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Improved spectrometric performance of CdTe radiation detectors in a *p-i-n* design

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CdTe radiation detectors were fabricated using a *p-i-n* design and a significant improvement in the spectral properties was obtained during room temperature operation. An iodine doped *n*-CdTe layer was grown on the Te faces of the (111) oriented high resistivity CdTe crystals at the low substrate temperature of 150 °C. An aluminum electrode was evaporated on the *n*-CdTe side for the *n*-type contact, while a gold electrode on the opposite side acted as the *p*-type contact. Very low leakage currents, typically 60 pA/mm^2, were attained at room temperature (25 °C) for an applied reverse bias of 250 V. Detectors exhibited excellent spectral responses with an energy resolution of 1.42, 1.7, and 4.2 keV FWHM at 59.5, 122, and 662 keV γ peaks, respectively. © *1999 American Institute of Physics.* [S0003-6951(99)03141-1]

CdTe has been known as a material used in γ-ray detectors for a long time because of its high stopping power and considerably large band gap. Along with the recent advances in crystal growth technology, the performance of CdTe detectors has significantly improved. Nevertheless, limitations of the CdTe nuclear detector technology have been primarily due to the poor charge collection efficiency and junction formation technique to produce good device reproducibility.[1,2] The charge collection efficiency and, hence, the energy resolution of the detector, can be improved by operating it at a high applied bias. However, the large leakage current of a CdTe detector in the usual metal–semiconductor–metal (MSM) configuration imposes a limitation on its operation at high biases. Leakage currents can be suppressed by processing the CdTe detector into a *p-i-n* structure.[3–6] Two methods are commonly used to fabricate the *p-i-n* detectors. The first one employs indium diffusion on one side of the crystals for the *n* layer and a gold or platinum electrode on the other side is used for the *p*-type contact.[7,8] This is a kind of Schottky barrier device. In the second approach, as reported by Shin and co-workers,[2,9] *p*- and *n*-type heteroepitaxial HgCdTe layers are grown on opposite sides of the crystal. These approaches are effective for reducing the leakage current compared to that of MSM detectors, producing good spectrometric performance, and have been widely adopted. However, the limitations of these methods are primarily the high temperature processing of the crystals and the difficulty in achieving good device reproducibility.

We have fabricated *p-i-n* CdTe detectors in a different approach which employs iodine-doped *n*-CdTe layers followed by aluminum metallization on one side of the crystals as the *n* layer while a thin gold layer on the other side acts as the *p*-type contact. This is a low temperature process and this approach offers high energy resolution, stability, and good device reproducibility.

The substrates used in this study were 5 mm×5 mm×0.5 mm (111) oriented Cl-doped single crystal CdTe wafers with a resistivity on the order of $10^9\ \Omega$ cm. They were obtained from ACROTEC, Japan Energy Corporation. The wafers were first cleaned in organic solvents and etched in 1% Br–methanol solution for 90 s. About a 400 nm thick iodine-doped *n*-CdTe layer was homoepitaxially grown on the Te face of the crystal using the hydrogen plasma-radical-assisted metalorganic chemical vapor deposition technique at a rather low substrate temperature of 150 °C.[5,10,11] Iodine is a suitable *n*-type dopant for CdTe because of its low diffusivity in the host lattice and also because of its similar size and electronegativity with respect to the tellurium atom;[12] iodine resides on the tellurium site and its impact on the host lattice is small. The Hall measurement at room temperature showed a donor concentration of $1.12\times10^{17}\ \mathrm{cm}^{-3}$ and an electron mobility of 296 cm^2/V s in this iodine-doped layer. An aluminum contact was placed on the *n*-CdTe side and a gold electrode was placed on the other side at a low pressure in a physical vapor deposition system without heating the crystal to make the *p-i-n* detector. Prior to the gold deposition, the crystals were treated in an aqueous H_2O_2 solution for few tens of seconds. Proper protection was done for the aluminum electrode deposited side. Finally, detectors were cut into 2 mm×2 mm×0.5 mm pieces and their performances were examined using a high voltage current–voltage ($I-V$) measurement and the radiation detection tests at room temperature were done using Am-241, Co-57, and Cs-137 radioisotopes.

The *p-i-n* CdTe detectors showed good diode characteristics, as expected, with a well saturated reverse bias current (leakage current). The typical leakage current of the detector has been plotted in Fig. 1. A leakage current as low as 60

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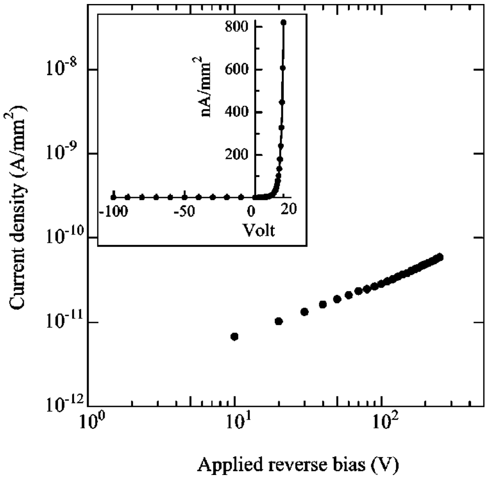

FIG. 1. Typical leakage current characteristic of p-i-n CdTe detector at 25 °C. The detector has the dimensions of 2 mm×2 mm×0.5 mm. The insert shows the $I-V$ curve of the same detector where forward current increases steeply with the applied bias.

pA/mm^2 was observed at room temperature for the 2 mm×2 mm×0.5 mm detector at an applied reverse bias of 250 V. The forward current of the detector increases steeply with the applied forward bias and has also been plotted in Fig. 1(inset). The low value of the leakage current indicates that the *p* and *n* layers are acting as efficient blocking contacts. The equivalent resistivity of the detector in the reverse direction is $9\times10^{11}\,\Omega$ cm to about 200 V negative bias, which is nearly three orders higher than the resistivity of the intrinsic crystal used. The leakage current has a square-root dependence on the applied voltage up to 100 V, but the dependence then increases to the 0.6 power of the applied voltage (up to the voltage range investigated). This indicates the leakage current generated from the depletion layer is prominent in the low voltage region, whereas the surface leakage current is also taken into account at the higher biases. Further optimization of the device fabrication process should suppress the surface leakage current, which is currently under investigation.

The radiation detection test of the detectors was performed next. The spectra were taken with a charge sensitive preamplifier,[13] amplifier shaper and a multichannel analyzer.[14] All spectra were taken at room temperature without the use of any rise-time discriminator or pulse height correction electronics. γ rays from each radioactive source irradiated the device through the negatively biased gold electrode. Figure 2 shows the spectra of the various radioisotopes obtained by the detector. The maximum possible bias voltage was applied to create a high electric field inside the detector for the efficient charge collection and to obtain the best energy spectrum. The FWHM value of the 59.5 keV photopeak of Am-241 is 1.42 keV [see Fig. 2(a)]. The time constant of the shaping amplifier was 2 μs, while the detector was biased at 440 V. Figure 2(b) shows the energy spectrum of Co-57 obtained with the detector under the same operating conditions, but with a bias voltage of 480 V. Here, the 6.4 and 14 keV lines are also clearly observed. The FWHM value of the 14 keV line is 1.34 keV and that of the 122 keV line is 1.7 keV. In order to examine the performance of the detector in the high energy region, Cs-137 radiation was detected by applying a bias voltage of 470 V, a shaping time constant of 2 μs. The result is shown in Fig. 2(c). Here, the 662 keV photopeak could be clearly detected with a FWHM value of 4.2 keV. Very good energy resolution and photopeak efficiency could be obtained with our device, which is clearly seen in the energy spectra. The photopeaks are almost symmetric, indicating that complete charge collection is possible in our 0.5 mm thick p-i-n detector at room temperature with a bias voltage of 400–500 V. There are no significant trappings and recombinations in the bulk crystal as well as at the junctions. This indicates the grown homoepilayers are of good quality, which can also be justified by the high mobility value in these layers, and the p-i-n junctions are well formed. Moreover, good device reproducibility was also achieved. These detectors have a better energy resolution than our previous detectors which had an indium electrode instead of aluminum and were 1 mm thick.[5] This improved resolution can be attributed to the better crystal quality and also advances in our detector fabrication technology which gave a negligibly low leakage current so that we were able to apply a higher electric field on the detector.

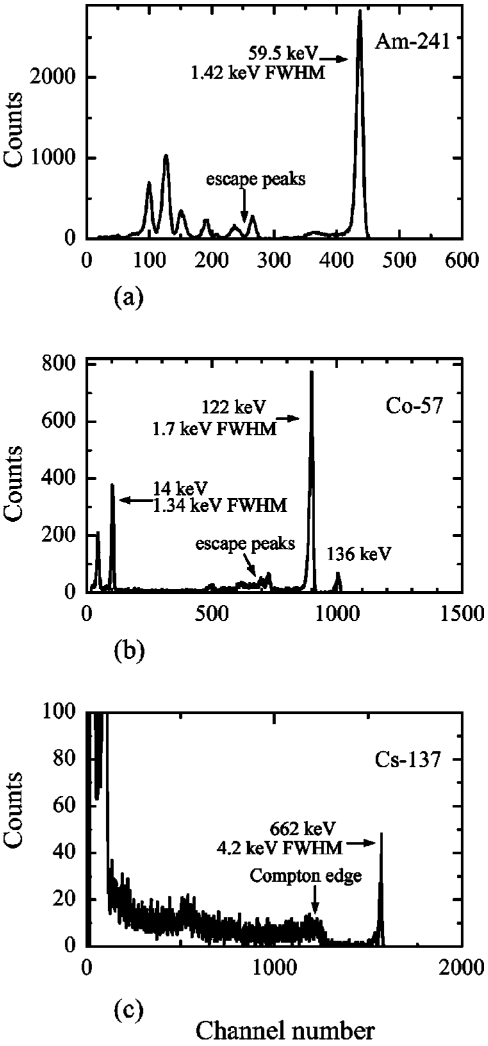

FIG. 2. Energy spectrum of: (a) Am-241, (b) Co-57, and (c) Cs-137 radioisotopes detected by the 4 mm^2, 0.5 mm thick CdTe p-i-n detector at 25 °C. The shaping time constant was 2 μs in all cases. A reverse bias of 440, 480, and 470 V was applied in (a), (b), and (c), respectively, while collecting the spectra. No charge loss correction electronics were applied in the spectra.

The degradation of γ peak height with time is an existing problem in radiation detectors. Although not presented in this letter, the change in the spectrum height was low in our detector for collection times as long as 1 h at a 460 V bias at 25 °C. However, the height of the spectrum decreased to 0.7 times the initial height after 5 h, and the FWHM value of the 122 keV Co-57 peak increased from 1.8 to 3.3 keV. Further study of the stability is now in progress and will be presented later.

We have presented our progress in fabricating CdTe radiation detectors in a p-i-n design, which provides a significant improvement in spectral responses, good device reproducibility, and offers advantages over other currently available CdTe detectors. This device is suitable for suppressing the leakage current that allowed us to apply a high bias voltage even for room temperature operation. As a result, a good charge collection and high energy resolution could be obtained over a wide energy range.

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[14] Manufactured by Seiko EG & G Co. Ltd., 1-8 Nakase, Mihama-ku, Chiba 261, Japan. Series No. MCA 7700.