ION BEAM INDUCED CHARGE COLLECTION (IBICC) STUDIES OF CADMIUM
ZINC TELLURIDE (CZT) RADIATION DETECTORS¹

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Cadmium Zinc Telluride is an emerging material for room temperature radiation detectors. In order to optimize the performance of these detectors, it is important to determine how the electronic properties of CZT are related to the presence of impurities and defects that are introduced during the crystal growth and detector fabrication. At the Sandia microbeam facility IBICC and Time Resolved IBICC (TRIBICC) were used to image electronic properties of various CZT detectors. Two-dimensional areal maps of charge collection efficiency were deduced from the measurements. In order to determine radiation damage to the detectors, we measured the deterioration of the IBICC signal as the function of dose. A model to explain quantitatively the pattern observed in the charge collection efficiency maps of the damaged detectors has been developed and will be discussed in the paper.

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Introduction

Cadmium Zinc Telluride (CZT) is one of the most promising materials for room temperature radiation detectors. Since it does not need the bulky and expensive cryogenic system, portable gamma ray imaging arrays can be built with spectroscopic capabilities. Unfortunately, the manufacturing yield of high quality CZT detectors is quite low due to the impurities and defects introduced during the detector fabrication. These detectors are usually tested using α beams from radioactive sources. Recently CZT detectors' charge collection efficiency was mapped by moving the detectors under a collimated α particle beam [1]. These charge collection efficiency maps allow to calculate the electronic transport properties of CZT, such as the electron mobility and lifetime. The same experiment can be carried out with much higher spatial resolution using a nuclear microprobe. Ion Beam Induced Charge Collection (IBICC) [2-4] and Time Resolved IBICC (TRIBICC) [5] have been used routinely by several laboratories to study microelectronics circuits. The same techniques can be applied to semiconductor detectors.

During these studies, the probing beam damages the detectors. Therefore, it is important to know how the deterioration of the detector signal relates to the ion dose, dose rate, scan area, etc. A summary of recent broad beam studies can be found in [6] and a preliminary study with a nuclear microprobe can be found in [7]. During these microbeam experiments, a characteristic pattern was observed a higher charge collection efficiency area at the edges of the scanned area (Figure 1). Similar pattern was observed by Jaksic on PIN diodes [8]. This edge region was also observed in experiments where thin p-n junctions were studied by IBICC and a model was worked out [9-11]. Although the phe-

nomenon is similar (but it is the inverse of what can be observed in PIN diodes and CZT detectors; the charge collection efficiency goes to zero at the edges in case of thin junctions, while it increases in case of the PIN diodes and CZT detectors), the mechanism is quite different. In case of the thin junctions, the charge collection occurs mainly through diffusion (almost all the charge is generated under the junction in a field free regions so the charge has to diffuse back to the junction) while in case of the fully depleted devices the charge collection is due to the drift of electrons and holes in an electric field.

In this paper we will present a simple model for the charge collection in CZT detectors through a heavily damaged region.

Experimental methods

The Sandia microbeam facility [12] was used in these damage study experiments. The entire beam line is mounted on a vibration isolation table and a cryogenic pump is used during the experiments to reduce vibrations. The CZT detectors (3 mm x 3 mm x 2 mm) were irradiated with a 5.4 MeV α beam at the negative contact of the detector with a spot size of 0.6 μm in diameter. In the IBICC experiments the beam was scanned over areas from 30 μm x 30 μm to 100 μm x 100 μm at 512 and 256 step resolution in both the x and y directions. Because of the low number of detected ions per pixel, the data were compressed into 64x64 maps. The current was kept between 100 and 1000 ions per seconds. The charge induced by each ion was integrated through a charge sensitive preamplifier and sent through a spectroscopy amplifier (1.5 μs shaping time) into a PC base multi-channel analyzer system.

The Sandia TRIBICC system is described in details in [5]; here we give only a brief description. The output of the charge sensitive preamplifier for each individual ion strike was digitized using a fast computer controlled Tektronix 680B digital oscilloscope (1 GHz analog equivalent). The usual resolution was 1-4 ns and the transient was stored in 500 points. To avoid a signal from a second ion while the transient was processed and the data transferred (~ 100 ms), we used a high-speed (< 200 ns) on-demand beam deflector to remove the beam from the target. Full scans were recorded at 64×64 resolution and partial scans (line scans) were recorded at 3×64 and 1×64 resolutions. The rise time of the signal (from 0.1 to 0.9) was extracted from the waveforms, which is a good estimate of the T_r transit time (see definition later). One damaged spot was measured the following morning to see if the damage healed or not.

The Model

The CZT detectors used in these experiments were planar detectors having gold contacts on the opposite sides of the CZT crystal. The induced charge on the contacts is given by the Hecht equation [13,14]:

$$Q(z) = eN_0 \left[\rho_e \left(1 - e^{-\frac{z_e}{\rho_e d}} \right) + \rho_h \left(1 - e^{-\frac{z_h}{\rho_h d}} \right) \right] \quad (1)$$

where e is the unit charge, N_0 is the total number of charge carrier produced, z is the distance the carrier has to travel, d is the thickness of the detector, and ρ is the carrier extraction factor (CEF). The indices e and h refer to electrons and holes, respectively. CEF is defined as follows:

$$\rho = \frac{\tau}{T_r} \frac{z}{d} \quad (2)$$

where τ is the mean free drift time (life time) and T_r is the time required for the carrier to be collected. Since all the charge is collected in the top 20 mm the holes contribute very little to the signal ($\sim 1\%$), we can take into account only the electrons.

The deterioration of the measured signal is due to the decrease of P_e that can occur in two ways: increase in T_r or decrease in τ .

There are three factors that cause the border area:

- Since the beam size was larger than the scan step size, the scans overlapped except on the border of the scan. This would produce a higher charge collection efficiency region at the edges with a width in the order of the beam size ($0.6 \mu\text{m}$).
- The damage profile of one ion has a finite width and the overlap of damaged regions produced by individual ions would produce a less damaged region at the edges. The lateral extent of the damage caused by a 5.4 MeV α particle is less than $1 \mu\text{m}$ [15] so the width of the band at the edges would be in the same order.
- While the electrons drift toward the positive electrode in the z direction they also diffuse in the x - y plane. Some of the electrons can get outside of the damaged region; therefore, they will not be trapped.

Since our experiments showed significantly larger border width than $1 \mu\text{m}$, we have to assume that the third mechanism is responsible for the border width.

In our model we made the following assumptions:

- The electrons drift in the z direction and diffuse in the x - y plane.
- There is a heavily damaged region at $z=Z$ where the electrons are trapped permanently with $p=\alpha$ probability. If the electrons are outside of the damaged region (in the x - y plane) when they reach the damage depth they are collected with $p=1$

probability. This assumption is not far from reality. Figure 2 shows the damage profile of the 5.4 MeV α particles in CZT [15]. From the figure it is obvious that there is a heavily damaged region around $z=20 \mu\text{m}$ while the damage is about 50 times less in the region toward the surface.

- There is no additional trapping and detrapping. This is not strictly true, however it is a good estimate when the electrons already got through the damaged region. (Typical value of electron lifetime is a few μs , while the electrons cross the 2 mm in about 200 ns.)

The electron diffusion profile at (x,y,z) if the electrons were created at (x_0,y_0,z_0) is:

$$f(x,y,z,x_0,y_0,z_0) = \frac{1}{2\pi Dt} e^{-\frac{(x-x_0)^2 + (y-y_0)^2}{2Dt}} \quad (3)$$

where D is the diffusion coefficient and $t = \frac{z-z_0}{\mu E}$, μ being the electron mobility and E being the electric field. At this point it is worth making an observation. According to Einstein's relation the diffusion coefficient and the mobility are related the following way:

$$\frac{D}{\mu} = \frac{kT}{e} \quad (4)$$

where k is the Boltzmann constant and T is the temperature. The width of the diffusion profile at the depth of the damaged region

$$\sqrt{D \frac{Z-z_0}{\mu E}} = \sqrt{\frac{kT}{eE} (Z-z_0)} \quad (5)$$

is independent of the materials parameters, and depends only on the electric field at fixed temperature and damage depth.

The charge collection efficiency from an electron created at (x_0,y_0,z_0) is:

$$F(x_0, y_0, z_0) = \int_{outside} f(x, y, Z, x_0, y_0, z_0) dx dy + (1 - \alpha) \int_{inside} f(x, y, Z, x_0, y_0, z_0) dx dy \quad (6a)$$

$$F(x_0, y_0, z_0) = 1 - \alpha \int_{inside} f(x, y, Z, x_0, y_0, z_0) dx dy \quad (7b)$$

where *inside* and *outside* refers to the inside and outside of the damaged area in the x - y plane. In case of a rectangular damaged are (such as our scanned area) the integral can be evaluated easily. Assuming that the damaged area is defined by the $((-X, -Y), (X, Y))$ rectangle we have:

$$F(x_0, y_0, z_0) = 1 - \frac{\alpha}{4} \left[\operatorname{erf} \left(\frac{X + x_0}{\sqrt{2Dt_z}} \right) + \operatorname{erf} \left(\frac{X - x_0}{\sqrt{2Dt_z}} \right) \right] \left[\operatorname{erf} \left(\frac{Y + y_0}{\sqrt{2Dt_z}} \right) + \operatorname{erf} \left(\frac{Y - y_0}{\sqrt{2Dt_z}} \right) \right] \quad (7)$$

where erf is the error functions and $t_z = \frac{Z - z_0}{\mu E}$. To calculate the charge collection efficiency we have to integrate $F(x_0, y_0, z_0)$ over z_0 from 0 to Z weighted by the electronic energy loss distribution.

$$Q(x_0, y_0) = \int_0^Z F(x_0, y_0, z_0) S_e(z_0) dz_0 \quad (8)$$

where $S_e(z_0)$ is from a TRIM calculation [15] and is shown in Figure 2.

Results

In this experiment we used a counter grade detector that we found more vulnerable to damage in the past than spectroscopy grade detectors [7]. In several IBICC and TRIBICC measurements we found as much as 50% loss of peak height in certain areas while the rise time of preamplifier signal changed less than 10% in those areas. This suggests that decrease in the τ lifetime of electrons in these areas is mainly responsible for the peak height loss. Several spots were irradiated until the peak height loss became 10-20 % in

the center. A slight dose rate effect was observed, in the center of the scan the peak height loss after 40 ions/mm² was ~ 6.6% for 100 ions/s and 8.5% for 1000 ions/s current, respectively. In the corner of the scan the difference was even less. Figure 5 shows slices of the charge collection efficiency map shown in Figure 1 along the x -axis in the center. This sample was irradiated by a 63 μm x 60 μm scan and the analysis was done by a 125 μm x 118 μm scan. The dashed line shows a fit with $E=44$ V/cm electric field (which is significantly smaller than the nominal field (1000 V/cm) and $\alpha=0.05$. The curve fits well the data points in the original scan area, but gives much larger charge collection efficiency around it. We assume that our beam, which was a He^{++} beam, had a small halo from unfocused He^+ ions that were created by charge exchange in the beamline. This halo did not show up in the short measurements, but it caused observable damage in the long damage measurements. The above model can be easily modified to include a low damage region outside of the original scan area. The solid line shows the fit with $\alpha_2=0.01$, $\alpha_1=0.05$, and $E=44$ V/cm, where 1 and 2 indices refer to the original scan area and the halo around it. Figure 6 shows the transient waveforms from three different areas of a scan. It not only shows that the preamplifier signal is significantly smaller in the center region (~18% loss), but the rise time of the signal is significantly longer in the damaged center than on the virgin area (236 ns vs. 160 ns). In the halo area where the damage is less, the rise time is between the signals from the virgin and the highly damaged areas. Figure 7 shows the same transients 16 hours after the first measurement. The preamplifier signal became higher (~13% loss) and the rise time become smaller (188 ns). The halo area seems to be almost completely recovered. The wide border region definitely shows a lower electric field. We also noticed that the border width become narrower.

There may be two sources of this lower electric field:

- The field is originally lower at the contact that was observed CZT and CdTe detectors [16], which may be due to gold diffusion from the contact.
- Charge can be trapped in the damaged region that can modify the local electric field. The increase in the preamplifier signal rise time in the damaged area supports that assumption. Also the charge can bleed away in time that was indicated by the shorter rise time and narrower border width after 16 hours.

Summary

We presented a simple model that can explain the wide border region that was observed on CZT detectors damaged by a scanned microbeam. During the experiments we found a small halo of unfocused ions around our beam that caused slight damage outside of the scan area. According to the model the wide border is due to lower than nominal electric field in the region where the electron-hole pairs are generated. The reason for the lower electric field is not exactly known but longer rise time of the detector signal from the damaged areas support charge build up in the damaged area. The signal deterioration improves after some time. The halo damaged areas recover almost completely, but the area damaged by the focused beam has permanent loss of charge collection, although somewhat less than during and immediately after irradiation.

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Figure captions

Figure 1

Peak height distribution map across the scan area. The scan was done on a previously damaged spot. The black rectangle shows the location of the previous spot.

Figure 2

Electronic energy loss and damage profile of 5.4 MeV α particles in CZT calculated by TRIM [15].

Figure 3

Calculated charge collection efficiency profile dependence on the α trapping probability. The calculations were done for $E=1000$ V/cm electric field and for a $100 \mu\text{m} \times 100 \mu\text{m}$ scan area. Only the edge region of the scan area is shown. Notice that the width of the border region is approximately the same for all curves.

Figure 4

Calculated charge collection efficiency profile dependence on the electric field for a $100 \mu\text{m} \times 100 \mu\text{m}$ spot with $\alpha=0.5$ trapping probability.

Figure 5

Relative peak height profile along the X-axis in the center of scan shown in Figure 1. ($\blacktriangle$) after 0.1 ions/mm² dose, ($\blacksquare$) after 55.6 ions/mm² dose, (—) calculation without halo, (--) calculation with halo. The arrow indicates the scan size at which the damage was done.

Figure 6

Transient waveforms from (▲) virgin, (■) halo, and (★) center region of the sample immediately after irradiation

Figure 7

Transient waveforms from (▲) virgin, (■) halo, and (★) center region of the sample 16 hours after irradiation.

Figures

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7