X and Y tails. Bubbles accompanying the former (X bubbles) have been recognized as ones without Bloch lines in the domain walls, and bubbles accompanying the latter (Y bubbles) as ones with two Bloch lines.

The authors wish to thank Professor S. Chikazumi for helpful discussions and F. Ishida, K. Ando, and N. Koiso for sample preparation.

---

*Work contracted with the Agency of Industrial Science and Technology, Ministry of International Trade and Industry, as a part of the National Research and Development Program "Pattern Information Processing System".

†Present address: Rockwell International, Anaheim, *California* 92804.

[1] M. Takahashi, H. Nishida, T. Kobayashi, and Y. Sugita, J. Phys. Soc. Jpn. **34**, 1416 (1973); Y. S. Lin and G. E. Keefe, Appl. Phys. Lett. **22**, 603 (1973).
[2] R. Carey and E. D. Isaac, *Magnetic Domains and Techniques for Their Observation* (Academic, New York, 1966).
[3] R. Wolfe and J. C. North, Appl. Phys. Lett. **25**, 122 (1974).
[4] G. P. Vella-Coleiro and W. J. Tabor, Appl. Phys. Lett. **21**, 7 (1972).
[5] J. C. Slonczewski, A. P. Malozemoff, and O. Voegeli, AIP Conf. Proc. **10**, 458 (1973).
[6] A. P. Malozemoff, J. Appl. Phys. **44**, 5080 (1973).
[7] H. Nishida, T. Kobayashi, and Y. Sugita, IEEE Trans. Magn. **MAG-9**, 517 (1973).

Gamma-ray spectroscopy with single-carrier collection in high-resistivity semiconductors*

H. L. Malm[†], C. Canali[‡], J. W. Mayer, and M-A. Nicolet

California Institute of Technology, Pasadena, California 91125

K. R. Zanio and W. Akutagawa

Hughes Research Laboratories, Malibu, California 90265

(Received 2 December 1974)

With the standard plane-parallel configuration of semiconductor detectors, good γ-ray spectra can only be obtained when both electrons and holes are completely collected. We show by calculations (and experiments) that with contacts of hemispherical configuration one can obtain γ-ray spectra of adequate resolution and with signal heights of nearly full amplitude even when only one type of carrier is collected. Experiments with CdTe detectors for which the $\mu\tau$ product for electrons is about 10^3 times that of the holes confirm these calculations. The adoption of hemispherical contacts thus widens the range of high-resistivity semiconductors potentially acceptable for γ-ray detection at room temperature.

PACS numbers: 76.80., 29.40.P, 06.70.D

There is a need for semiconductor materials suitable for room-temperature γ-ray spectroscopy. Considerable attention has been directed towards wide-band-gap high-Z semiconductors. For spectroscopy, the carriers created in the sensitive volume must have a mobility-lifetime product $\mu\tau$ sufficiently high to insure complete traversal of the high-field region. In the plane-parallel contact configuration a necessary condition for a full-energy peak (photopeak) in the pulse height spectrum is that both the electron and hole mean free lifetimes τ_e and τ_h, respectively, must exceed the transit times across the field region. The requirement for full collection of both carrier types together with the large volumes necessary for high γ-ray sensitivity severely restricts the choice of suitable materials.[1]

The purpose of this letter is to demonstrate by calculation and experiment that by a proper choice of the contact configuration a remarkable improvement in resolution of γ-ray spectra is possible when only one carrier has a high $\mu\tau$ product. The ability to achieve good γ-ray spectra with one-carrier collection widens the range of potential materials for γ-ray spectroscopy.

For one-carrier collection the effect of the $\mu\tau$ product and of the electrode configuration on the shape of the spectrum is shown schematically in Fig. 1. We assume a uniform density of γ-ray interactions with full energy absorption throughout the material and either small (A) or large (B) values of the electron $\mu\tau$ product. For the plane-parallel configuration with a uniform electric field E [Fig. 1(a)], the drift length $\mu\tau E$ is uniform throughout the device. When $\mu\tau E$ is much less than the electrode separation L, most of the electrons drift an equal distance and the spectrum shows a peak at a low fraction of the full collection amplitude.[2] When $\mu\tau E \gg L$, all the electrons reach the positive contact. Since the charge induced is proportional to the electron path length in a uniform electric field, a rectangular spectrum extending to full collection amplitude is obtained in material B.

With a spherical (or hemispherical) configuration the drift length of an electron is a function of its radial position in the detector because of the nonuniform electric field. In such a nonuniform field most of the induced charge is produced by the carrier traversal

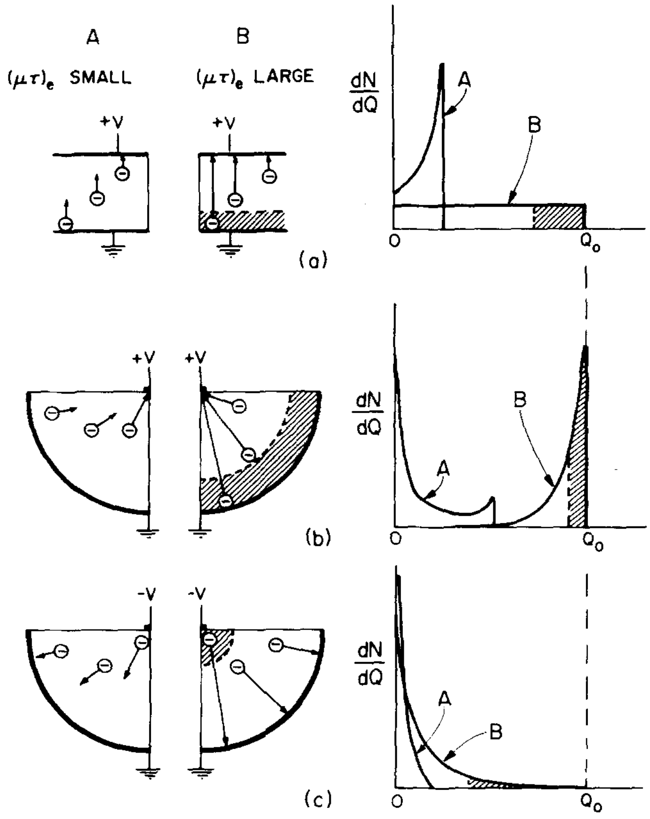

FIG. 1. For electron collection only and small (A) or large (b) values of the $\mu\tau$ product, the pulse height spectra are shown in (a) for a plane-parallel configuration, (b) for a spherical configuration with the inner contact positive, and (c) with the inner contact negative. In the spectra, Q_0 represents full charge collection. γ-ray interactions with the semiconductor in the shaded region of the detectors give pulses in the shaded region of the spectrum.

across the high-field region.[3] For geometrical reasons many more electrons are created in the low-field region near the outer electrode. With the small contact positive [Fig. 1(b)], in material A (small $\mu\tau$) where partial charge collection occurs, only a small photopeak is observed. However, for material B where all the electrons are collected, a clear photopeak appears in the spectrum. This contrasts with the plane-parallel case where only a steplike spectrum occurs.

With the small contact negative [Fig. 1(c)] the number of pulses of large amplitude is small because of the reduced volume near the negative contact. For both positive and negative polarities, γ-ray interactions in the shaded regions of Fig. 1 produce the largest pulses.

The general approach to calculating the pulse height spectrum for spherical geometry has been given before.[4] In contrast with the previous calculation which assumed that the charge dQ induced was independent of the electric field, we use the correct expression for a space-charge-free region,[3]

$$dQ = (q/V)E(r)\,dr,$$

where $E(r)$ is the electric field at r, V is the applied voltage, and dr is the displacement. The same formulation was used in evaluating the response of coaxial germanium spectrometers.[5] For a spherical configuration, and for the small contact positive and N_0 electron-hole pairs generated at r_0, the induced charge by electrons with a mean free drift time τ_e is

$$Q_e = \frac{N_0 q}{1/r_1 - 1/r_2}\int_{r_0}^{r_1} \exp\left(\frac{(r^3 - r_0^3)(1/r_1 - 1/r_2)}{3(\mu\tau)_e V}\right)\frac{dr}{r^2},$$

where r_1 and r_2 are the inner and outer contact radii, respectively. Analogous expressions may be obtained for holes and for the small contact negative.

In the limiting case, $\tau_e \to \infty$, it is possible to obtain an analytic expression for the spectrum dN/dQ generated by fully absorbed γ rays when only electrons are collected and the small contact is positive:

$$\frac{dN}{dQ} = \frac{4\pi I r_1^3(1 - r_1/r_2)}{N_0 q[1 - (Q/N_0 q)(1 - r_1/r_2)]^4},$$

where I is the number of fully absorbed γ rays per unit volume. The contribution of the hole collection to the spectrum is assumed to be negligible. To avoid polarization effects, however, it is necessary that the holes eventually recombine or be swept out of the detector. These processes generate background noise.

Figure 2 shows the result of calculations for a spherical radiation detector for $(\mu\tau)_e \gg (\mu\tau)_h$. A peak is obtained only when the center contact is positive; a polarity reversal gives a spectrum without a photopeak. With the condition $(\mu\tau)_e \gg (\mu\tau)_h$, hole traversal has almost no influence on the spectrum shape.

It is sufficient that one carrier have a drift length of the order of the contact separation for a peak to appear in the spectrum. This result differs completely from that of the planar configuration[2] where, for the single-carrier collection, the peak disappears as the drift length increases (see also Fig. 1). Moreover, with

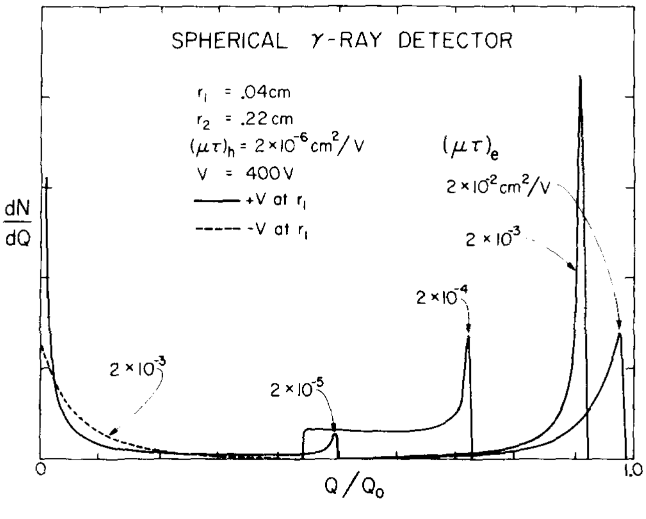

FIG. 2. Calculated pulse height distributions for the spherical configuration with inner and outer radii of 0.04 and 0.22 cm, respectively. The spectra are shown for $(\mu\tau)_e$ values between 2×10^{-5} and 2×10^{-2} cm^2/V and $(\mu\tau)_h$ of 2×10^{-6} cm^2/V. The solid lines apply when the inner electrode is positive and the dashed line applies when this electrode is negative.

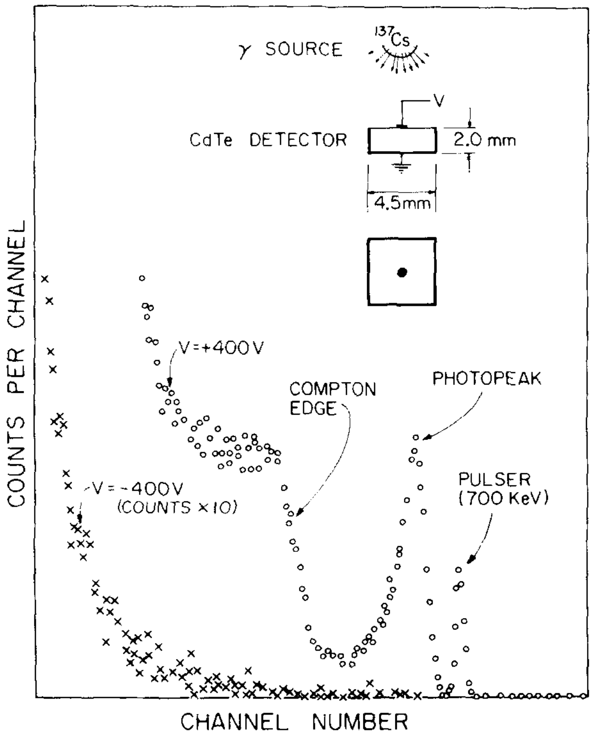

FIG. 3. Pulse-height spectra for ^{137}Cs γ rays (662 keV) obtained with a CdTe detector of roughly hemispherical contact configuration (see insert), $(\mu\tau)_e \sim 1.2\times10^{-3}$ cm^2/V and $(\mu\tau)_h = 4\times10^{-6}$ cm^2/V. Complete absorption by photoeffect generates the photopeak. Incomplete absorption by the Compton effect generates additional low-energy signals. Only when the center contact is positive (+400 V) do the photopeak and the Compton edge appear. Compare photopeak with calculated spectra shown in Fig. 2.

spherical contacts, there is a best value of $(\mu\tau)_e V$ for each value of r_1/r_2 which gives the sharpest peak.

An experimental test was made by selecting a sample of CdTe for which the electron $\mu\tau$ product was much greater than that for holes. The carrier lifetimes were measured from the α-particle response using a plane-parallel configuration: $(\mu\tau)_e = 1.2\times10^{-3}$ cm^2/V and $(\mu\tau)_h < 4\times10^{-6}$ cm^2/V. In this configuration the response for ^{137}Cs did not show a photopeak but rather a step spectrum similar to that shown in Fig. 1(a) for material B.

A near hemispherical device was made by forming the large contact on the five sides of this sample ($4.5\times4.5\times2.0$ mm thick) and the small (0.8 mm diameter) contact on the center of the remaining surface (Fig. 3). For these dimensions irradiation by ^{137}Cs gives a nearly uniform production of electron-hole pairs by two processes, one of which (photoelectric effect) leads to a complete absorption of the γ energy, while the other (Compton effect) does not. Only when the center contact is positive does the spectrum exhibit a photopeak, in agreement with the theoretical prediction. Such polarity reversal effects on the spectrum have been observed before,[4] but it was not clear that such effects arose from single-carrier collection.

In summary, we have predicted and shown experimentally that a photopeak may be observed at nearly full collection with only single-carrier collection and spherical electrode configuration. The significance of this lies in the application of materials with single-carrier collection for γ-ray spectrometers.

[*] Work supported in part by the AEC (H. Wasson) through funds administered by the UCLA School of Nuclear Medicine (G. Huth).

[†] Permanent address: Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

[‡] Permanent address: Istituto di Fisica, Università di Modena, Italy.

[1] J.W. Mayer, *Semiconductor Detectors*, edited by G. Bertolini and A. Coche (North Holland, Amsterdam, 1968), p. 445.
[2] W. Akutagawa and K.R. Zanio, J. Appl. Phys. 40, 3838 (1969).
[3] S. Ramo, Proc. IRE 27, 584 (1939).
[4] K.R. Zanio, W. Akutagawa, and H. Montano, IEEE Trans. Nucl. Sci. NS-19, 257 (1972).
[5] E. Sakai, IEEE Trans. Nucl. Sci. NS-15, 310 (1968).