LBL-25373 c. 2
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Engineering Division

Submitted to Journal of Applied Physics

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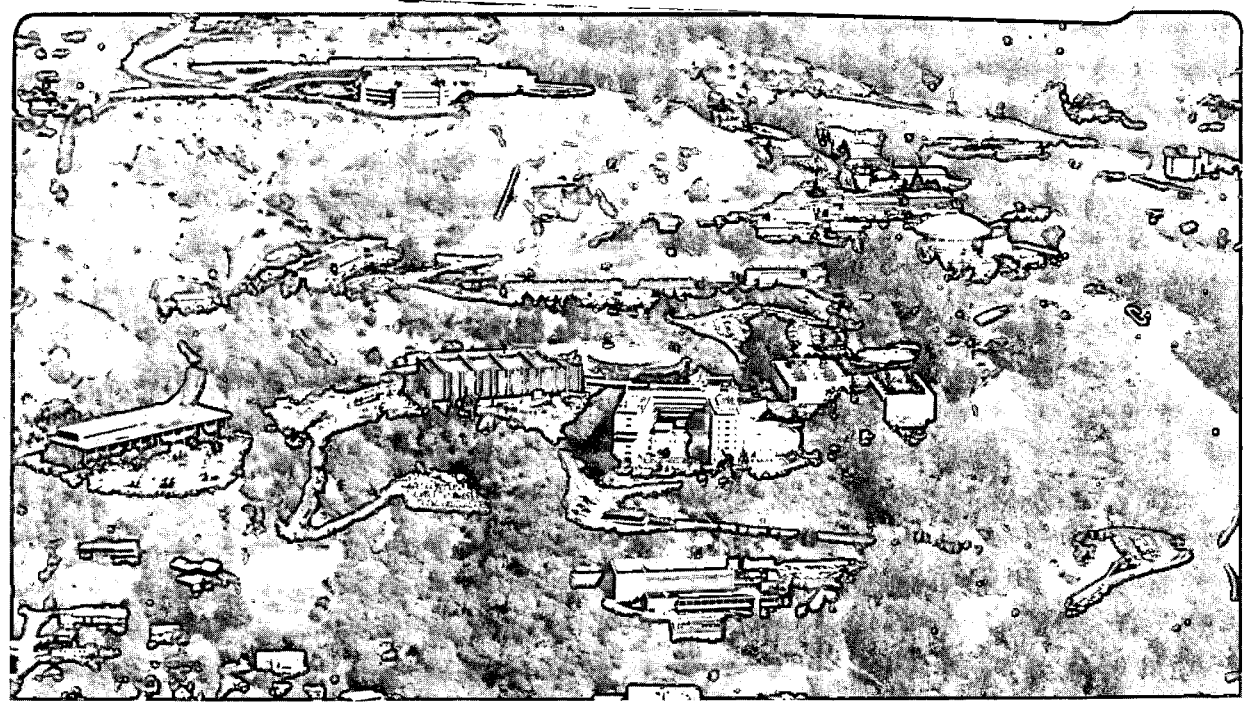
June 1988



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

Voltage-Assisted Calorimetric Ionization Detector*

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A new approach to ionizing radiation detection is proposed. The amount of ionization produced in a detector medium is measured by the heat generated as the charged carriers are drifted across the device under an applied voltage. The amount of energy generated can be orders of magnitude larger than that deposited by the radiation itself. A dramatic increase in detector mass can be achieved compared to simple calorimetric particle detectors for equivalent energy thresholds. It is possible to obtain a sensitivity level sufficient for single carrier detection. The principle of operation has been demonstrated with an experimental device operated at a temperature of 1.8 K and improved performance is expected at lower temperatures.

* This work was supported by the Director's Office of Energy Research, Office of Health and Environmental Research, Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Energy dispersive detectors capable of measuring low energy ionization events ($\lesssim 1$ keV) with good energy resolution are of interest in x-ray spectroscopy and in other areas of research. In particular, if low threshold detectors with large mass can be developed, applications would be found in the search for dark matter particles by direct impact process[1] or perhaps in the study of low energy neutrino scattering.[2]

Among traditional energy dispersive detectors, semiconductor p-i-n diode ionization detectors offer the best resolution and the lowest energy threshold. Their operation relies on the creation of free charged carriers, in this case electron-hole pairs, by absorbed radiations. The number of electron-hole pairs created is given by $N = E/\epsilon$, where E is the energy deposited by the radiation and ϵ is the average energy expended in creating one electron-hole pair. In a detector, the number of electron-hole pairs is determined by collecting them using an applied reverse bias voltage and measuring the resultant electric charge flowing in the external circuit. The ultimate resolution achievable is limited by the fluctuations in this number as a result of the statistical sharing of energy between ionization and phonon generation.[3] This is given by:

$$\Delta E = \sqrt{E\epsilon F} \qquad (1)$$

where F is the Fano factor which depends on the detail of the ionization process and is material dependent. Semiconductor detectors exhibit low values of F (~ 0.1) and ϵ (3 eV for Ge and 3.7 eV for Si), thus giving excellent resolution and responding to radiations with very low energies. However, the presence of noise in the charge measuring electronics limits the detection of single events to those with $E \gtrsim 100$ eV and limits the energy resolution at low energies.

In recent years, calorimetric X-ray and particle detectors have been developed that can achieve better energy resolution and lower energy threshold than conventional semiconductor detectors.[4] In this case, the energy

deposited by the radiation in an absorber is converted into heat which is then measured as a temperature rise of the device. To achieve the neccessary sensitivity, a low heat capacity is required. This is accomplished by cooling to low temperature and using materials with high Debye temperatures. The ultimate energy resolution for a device with heat capacity C at temperature T is related to the thermodynamic noise which is given by:

$$\Delta E = \sqrt{k_B T^2 C} \tag{2}$$

where k_B is the Boltzmann's constant. It has been shown that with optimized design and signal processing, noise in a practical detector is given by this expression multiplied by a dimensionless factor whose value depends mainly on the responsivity of the temperature sensor.[4] Using semiconductor thermistors, a factor $\lesssim 2$ can be achieved. For materials that obey the Debye T^3 law at low temperatures, we have $C \propto MT^3$, where M is the mass of the device, and thus $\Delta E \propto \sqrt{T^5 M}$. Therefore, at sufficiently low temperature, very good energy resolution and low threshold can be obtained. Indeed, calorimetric detectors with a noise level of ~ 10 eV full width at half maximum (FWHM) and comparable energy resolution have been demonstrated.[5] However, these devices have very small volumes, of the order of 10^{-5} cm^3, and have to be operated at temperatures of $\lesssim 0.1$ K. Devices with much larger volumes are, in principle, feasible but they would require extremely low operating temperatures. At these temperatures, however, other problems may arise such as deviations of the device's heat capacity from T^3 dependence, and decoupling of phonons and electrons which can affect the response of the thermal sensor.[5,6]

In this paper, I propose and demonstrate a new approach to detection which combines the calorimetric and ionization measurement techniques. This could lower the detection threshold of ionization detectors drastically while allowing much larger masses than simple calorimetric detectors at the same operating temperature. The idea is simply to determine the amount of

ionization in a detector using thermal instead of charge measurement. The heat to be measured in this case is generated as the charged carriers are drifted across the detector under an applied bias voltage. The amount of energy dissipated by a carrier is equal to the change in its potential energy. In most situations this energy will be converted entirely into heat. Provided the carriers are fully collected, the total energy generated as a result of the absorption of radiation with energy E is given by:

$$E_T = \frac{E}{\varepsilon} eV_b + E(1 - \frac{\delta}{\varepsilon}) \qquad (3)$$

where V_b is the bias voltage across the detector, e is the electronic charge, and δ is the minimum ionization energy which is equal to the band gap of the material. The last term in the equation is that part of the radiation's energy that goes directly into thermal processes. For large V_b, the amount of energy generated can be much higher than that of the radiation itself, giving an effective energy gain of $\approx eV_b/\varepsilon$. Therefore, a large gain in signal can be obtained compared to that from a simple calorimeter under otherwise identical conditions. Since the noise of a calorimetric detector varies as the square root of the thermal mass, a factor of $(eV_b/\varepsilon)^2$ increase in mass can, in principle, be achieved or the operating temperature can be increased substantially while maintaining the same equivalent energy threshold.

It should be emphasized, however, that since the calorimetric ionization detector still relies on ionization detection, its energy resolution is limited by statistical variations in the ionization process and thus cannot compete with simple calorimeters in terms of ultimate resolution. On the other hand, the increased signals result in excellent signal-to-noise ratios which lead to a much lower detection threshold and improved resolution at low energies compared with conventional ionization detection techniques. Calculations show that for a 1 cm^3 germanium or silicon crystal at 0.1 K, the noise for normal calorimetric operation would be ~ 1 keV FWHM, assuming a

factor of ~ 4 increase above the thermodynamic noise. If they are operated with a bias voltage of 3000 V which gives an energy gain of ~ 1000, the equivalent noise would be ~ 1 eV FWHM. A noise level less than ϵ means that a single electron-hole pair can be resolved and any ionizing events can be detected, including single photons with energy greater than the band gap of the material (i.e., the near infrared region).

The construction of a calorimetric ionization detector is identical to a conventional calorimeter except for the radiation absorber which, in this case, is basically a conventional ionization detector. The detector must be able to function at low temperatures with low heat capacity and with good charge collection efficiency. Semiconductor detectors are the most obvious candidates for this application.

To demonstrate the principle of operation and the possibility of obtaining large energy gain, an experimental device has been fabricated and tested (Fig. 1). It consists of a high-purity germanium p-i-n diode in the form of a cube 5 mm on a side. N-type germanium with a net donor impurity concentration of 2×10^{10} cm^{-3} was used. Full depletion of the diode occurs at a bias voltage of 250 V. The p- and n-type contacts were formed by ion implantation of boron and phosphorus respectively. This produces degenerately-doped contacts which will not totally deionize at the low operating temperature. The diode is thermally coupled to a copper heat sink via a small block of glass (~ 1 mm^3) which acts as a thermal impedance and a rigid mechanical support. The glass block has Cr-Au metalizations on opposite faces and is indium soldered to the heat sink and the diode. A neutron-transmutation-doped (NTD) germanium thermistor[7] is used as the temperature sensor. It is in the form of a cube, 0.25 mm on a side, with boron-ion-implanted contacts on opposite faces. It is attached to the p-type contact of the diode using silver epoxy. Electrical connections to the diode and the thermistor were made using 1 mil diameter brass wires which were also attached using silver

epoxy. The heat capacity of the device is dominated by the germanium diode with negligible contributions from the other parts.

The thermistor and the diode shared a common electrical ground through the diode's p-type contact while bias voltage for the diode was applied to the n-type contact. The thermistor was biased with a constant current. Variations in its resistance in response to temperature changes produced voltage signals which were sensed using an amplifier with a cooled junction field effect transistor input stage. The device was tested at a heat sink temperature of 1.8 K. A mixed ^{241}Am - ^{244}Cm source was used to supply alpha particles with energies of $\approx$5.4 MeV and $\approx$5.8 MeV. The alpha particles entered the diode through the n-type contact.

A concern in the operation of this detector is that at the low operating temperature, the ionized impurities in the diode may act as traps for the free carriers thereby preventing complete carrier collection and thus degrading the energy resolution. To determine if this is a problem, the charge signal from the diode was observed using a charge-sensitive amplifier AC-coupled to the bias voltage supply. Figure 2 shows the alpha spectra taken using this arrangement. Trapping effects were indeed seen at 600 V bias. However, the amount of trapping decreased with increasing bias and became quite small past 800 V. Near perfect charge collection was apparently obtained at 1000 V.

The device was then operated in the thermal detection mode, observing the signals derived from the thermistor. When no bias voltage was applied to the diode, the device functioned as a simple calorimeter with the diode serving as a passive absorber. In this case, no signal from the alpha particles could be detected above the noise level. With the application of bias, the signal began to rise above the noise level and its amplitude increased with increasing bias. Figure 3 shows a typical signal pulse taken at a bias of 1000 V. Its amplitude corresponds to a temperature rise of $\approx 1.1 \times 10^{-4}$ K which is in close agreement with the calculated value of 1.2×10^{-4} K based on

equation 2 and the heat capacity of the germanium diode. The signal rise time was < 100 μs. Pulse height spectra were obtained using the thermistor signals which were electronically filtered using standard analog nuclear pulse shaping electronics. A pulse peaking time of 128 μsec was used. As seen in Fig. 4, the dependence of signal amplitude on the diode bias voltage is evident. Taking into account the trapping effects also reflected in this measurement, the pulse height is linearly proportional to the bias, as expected. At 1000 V, the equivalent noise is ~ 50 keV FWHM which is derived from root mean square voltage measurements taken at the output of the pulse shaping electronics. The signal filtering and the thermistor parameters were not optimized for noise or count rate considerations. The thermodynamic noise at 1.8 K should give an equivalent noise of about 0.5 keV FWHM taking into account the energy gain. The signal decay time can be shortened by increasing the heat link's thermal conductance without affecting the optimal signal-to-noise ratio.[4]

These results show that the proposed calorimetric ionization detection technique is viable, and they demonstrate that large gain in signal can be obtained compared to simple calorimeters. The possibility of achieving large improvements in sensitivity for detecting low energy ionization events makes this technique interesting in many applications. Further investigations are in progress.

We thank E. E. Haller, F. S. Goulding, and E. Silver for many valuable discussions. We are grateful to J. Beeman for his expert assistance in the fabrication of the test device. This work was supported by the Director's Office of Energy Research, Office of Health and Environmental Research, Pollutant Characterization and Safety Research Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

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Figure Captions

Fig. 1. Structure of the experimental device.

Fig. 2. Pulse height spectra of alpha particles obtained with charge signals from the diode.

Fig. 3. Amplified unfiltered signal from the thermistor due to an alpha particle taken with a diode bias voltage of 1000 V.

Fig. 4. Pulse height spectra of alpha particles obtained from the thermistor signals.

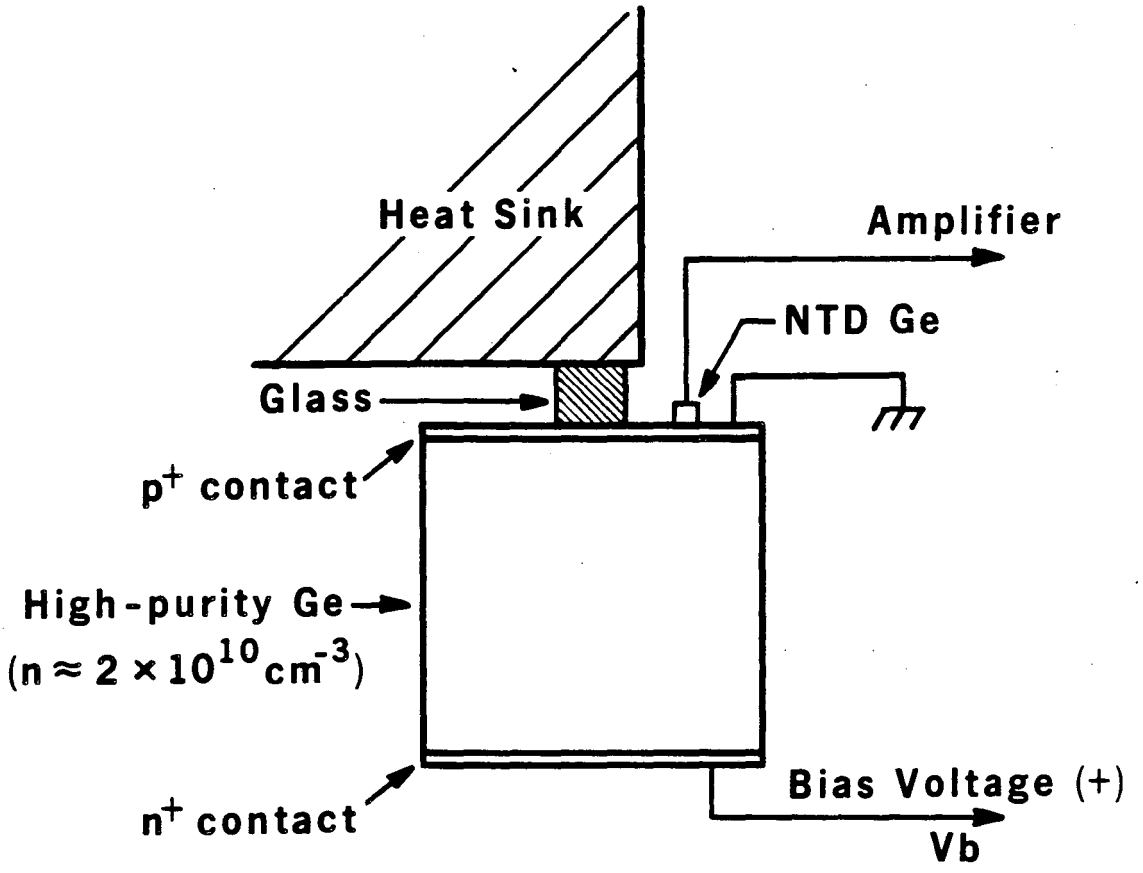

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Fig. 1.

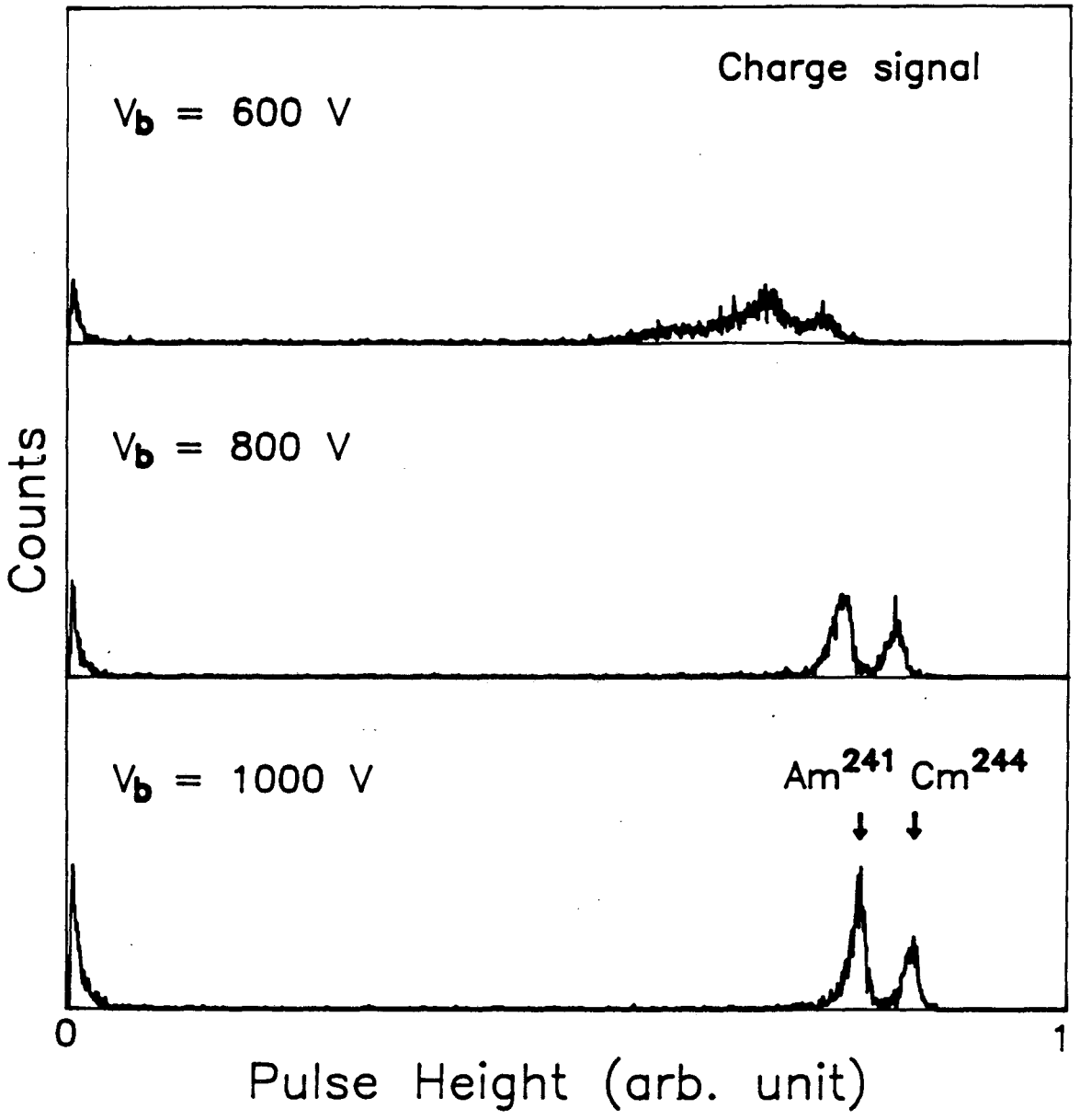

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Fig. 2.

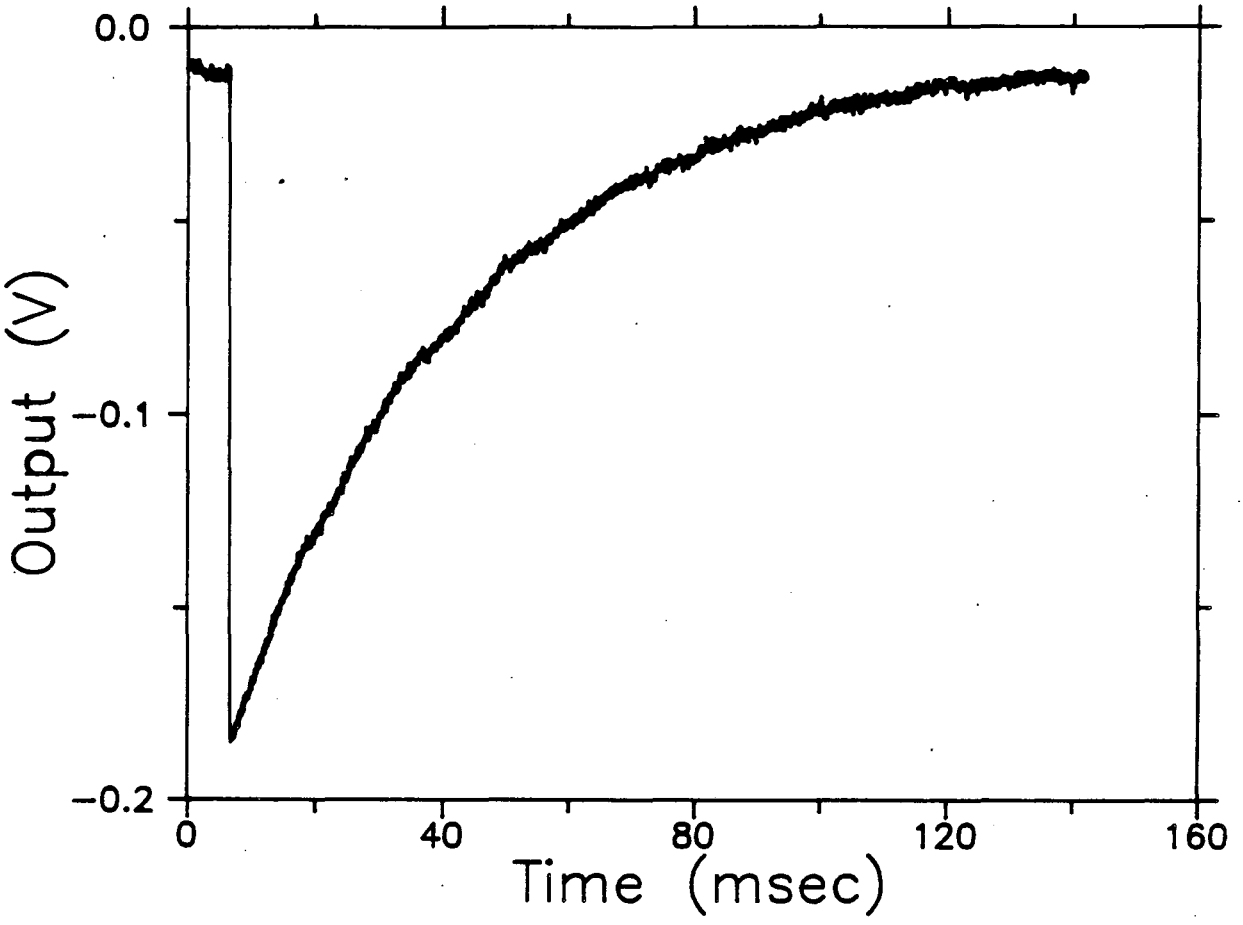

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Fig. 3.

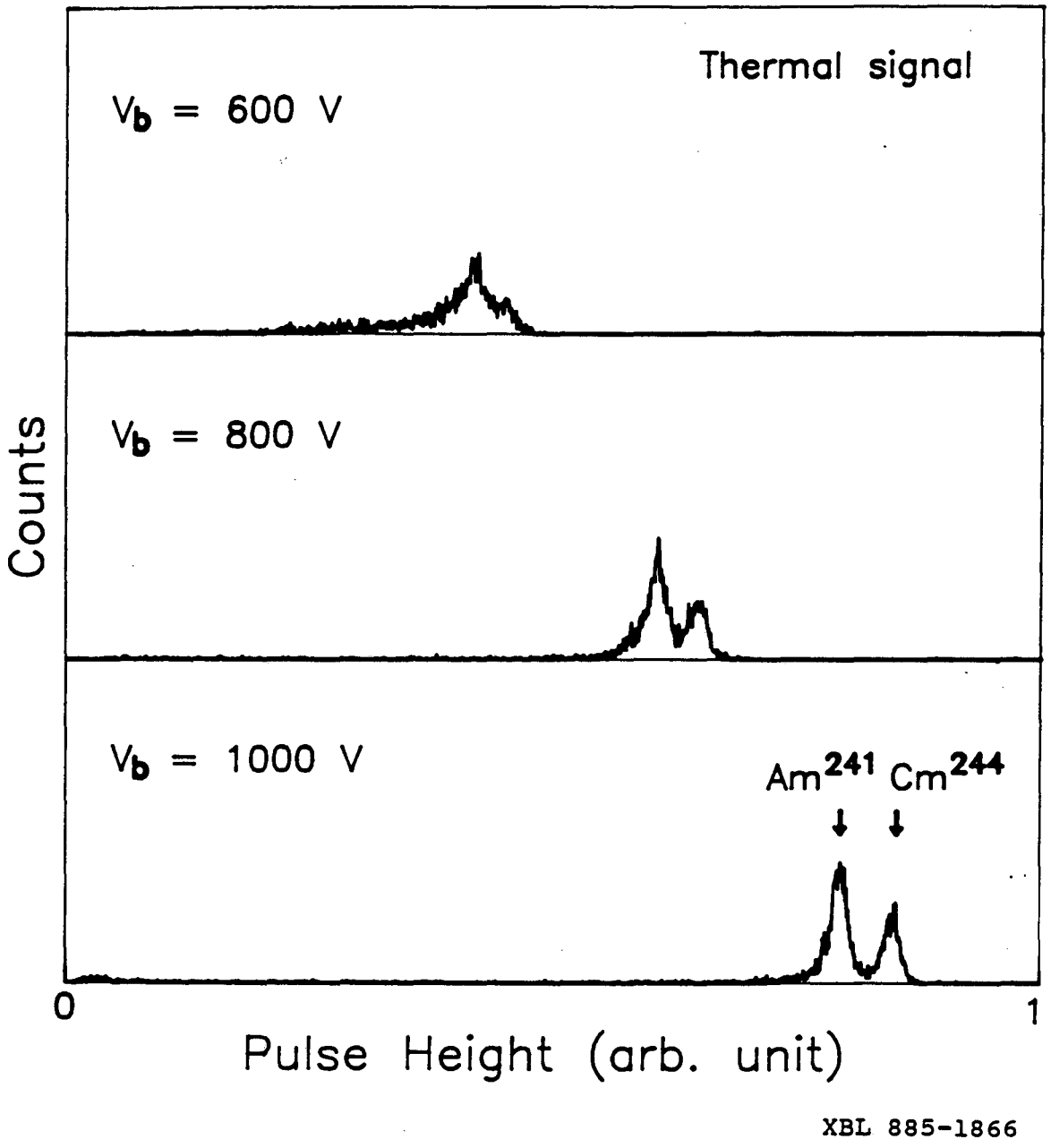

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Fig. 4.

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