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Investigation of the electronic properties of Cadmium Zinc telluride (CZT) detectors using a nuclear microprobe*

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Abstract

The electronic transport properties of Cadmium Zinc Telluride (CZT) determine the charge collection efficiency (i.e. the signal quality) of CZT detectors. These properties vary on both macroscopic and microscopic scale and depend on the presence of impurities and defects introduced during the crystal growth. Ion Beam Induced Charge Collection (IBICC) is a proven method to measure the charge collection efficiency. Using an ion microbeam, the charge collection efficiency can be mapped with submicron resolution, and the map of electronic properties (such as drift length) can be calculated from the measurement. A more sophisticated version of IBICC, the Time Resolved IBICC (TRIBICC) allows us to determine the mobility and the life time of the charge carriers by recording and analyzing the transient waveform of the detector signal. Furthermore, lateral IBICC and TRIBICC can provide information how the charge collection efficiency depends on the depth where the charge carriers are generated. This allows one to deduce information on the distribution of the electric field and transport properties of the charge carriers along the detector axis.

IBICC and TRIBICC were used at the Sandia microbeam facility to image electronic properties of several CZT detectors. From the lateral TRIBICC measurement the electron and hole drift length profiles were calculated.

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Introduction

Nuclear microprobes have been routinely used to test and study room temperature radiation detector materials, such as CdTe and CZT [1, 2, 3]. Usually alpha particles or protons are used to minimize the damage from the probing beam. There are two versions of this technique, frontal and lateral IBICC (Ion Beam Induced Charge Collection). In case of the frontal IBICC, the detector's cathode or anode is irradiated. At a few MeV, ion energy the ions only penetrate the top layer (a few times ten μm); therefore, the signal is almost entirely due to the electrons (cathode irradiation) or to the holes (anode irradiation). This allows one not only to determine the detector's charge collection efficiency, but the mobility-life time product can be calculated for both charge carriers (assuming uniform electric field, mobility, and life time through the detector volume). In a lateral IBICC measurement, the ion beam is scanned on the side of the detector from the cathode to the anode. The measured signal height will contain information about the drift length dependence on the distance from the cathode. These kinds of measurements were used to determine the electron and hole drift length profiles in CdTe detectors [1, 2]. A variation of the IBICC measurement is Time Resolved IBICC, in which the preamplifier signal is recorded as a waveform. This carries even more information. In a frontal TRIBICC measurement, the average lifetime and collection time (drift velocity) can be determined. Unfortunately, the measurement performed recently had problems interpreting the data; the measurements resulted in unrealistically short electron life times and the calculated life time varied significantly with the bias [3,4].

The lateral IBICC measurements have a serious drawback. The charge collection efficiency profile strongly depends on the shaping time of the amplifier [2]. Since the usual shaping time is a few μs , the charge due to the low drift velocity holes will be missing from the signal. On the other hand, we cannot consider the IBICC signal completely due to the electrons, since the holes do contribute during the shaping time. This makes the interpretation of the charge collection efficiency profile difficult. The solution to this problem is to use lateral TRIBICC instead of lateral IBICC. By recording the preamplifier waveform we can determine the total collected charge. From the waveform the electron and hole contributions can be separated, and the drift length profiles can be calculated independently for both the electrons and holes. Figure 1 shows IBICC and TRIBICC profiles recorded on the same line from the cathode to the anode. While the IBICC signal decreases almost linearly toward the anode, the TRIBICC signal remains practi-

cally constant. In this paper we will present the results of a lateral TRIBICC measurement on a CZT detector.

Experimental

The measurements were carried out using the Sandia microbeam facility [5]. A 3x3x2 mm³ spectroscopy grade CZT detector from eV Products was used for this experiment. The one of the detector's was polished to optical finish. Contact to one surface of the detector was achieved by using conducting rubber while on the other side a spring-loaded gold contact was used. The applied bias was 400 V, which means 2 kV/cm nominal electric field. The 5.4 MeV He⁺⁺ beam was focused to a spot of about 1 μm size and was electronically scanned over ~150 μm at about 100 ions/s. Several line scans were done at about 2 μm apart from each other. Then the sample was mechanically moved to the next 150 μm area. The output signal of the preamplifier for each individual ion strike was digitized and stored using a fast, computer-controlled Tektronix TDS 680B digital oscilloscope (1 GHz analog equivalent). Beam damage effects and multiple ion-strikes were virtually eliminated by the use of a high-speed (<200 ns) on-demand beam deflector to remove the beam from the target during the relatively long period (~0.1s-1s) of time the system takes to process and store each transient. Thus each recorded transient was the result of a single ion strike at that particular point in the scan. Very rarely a double ion hits occurred, those wave forms were removed from the measurement.

Results and discussion

Figure 2 shows typical waveforms close to the cathode, around the center of the detector, and close to the anode. The maximum value of the waveform decreases slightly and the rise time increases toward the anode. The waveform from the center of the detectors clearly shows that the electrons are collected quickly, then the holes collection continues at slower speed. The theory of the charge collection process is described in detail in [6]. The wave form due to electron hole pairs created at x distance from the cathode is:

$$q(x,t) = \frac{Ne}{d} \left\{ \int_0^{\min(t, T_n)} v_{d_n}(t') e^{-\frac{t'}{\tau_n(t')}} dt' + \int_0^{\min(t, T_p)} v_{d_p}(t') e^{-\frac{t'}{\tau_p(t')}} dt' \right\} \quad (1)$$

where d is the detector thickness, v_{d_n}, v_{d_p} , are the drift velocities, τ_n, τ_p , are the lifetimes, and T_n, T_p are the transit times of the electrons and holes, respectively. In principle, by measuring the transient waveforms along the axis of the detector, one would be able to calculate the drift velocity and lifetime profiles of electrons and holes by fitting Eq. (1) to the waveforms. Practically, it is not feasible. Many waveforms with high resolution (many measurement points) have to be recorded in order to determine the details of the profiles. The large amount of data requires several hundred megabytes in a non-linear fitting procedure and takes extremely long time. Another problem is the selection of the initial parameters for the non-linear fit. Most non-linear fitting algorithms are very sensitive to the initial parameters; therefore, in order to achieve a satisfactory fit a good estimate of the fitting parameters is necessary. Unfortunately, we were unable to find an algorithm that would provide sufficiently good estimates based on the measurement. Instead of taking up this enormous task we simply calculated a few parameters from the waveforms, such as the signal height, rise time, and the contribution due to the electrons. The signal rise time (not very close to the cathode) gives us the transit time of the holes in which the whole drift velocity profile is incorporated. Taking into account that the mobility of the holes is about ten times smaller than the mobility of the electrons, the signal rise time is the hole transit time when the charges are generated farther than 200 μm from the cathode. The separation of the electron and hole contributions to the signal allows us to calculate the drift length of both charge carriers independently. Figure 3 shows these parameters for a typical waveform. The drift lengths can be calculated by fitting the electron and hole profiles to Eq. (2a-2b) [5]

$$q_n(x) = \frac{Ne}{d} \int_x^d e^{-\int_x^{x'} \frac{dx''}{\lambda_n(x'')}} dx' \quad (2a)$$

$$q_p(x) = \frac{Ne}{d} \int_0^x e^{-\int_0^{x'} \frac{dx''}{\lambda_p(x'')}} dx' \quad (2b)$$

where $\lambda = v_d \tau = \mu E \tau$, μ is the mobility, and E is the electric field.

The hole transit time is given by Eq. 3.

$$T_p(x) = \int_0^x \frac{1}{v_{d_p}(x')} dx' \quad (3)$$

Since we did not expect sharp changes in the drift length and drift velocity profiles, we followed the example of [1] and expanded the profiles in terms of Legendre polynomials up to sixth degree.

Figures 4a and 4b show the measured charge collection efficiency, the contributions of the electrons and holes (4a), and the signal rise time (4b) as the function of the distance from the cathode. It is obvious from the figures that this detector has very good hole collection; the height of the preamplifier signal decreases slowly. It is still 88% of the maximum at 200 μm from the anode, and after that it quickly drops. The electron contribution decreases almost linearly as it is expected, but the hole contribution seems to be responsible for the step around the center. Since the sharp drop after the step shows up in both contributions, we have to assume that some surface imperfection caused it. The rise time (hole transit time) almost linearly increases, becoming steeper close to the anode where the collected charge sharply drops. Before this drop the hole transit time is extremely ($\sim 40 \mu\text{s}$ at 1800 μm) long although the collected charge does not decrease significantly (still $\sim 88\%$ of the maximum). This suggests hole life times as large as the transit time, which is significantly larger than the values from the literature (up to 2 μs) [7]. Hole trapping-detrapping can explain this, but it needs other experimental justification.

The results of the fits are shown in Figure 5. The hole drift velocity profile is has a maximum at the cathode, then becomes more or less flat and from the center of the detector it is decreasing linearly. The average mobility from these data would be less than ten. This is about ten times smaller than the reported values [7]. This suggests hole detrapping, too.

Summary

Using lateral TRIBICC, we were able to measure the total collected charge as the function of the distance from the cathode. This measurement included the contribution from the slow moving holes in contrast to the lateral IBICC measurement. From the rise time of the waveforms we calculated the drift velocity profile of the holes. The rise time increase to several ten ns close to the cathode while the signal height changed less than 20%. This requires hole life times as long as the rise time. Since lifetimes over ten ns have not been reported we suspect that the long hole transit time is due to hole trapping-detrapping. Further experiments are planned to prove this assumption.

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Figure captions

Figure 1

IBICC and TRIBICC lateral scans on the same spot. The IBICC scan (+) decreases linearly toward the cathode, the slow moving holes do not contribute to it because of short shaping time (1.5 μ s). On the other, hand the TRIBICC signal (■) stays almost constant, it includes the collected charge due to both the electrons and holes.

Figure 2

Typical transient waveforms from near the cathode, from the center, and from near the anode. Notice how well the electron and hole collection times are separated in case of the signal from the center.

Figure 3

A typical waveform with the calculated parameters shown. The electron contribution was calculated by fitting the sum of two linear functions (one becomes constant when the electron collection is finished) to the marked region.

Figure 4a

Preamplifier signal height (■), electron (○) and hole (+) contributions to the collected charge as the function of the distance from the cathode

Figure 4b

Rise time of the preamplifier signal as the function of the distance from the cathode. The line and arrow marks the distance where the hole transit time becomes larger than the electron transit time.

Figure 5

Drift length and drift velocity profiles

Figures

Figure 1

Figure 2

Figure 3

Figure 4a

Figure 4b