High resolution mapping of mobility lifetime product in CdZnTe using a nuclear microprobe

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Abstract. We present frontal ion beam induced charge (IBIC) imaging with a 2.05 MeV He microbeam on a Cadmium Zinc Telluride (CZT) device. Two sets of voltage dependent $3\text{ mm} \times 3\text{ mm}$ scans were acquired at room temperature and 250 K respectively and the corresponding charge collection efficiency (CCE) images are extracted. The reduction of CCE with reduced bias voltage can be described using the simplified Hecht equation as the contribution of hole transport to the induced charge signal is negligible. This allows us to fit the mobility lifetime product for electrons ($\mu_e\tau_e$) for each pixel of the two datasets, yielding $\mu_e\tau_e$ images at 296 K and 250 K. At 296 K, CCEs up to 96 % were observed for the electric field of 3570 V/cm. In general, the CCE values at 250 K are lower than the comparable values at 296 K with $\mu_e\tau_e$ decreasing from $4.7 \times 10^{-4}\text{ cm}^2/\text{V}$ to $1.2 \times 10^{-4}\text{ cm}^2/\text{V}$, about 1/4 of its original value. Additionally, we observe an increase in CCE at 250 K due to previous irradiation of the material, caused by partial filling of electron traps by the ion beam.

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1. Introduction

Cadmium Zinc Telluride (CZT) is a promising material for radiation detection applications. The advantage of high resistivity, low leakage current even at room temperature and a high absorption cross section for X- and γ -rays makes CZT a suitable candidate for portable detection systems and imaging arrays with spectroscopic properties [1]. To improve the spectroscopic performance, a detailed understanding of the parameters affecting the charge transport in the material is required and a lot of research is presently carried out on CZT.

Ion beam induced charge (IBIC) imaging using a nuclear microprobe has shown to be a powerful tool for the characterization of this detector material with micrometer spatial resolution, probing the uniformity of the detector response over its area [2, 3, 4, 5]. In this study, we use the frontal IBIC technique to acquire voltage dependent charge collection efficiency (CCE) images at two different temperatures. Application of the Hecht equation to CCE images allows us to generate maps of the mobility lifetime product ($\mu_e\tau_e$) [4, 6], which is an important parameter for the detection properties of

the material. Specifically, we wanted to investigate the use of a nuclear microbeam to produce quantitative maps of $\mu_e\tau_e$ and so investigate any non-uniformity in the CZT material.

2. Experimental details and data analysis

The IBIC experiments described in this paper were performed at the University of Surrey microbeam, with 2.05 MeV He ions, focussed to a beam spot size of less than 4 μm diameter. The detector grade single crystalline $\text{Cd}_{1.0}\text{Zn}_{0.8}\text{Te}_{0.2}$ sample had a thickness of $d = 700 \mu\text{m}$. Ohmic gold contacts were evaporated onto the sample, a square 5 mm $\times$ 5 mm contact onto the top surface and a planar contact on the back. The device was biased and irradiated through the top contact. The ion beam raster scans over the top surface of the sample (500 μs per spot). The induced charge signal was amplified by a charge sensitive preamplifier and a shaping amplifier (shaping time = 0.5 μs). The resulting pulses were digitized by a multi channel analyzer (MCA) and stored as event by event data [7]. The electronic noise measured from our sample was below the MCA threshold. This threshold implies that we were insensitive to events below 8 % CCE.

We acquired voltage dependent IBIC images in 50 V steps from -50 V up to -250 V bias voltage at 296 K and at 250 K, each with a scanning area of 3 mm $\times$ 3 mm. At 250 K a 270 $\mu\text{m} \times$ 270 μm scan was also carried out to reveal more spatial detail. The sample was mounted on a temperature controlled copper cold finger, cooled with liquid nitrogen.

The induced charge signal measured from the CZT sample was calibrated using a Si-detector with a nominal charge collection efficiency of 100 % using electron-hole-pair creation energies of 3.6 eV and 4.4 eV for silicon [8] and CZT [3, 9] respectively. The event rate detected during the measurements was typically 1500 – 2000 Hz and each image of 256 $\times$ 256 pixels was acquired for 12 minutes, yielding ≈ 40 events per pixel. Spatially resolved CCE maps were produced by calculating the mean value of the calibrated induced charge signal at each pixel position.

The He ion interaction depth $x = 4.7 \mu\text{m}$ is determined using TRIM [10]. The charges are created close to the cathode and the induced charge signal originates from electrons moving to the anode. The variation of CCE with bias voltage can be described by the simplified Hecht equation(1) under the assumption of a homogeneous electric field $E = v/d$ and negligible contribution of holes to the induced charge signal [8, 11].

$$CCE = \frac{\mu_e\tau_e E}{d} \left[1 - \exp \left(- \left(1 - \frac{x}{d} \right) \left(\frac{\mu_e\tau_e E}{d} \right)^{-1} \right) \right] \quad (1)$$

CCE images were acquired at five different bias voltages. We obtained a set of voltage versus CCE data for each pixel position and extracted $\mu_e\tau_e$ by fitting these data sets to equation(1) using a Levenberg Marquardt algorithm, yielding $\mu_e\tau_e$ images.

Figure 1. CCE images at bias voltage -250 V: a) $3\text{ mm} \times 3\text{ mm}$ scan at 296 K . The indicated areas are used for further analysis; b) $270\text{ }\mu\text{m} \times 270\text{ }\mu\text{m}$ scan of the indicated area in c) at 250 K ; c) $3\text{ mm} \times 3\text{ mm}$ scan at 250 K .

3. Results and discussion

Figure 1 shows the CCE images of our sample biased at -250 V , whose main features are representative for all maps acquired at these temperatures. The contour of the gold contact is clearly visible in all the images, as well as a long vertical scratch across the contact, which can be seen by eye on the sample. Additionally, the images show a regular pattern of low CCE spots $\approx 1\text{ mm}$ apart from each other. They originate from a probing procedure which damaged the sample mechanically at these positions before deposition of the gold contact. The higher resolution $270\text{ }\mu\text{m} \times 270\text{ }\mu\text{m}$ scan shows the three dot structure of these marks more clearly. Apart from these damaged regions, the spatial distribution of CCE across the device is very homogeneous. The regions showing maximum CCE at 296 K are concentrated at the edges of the gold contact. At 250 K the maximum CCE is found in a rectangular shaped region at the right hand side. Additionally, diagonal lines of slightly reduced CCE which are present at 296 K are not resolved at 250 K . The CCE generally decreases over the whole area with with reducing bias, as expected by the Hecht equation. Reducing the temperature also leads

Figure 2. Pulse height spectra of the 3 mm× 3 mm scan area at the indicated bias voltages, the inset shows the FWHM/peak centroid ratio. a) at 296 K b) at 250 K

to a reduction of CCE over the whole area, but instead of the evenly distributed values at 296 K, the images show an increasing trend from the left to the right hand side.

The pulse height spectra obtained from the whole scanning area are shown in figure 2. They show various features corresponding to different regions on the sample. The full width half maximum (FWHM) of the main peak is constant at both temperatures at bias voltages from -250 V to -150 V and increases at lower bias values. The resolution FWHM degrades from $1.2(2)$ % at high biases to $4.6(4)$ % at -50 V at 296 K and from $3.6(4)$ % to $6.1(6)$ % at 250 K respectively. A separate set of data was acquired with the polarity of the sample bias reversed, so that the ion beam irradiated the anode. In

Figure 3. $\mu_e\tau_e$ images of the 3 mm $\times$ 3 mm scan area: right: 296 K; left: 250 K.

this configuration, where the observed signal is due hole transport in the CZT, hardly any pulses were observed above our MCA threshold. This behaviour is expected since the charge collection length λ_h of holes is short compared to thickness of our detector, due to the short $\mu_h\tau_h$ [1].

The sequence of five CCE images acquired at the different voltages were used to produce the $\mu_e\tau_e$ images shown in figure 3. Each pixel in figure 3 represents the $\mu_e\tau_e$ value obtained from a fit to equation(1). Pixels with high χ^2 values - corresponding to data which do not provide a good fit to equation(1) are shown in white. They appear mainly in regions with low statistics due to only a few registered events. The distribution of $\mu_e\tau_e$ follows the same pattern which is expected from the CCE maps. Typically, values of $\mu_e\tau_e$ at 250 K are reduced to $\approx 25\%$ of their value at 296 K, e.g. $\mu_e\tau_e = 4.7 \text{ cm}^2/\text{V}$ and $\mu_e\tau_e = 1.2 \text{ cm}^2/\text{V}$ respectively (figure 4).

The $\mu_e\tau_e$ images of the two different temperatures differ significantly in quality, which reflects the accuracy of the fitted data. As the reduction of CCE between -250 V and -50 V is only about 5% , the fit is very sensitive to statistical fluctuations of the CCE values in each pixel, which can be of the same magnitude as the observed change in CCE with bias voltage. This leads to a broad distribution of $\mu_e\tau_e$ values within a few pixels, which has no physical significance. In contrast, at 250 K, larger changes in CCE are observed and the resulting fit to equation(1) is less affected by statistical fluctuations. However, it is evident that the CCE is evenly distributed at 296 K. The 250 K images show a distinct region of high $\mu_e\tau_e$ at the right hand side.

Schlesinger *et al* [1] report that the resolution of a CZT detector in α -particle spectroscopy is not affected by variations in electron drift length λ_e within 10% , if λ_e is large compared to the detector thickness. This corresponds to our constant resolution observed at 296 K between -250 V and -150 V , which corresponds to λ_e between 1.7 mm and 1 mm .

The pulse height spectrum (figure 5 - top) for the selected area marked as 1) in fig-

Figure 4. Peak centroids of the pulse height spectra in figure 2 versus bias voltage. The lines present to the Hecht equation(1).

ure 1 a, clearly shows two separate peaks at 250 K independent of bias voltage. The separation of the two peak centroids increases with decreasing bias voltage from 3 % CCE at -250 V to 9 %. The effect is not found at 296 K. Further analysis reveals that the lower peak occurs when the scanning beam hits the region for the first time during the scan. The higher peak occurs after the ion beam reached the edge of the image and scans back over the same area. The effect occurs consistently throughout the data run. In contrast the pulse height spectrum projected from region 2 contains only counts corresponding to the lower CCE peak. The data of the small scan size shows a similar effect, but the separation of the two peaks is less (figure 5 - bottom). This data shows that the CZT signal amplitude increases, when scanned with the beam shortly after a previous event. This indicates priming of the material by the ion beam, due to filling of electron traps. The traps release the electrons with a time constant in the order of several 10 s, which will lead to a lower electron lifetime (and thus lower CCE) again, as observed in our data. Fitting the two peak positions yields an increase of $\mu_e \tau_e$ from 1.1×10^{-4} cm^2/V to 2.0×10^{-4} cm^2/V . Medunić *et al* [3] also suggest an electron trapping - detrapping mechanism to be responsible for an increasing signal amplitude with measuring time [3]. Due to the dependence of CCE on previous irradiation, the

Figure 5. Pulse height spectra of a single movement of the beam over the sample area, resolved in the two different directions of scanning movement of the ion beam: top: extracted from area 1) indicated in figure 1; bottom: extracted from the indicated area as shown in the inset of the $270 \mu\text{m} \times 270 \mu\text{m}$ data

trapping detrapping mechanism determines also the resolution of the device. The priming effect cannot explain the increase in $\mu_e\tau_e$ observed in the image from the left to the right hand side, because it is not seen on the left hand edge of the images. Toney *et al* [12] calculated the variation of resolution with temperature taking into account the changes in band gap and leakage current. Their result yields 250 K as a better operation temperature for CZT compared to 296 K if trapping is not taking into account. Our result shows that the resolution is worse at 250 K, due to spatial variation in the detector performance and the trapping effects.

4. Conclusions

We applied the frontal IBIC imaging technique to investigate a planar CZT device. CCE and $\mu_e\tau_e$ images show that mechanical damage strongly affects the detector performance at the damaged regions. The investigated material shows a uniform response at 296 K, close to 100 % CCE at an electric field of 3570 V/cm. The CCE

reduces at lower temperature and the resolution of the detector drops. The decrease in CCE with bias voltages can be described with the Hecht equation, which allows us to calculate $\mu_e\tau_e$ images by fitting the voltage dependent CCE data, extracted from each pixel position in the CCE maps. $\mu_e\tau_e$ shows $\approx 1/4$ of its value at 296 K at lower temperature. Finally, we observed an electron trapping effect in the 250 K data. The signal amplitude will increase, if the area had been irradiated a few seconds before. This will affect the resolution of the device dependent on the applied dose rate.

Acknowledgments

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