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ABSTRACT

Diode characteristics and spectral response to ^{137}Cs γ-rays of a gold-barrier detector made from hyper-pure germanium (net donor concentration 3×10^{11} cm^{-3}) were examined over the temperature range 5 – 78°K. Trapping at the primary shallow donor is believed responsible for poor energy resolution at low temperatures. At 5°K a best resolution of 10 keV FWHM was obtained.

Efficiency measurements indicate no change in depletion depth on cooling to 5°K with constant bias, in contrast to capacitance measurements. The latter variation, however, can be explained in terms of the response of the detector equivalent circuit to bridge frequency and carrier freeze-out effects.

Field-assisted de-trapping at the primary shallow donors is believed responsible for the temperature independent depletion depth and an improvement in resolution with bias in the low temperature carrier freeze-out region (< 10°K).

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CONTENTS

1. INTRODUCTION

The results obtained from the operation of a germanium gold-barrier γ-ray detector near liquid helium temperature (5 °K) are discussed. The detector was fabricated from hyper-pure n-type germanium. Diode characteristics (leakage current and capacitance) and spectral performance (resolution and efficiency) were examined in detail at this temperature and at 78 °K and some additional measurements were made at intermediate temperatures.

Very few references in the literature describe the operation of germanium p-n junction detectors near liquid helium temperature and the reported information is scant and somewhat conflicting (Airapetiants et al. 1957, Walter et al. 1961, Goulding 1964 and Tambovtsev 1969). Some of the available information is reviewed by Martini et al. (1970). Some α- and/β-particle spectra are published in these references but no γ-ray spectra or numerical data for efficiencies to β- and γ-radiations. Walter et al. 1961 observed qualitatively an increased detector sensitivity to these radiations at the lowest temperatures.

The ^{137}Cs spectra recorded here are the first reported from a germanium p-n junction detector at liquid helium temperature.

Hyper-pure germanium with doping densities down to a few times 10^{10} cm^{-3} has recently become available*. Depletion depths of several mm can be obtained at 78 °K with such material without recourse to lithium-ion drifting (Baertsch and Hall 1970, Tavendale 1970, Baertsch 1970, and Sakai et al. 1970). Unlike the Ge(Li) variety such detectors are stable and can be stored at room temperature without deterioration. In some studies, for example on nuclear orientation, it may be desirable to operate γ-ray detectors made from this material at liquid helium temperatures.

2. EXPERIMENTAL DETAILS

A surface barrier detector was fabricated from hyper-pure n-type germanium. A 2 mm thick slice was cut from the parent crystal and lapped into the shape of a disc with a diameter of 19 mm. The purity of this particular slice was determined, from measurements of the diode capacitance at 78 °K, to be 3×10^{11} cm^{-3}.

A low resistance ohmic contact and a blocking p-contact were prepared on the sample after etching to remove lap damage. The ohmic contact was obtained by lithium diffusion (5 min. evaporation at 350 °C). It was ~0.4 mm thick and stable since the solubility of lithium in germanium at room temperature is ~ 3×10^{13} cm^{-3} (Hall and Soltys 1970). The blocking contact was produced by vacuum evaporation of a thin layer (~ 200 Å) of gold onto a freshly etched surface. The techniques have been described in Tavendale (1970).

The cryostat was 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 liquid helium boil-off rate. The detector was surrounded by two radiation shields, the inner at liquid helium temperature and the outer at liquid nitrogen temperature. Temperature was measured with a gold (0.03 atomic percent iron) – chromel thermocouple which has a high sensitivity at liquid helium temperature (~ 15 μV/°K). The reference junction was maintained at the boiling point of liquid nitrogen.

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* Supplied by General Electric Co., Schenectady, U.S.A.

The analysis system consisted of a charge sensitive preamplifier with a first stage F.E.T. at room temperature (Ortec 118A), an active filter amplifier (Ortec 440) and a 1024 channel pulse-height analyser (Nuclear Data 1024).

3. MEASUREMENTS

3.1 Diode Characteristics

On cooling from 78°K 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 (see Figure 1). At 5°K the form of the leakage current characteristic was similar to that at 78°K as is shown in Figure 2. For low values of reverse bias the difference in magnitude was only a factor of ~ 10. However at the lower temperature, breakaway occurred later with the result that higher biases could be applied during spectrometer operation.

Capacitance characteristics of the diode were measured at 78°K and 5°K and these are shown in Figures 3 and 4. The capacitance was determined at 1 kHz by a conventional RC bridge and at 130 kHz by a Type 130 Tektronix LC meter. The 130 kHz capacitance was examined between 78°K and 5°K and a marked change was observed between 5°K and 10°K. These data are shown in Figure 5.

3.2 Spectral Performance

Spectra from ^{137}Cs were examined at 78°K and 5°K for several values of reverse bias. A marked deterioration in resolution was observed on cooling below 10°K. Spectra at 200 volts are shown in Figures 6 (78°K, 5.8 keV FWHM) and 7 (5°K). By increasing the bias, the spectral response at 5°K was markedly improved, as shown in Figure 8 at 600V bias (10.0 keV FWHM). Figure 9 shows a 200V spectrum recorded between 11°K and 15°K as the detector warmed up. The resolution of 4.2 keV FWHM (system limited) was the best measured.

Relative efficiency measurements at 662 keV were made by adopting a fixed ^{137}Cs source geometry. Figure 10 shows relative efficiency measurements taken at 78°K and 5°K. It should be noted that no change in the efficiency at 200V occurred over this temperature range.

4. DISCUSSION

The saturation of the diode current observed for fixed bias at temperatures < about 25°K is considered to arise from external sources such as seal leakage rather than from the detector. No current breakdown that might be ascribed to impact ionisation of impurities at low temperatures (discussed by Martini et al. 1970) was observed.

Capacitance measurements at 130 kHz (Figures 4 and 5) suggest a marked increase in the depletion depth. The change in capacitance is reduced towards higher bias values but the difference is still significant in the region above 100V where the efficiency measurements were made. At 130 kHz the change in capacitance with temperature is dramatic and occurs at about 10°K (see Figure 5). Data at 1 kHz (taken from Figure 3) indicate a similar change in capacitance but at a lower temperature (the capacitance at 1 kHz was not recorded at temperatures other than 5°K and 78°K).

The observed rapid change in detector capacitance with temperature may be explained qualitatively in terms of the response of the equivalent circuit of the detector represented by the depletion region capacitance in series with the parallel combination of capacitance and resistance of the undepleted region (see Figure 11 and also Martini et al. 1970). At temperatures > about 10°K, carrier freeze-out on the primary shallow donors is not significant and therefore the resistance of the undepleted layer remains low enough to short the capacitative component giving a measured value of the depletion layer capacitance only. However, at temperatures < about 10°K freeze-out increases, giving a high value of resistance for the undepleted layer. The detector capacitance measured under these circumstances will tend towards the series combination of the depleted and undepleted regions, which equals that of the detector when wholly depleted. The detector equivalent circuit is such that at a fixed temperature the effect of carrier freeze-out on the detector capacitance will be first sensed at higher frequencies, as observed.

The ^{137}Cs efficiency measurements (Figure 10) indicate no change in the depletion depth on cooling to 5°K. It is proposed that this observation may be explained by a model based on field-assisted de-trapping. Application of bias allows complete ionisation of the shallow donors, restoring the depletion depth and field distribution obtained at high temperatures. The efficiency therefore remains constant. Field-assisted de-trapping is discussed by Martini and McMath (1970) and Mayer et al. (1970) in relation to the low temperature spectral performance of semiconductor detectors. The measurements of Martini and McMath for a Ge(Li) detector indicate that the average time for de-trapping, and therefore restoration of the depletion layer (following the application of bias), in the detector used in this experiment is very short, $\sim 10^{-9}$ sec.

The good ^{137}Cs energy resolution measured at 78°K is maintained at first as the temperature is lowered. The resolution in fact improves owing to a decrease in the leakage current. Below $\sim$ 10°K, however, there is a marked deterioration in the resolution. Figures 6, 9 and 7 illustrate these effects. On examining source pulses from the preamplifier, two components were observed in the risetime at 5°K. 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 perhaps 100 times less. Increasing the bias reduced the relative magnitude of the slow component and improved the resolution. Figure 8 shows a spectrum obtained at 600 volts and comparison with Figure 7 indicates the improvement obtained. Lengthening the amplifier time constant also improved the resolution.

Since the worsening of the resolution took place at low temperatures, below 10°K, it is proposed that the observed effects are due to trapping by a shallow level followed by subsequent de-trapping. Since the material is n-type it is probable that at low temperatures the donors act as electron traps. There is evidence for the trapping of only one carrier in the slight shift with bias of the ^{137}Cs photopeak upper edge. Experiments by Martini and McMath 1970 with Ge(Li) and Si(Li) detectors also suggest that the primary shallow dopants act as traps at low temperatures. However they find that for Ge(Li) detectors the resolution deteriorates at a higher temperature (20 – 30°K). This difference may be due to the doping densities involved. It is proposed that the improvement in resolution with applied bias is due to the field-assisted de-trapping effect discussed earlier.

While it is possible that the slow components and hence the poor resolutions found below 10°K, are due to the resistance and capacitance of the undepleted region becoming significant, it is considered that the time constant due to this effect would be at least one order of magnitude smaller than the trapping time constant seen. An explanation in these terms is considered less plausible than the trapping-de-trapping proposal but should not be forgotten. It is conceivable that both effects occur simultaneously. Further experimental work will be done to investigate this problem.

5. SUMMARY

This investigation has two important results. Firstly we report the first γ-ray spectra obtained with a germanium p-n junction detector at liquid helium temperature. Extrapolation of the published ^{137}Cs results using Ge(Li) or Si(Li) detectors at temperatures above 10 °K suggests resolutions at 5 °K poorer than the best measured in this work.

Secondly, the germanium used in this experiment was of ultra high purity (3×10^{11} cm^{-3}). No previous investigations on this material at liquid helium temperature have been reported. Since the doping density of this material is 100 times lower than that used in Ge(Li) and Si(Li) detectors, the mean free path for trapping is increased by this factor. Since resolution can be characterised (to a first approximation) by d/λ where d is the depletion depth and λ the mean free path, the resolution of this detector should be much better than that from Ge(Li) or Si(Li) devices.

The investigation also suggests that trapping and de-trapping at the shallow primary dopant is responsible for the poor energy resolution found below 10 °K. We suggest that field-assisted de-trapping is the mechanism responsible for both the improvement in resolution at high bias and the independence of detector depletion depth with temperature at constant bias.

6. ACKNOWLEDGEMENTS

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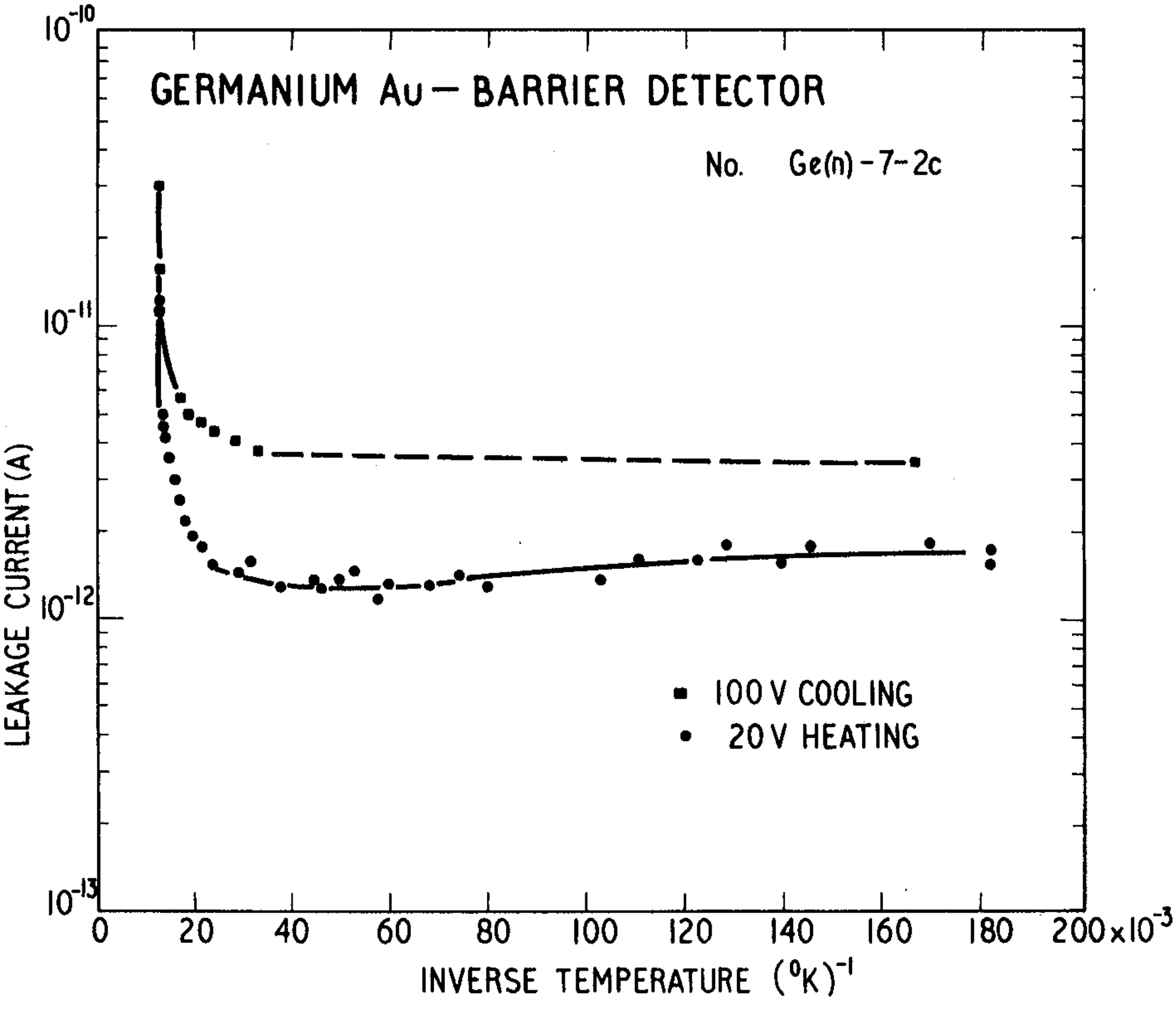

FIGURE 1. LEAKAGE CURRENT v. INVERSE TEMPERATURE

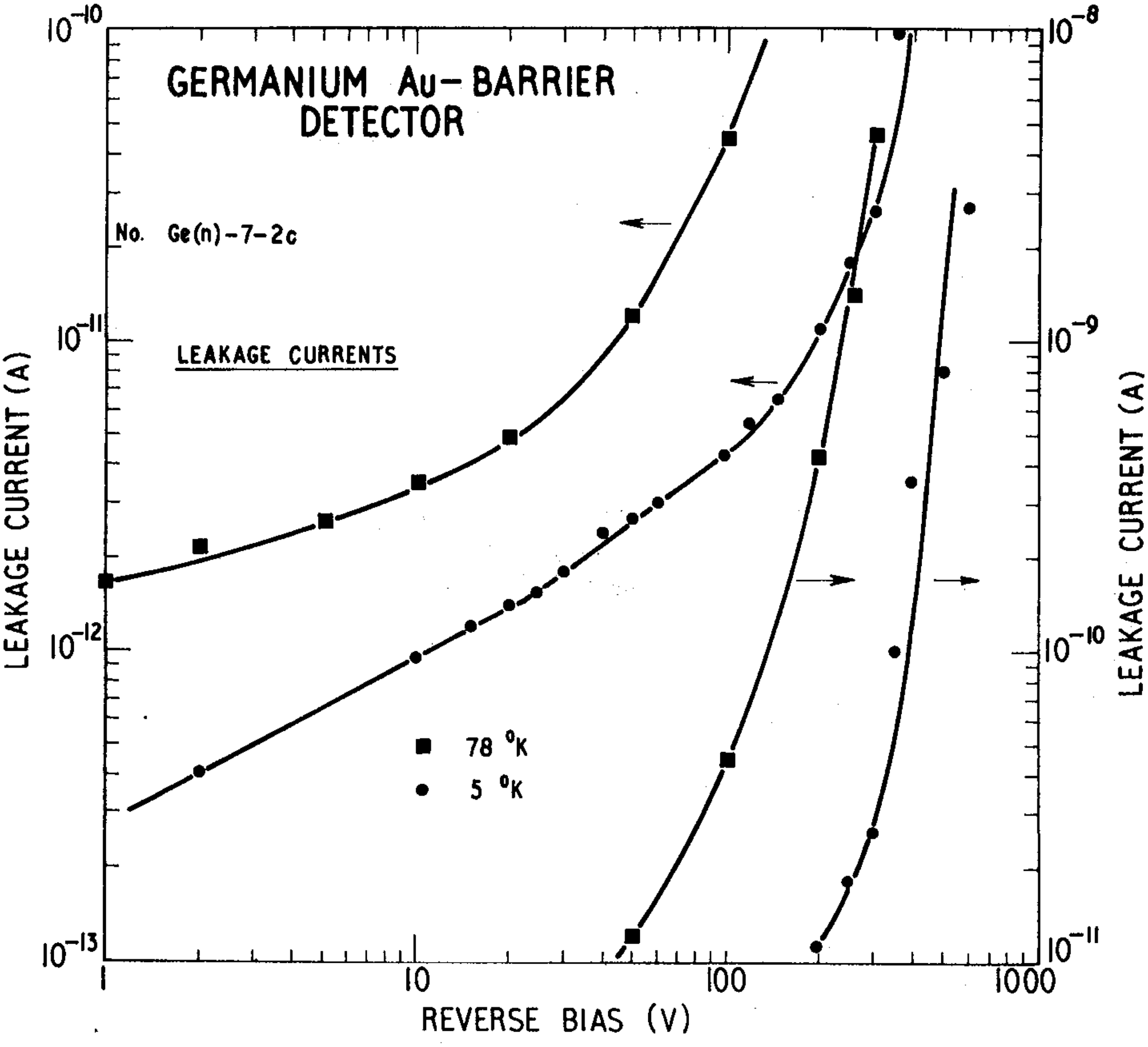

FIGURE 2. LEAKAGE CURRENT v. BIAS AT 78°K AND 5°K

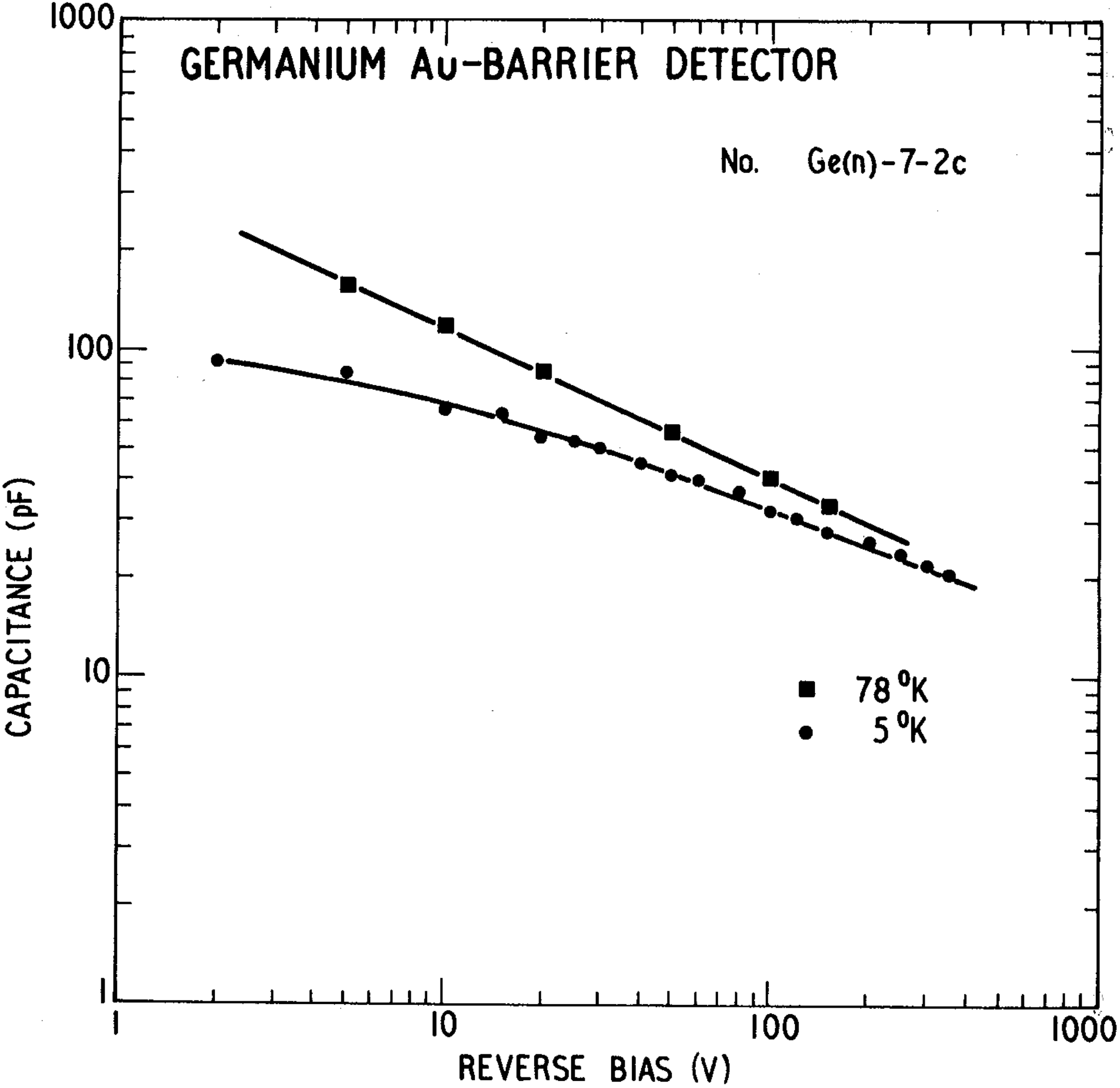

FIGURE 3. CAPACITANCE (1kHz) v. BIAS AT 78°K AND 5°K

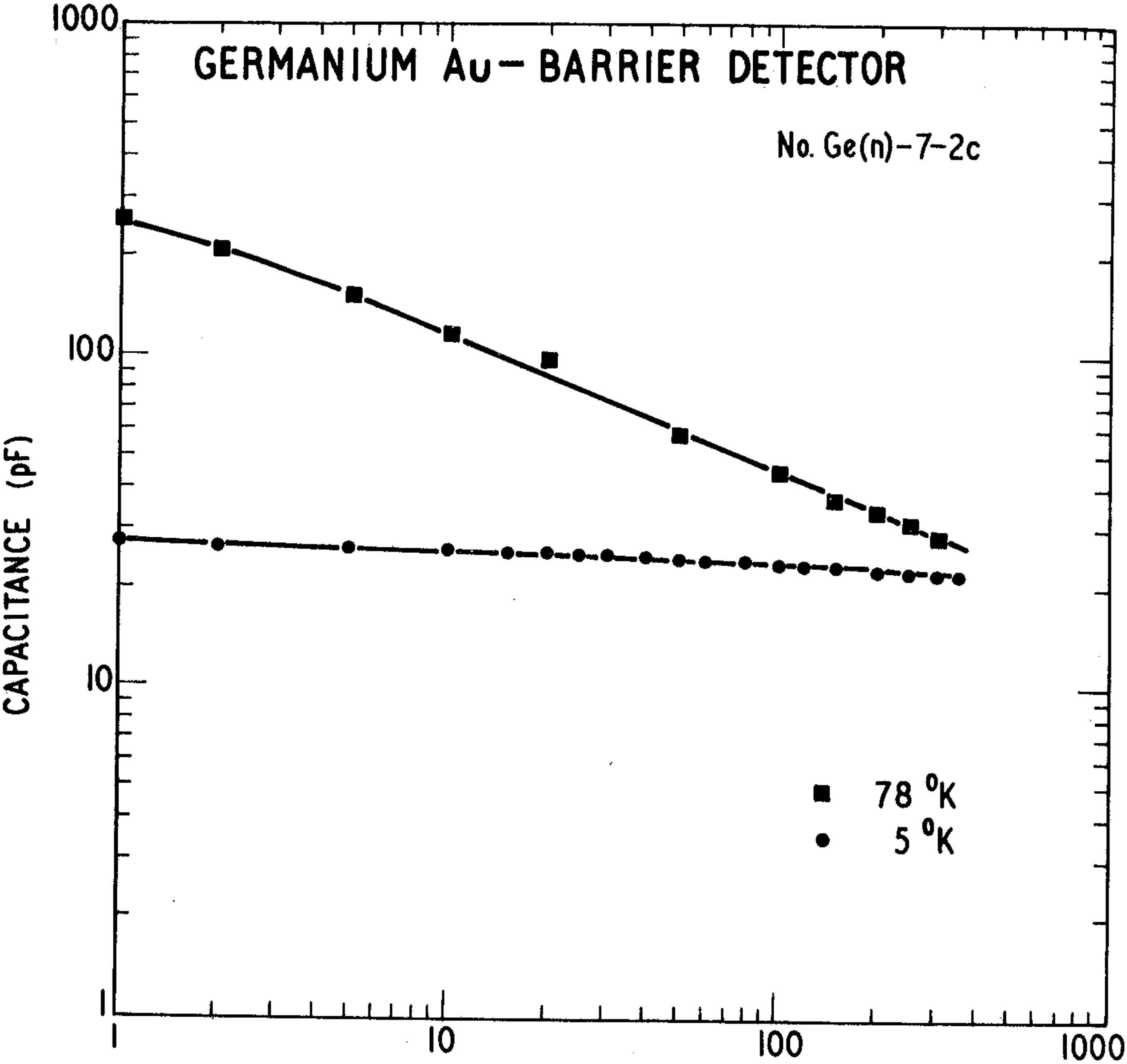

FIGURE 4. CAPACITANCE (130 kHZ) v. BIAS AT 78°K AND 5°K

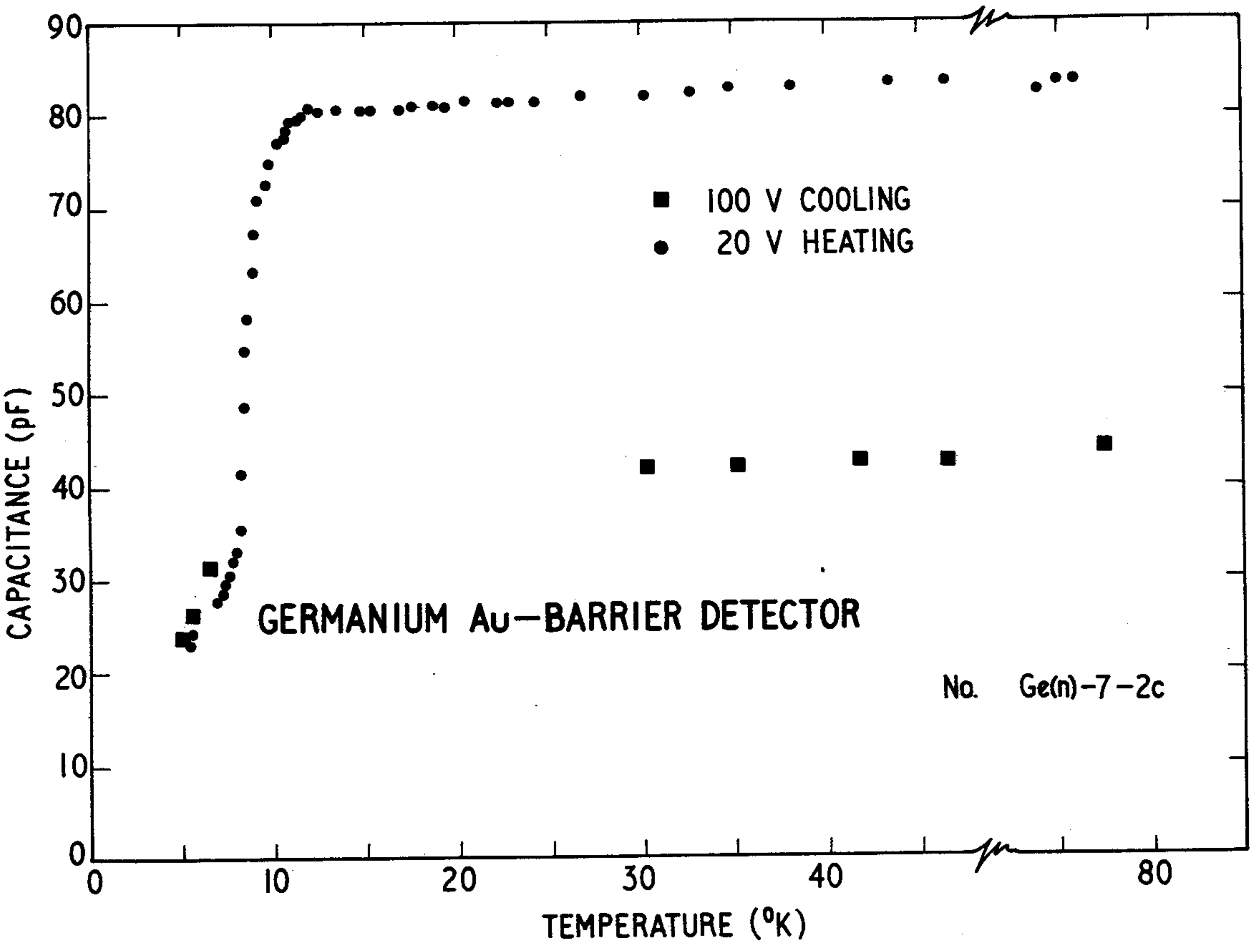

FIGURE 5. CAPACITANCE (130kHz) v. TEMPERATURE

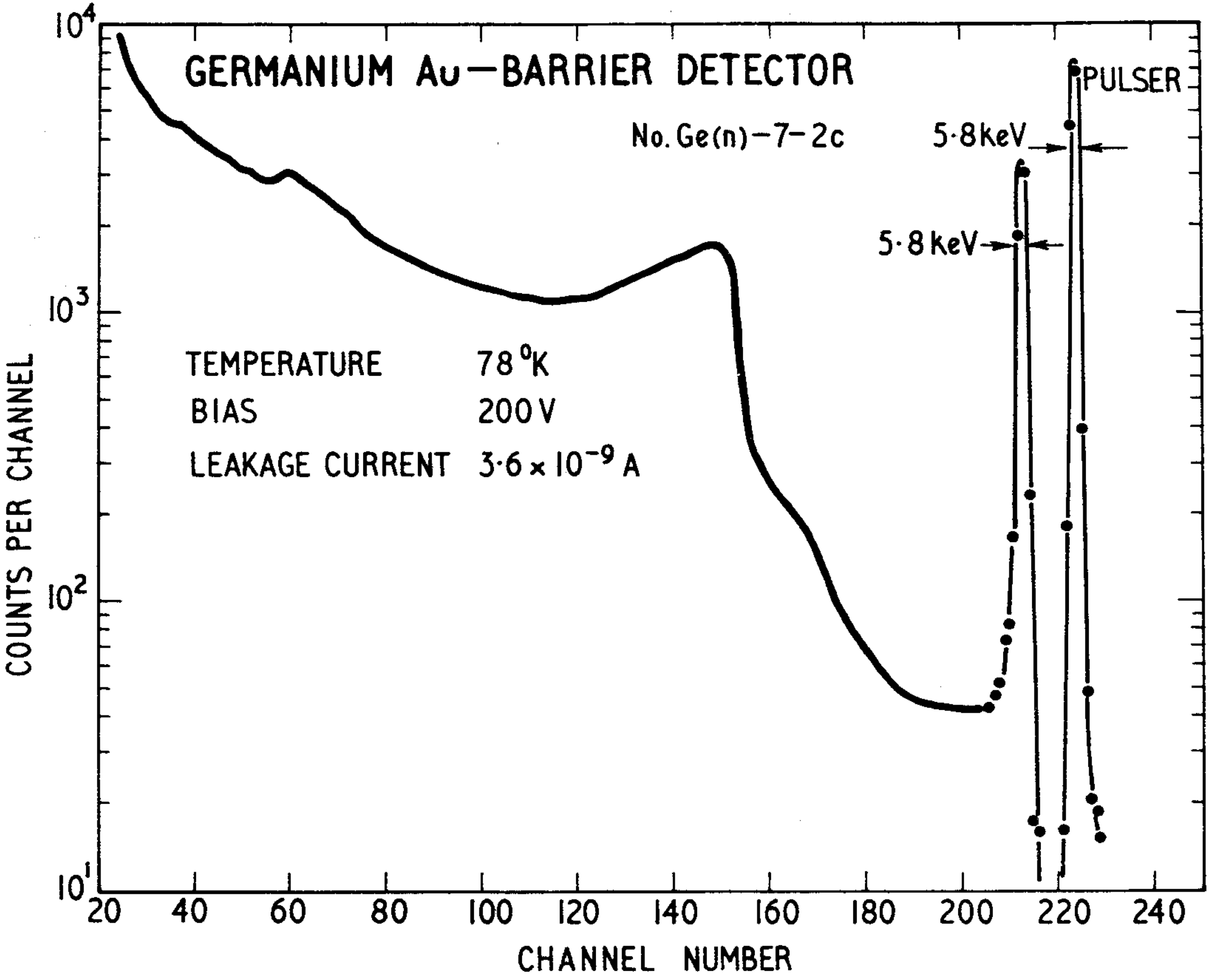

FIGURE 6. ^{137}Cs SPECTRUM AT 78°K AND 2000V BIAS

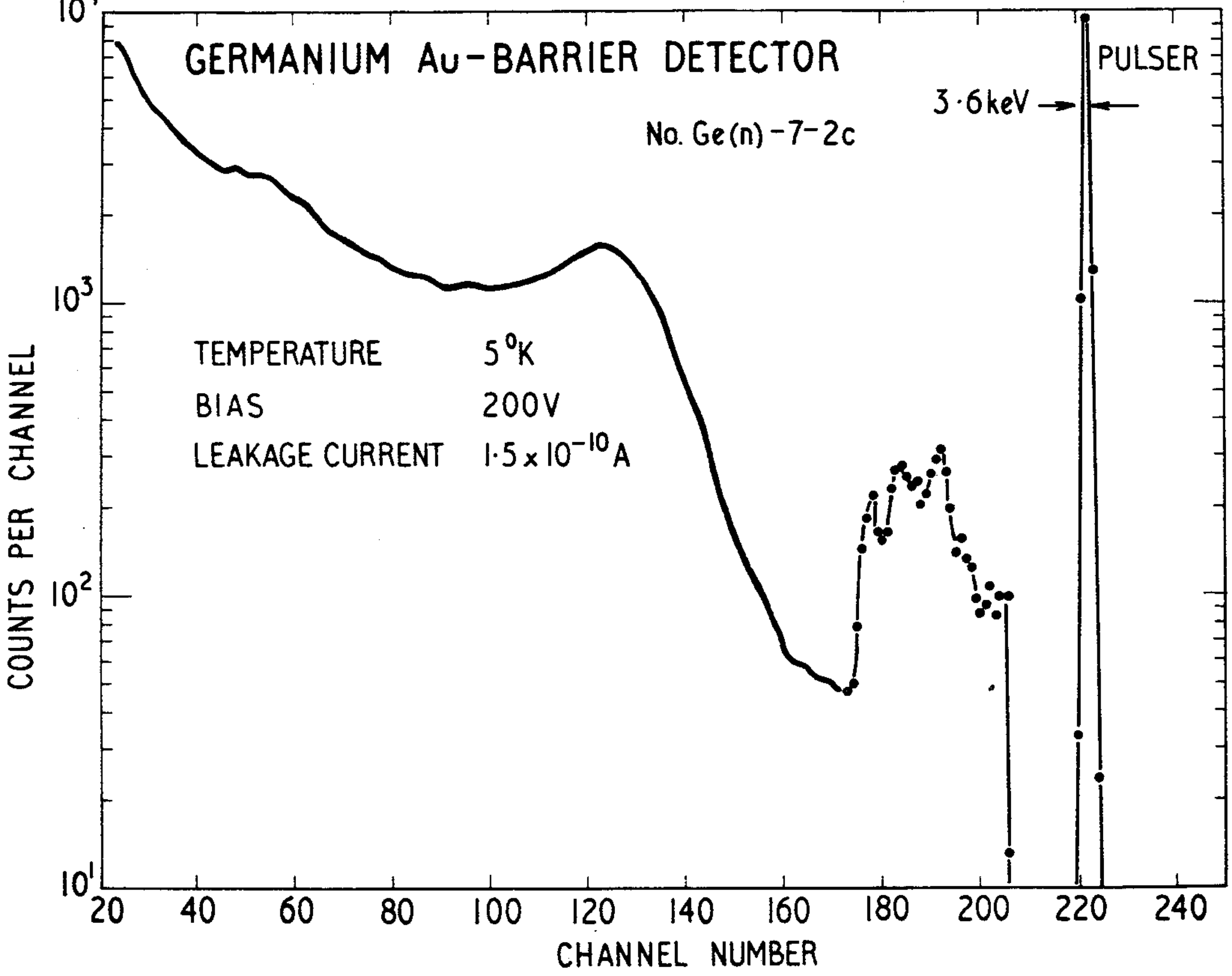

FIGURE 7. ^{137}Cs SPECTRUM AT 5°K AND 200V BIAS

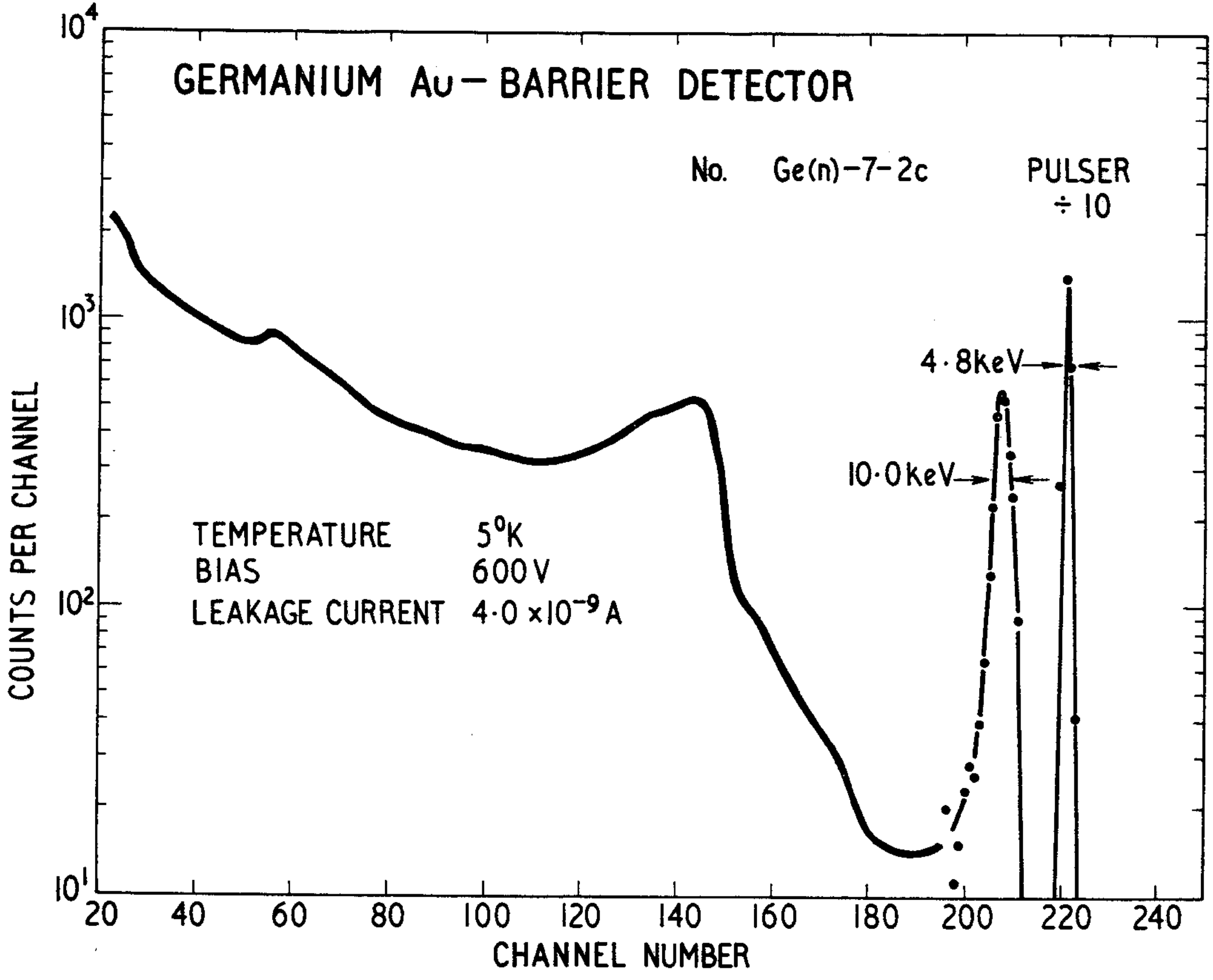

FIGURE 8. ^{137}Cs SPECTRUM AT 5°K AND 600V BIAS

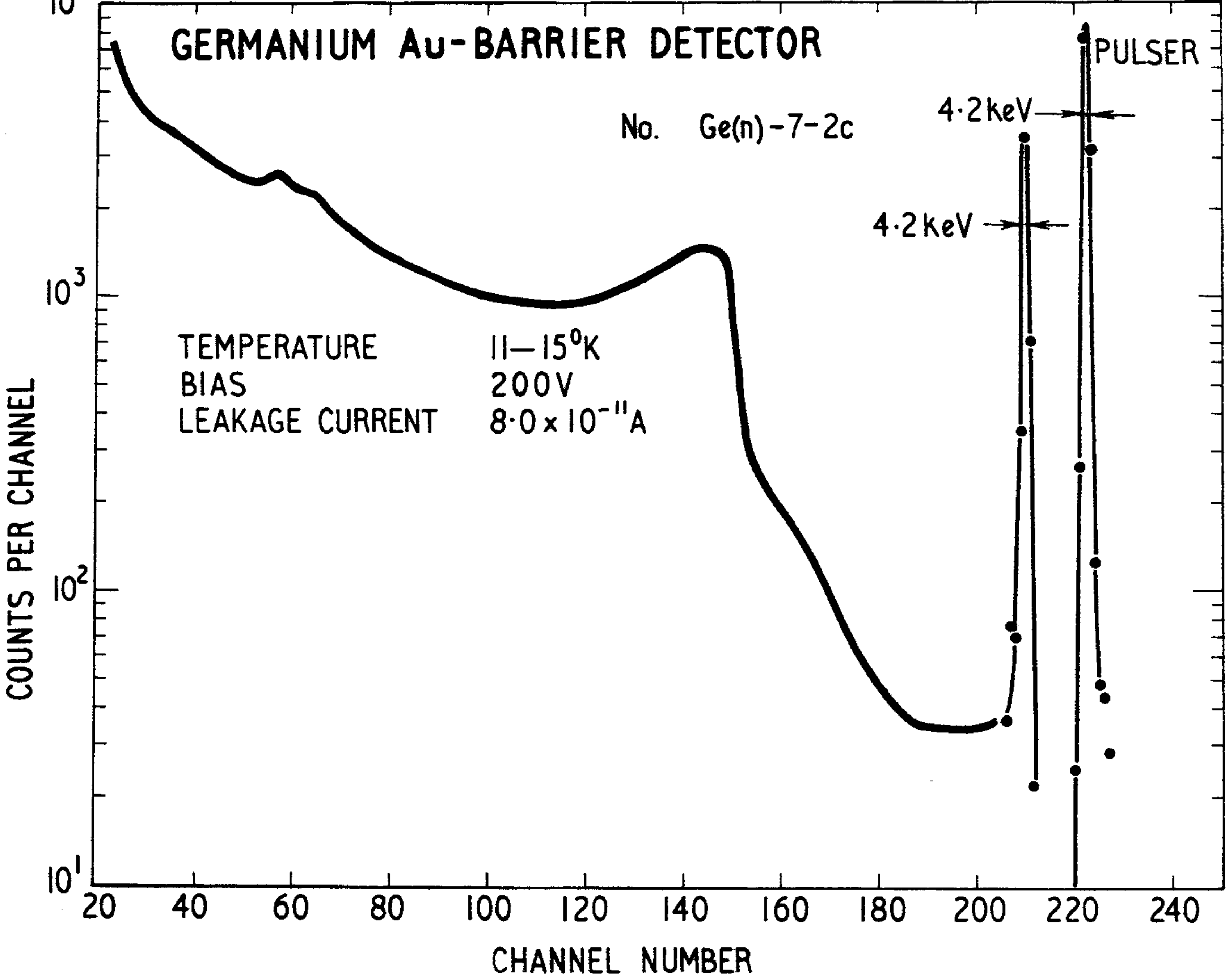

FIGURE 9. ^{137}Cs SPECTRUM AT 11-15°K AND 200V BIAS

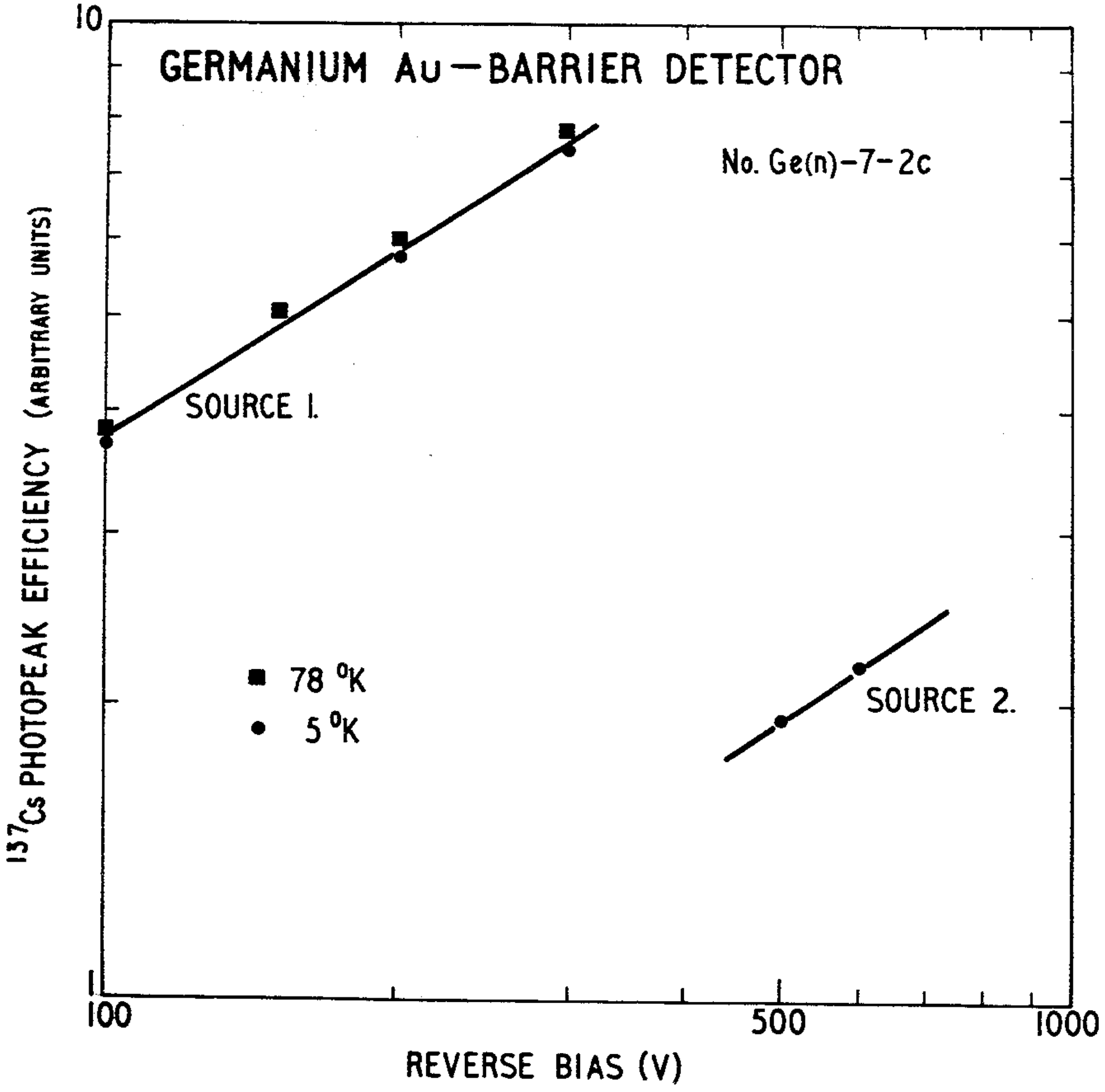

FIGURE 10. ^{137}Cs RELATIVE EFFICIENCY MEASUREMENTS AT 78°K AND 5°K

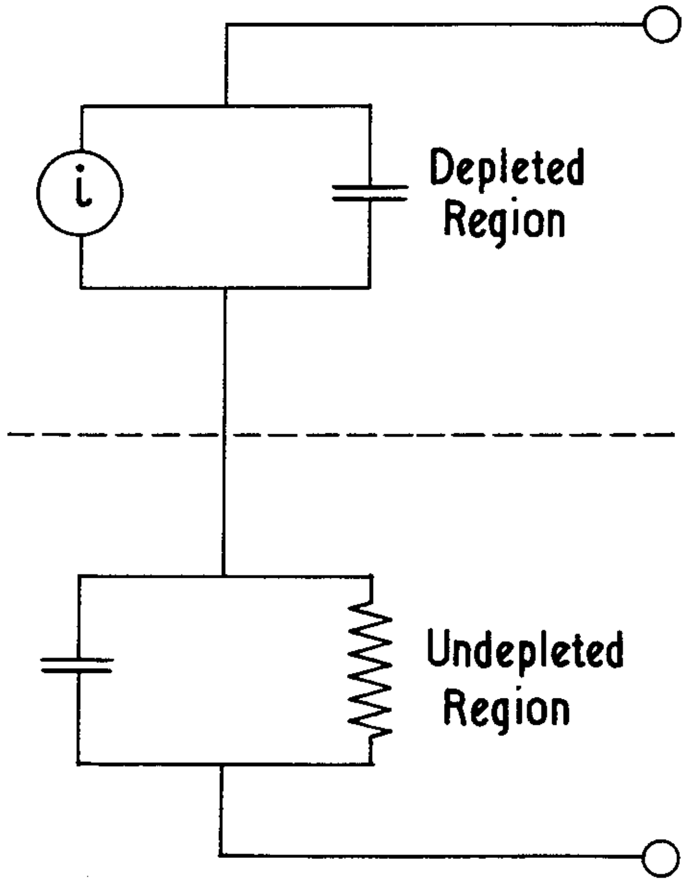

FIGURE 11. EQUIVALENT CIRCUIT OF A p-n JUNCTION DETECTOR