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INTERNAL ELECTRIC FIELD BEHAVIOR OF CADMIUM ZINC TELLURIDE RADIATION DETECTORS UNDER HIGH CARRIER INJECTION

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Abstract

The behavior of the internal electric-field of nuclear-radiation detectors substantially affects the detector's performance. We investigated the distribution of the internal field in cadmium zinc telluride (CZT) detectors under high carrier injection. We noted the build-up of a space charge region near the cathode that produces a built-in field opposing the applied field. Its presence entails the collapse of the electric field in the rest of detector, other than the portion near the cathode. Such a space-charge region originates from serious hole-trapping in CZT. The device's operating temperature greatly affects the width of the space-charge region. With increasing temperature from 5 °C to 35 °C, its width expanded from about 1/6 to 1/2 of the total depth of the detector.

Keywords: CZT; Pockels effect; Electric field; Hole trapping; Polarization

Introduction

Cadmium zinc telluride (CZT), a very promising material for high-efficiency, high-resolution room-temperature radiation detectors, offers a wealth of applications, including nuclear medical imaging, security inspections, industrial monitoring, and scientific X- and gamma-ray imaging and spectroscopy.^{1,2} Among the several parameters that substantially affect the detectors' performance, an important one is the distribution of the internal electric field. As is well known, its distribution can be changed significantly by the build-up of space charge, as was demonstrated in detectors made from crystals of Si, Ge, GaAs, and CdTe.³⁻⁶ This behavior usually results in a polarization effect. Seemingly, CZT suffers much less from polarization than does CdTe. However, recent reports suggest that the polarization effect possibly occurs in CZT detectors when a high photon flux is applied, as often encountered in x-ray imaging applications.⁷ Such a phenomenon will degrade the performance of CZT detectors, and might even completely inactivate the detector by causing the internal electric field to collapse. Therefore, an understanding is needed of the behavior of the internal electric field under high photon flux; it would clarify the mechanism of polarization, and help in designing a better-performing detector.

At Brookhaven National Laboratory (BNL), we injected a high flux of carriers into a CZT detector via a laser, and then monitored the changes in the internal electric field via Pockels-effect measurements. We also varied the temperature of the CZT detector to adjust the extent of polarization. Here, we report our findings on the change of the internal electric field after injecting a high flux of carriers.

Experimental

The CZT crystal, 10 x 10 x 10 mm³, was grown by the modified low-pressure Bridgman method. We lapped it with 5- μ m grit Al₂O₃ abrasive papers, sequentially polished the surfaces

with 1- μm , 0.1- μm , and 0.05- μm particle-size alumina suspensions, and then rinsed them in methanol. After removing the mechanically damaged layers from the crystal's surfaces with a 2% bromine-methanol solution, we placed Au electrodes on the crystal's top and the bottom surfaces by electroless chemical deposition.

Fig. 1 shows the Pockels effect measurement system we used to measure the corresponding distribution of the internal electric field. In this system, a collimated Xenon lamp with a 950-nm IR filter illuminated the entire detector. A Keithley 237 high-voltage source-measure unit provided the bias voltage for the CZT detector and monitored the change of photocurrent. Two linear polarizers separately acted as the polarizer and the analyzer. The transmitted light, focused on a CCD camera controlled by SynerJY software, generated satisfactory PE images. Meanwhile, we impinged a HeNe laser beam operating at 633 nm on the side surface of the CZT detector to generate a high flux of carriers; this simulated the high flux of X-ray irradiation used in X-ray radiography. A Peltier stage below the sample controlled the temperature during measurements.

Results and discussion

We obtained information on the distribution of the internal electric field by measuring the Pockels effect (PE) image. According to Guenther,⁸ the intensity of transmitted light passing through the crossed polarizer and analyzer is described by

$$I = I_0 \sin^2\left(\frac{\pi n_0^3 r d}{\lambda} E\right), \quad (1)$$

where I_0 is the maximum light-intensity passing through uncrossed polarizers, n_0 is the field-free refractive index, r is the linear electro-optic coefficient for CZT, d is the light path's length through CZT crystal, λ is the free space wavelength of the illuminated IR light, and E is the mean electric-field along the optical path. Thus, we have

$$E = \frac{\lambda}{n_0^3 r d} \arcsin\left(\sqrt{\frac{I}{I_0}}\right) . \quad (2)$$

Accordingly, the distribution of the electric field can be deduced from the intensity distribution of the transmitted light in the PE image.

Fig. 2 shows the electric-field distribution of the CZT detector under 0 V and under 1000 V. The temperature during the measurements was 20 °C. After applying the bias voltage, the intensity of the electrical field increased slowly towards the cathode side. Then, we introduced a high flux of carriers by injecting a 633-nm laser beam on the side surface of the CZT detector, near the cathode side. Fig. 3 shows the corresponding change of the electric field. Clearly, a very bright region formed near the cathode during the injection, signifying that most of the electric field was compressed into a narrow region below the cathode; this high field occupies only about 1/3 of the whole depth of the detector. In the other 2/3 portion, the electric field appears to have collapsed completely. We ascribe this phenomenon to a build-up of a space-charge region that produces a built-in field opposing the applied field. In CZT material, the mobility-lifetime product of an electron is much higher than that of a hole, thereby entailing serious hole-trapping and relatively weak electron-trapping. Accordingly, the density of trapped holes is described as an exponential profile from the cathode to the anode, while the distribution of the trapped electrons is spatially uniform. According to the modeling result of Bale and Szeles, such a distribution of trapped charges will lead to the build-up of net space charges, so creating a minimum point (pinch point) in the electric field.⁹ Most of the electric field will be concentrated between the pinch point and the cathode. Since the ‘effective’ field only exists within a small part of the depth of the entire detector, it usually results in incomplete charge collection. The presence of a space-charge region reflects a dynamical balance between the high flux of carrier injection and strong hole trapping; this means that the charge generated by the radiation cannot be removed

from the device at a sufficiently high rate. Therefore, CZT material with high hole mobility-lifetime product is desirable for high-rate photon irradiation.

Meanwhile, we monitored the change in photocurrent during the high flux of carrier-injection process, as shown in Fig. 4. Unsurprisingly, the photocurrent increased when we started to inject the carriers, because the 633-nm laser beam excited many electron-hole pairs. However, interestingly, the photocurrent improved dramatically when we moved the laser-injection site from the anode side to the cathode side. Compared with the leakage current of CZT under 1000 V, the photocurrent was twice as high and four times higher, respectively, when the injection site was near the anode side, and in the middle part. Indeed, after moving the injection site to the cathode side, the photocurrent increased over one order-of-magnitude. This phenomenon further confirms that trapping of the holes dominates electron trapping during the injection of a high-flux of carriers.

Furthermore, we investigated the effect of temperature on the internal electric field, measuring it at 5 °C, 20 °C, and 35 °C. Fig. 5 illustrates that the uniformity of the field improved markedly with increasing temperature. As we mentioned earlier, the space-charge region occupied about 1/3 portion of the detector's total depth at 20 °C. Lowering the temperature to 5 °C compressed this region into a very narrow band (about 1/6 of the detector's depth). In contrast, raising the temperature to 35 °C caused the extension of the space-charge region into almost half of the detector. The formation of the space-charge region is ascribed to by the strong hole trapping and slow de-trapping. For CZT, the trapping centers of the holes are at some deep acceptor levels. Increasing the temperature affords more energy to fully ionize those deep acceptor levels, and therefore, promotes the de-trapping of holes. Consequently, the accumulation of space charge was weakened. From this point onwards, increasing the operating temperature is expected to reduce the polarization effect in CZT detectors operating under high-flux conditions.

Conclusions

In summary, exploiting a Pockels effect system, we investigated the distribution of the internal electric field of a CZT detector under high-flux carrier injection. A space-charge region built up near the cathode, generating a built-in field that opposes the applied field. This causes the collapse of the electric field in the rest of the detector. Such a space-charge region is related to serious hole trapping in CZT. The operating temperature considerably affects the width of the space-charge region in CZT. With increasing temperature from 5 °C to 35 °C, the width of space-charge region expanded from about 1/6 to approximately half of the detector's total depth.

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Figure Captions

Fig. 1 Schematic diagram of the Pockels-effect measurement system equipped with a laser carrier- injection function.

Fig. 2 Internal electric-field distribution of the CZT detector under 0 V and 1000 V. After applying the bias voltage of 1000 V, the intensity of the electrical field increased slowly towards the cathode side. Measurements were taken at 20 °C.

Fig. 3 Internal electric-field distribution of the CZT detector under 1000 V. Left: no carrier injection; and, right, under carrier injection. With a high flux of carriers, a very bright region formed near the cathode during the injection, signifying that most of the electric field was compressed into a narrow region below the cathode. Measurements were taken at 20 °C.

Fig. 4 Change of photocurrent during the high flux of carrier injection. The measurement temperature was 20 °C.

Fig. 5 Internal electric-field of the CZT detector under high flux carrier injection at 5 °C, 20 °C and 35 °C. The uniformity of the field improved markedly with increasing temperature.

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