Development of Large-Area CdTe/n$^+$-Si Epitaxial Layer Based Heterojunction Diode-Type Gamma-Ray Detector Arrays

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***Abstract*—Growth of large area single crystal CdTe layers was studied on 25x25 mm^2 (211) Si substrates using metalorganic vapor phase epitaxy. High crystalline quality thick crystals with very good material uniformity were obtained. A 2D monolithic detector array comprising (20x20) pixels was developed and evaluated. Each pixel is 1.12x1.12 mm^2 size in a 1.17 mm pitch and consists of a p-CdTe/n-CdTe/n$^+$-Si heterojunction diode structure, which is isolated from the surrounding pixels by making deep vertical cuts. The detector array exhibited highly uniform and low dark current, typically less than 0.5 μA/cm^2 per pixel at an applied reverse bias of 50 V. The spectroscopic performance was separately confirmed by dicing out a small portion from the array which clearly resolved energy peaks from ^{241}Am gamma isotopes at room temperature. On the other hand a significant improvement in the detection property was observed by cooling it to -30 ºC.**

***Index Terms*—CdTe, Epitaxial growth, Large-area crystal, gamma detectors, arrays, response uniformity**

I. Introduction

THE II-VI compound semiconductor Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CdZnTe) have properties that make them most suitable material for room temperature X-ray, gamma ray detection. Recent advancement in the crystal growth technique has resulted large volume ingots, and high energy resolution detectors are developed using carefully screened crystals [1]-[3]. However, it is still challenging to achieve large-area crystals with uniform material properties at low cost using the melt-growth technique. As-grown crystals consist of different defects that lower the yield of the ingots [4]. Additionally, CdTe/CdZnTe crystals are highly fragile and easily suffer from the process induced damage during crystal handling. This makes larger imaging array development task very challenging. In order to obtain large-area crystals with uniform properties, we have been studying metalorganic vapor phase epitaxy (MOVPE) growth of single crystal CdTe on Si substrates [5]-[7]. This vapor-phase growth technique not only allows large area crystals, but also makes crystal handling very easy as the CdTe crystals are supported by robust Si substrates. We have previously reported the details about the direct growth of thick (~260 μm) CdTe single crystals on 12x12 mm^2 Si substrates, which exhibited highly uniform material properties. We fabricated small size detectors for gamma ray spectroscopy, and further developed a 2D monolithic imaging array in a p-CdTe/n-CdTe/n$^+$-Si heterojunction diode structure [5]-[7]. The detector array had (8x8) pixels on a 1.27 mm pitch which successfully confirmed the energy discriminating imaging properties. In order to achieve larger and efficient imaging arrays we have been studying CdTe growth and detector fabrication using 25 x 25 mm^2 size Si substrates. Although we successfully obtained 25 x 25 mm^2 size single crystal CdTe on Si substrates, however, further improvement in the material uniformity was necessary. In this study we optimized the growth conditions further focusing on the growth temperature as well as adjustment of tellurium and cadmium precursors flow rates and the ratio. This led us to obtain highly uniform single crystal CdTe on 25 x 25 mm^2 size Si substrates with high material quality. We further developed a (20x20) pixel array, which exhibited very uniform distribution of leakage currents throughout the pixels. The spectroscopic performance of the detector also improved significantly. Details on the growth, crystal properties as well as properties of the array developed are presented.

II. Crystal Growth Details

Undoped CdTe crystals were grown on (211) Si substrates in a custom-designed vertical-type MOVPE reactor working at an atmospheric pressure. Dimethylcadmium (DMCd) and diethyltellride (DETe) were used as the Cd and the Te precursors, respectively and the growth was carried out at 450 ºC. A supply rate ratio of DETe to DMCd was kept constant at 3.0. These undoped CdTe crystals exhibit a high-resistivity p-type conductivity [5]. The n-type CdTe layers, on the other hand, were grown using n-butyl iodine as a dopant precursor, at a growth temperature of 350 ºC, and a DETe/DMCd ratio of 0.25. Growth interruption or/and post growth annealing of grown CdTe crystals were carried out to reduce the residual

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strain in the grown layers [5], [6]. Other details of direct growth of CdTe on Si substrates are reported elsewhere [5]. The grown CdTe crystals were characterized by X-ray diffraction (θ-2θ scan and the double crystal rocking curve (DCRC) measurement).

III. Detector Array Development

The monolithic imaging detector array was fabricated using a 40-50 μm thick CdTe epitaxial layer grown on 25 x 25 mm^2 (211) n$^+$-Si substrate. Shown in Fig. 1 is the cross-sectional diagram of the detector array which was fabricated in the following way: First a typically 5 μm thick iodine doped n-CdTe was grown on the n$^+$-Si substrates, and then approximately 40 to 50 μm thick updoped p-like high resitivity CdTe layer (p-CdTe) was grown on the top of the n-CdTe layer to make a p-CdTe/n-CdTe/n$^+$-Si heterojunction diode structure. Growth interruption/post growth annealing as described in Section II were carried out during early stage of n-CdTe growth as well as during the thick p-CdTe growth. Gold electrodes were then evaporated on the p-CdTe side and on the back side of n$^+$-Si substrate after some surface treatments to make the ohmic contacts. Finally (20x20) pixel pattern, where each pixel is 1.12 x 1.12 mm^2 in a 1.17 mm pixel pitch, was formed on the p-CdTe side of the detector using a diamond blade. In this technique a physical cut through half of the Si substrate is used to pattern the pixels, which isolates each pixel from the surrounding pixels [7], [8]. Fig. 1 also exhibits the photograph of the detector array developed.

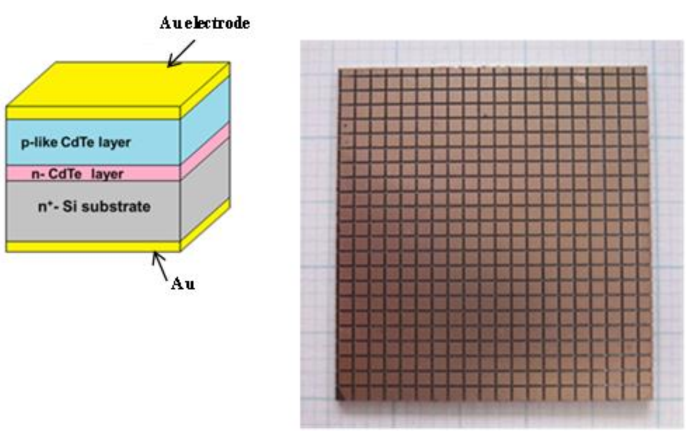

Fig. 1. Cross-sectional diagram of the detector (left), and a photograph of the (20x20) pixel imaging array developed (right).

IV. Results and Discussion

A. Properties of 25x25 mm^2 CdTe crystals grown

With our optimized crystal growth technique, we were able to obtain high crystal quality and uniform single crystal of CdTe on 25 x 25 mm^2 Si substrates consistently. We could achieve four such large area and uniform crystals in each growth run. Each grown crystal shows very uniform thickness throughout the crystal wafer. Fig. 2 shows results of X-ray diffraction measurements performed at the different locations within a 40 μm thick crystal, and a photograph of the grown crystal is also shown in the figure (inset). The result shows single diffraction peak corresponding to CdTe (422) reflection, indicating the grown crystal is monocrystalline through the wafer region. The typical DCRC FWHM values for these crystals were 150 arcsec, which confirms high crystalline quality.

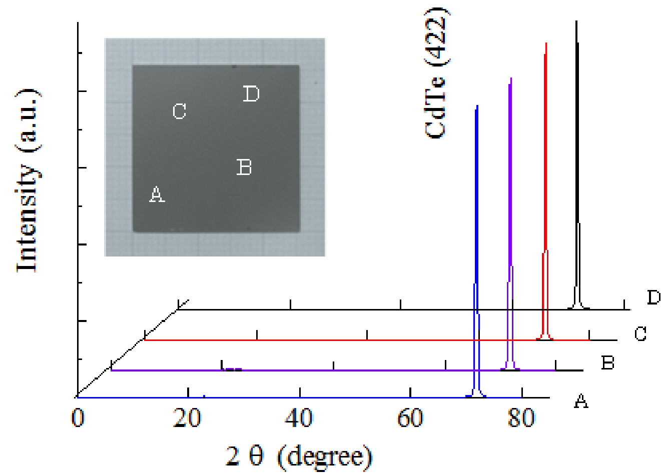

Fig. 2. X-ray diffraction spectra obtained at four different locations on the 25 x 25 mm^2 CdTe crystal grown on (211) Si substrate. The inset shows photograph of the crystal, where the marks A~D correspond the approximate locations on the crystal from where the XRD spectra were obtained.

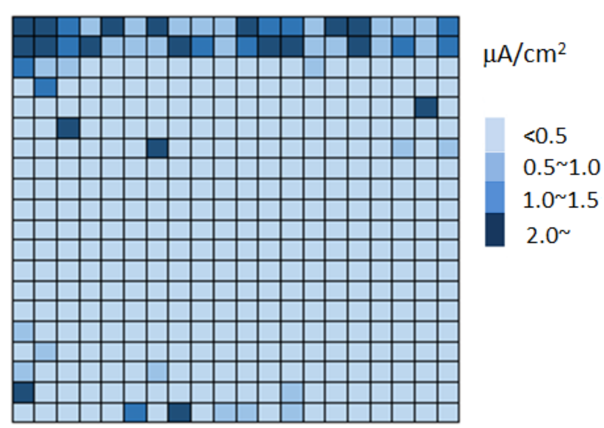

Fig. 3 Distribution of dark current across all 400 pixels in the (20x20) array measured at room temperature by applying a reverse bias of 50 V. Almost all pixels in the array shows uniform values of dark current which was less than 0.5 μA/cm^2 at 50 V bias.

B. Detector Array Evaluation

As described in section III, each pixel in the array possesses a p-CdTe/n-CdTe/n+-Si heterojunction diode structure. We operate the detector array by applying a positive bias on the continuous electrode on the back side of n^+-Si substrate (reverse bias mode). We first measured the reverse dark current from all 400 pixels in the (20x20) array at room temperature using a probe station connected to an Agilent power device analyzer. The system consists of spring loaded probe tips, and is capable of evaluating whole wafer with high precision positioning without causing any damage to the detector electrodes. Fig. 3 shows distribution of dark currents across all pixels in the (20x20) array at an applied reverse bias of 50 V. The result shows very uniform distribution of dark currents among the pixels, where a majority of pixels showed dark current density less than 0.5 $\mu A/cm^2$ at a 50 V reverse bias. This uniformity of dark current indicates the uniform material property of the grown CdTe crystal.

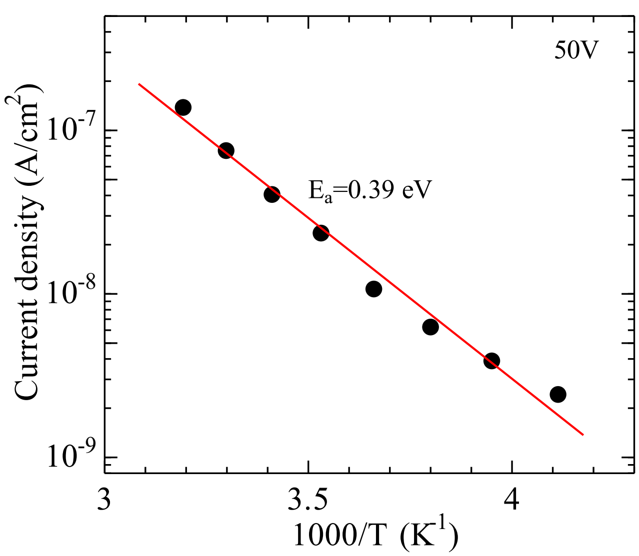

Fig. 4. Arrhenius plot of reverse dark currents of an arbitrarily chosen pixel in the array measured at 50 V bias. The activation energy was calculated as 0.39 eV.

We further measured the temperature dependence of the dark currents in the range of -30 ºC to 60 ºC on arbitrarily chosen pixels. Shown in Fig. 4 is the Arrhenius plot of dark currents at a fixed reverse bias of 50 V for an arbitrarily selected pixel in the array. It was observed that dark currents from all investigated pixels follow the thermally activated generation process with activation energy of 0.4±0.04 eV for an applied bias of 50V. The value of the activation energy slightly changed when the applied bias was varied (e.g. 0.46 eV at 2 V, 0.39 at 20 V bias). Again all investigated pixels showed same variation when the bias was varied. Comparing this with our previous arrays, where the pixels from the different portions of the array exhibited different values of activation energies varying from 0.4 to 0.6 eV [9]. In those arrays, pixels with higher dark currents exhibited high values of activation energies. That was related to different defect levels with varying energies formed due to Cd-vacancies and their complexes as a result of non-uniform variation of effective Te/Cd ratio at the growth surface [9]-[11]. The uniformity of dark current and their activation energies in our recent arrays indicate single energy level is responsible for the observed dark current. This implies improved material uniformity obtained due to the improvement in the uniformity of the effective Te/Cd ratio at the growth surface. By further tailoring the growth parameters it would be possible to reduce the defect level and decrease the detector dark current further.

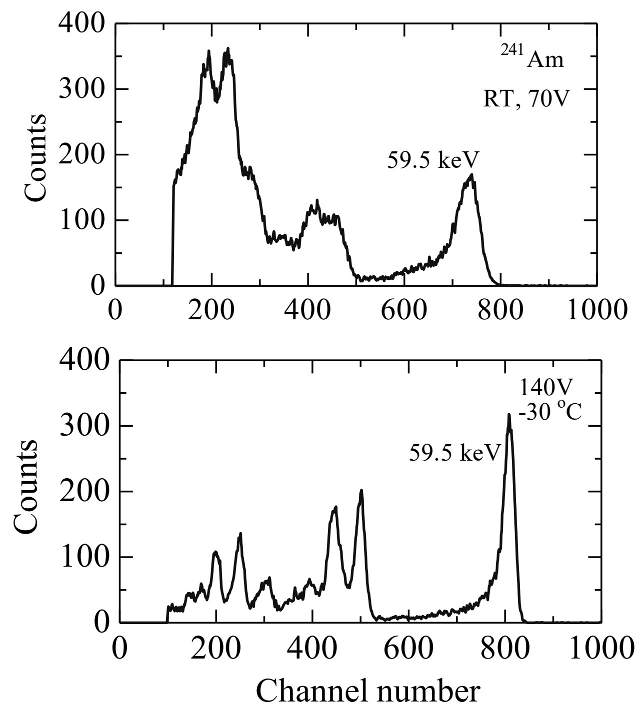

Fig. 5. (top) Representative ^{241}Am gamma spectrum recorded from a single pixel in the array at room temperature. The detector was biased at 70 V to obtain a high detector S/N ratio. (Bottom) spectrum recorded when the detector was cooled to -30 ºC. Due to cooling the dark current decreased that led us to apply a higher bias voltage which improved the detector performance.

Fig. 5(top) shows a representative ^{241}Am spectrum taken with a single pixel in the detector array at room temperature. For this a nearly 5 mm square portion was diced out from the array in order to mount it on a standard TO-8 metal-can package for the spectroscopic measurement. It was diced out from the portion that shows a small and uniform dark current values less than 0.5 $\mu A/cm^2$ (see Fig. 3). This diced portion consists of 16 pixels in (4x4) array, where only one pixel at a time was used and connected to the readout electronics, whereas other pixels remained open. The same process was repeated for remaining pixels. The spectrum was collected with a standard set up consisting of a preamp, shaping amp and a multichannel analyzer. A positive bias (70V) was applied on the electrode on the back of the n^+-Si substrate. Uncollimated gamma rays from the ^{241}Am radionuclide were irradiated on the detector through the gold contact on the p-CdTe side, and the signal induced was collected through the contact on the n^+-Si side. Shown in the figure is the typical response, where all pixels investigated showed similar spectrum. The result shows the detector can resolve all energy peaks associated with the radionuclide at the room temperature. The energy resolution of 59.5 keV gamma peak is about 7%. On the other hand, by cooling the TO-8 mounted detector to -30 ^oC the dark current of the pixels decreased by nearly two orders of magnitude. This allowed us to operate the detector at higher applied bias. Also shown in Fig. 5(bottom) is the response from the same pixel that was used in the top figure at -30 ^oC. The spectrum was collected by applying a bias voltage of 140 V, all other operating condition remained same. A significant improvement in the detector response can be seen. The energy resolution of 59.5 keV gamma peak is now improved to about 3.2%. The collected spectrum is similar to that obtained with a high spectroscopic grade bulk CdTe detector. The crystal growth and detector fabrication process presented here open a new possibility to achieve highly efficient and large area imaging arrays.

V. Conclusion

Large area and thick single crystal CdTe epitaxial layers with high uniform material properties were obtained on 25 x 25 mm^2 size (211) Si substrates. A monolithic 2D imaging detector which comprises 400 pixels arranged in (20x20) array was developed using the grown epitaxial layer and evaluated. Each pixel in the array consists of a p-CdTe/n-CdTe/n^+-Si heterojunction diode structure, which is isolated from the surrounding pixels by making deep vertical cuts. The detector array exhibited highly uniform and low dark current distribution among the pixels which was typically less than 0.5 $\mu A/cm^2$ at an applied bias of 50 V. The spectroscopic performance of the detector was separately evaluated by dicing out a small portion from the (20x20) array and mounting it on a standard TO-8 metal-can package. The pixels evaluated clearly resolved gamma energy peaks from a ^{241}Am radionuclide at room temperature. On the other hand a significant improvement in the spectroscopic performance was observed by cooling the detector to -30 ^oC. The crystal growth and detector array fabrication presented here offers flexibility in the detector design and open new possibility to make larger and efficient imaging arrays.

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