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Polarization Effects on Diode-type Cadmium Telluride Detector with High Current Density

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Polarization poses a significant challenge in cadmium telluride (CdTe) detectors, preventing the simultaneous achievement of high energy resolution and long-term stability at room temperature. The mechanism driving bias-induced polarization is presumed to involve an increase in the number of ionized acceptors resulting from hole detrapping. Simultaneously, the accumulation of negative charges is suppressed as the hole density in the bulk increases. Consequently, polarization effects occur in diode-type detectors with low current densities but not in ohmic detectors with high current densities. In this study, we fabricated a diode-type detector with a high current density, which is between those of the ohmic and diode types, and evaluated its long-term stability. The detector had dimensions of 3 × 3 × 0.75 mm^3, comprising a central electrode of 0.5 × 0.5 mm^2 surrounded by a guard-ring electrode. By finely patterning the anode, we increased the current density, achieving a current density comparable to that of the ohmic type while enabling the application of a higher bias voltage.

1. Introduction

Room-temperature semiconductor radiation detectors are semiconductor devices characterized by high atomic numbers and densities, enabling them to exhibit high sensitivity to radiation. These detectors exhibit bandgaps that allow their efficient operation at room temperature. Several of these advanced detectors employ compound semiconductors, with noteworthy examples being cadmium telluride (CdTe) and thallium bromide detectors, which have demonstrated excellent radiation detection results in previous studies.(1–3) Long-term stability is another critical aspect of radiation detectors, which, however, is limited by several factors.(4–6) For historical reasons, the term "polarization phenomena" is used collectively to describe the time-dependent instability observed in semiconductor radiation detectors. This study specifically investigates polarization phenomena in CdTe detectors, focusing on the

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accumulation of negative charges in the deep acceptor level during the application of a bias voltage to the detector.

This bias-induced polarization changes the distribution of the electric field by accumulating negative charges in the detector over time while a bias is applied.(2) This results in a progressive degradation of the energy resolution and a gradual shift of the photopeak towards lower energies as time elapses.(7,8) During this accumulation process, there is a simultaneous increase in the number of ionized acceptors due to hole detrapping and a decrease in it due to hole capture, ultimately converging to an equilibrium state.(9,10) The probability of hole capture is dependent on the hole density, which increases with the current density. Conversely, a high current density during biasing results in a low resistance, which leads to a decrease in the time constant of polarization effects.(11) Among the CdTe detectors, diode-type detectors, represented by indium (In) contacts [for example, In/CdTe/platinum (Pt)], exhibit bias-induced polarization, while ohmic detectors with Pt contacts (such as Pt/CdTe/Pt) have been reported not to exhibit this phenomenon.(12,13) A distinctive threshold in the current density exists between conventional diode-type and ohmic detectors.

In this study, we fabricated a diode-type detector that can operate under a bias condition with the current density comparable to that of ohmic detectors at room temperature. We evaluated the polarization effects on the spectral detection characteristics of this detector.

2. Materials and Methods

A diode-type CdTe detector (In/CdTe/Au) with a high current density was fabricated by the following process:

1. Etch both sides of a CdTe crystal with bromethanol.
2. Use photoresist to form a pattern for the In electrode on the Te face of the crystal.
3. Deposit In on the Te face of the crystal.
4. Remove the remaining photoresist using acetone and lift off In on the gap.
5. Deposit gold (Au) on the opposite side.
6. Dice the crystal to a size of 3×3 mm^2.

A p-type crystal, manufactured by Acrorad Co., Ltd., was used as the CdTe crystal, resulting in a final detector size of $3 \times 3 \times 0.75$ mm^3. On one side, an In electrode was patterned as an anode, comprising a central electrode measuring 0.5×0.5 mm^2 and a guard-ring electrode extending to the edge of the detector with a gap of 0.1 mm between the electrodes. The opposite side was covered with a Au cathode. Figure 1 shows the geometry of the fabricated detector.

The leakage current in Schottky diodes depends on the height of the Schottky barrier. It is conceivable to use a metal such as Ni, which has a work function between those of In and Pt, as the electrode material to increase the current density. However, the properties of Schottky junctions are highly dependent on the surface treatment of the CdTe crystal.(14) Consequently, it is difficult to change the barrier height based on the work function by changing only the metal. Nevertheless, a previous report has indicated that the leakage current of diode-type CdTe detectors can be increased by finely patterning the anode.(11) In the same study, patterning to a large size did not significantly increase the leakage current, suggesting that the electric field

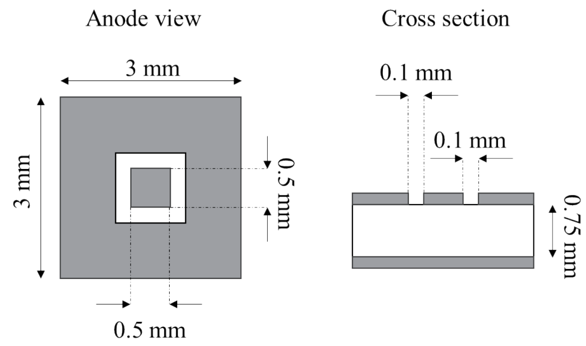


Fig. 1. Geometry of the patterned anode.

concentration at the electrode edge was the primary cause. As a result, we successfully increased the current density during reverse bias operation through the fine patterning of In electrodes.

The resistivity of ohmic detectors using a p-type CdTe crystal (manufactured by Acrorad) has been reported to be in the range of 2–3 × 10^9 Ωcm.(15) Assuming that the operating condition of the ohmic detectors was 1000 V/cm, its current density was 2–3 × 10^{-6} A/cm^2. Accordingly, the fabricated detector exhibited an operating current of approximately 1 nA. This value is expected to provide a sufficiently low noise level for spectral measurements.

Current–voltage (*I*–*V*) and gamma-ray spectral measurements were performed using the fabricated detector. A B1505A power device analyzer (Keysight Technologies) was used for the *I*–*V* measurements. For the spectral measurements, a CSP02 preamplifier (ANSeeN Inc.), a 4419HI main amplifier (by CLEAR-PULSE Co., Ltd.), and a ZMCAN-CH04-01 waveform analyzer (ANSeeN Inc.) were used. The measurement data were stored as list-mode data, with data recorded for each gamma-ray photon event, and spectra were generated on the basis of the elapsed time from the start of each measurement. An MDO3104 oscilloscope (Tektronix, Inc.) was used to analyze the shape of the waveform.

Figure 2 illustrates the spectral measurement setup used in this study. A preamplifier was connected to the central electrode of the anode and biased through a 1 GΩ resistor. The guard-ring electrode was biased through a noise filter comprising a 1 MΩ resistor and a 10 nF capacitor. The cathode was grounded and the shaping time constant of the main amplifier was set to 2 μs.

3. Results and Discussion

3.1 Experimental results

Figure 3 presents the *I*–*V* measurement results of the fabricated detector. The horizontal axis represents the applied voltage, with the positive and negative values indicating the forward and reverse biases, respectively. The vertical axis represents the current. Figure 4 displays the spectral measurement results obtained when the detector was operated under a reverse bias of 300 V. Gamma rays from an americium-241 (^{241}Am) radioisotope were used as the radiation source, which was irradiated from the anode side. Figure 4(a) shows the spectra collected at

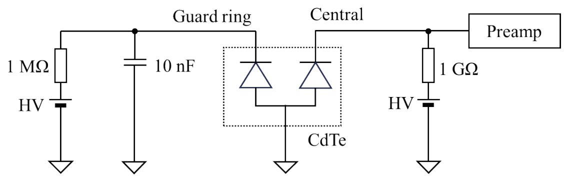


Fig. 2. (Color online) Spectral measurement setup used in this study.

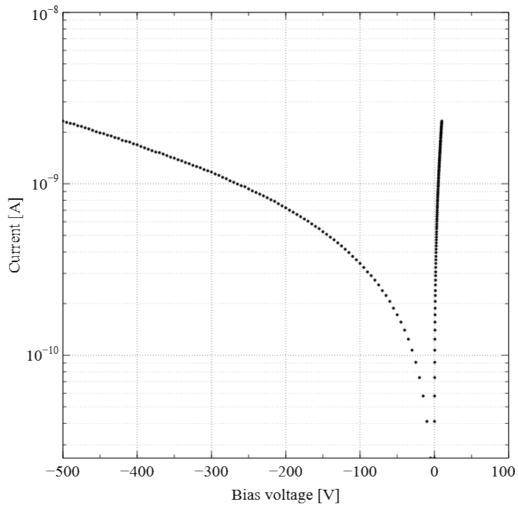


Fig. 3. *I*–*V* measurement results of the fabricated detector.

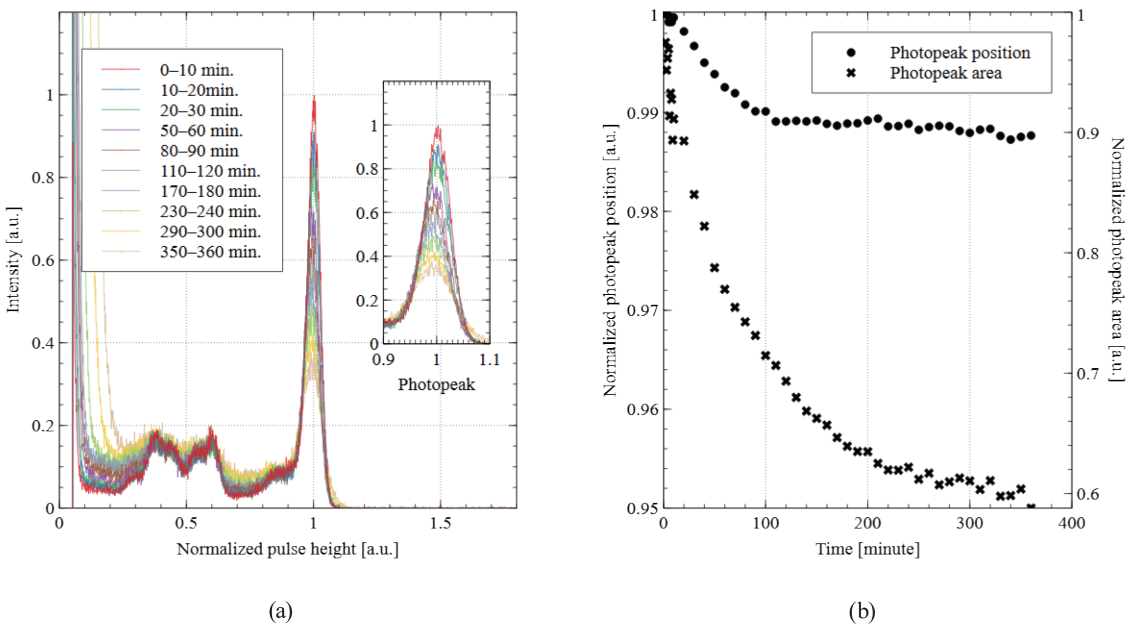


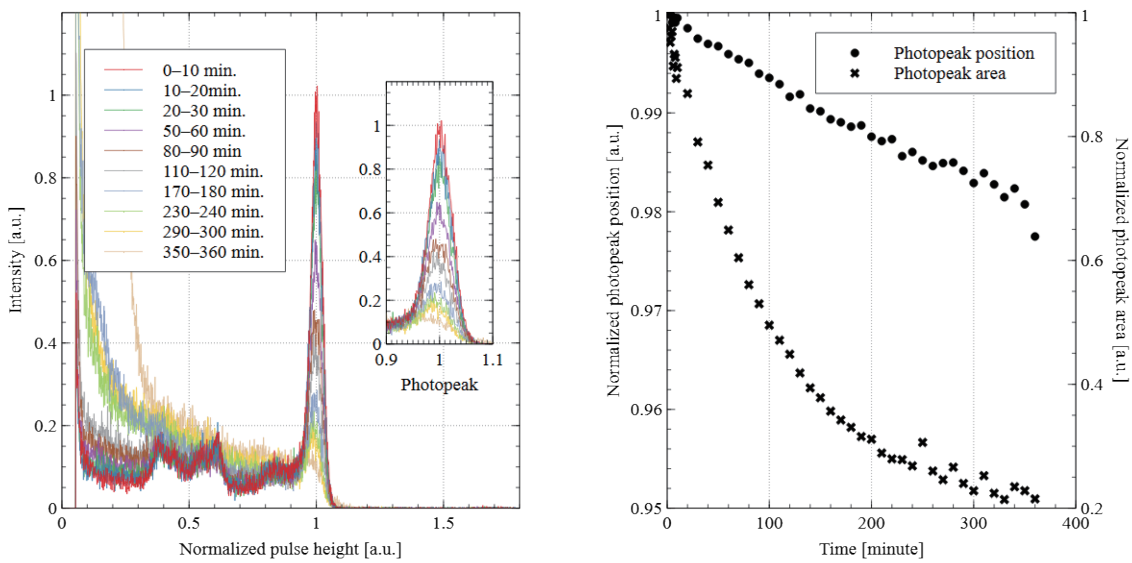
Fig. 4. (Color online) Spectral measurement results under irradiation from the anode side: (a) spectral and (b) photopeak changes with time.

various elapsed times after the application of the bias. For example, the spectrum named "0–10 min." was generated using the measurement results from 0 to 10 min. Figure 4(b) shows the time variation of the photopeak position and the magnitude of the photopeak area (product of the peak height and the full width at half maximum). The shape of the peak was obtained by the Gaussian fitting of the measured ^{241}Am photopeaks. Figure 5 displays the measurement results of gamma-ray irradiation from the cathode side. Figures 5(a) and 5(b) show the spectra collected at various elapsed times and the time variation of the result of Gaussian fitting, respectively. Figure 6 shows the pulse waveforms of the preamplifier output measured using an oscilloscope. The horizontal axis represents time and the vertical axis represents voltage. The graphs show waveforms with a fast rise time, mainly due to electron drift, immediately after applying the bias (solid line) and after 6 h (dashed line). The radiation sources used to obtain Figs. 6(a) and 6(b) were ^{241}Am and cesium-137 (^{137}Cs), respectively.

3.2 Discussion

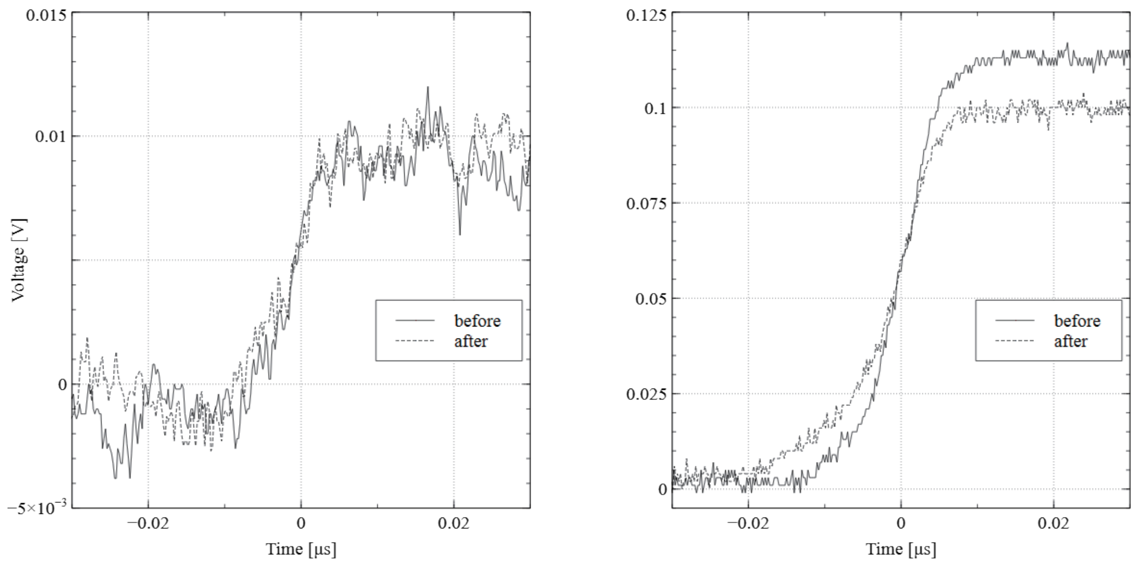
The *I*–*V* measurement results (Fig. 3) confirm that the fabricated detector exhibits rectifying characteristics. The leakage and forward currents were respectively higher and lower than those of conventional diode-type CdTe detectors.[2,9,11,14] These *I*–*V* characteristics are comparable to those of a diode with a low Schottky barrier height. On the basis of these results, a bias voltage of 300 V was selected to operate the detector at the same current density as that of the ohmic CdTe detector.

Notably, the measured gamma-ray spectra [Figs. 4(a) and 5(a)] reveal minimal peak shifts with time. After 6 h of continuous measurements, the peak shifts were approximately 1 and 2%



(a) (b)

Fig. 5. (Color online) Spectral measurement results under irradiation from the cathode side: (a) spectral and (b) photopeak changes with time.



(a) (b)

Fig. 6. Waveforms before and after bias application for 6 h with (a) 241Am and (b) 137Cs.

for irradiation from the anode and cathode, respectively. As a result of irradiation from the cathode, the count increase in the low-energy region approached the vicinity of the photopeak. Therefore, it is considered that the shift was larger than that for irradiation from the anode. On the other hand, conventional diode-type detectors experience peak shifts of more than 10%.(7-9,12) This is due to the decrease in the width of the depletion layer owing to the accumulation of negative charges.(4,6,9,10,13) In our detector, the electric field under the central electrode did not change because the rise time of the signal with ^{241}Am did not vary with time [Fig. 6(a)]. This indicates that the full depletion of the region was maintained; in other words, the accumulation of negative charges was suppressed.

Although the peak shifts were small, the energy resolution and detection efficiency of the photopeak decreased with time [Figs. 4(b) and 5(b)]. This suggests an increase in charge sharing, where the signal is split between the central and guard-ring electrodes. This is supported by a significant drop in detection efficiency observed in the results of irradiation from the cathode side (Fig. 5). This is because the diffusion of electrons when traveling toward the central electrode affects the splitting of the signal. The effect of electron diffusion was observed in the measurement result for ^{137}Cs [Fig. 6(b)], where the rise time of the signal became longer. The mechanism underlying the increase in charge sharing is as follows. The current density of the central electrode was increased by fine patterning, whereas that of the guard-ring electrode remained low. Therefore, polarization occurred under different conditions in the guard-ring region. The accumulation of negative charges progressed to the extent that full depletion could not be maintained under the guard ring, and the electric field near the cathode was weakened. Consequently, the electric field in the region near the guard ring was weakened even under the central electrode, causing an increase in charge sharing.

Notably, the time constant of polarization effects was very small because the time instability appeared immediately after the measurement began. This timeframe was too short to estimate the value using the measurement method employed.

4. Conclusions

We successfully fabricated a diode-type CdTe detector with high current density during operation and evaluated its polarization effects. This approach utilized higher current densities, which resulted in increased hole densities and reduced negative charge buildup, which causes polarization. A bias voltage that provided a current density equivalent to that of an ohmic detector was chosen because it was not affected by polarization. The measurement results of ^{241}Am demonstrated that the peak shift due to polarization was suppressed. However, the spectral shape, such as the energy resolution, varied over time. This is because charge sharing increased with time owing to the detector geometry. Notably, the time constant for this change was considerably smaller than that for conventional diode-type detectors, with significant changes in characteristics occurring immediately after the bias was applied.

Thus, on the basis of the findings presented above, it is evident that the polarization effect can be effectively suppressed in Schottky diodes operating at high current densities. This suggests that a detector capable of applying a higher electric field than an ohmic detector may experience less characteristic deterioration due to the polarization phenomena. This can be realized by adopting an electrode structure that ensures a uniformly high current density across the entire detector. This study provides valuable insights into the development of detectors with superior stability and performance, making them more suitable for various radiation detection applications.

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References

1 K. Nakazawa, K. Oonuki, T. Tanaka, Y. Kobayashi, K. Tamura, T. Mitani, G. Sato, S. Watanabe, T. Takahashi, R. Ohno, and A. Kitajima: Nucl. Phys. A **5** (2003): 3583. https://doi.org/10.1109/TNS.2004.832684
2 C. Matsumoto, T. Takahashi, K. Takizawa, R. Ohno, T. Ozaki, and K. Mori: IEEE Trans. Nucl. Sci. **45** (1998) 428. https://doi.org/10.1109/23.682421
3 K. Hitomi, T. Onodera, K. Seong-Yun, T. Shoji, and K. Ishii: Nucl. Instrum. Methods Phys. Res. A **747** (2014) 7. https://doi.org/10.1016/j.nima.2014.02.020
4 A. Cola and I. Farella: Appl. Phys. Lett. **94** (2009) 102113. https://doi.org/10.1063/1.3099051
5 K. Hitomi, T. Shoji, and Y. Niizeki: Nucl. Instrum. Methods Phys. Res. A **585** (2008) 102. https://doi.org/10.1016/j.nima.2007.11.012
6 D. S. Bale and C. Szeles: Phys. Rev. B **77** (2008) 035205. https://doi.org/10.1103/PhysRevB.77.035205
7 R. O. Bell, G. Entine, and H. B. Serreze: Nucl. Instrum. Methods **117** (1974) 267. https://doi.org/10.1016/0029-554X(74)90408-X
8 H. L. Malm and M. Martini: IEEE Trans. Nucl. Sci. **21** (1974) 322. https://doi.org/10.1109/TNS.1974.4327478
9 H. Toyama, A. Higa, M. Yamazato, T. Maehama, R. Ohno, and M. Toguchi: Jpn. J. Appl. Phys. **45** (2006) 8842. https://doi.org/10.1143/JJAP.45.8842
10 I. Farella, G. Montagna, A. M. Mancini, and A. Cola: IEEE Trans. Nucl. Sci. **56** (2009) 1736. https://doi.org/10.1109/TNS.2009.2017020
11 A. A. Turturici, L. Abbene, G. Gerardi, and F. Principato: Nucl. Instrum. Methods Phys. Res. A **763** (2014) 476. https://doi.org/10.1016/j.nima.2014.07.011

12 K. Okada, Y. Sakurai, and H. Suematsu: Appl. Phys. Lett. **90** (2007) 063504. https://doi.org/10.1063/1.2457971
13 R. Grill, E. Belas, J. Franc, M. Bugár, Š. Uxa, P. Moravec, and P. Hoschl: IEEE Trans. Nucl. Sci. 58 (2011) 3172. https://doi.org/10.1109/TNS.2011.2165730
14 L. A. Kosyachenko, V. M. Sklyarchuk, O. F. Sklyarchuk, O. L. Maslyanchuk, V. A. Gnatyuk, and T. Aoki: IEEE Trans. Nucl. Sci. **56** (2009): 1827. https://doi.org/10.1109/TNS.2009.2021162
15 M. Funaki, T. Ozaki, K. Satoh, and R. Ohno: Nucl. Instrum. Methods Phys. Res. A **436** (1999) 120. https://doi.org/10.1016/S0168-9002(99)00607-5