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Advances in CdMnTe Nuclear Radiation Detectors Development

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Abstract–**Cadmium manganese telluride (CdMnTe) is one of the tertiary compounds of cadmium telluride (CdTe) that has shown great promise in the detection of X-rays and gamma-rays at room temperature without cryogenic cooling. While cadmium zinc telluride (CdZnTe) wide band gap semiconductor has been widely researched and developed to high resolution detector, CdMnTe has comparatively received less effort in development. It is however expected that a more homogeneous CdMnTe crystal with lesser defects than CdZnTe will be easier to grow since the segregation coefficient of Mn in CdTe is closer to unity than that of Zn. This paper briefly reviews the material properties and growth techniques for CdMnTe and presents progress in the development of CdMnTe detectors. Three successive Bridgman growths of CdMnTe resulted in detector grade crystals.**

I. Introduction

Cadmium manganese telluride (CdMnTe) is one of the cadmium telluride (CdTe) based semiconductors that have generated recent interests in nuclear radiation detection applications [1]–[7]. CdTe-based wide band gap semiconductor radiation detectors have the advantage of operating at room temperature without cryogenic cooling, thus enabling the fabrication of miniaturized and portable devices for the detection of X-rays and gamma-rays. Among CdTe based materials, CdZnTe has stood out in high energy resolution detection with applications in medical imaging, astrophysics, and the detection of radiological and nuclear threats [8]–[11]. A lot of research and development (R&D) efforts have been put into CdZnTe detectors to reach its present status while CdMnTe has received a comparatively less R&D effort. The recent interests in CdMnTe have been due to its potential to result in a more homogeneous and detector-grade crystals with lesser defects because the segregation coefficient of Mn in CdTe matrix is ~1. The segregation coefficient of Zn in CdTe is 1.35. This implies that CdMnTe could produce more uniform Mn content in CdMnTe than Zn in CdZnTe during the crystal growth process [12], [13]. In this paper, we breifly review material properties and the present progress in the development of CdMnTe detectors.

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II. Material Properties

The composition of CdMnTe meets most requirements for the detection of high energy radiation (X-ray and gamma-ray) at room temperature. The required material properties for nuclear radiation detectors include large band gap energy to allow operation at room temperature, high density and atomic number (Z-number) for high efficiency, high resistivity needed for low dark current, high photosensitivity for charge generation, good transport properties for large collection of charge carriers, and single crystals relevant for uniformity of detector response.

CdMnTe has a wide tunability of the band gap (1.7 to 2.2 eV) due to the compositional effect of Mn that increases it by ~13 meV per atomic percent of Mn, compared to 6.7 meV for Zn [13]–[15]. CdMnTe has high average atomic numbers (48 for Cd, 25 for Mn, and 52 for Te). The ~1.0 segregation coefficient of Mn in CdTe is a good property that could result in the growth of large CdMnTe single crystals.

A major drawback in developing CdMnTe detectors lies in growing crystals that are free from defects that limit their performance. This drawback is also experienced in CdZnTe detectors [4]. These defects are attributed to Te inclusions, dislocations, sub-grain boundary networks, and precipitates. In applications that require large-volume detectors, these defects become a problem and they reduce the charge transport capabilities of the detectors, which then contribute to poor energy resolution. The key effects of these defects are the trapping of charge carriers that are generated by nuclear radiation, and reduce their mobility and lifetime, thus reducing the detector's overall performance. The performance of CdZnTe and CdMnTe detectors would be improved substantially if the effect of these defects could be minimized.

Taking the advantage of the good properties of CdMnTe to improve the radiation detection capabilities will need more research in reducing defects. The numbers of defects, such as

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Te inclusions, can be minimized using post-growth thermal annealing [1], [16]. Minimizing other defects, such as dislocations, is difficult via post-growth processing. Thus, it is important to find ways of reducing these types of defects during the process of crystal growth.

III. Crystal Growth

There are two major techniques for growing CdTe-based tertiary compounds (CdMnTe and CdZnTe). These include vertical Bridgman technique and traveling heater method (THM); see Fig. 1. In the vertical Bridgman technique, the ampoule containing the growth materials is passed from a high-temperature region to a lower-temperature region of the furnace. In THM, the heating element passes over the growth material and the process could reduce the amount of secondary phase particle (Te inclusions) produced. The purification of the start materials and doping also play important roles in growing detector-grade CdMnTe crystals.

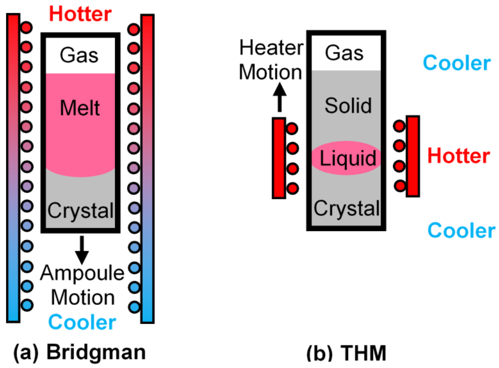

Fig. 1. Vertical Bridgman technique and traveling heater method (THM).

Some modifications have been made to the vertical Bridgeman technique to improve the crystal growth process. Du et al. [17] grew indium-doped $Cd_{0.9}Mn_{0.1}Te$ crystals from a Te solution via the vertical Bridgman approach using the Accelerated Crucible Rotation Technique (ACRT). The ACRT-grown CdMnTe was observed to have fewer twins compared to that one grown by the conventional vertical Bridgman approach. However non-uniformities and irregularities were observed in the microscopic growth-interface morphology [17]. It was suggested that a smooth interface can be obtained by optimizing the growth parameters.

IV. Results

The $Cd_{0.95}Mn_{0.05}Te$ crystals were synthesized from stoichiometric amount of 6N purity CdTe bought from 5N Plus, 99.9998% pure Mn and 6N purity Te from Alfa Aesar [18]. The crystals were grown in conically tipped ampoules. Three growth runs were made that progressively improved the resulting crystals. The first growth run resulted in a low resistivity crystal in the order of 10^5 Ω.cm, Te inclusions of 2 μm to 28 μm in diameter, and few grain boundaries. In the second growth run, Te inclusions and grain boundaries were greatly reduced and resistivity was increased to the order of 10^5 Ω.cm. The third growth run resulted in detector grade CdMnTe crystal. A high magnification infrared transmission image of grain boundary decorated with Te inclusions is shown in Fig. 2. An infrared image of 5.4 x 4.4 x 1.5 mm^3 wafer cut from the middle of the ingot is shown in Fig. 3. There are comparatively large volumes in the ingot that are free of Te inclusions and grain boundaries. Mobility-lifetime (μτ) products for electrons in the order of 10^{-3} cm^2/V were obtained. A Frisch grid detector of size 4.0 x 4.2 x 9.0 mm^3 fabricated from the third ingot gave a resolution of 7.5% (FWHM) for the 662-keV peak of ^{137}Cs [18].

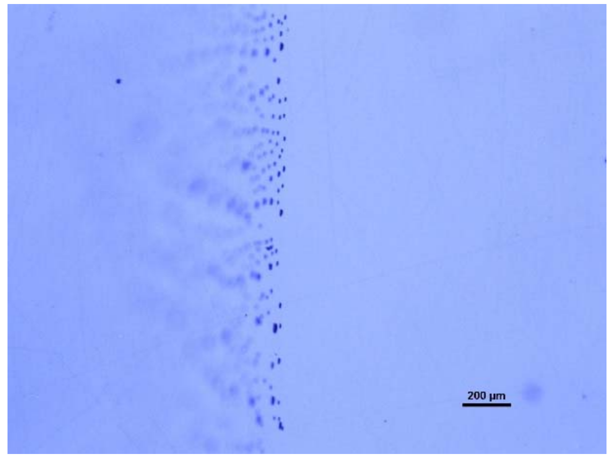

Fig. 2. High magnification infrared transmission image of grain boundary decorated with Te inclusions.

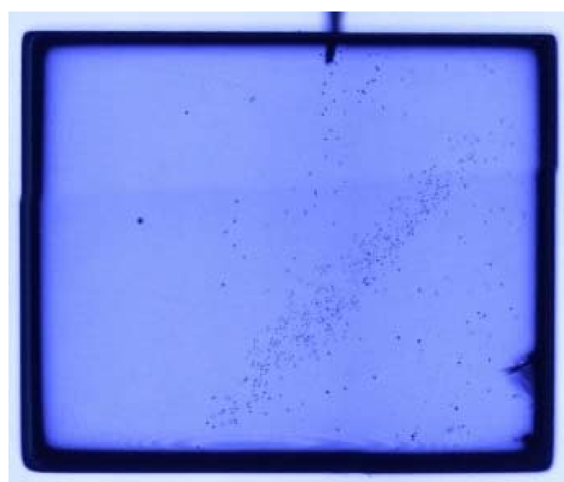

Fig. 3. IR image of the CdMnTe wafer near middle of the ingot. Size: 5.4 x 4.4 x 1.5 mm^3.

V. Summary

This paper has presented a brief review of material properties and growth techniques for CdMnTe. The key advantages of CdMnTe include its wide band-gap tunability (1.7 to 2.2 eV) and the ~1 segregation coefficient of Mn in CdTe matrix (that could lead to better crystal uniformity and yield). Three successive Bridgman growths CdMnTe resulted in detector grade crystals with 10^{10} Ω.cm resistivity and 10^{-3} cm^2/V electrons μτ-product. The resolution of 7.5% (FWHM) was obtained for the 662-keV peak of ^{137}Cs with a 4.0 x 4.2 x 9.0 mm^3 Frisch grid detector fabricated from the CdMnTe [18]. Further improvement could be made on crystal quality and yield through further purification of Mn, increase in the ingot diameter, and optimization of the growth parameters. The crystal growth process improvements could benefit greatly from the synergy of experiments and computational simulations.

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