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Resistance to Pressure in Laser-doped p–n and Schottky-type Barrier Junctions

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Cadmium telluride (CdTe) is used as an X-ray image detector for dental applications. However, it is difficult to fabricate the large CdTe chips for such applications. Therefore, it is necessary to increase the detection area by tiling. In this study, to minimize the dead space caused by bonding CdTe and application-specific integrated circuits (ASICs), the detector was three-dimensionally stacked by flip-chip bonding. Furthermore, to achieve a high spatial resolution, a diode-type detector that can apply a high electric field was used. However, in flip-chip bonding, layers were stacked while applying pressure and heat; therefore, Schottky-type detectors, which are diode-type detectors, were expected to have a low breakdown voltage because the Schottky junction was located at the interface between the CdTe layer and the electrode. However, the p–n junction was expected to have a high voltage resistance because it was located inside the CdTe layer. Therefore, we performed pressure tests on Schottky-type and p–n junction CdTe detectors, and the *I*–*V* and gamma-ray spectral characteristics before and after the tests were evaluated. As expected, the Schottky-type detector stopped exhibiting diode characteristics after pressurization, the reverse current increased, and gamma rays could hardly be detected; however, the p–n junction detector maintained its diode characteristics even after pressurization, and the *I*–*V* characteristics indicated a high voltage resistance with almost no change in both the *I*–*V* and the gamma-ray spectral characteristics.

1. Introduction

CdTe has been studied as a high-spatial-resolution X-ray image detector that operates at room temperature (300 K) for industrial and medical applications.(1-3) Moreover, using a diode-type detector, CdTe can collect a sufficient number of carriers for a high energy resolution by applying a high bias voltage, resulting in a much higher energy resolution than an ohmic detector.(4,5) Furthermore, it has been reported that laser-doped p–n junction-type CdTe detector

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has a higher resolution than the Schottky-type CdTe detector, and its future development is expected.[6,7] The use of application-specific integrated circuits (ASICs) in image detectors decreases the noise and increases the energy resolution, making it possible to fabricate image detectors with high spatial resolutions.[8-10]

When considering CdTe as an X-ray image detector, it is preferable to laminate CdTe and ASICs in three dimensions. This is because dental X-ray image detectors should have a detection size of 150 × 150 mm^2. However, because the size of one CdTe element is at most 10 × 10 mm^2, we must increase the detection area by tiling. To create a 3D stack of CdTe and ASICs, they have been subjected to flip-chip bonding, which involves the lamination of layers while applying pressure and heat. However, because CdTe is sensitive to heat, flip-chip bonding should be performed at low temperatures.[11] To create an X-ray image detector with a high spatial resolution, a diode-type detector should be used because it can collect a sufficient number of carriers. Although a Schottky-type CdTe detector is desirable because of its low heat resistance,[12] severe conditions are required to perform flip-chip bonding. However, because a p–n junction-type CdTe detector, which is also a diode-type detector, has a high heat resistance,[12] flip-chip bonding can be performed under a wide range of heating conditions.

Although the heat resistance of CdTe detectors has been discussed, their resistance to pressure has not yet been investigated. High-pressure resistance is crucial for flip-chip bonding. High-voltage resistance is also important in device fabrication because postprocessing can be performed under a wide range of conditions. However, the Schottky-type CdTe detector is expected to have a low breakdown voltage because the Schottky junction is located at the interface between the CdTe layer and the electrode. In contrast, a p–n junction in a CdTe detector is expected to have a relatively high breakdown voltage because it is inside the CdTe layer. Therefore, in this study, we performed pressure tests on Schottky-type and p–n junction-type CdTe detectors, evaluated the *I*–*V* and gamma-ray spectral characteristics before and after the tests, and discussed the differences in the effect of pressure.

2. Materials and Methods

We used a 5 × 5 × 0.75 mm^3 p-type CdTe(111) to fabricate Schottky-type and p–n junction diode-type detectors using the steps described below.

1. Etching treatment

   CdTe initially has stains on its surface owing to damage from processing or long-term storage; therefore, its surface was first cleaned using chemicals. After cleaning with acetone and methanol, etching was performed using 5% Br-CH_3OH. Finally, the surface of CdTe was completely rinsed with methanol.[13]
2. Vapor deposition of In electrode

   In was vapor-deposited on CdTe (Te face) by resistance heating using a vacuum device. The deposition area was 4 × 4 mm^2.
3. Direct interface laser doping (p–n junction diode only)

   Direct interfacial laser doping was performed to form p–n junctions. The optical system of the laser used is shown in Fig. 1. The In/CdTe interface was irradiated through the CdTe

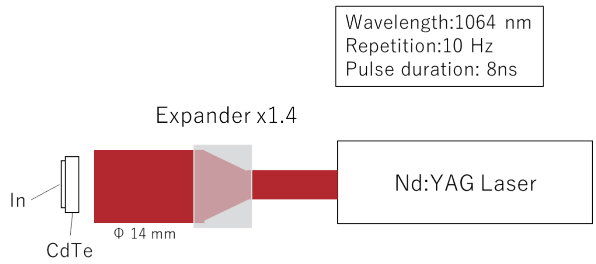


Fig. 1. (Color online) Schematic diagram of optical setup for laser irradiation of In/CdTe interface.

crystal using a laser pulse with a wavelength of λ = 1064 nm. A laser spot with a diameter of 12 mm was formed using an expander, and the entire surface of the sample with a size of 5 × 5 mm^2 was irradiated. The laser intensity was 75 mJ/cm^2 and the number of irradiations was 50.

4. Deposition of Au electrode
   Similarly to that in step 2, Au was deposited on the Cd surface through resistance heating. The deposition area was 4 × 4 mm^2.
5. Dicing
   Dicing was performed to render the entire CdTe surface a metal electrode. The 5 × 5 × 0.75 mm^3 sample was cut into 3 × 3 × 0.75 mm^3 pieces by dicing. Figure 2 shows the system diagram of the final sample.

The Schottky-type CdTe and p–n junction CdTe were pressurized at 0.5 MPa for 5 s using an MCT-1150 pressure tester (A&D Co., Ltd.), with pressure applied to the entire surface of CdTe. Figure 3 shows the system diagram for the pressure-testing machine. Before and after pressurization, *I*–*V* and gamma-ray spectral measurements were performed for both the Schottky and p–n junctions. The device used for the *I*–*V* measurements was a B1505A power device analyzer (Keysight Technologies). For the *I*–*V* measurements, only a reverse bias was applied because the Schottky and p–n junction detectors were intended for use as X-ray image detectors. The voltage range in these measurements was 0–1000 V. For the gamma-ray measurements, a CSP02 preamplifier (ANSeeN Corporation) and a ZMCAN-CH04-01 waveform analyzer (ANSeeN Corporation) were used. The preamplifier was connected to the central electrode of the anode and biased through a 1 GΩ resistor.

3. Results and Discussion

3.1 Experimental results

Figure 4 shows the results of the *I*–*V* measurements before and after pressurization. The horizontal axis shows the applied voltage and the vertical axis shows the current. For both the Schottky and p–n junctions, the dashed and solid lines represent measurements before and after pressurization, respectively. Because the compliance (current measurement limit) was set to 10 μA, the application of pressure to the Schottky ended at approximately 500 V at 10 μA. Figure 5

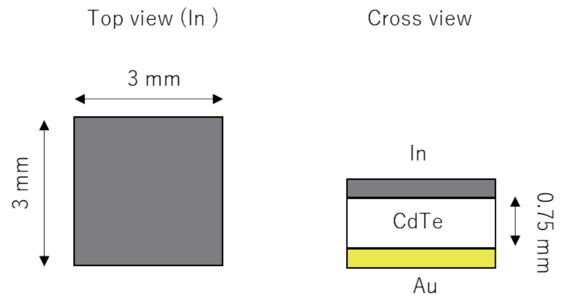


Fig. 2. (Color online) Geometry of Schottky and p–n junction device.

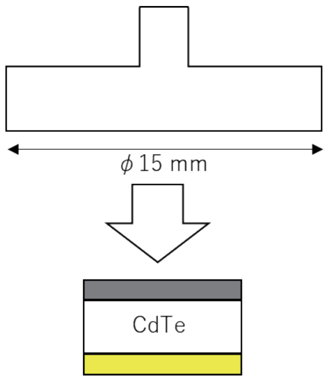
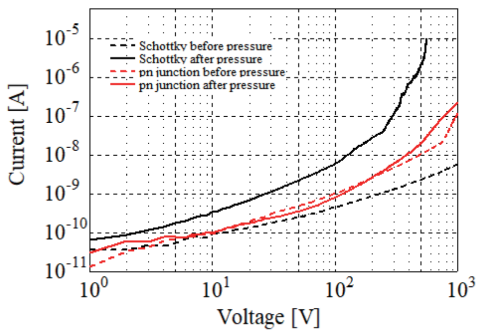


Fig. 3. (Color online) System diagram of pressure-testing machine.



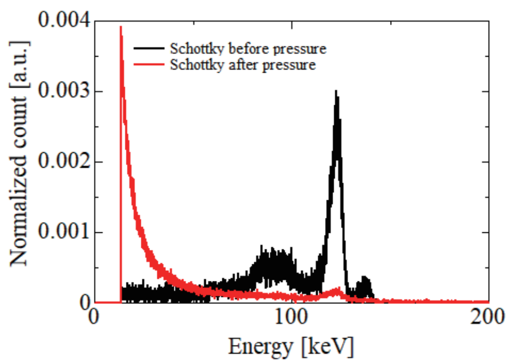


Fig. 4. (Color online) *I–V* characteristics of reverse-biased In/CdTe/Au diodes with Schottky barrier and p-n junction before and after pressure was applied to samples.

Fig. 5. (Color online) Spectra of 57Co radioisotope obtained using In/CdTe/Au diode detector with Schottky junction before and after pressure was applied.

shows the results obtained when the Schottky CdTe detector was operated at a reverse bias of 200 V before and after pressurization. Figure 6 shows the results obtained when the p–n junction CdTe detector was operated with a reverse bias of 200 V before and after pressurization. ^{57}Co was used as the radiation source for these measurements.

3.2 Discussion

According to the *I*–*V* measurements shown in Fig. 4, the Schottky-type and p–n junctions both exhibited diode characteristics before pressurization, and the reverse current was small; therefore, both could operate satisfactorily as X-ray image detectors. In contrast, the Schottky-type CdTe detector showed a significant increase in reverse current after pressurization. This is expected because Schottky junctions are established only under extremely limited surface conditions.(14) To form a Schottky junction, CdTe is subjected to a surface treatment suitable for metal forming,(15) which is strongly affected by the state of the metal–semiconductor junction interface. We consider that when a mechanical (thermodynamic) force is applied to the interface, as in the previously reported(12) heating test and in this test, the bond is easily destroyed, resulting in an increase in reverse current.

Conversely, the p–n junction of CdTe showed satisfactory resistance to pressurization, and the reverse current hardly increased after pressurization. We consider that even when a mechanical force is applied to the p–n junction metal–semiconductor interface, its electrical properties are maintained. This is because the rectifying properties of this diode originate from the p–n junction formed inside the crystal at the boundary between the n-type CdTe:In layer and the p-type CdTe bulk. This reveals that the applied pressure does not affect the In-doped CdTe region near the In/CdTe interface and does not degrade the built-in p–n junction. An important feature is that the p–n junction with a high potential barrier is connected not to the In/CdTe interface, as in the case of the Schottky barrier in In/CdTe/Au diodes, but to the underlying semiconductor region. This junction is formed inside the crystal at the boundary between the n-type CdTe:In layer and the p-type CdTe bulk.

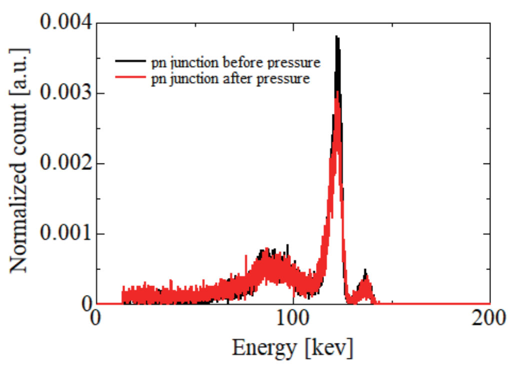


Fig. 6. (Color online) Spectra of ^{57}Co radioisotope obtained using In/CdTe/Au diode detector with p–n junction before and after pressure was applied.

According to the gamma-ray spectrum in Fig. 5, the energy resolution at 122 keV, which is the energy peak of ^{57}Co, was 7.5 keV before pressurization. However, after pressurization, the energy peak of ^{57}Co became almost undetectable. This is because the energy pulse of ^{57}Co is buried in the current noise, which increases with the reverse current. However, for the p–n junction CdTe detector, the detection results were almost unchanged after pressurization and the energy resolution was approximately 6.1 keV. This is because the p–n junction did not deteriorate owing to pressurization and the reverse current did not increase, making it possible to detect the energy pulse of ^{57}Co.

4. Conclusions

In this study, we investigated the stability of the *I–V* and gamma-ray spectral characteristics of Schottky-type and p–n junction CdTe detectors against pressure. Neither the *I–V* characteristics nor the gamma-ray spectral measurements of the Schottky type and p–n junctions changed significantly before pressurization; however, the Schottky type changed significantly after pressurization. In the Schottky-type CdTe detector, the Schottky barrier was broken by pressurization, the reverse current increased, and the gamma-ray sensitivity was significantly degraded. However, the p–n junction CdTe detector fabricated by laser doping had a sufficient energy resolution for use as an X-ray image detector even after pressurization and showed a high resistance to pressure. This is because the p–n junction was formed inside the CdTe layer; therefore, it was not affected by changes in the electrode when pressurized.

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