV cm^{-1} at 150 V (the lowest bias at which efficiency measurements were made), but our material is two orders of magnitude more pure than their basic material. It is possible that this difference in material purity will account for their failure to observe field-assisted detrapping.

Since the energy resolution below the critical temperature improved with increasing bias but worsened with decreasing temperature, even when the silicon detector was fully depleted it would appear that carrier trapping definitely takes place. With the detector only partially depleted it seems likely that the deterioration in resolution was due to a slow component produced by the increased resistivity of the base material. The time constant of this component was probably much greater than the preamplifier fall time (50 μsec) and therefore was not observed.

If the EC model is to apply, the amplitude of the fast component at low temperatures should have the same dependence on bias as the depletion depth (Dodge et al. 1964). An estimation of this amplitude was obtained from the position in the ^{57}Co spectra of the degraded 122 keV photopeak. The dependence on bias was found to be similar to that of the depletion depth at liquid nitrogen.

Our silicon results can be compared with those reported by Dodge et al. (1964, 1965). They observed a slow component in the pulse shape only in a very narrow temperature range (26–24 K). Below 22 K the pulse had a single fast component but was reduced in amplitude. Since our observations of pulse shape were made at isolated temperatures the two component range was presumably missed.

Our experimental results differ markedly from those of Dodge et al. in one respect. The amplitude of our pulses continued to fall with decreasing temperature whereas Dodge et al., using α- and β- particles, found a return to the high temperature amplitude on cooling below 17 K. Their explanation was based on the EC model. Their depletion depth increased due to increasing resistivity (reduction in net ionised donor density) at fixed bias, with restoration of pulse amplitude at full depletion. As stated previously, we found no significant change in the depletion depth and so expect no return to the high temperature pulse amplitude. While further experimental data will be necessary to resolve this obvious difference, we feel that the explanation will probably lie in the different impurity or possible defect concentrations of the materials.

4.3 Gallium Arsenide Detector

The data from the gallium arsenide detector although slight is significant. The energy resolution at 7 K is similar to that at high temperatures although the critical temperature is estimated to be 24 K. This is unusual as both the germanium and silicon detectors showed a worsening of resolution below their critical temperatures. This is as yet unexplained but the reason may be found in the very small ionisation energy of the donor impurities in gallium arsenide — typically 6 meV. Such a small ionisation energy should imply short detrapping times. Furthermore the high electron mobility in gallium arsenide would indicate a low resistivity with the result that the effects of the equivalent circuit are not appreciable at these temperatures. However further work will be necessary to investigate this effect.

5. SUMMARY

The spectral performance of the high purity germanium and silicon detectors examined here worsens on cooling to liquid helium temperatures. The rate of deterioration increases below the critical temperature so that high resolution performance can be maintained only by using more pure material.

The first results with a gallium arsenide detector reported here near liquid helium temperature are exceptional and warrant further investigation.

There is a mechanism – FAD, which tends to keep impurities ionised at low temperatures and to maintain the depletion depths of higher temperatures. The EC model explains satisfactorily the behaviour of the capacitance and pulse shape as a function of temperature.

At the moment there is a discrepancy between our silicon results and those of Dodge et al. (1964, 1965) which will require further investigation.

6. ACKNOWLEDGEMENTS

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TABLE 1

^{57}Co PHOTOPEAK EFFICIENCIES AT 150 V

Limits of Integration (Channel No.)	Temperature (K)	Efficiency (Counts)
360 – 435	72	15,974
360 – 435	40	15,773
346 – 426	31	15,854
230 – 350	20	15,925
215 – 344	6	16,451
221 – 344	6	15,955

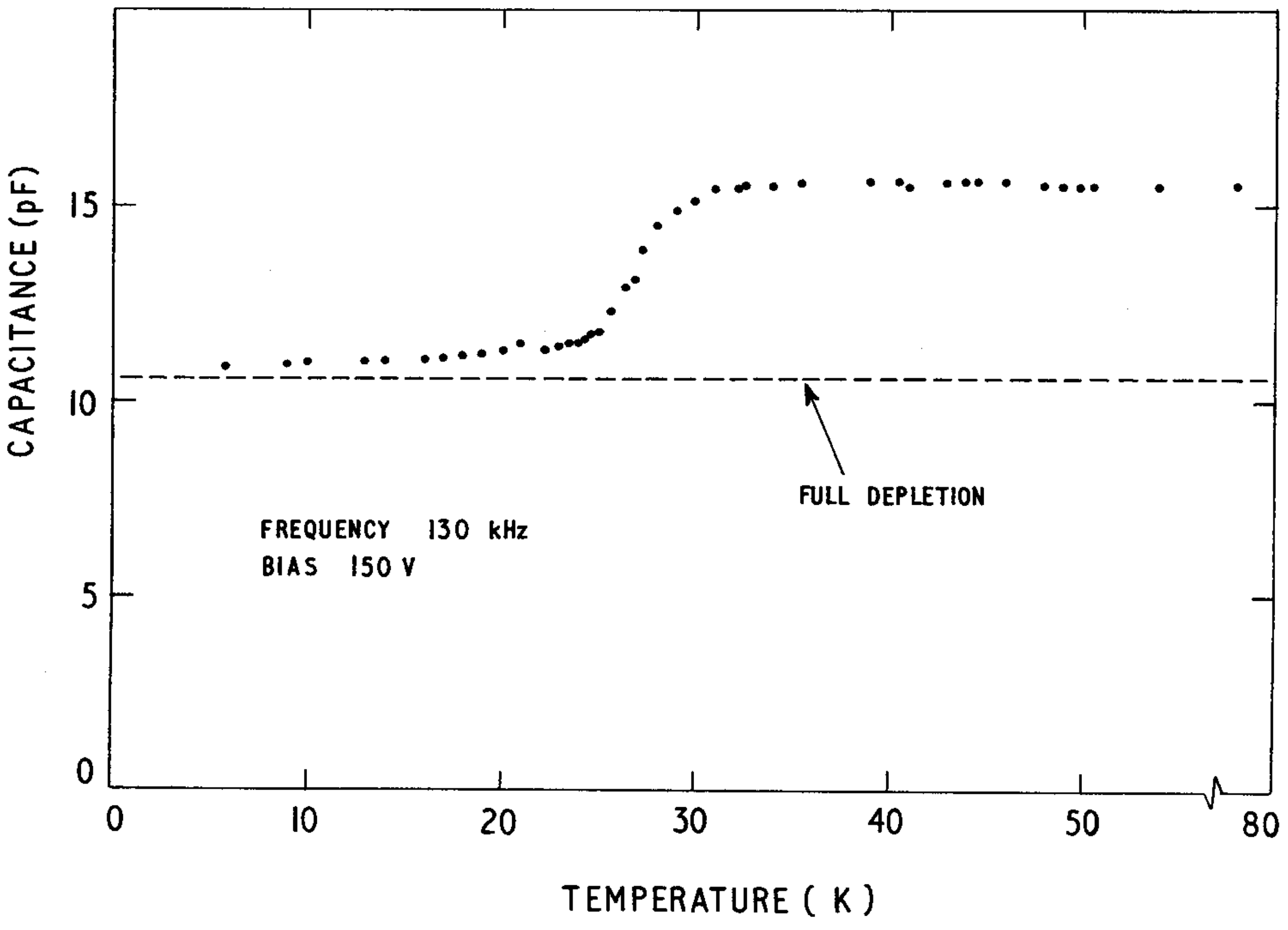

FIGURE 1. SILICON DIODE CAPACITANCE (130kHz) v. TEMPERATURE FOR A BIAS OF 150 V

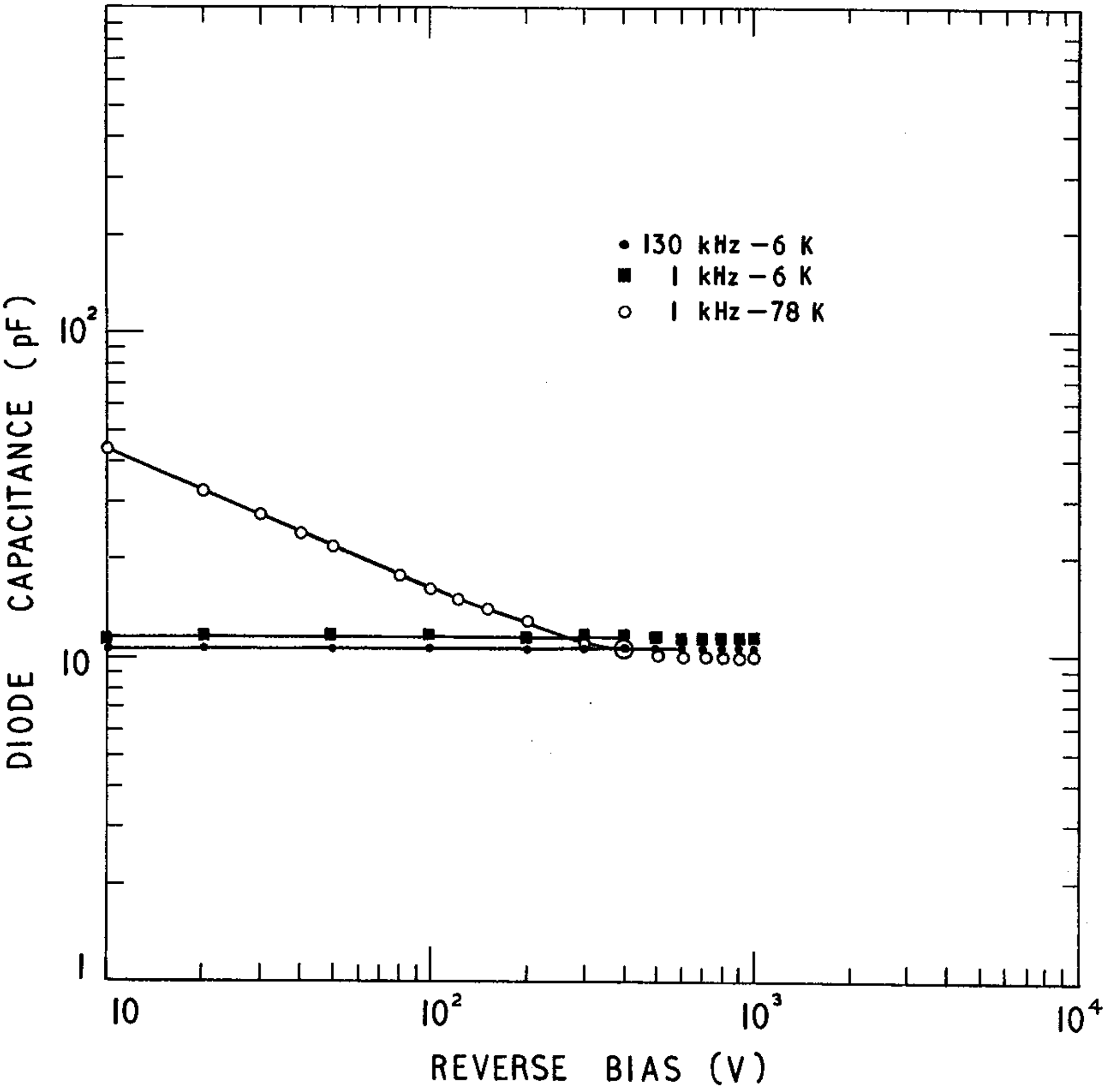

FIGURE 2. SILICON DIODE CAPACITANCE v. BIAS AT 78 AND 6 K

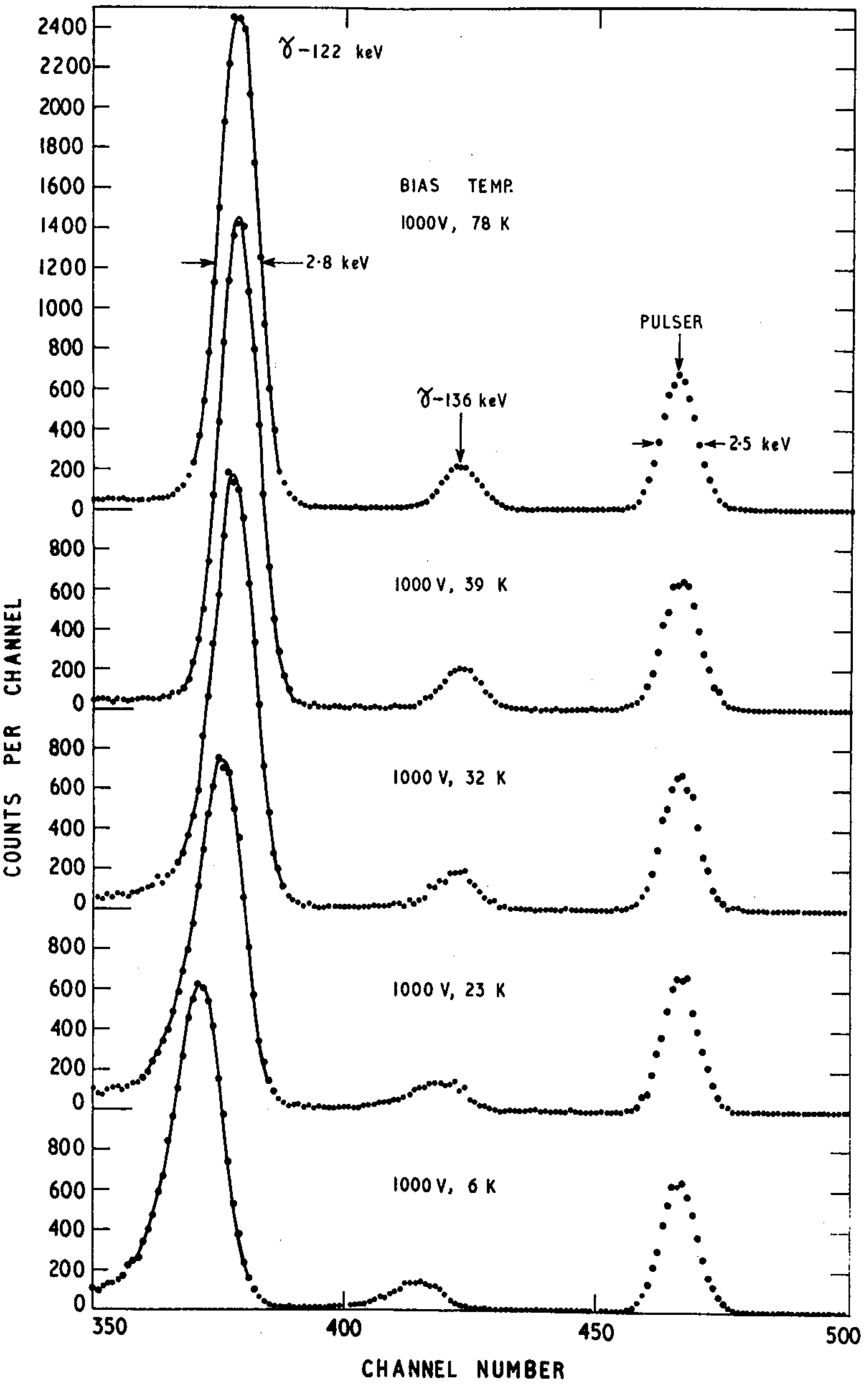

FIGURE 3. ^{57}Co γ-RAY SPECTRA BETWEEN 78 AND 6 K WITH SILICON DETECTOR AT 1000 V

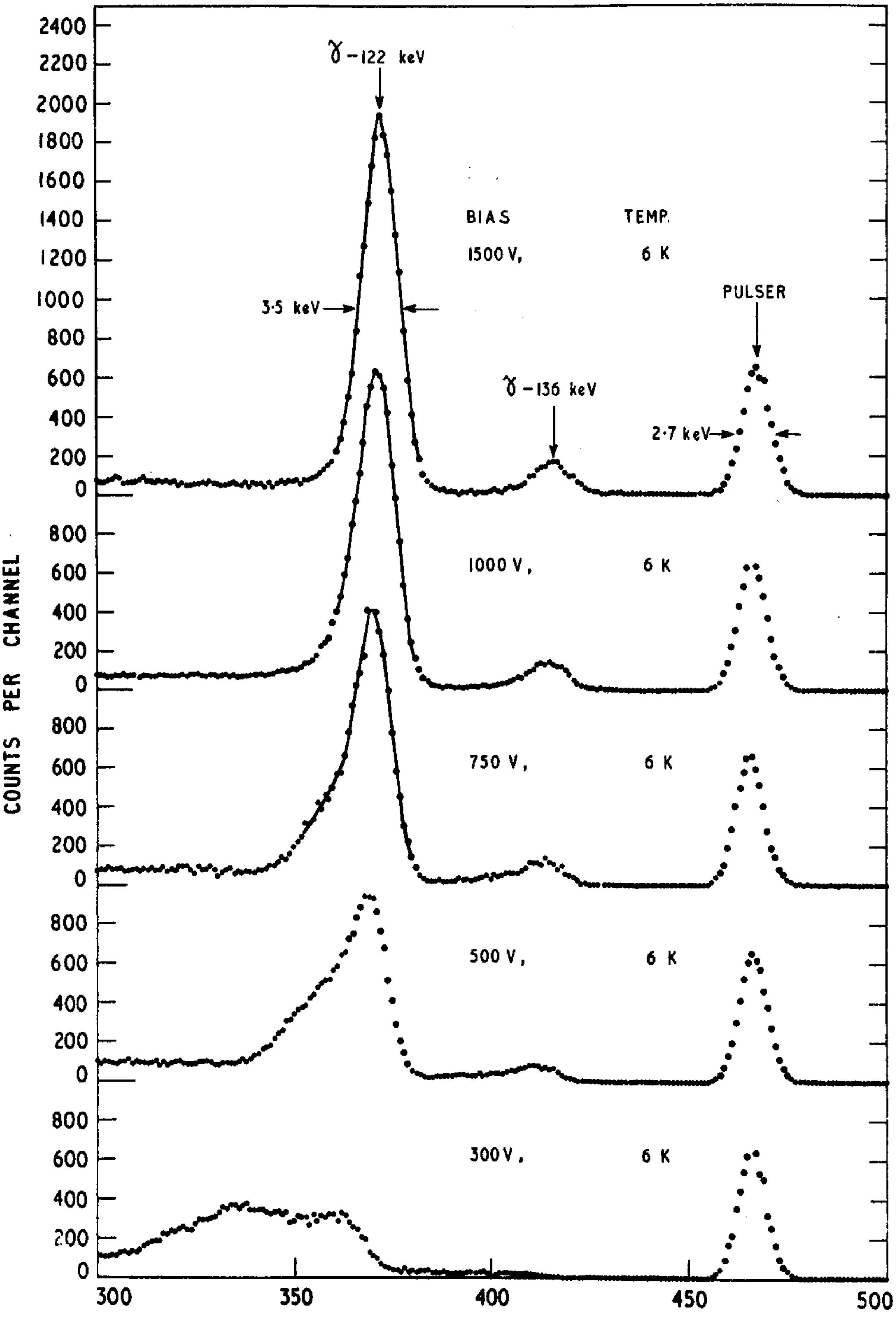

FIGURE 4. ^{57}Co γ-RAY SPECTRA AT 6 K WITH VARYING BIAS ON THE SILICON DETECTOR

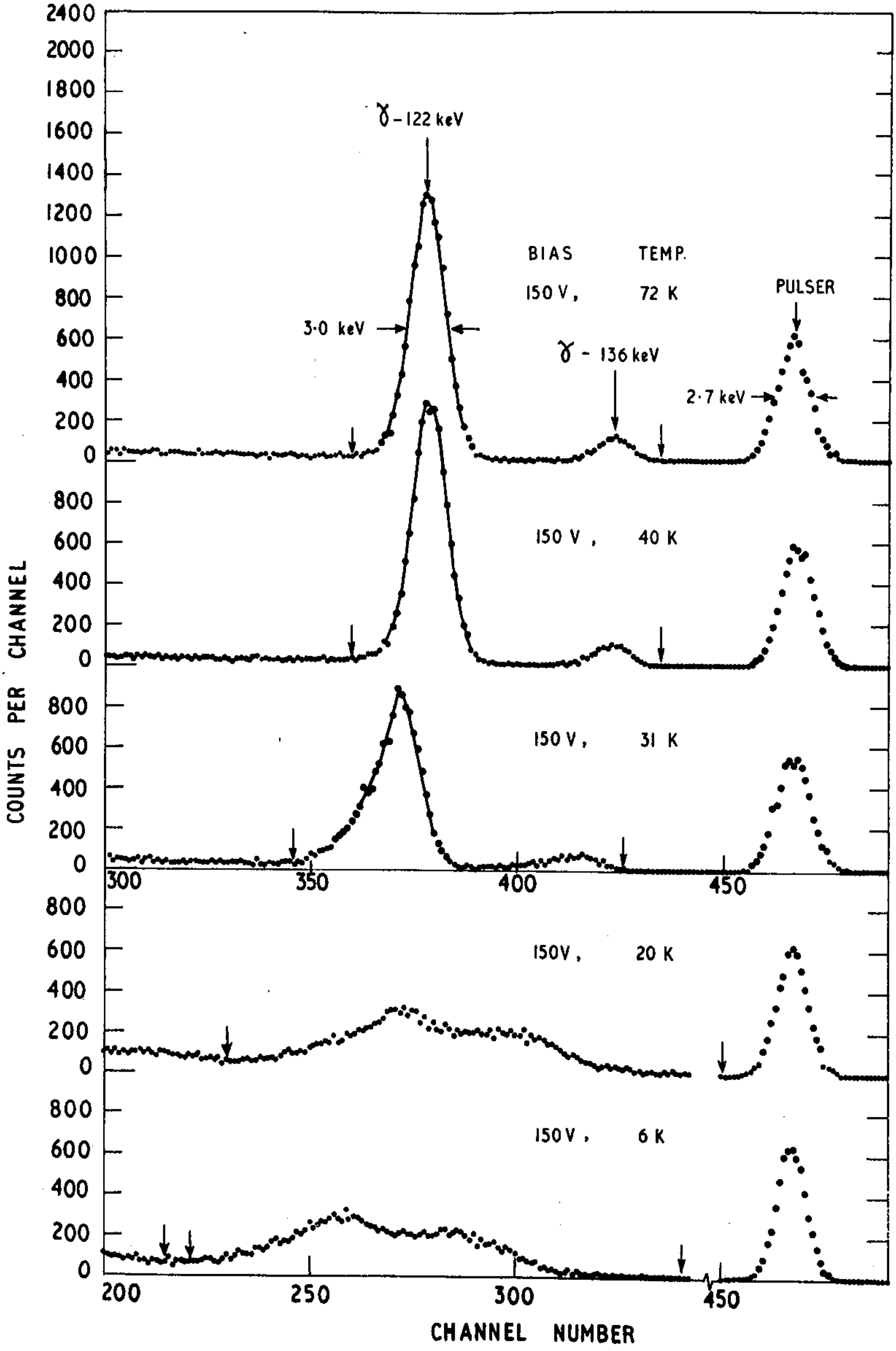

FIGURE 5. ^{57}Co γ-RAY SPECTRA BETWEEN 78 AND 6 K WITH 150 V ON THE SILICON DETECTOR

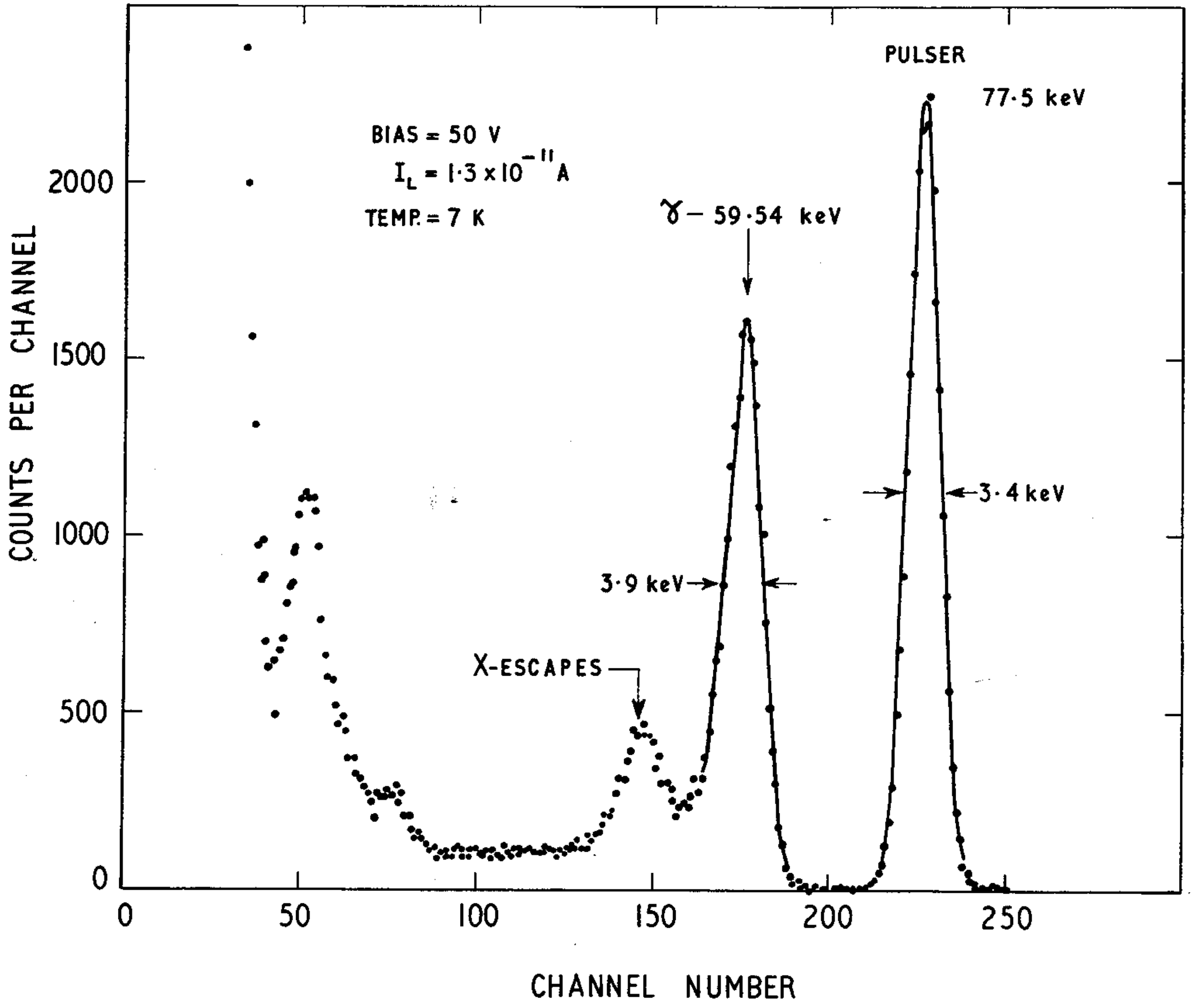

FIGURE 6. ^{241}Am γ-RAY SPECTRUM FROM A GALLIUM ARSENIDE DETECTOR AT 7 K