Time of Flight Experimental Studies of CdZnTe Radiation Detectors

J.C. ERICKSON,[1,2] H.W. YAO,[1,2] R.B. JAMES,[1] H. HERMON,[1] and M. GREAVES[1]

1.—Sandia National Laboratories, Livermore, CA 94551. 2.—University of Nebraska, Lincoln, NE 68588

A time of flight technique was used to study the carrier trapping time, τ, and mobility, μ, in CdZnTe (CZT) and CdTe radiation detectors. Carriers were generated near the surface of the detector by a nitrogen-pumped pulsed dye laser with wavelength ~500 nm. Signals from generated electrons or holes were measured by a fast oscilloscope and analyzed to determine the trapping time and mobility of carriers. Electron mobility was observed to change with temperature from 1200 cm^2/Vs to 2400 cm^2/Vs between 293 K and 138 K, respectively. Electron mobilities were observed between 900 cm^2/Vs and 1350 cm^2/Vs at room temperature for various CZT detectors. Electron mobilities in various CdTe detectors at room temperature were observed between 740 cm^2/Vs and 1260 cm^2/Vs. Average electron mobility was calculated to be 1120 cm^2/Vs and 945 cm^2/Vs for CZT and CdTe, respectively. Hole mobilities in both CZT and CdTe were found to vary between 27 cm^2/Vs and 66 cm^2/Vs. Electron trapping times in CZT at room temperature varied from 1.60 μs to 4.18 μs with an average value of about 2.5 μs. Electron trapping time in CdTe at room temperature varied between 1.7 μs and 4.15 μs with an average value of about 3.1 μs.

Key words: CdZnTe, radiation detectors, time of flight, mobility, electron trapping time

INTRODUCTION

Cadmium zinc telluride (CZT) is a leading technological material for room-temperature gamma-ray and x-ray detectors. CZT also has great potential for widespread commercial use in such applications as medical imaging, environmental monitoring, and possibly remote sensing x-ray and gamma-ray spectrometers. CZT's energy resolution, efficiency, and low bias voltage requirement are driving the material growth industry to produce larger detector grade crystals at a reasonable cost.

Characterization and improvement of the transport properties, mobility and trapping times, in CZT and CdTe are paramount to the production of better detectors, because carrier mobility and trapping time determine the charge collection efficiency. The charge collection efficiency in turn is directly related to the energy resolution in γ-ray and x-ray spectrometers.[1] Radiation detector materials with $\mu\tau$ products as high as possible provide the best energy resolution spectrometers.

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TIME OF FLIGHT TECHNIQUE

The time of flight technique consists of measuring the voltage transient response to the drift of carriers created by a short duration pulse of ionizing radiation. The samples have high resistivity with voltages applied on noninjecting contacts such that wide high-field regions can be obtained with low dc current flow. Measurement of the transit time of carriers across the high-field regions determines the drift velocity and hence the mobility. Analysis of the shape of the transient response provides information about the trapping time. A general feature of this type of analysis is that the motion of both carrier types can be observed separately by either reversing the polarity of the applied voltage or directing the ionizing radiation on the other contact.[2] For the ideal case when no carrier trapping occurs, the drift of electrons across the sample produces a constant current whose duration is the transit time T_R of the electrons. Assuming a uniform electric field distribution, a voltage sensitive charge collecting circuit will have a voltage signal that rises linearly with time, and the

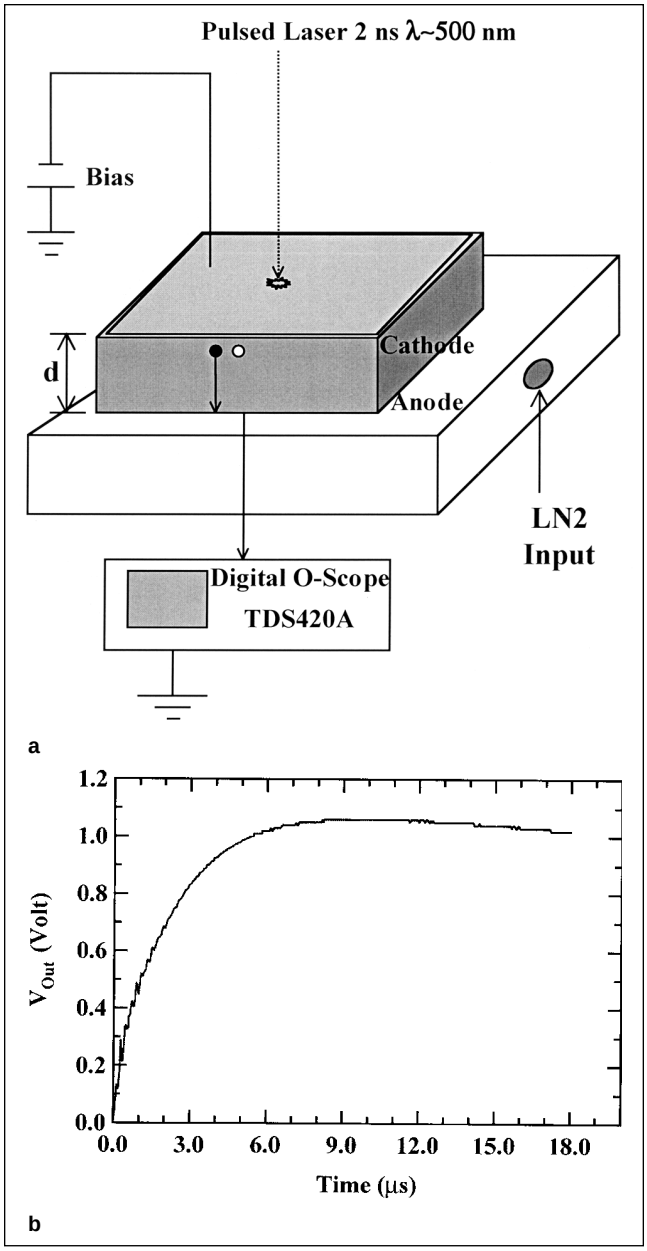

Fig. 1. (a) Experimental setup. (b) Typical voltage transient as observed on oscilloscope representing the total integrated charge.

pulse rise time can be used to determine T_R and hence the mobility.

For the waveform analysis, a single level with trapping but no detrapping and a uniform electric field throughout the sample were assumed. Due to the trapping of electrons or holes, the free carrier concentration, N, exhibits a simple exponential decay

$$N = N_0 \exp(-t/\tau) \quad (1)$$

where N_0 is the number of free carriers created.[3] For electrons which are injected at the negative electrode and drift with a constant velocity, the collected charge as a function of time is given by

$$Q(t) = \frac{N_0 q \tau}{T_R}[1 - \exp(-t/\tau)] \quad t < TR \quad (2)$$

or in terms of voltage the expression becomes

$$V(t) = \frac{N_0 q}{C}\frac{\tau}{T_R}[1 - \exp(-t/\tau)] \quad t < TR \quad (3)$$

Here q is the electron charge, C is the capacitance of the device, T_R is the transit time and τ is the trapping time.[1,4,5]

EXPERIMENTAL

Planar detectors grown by a vertical high-pressure Bridgman method were used in the experiment. Detectors had either gold or platinum contacts on two parallel surfaces, and they varied in thickness from 2 mm to 5 mm. Typical detector dimensions were $15 \times 15 \times 2$ or $15 \times 15 \times 5$ mm. Although we were primarily interested in generating data on CZT, CdTe detectors were also used for comparison. A nitrogen-pumped dye laser was used to create electron-hole pairs near one surface of the detector. The laser had a pulse duration of ~2 ns and a wavelength ~500 nm. The laser had a maximum power output of 0.4 mW and a corresponding maximum energy of 120 μJ/pulse, which could theoretically produce up to 10^{14} electron-hole pairs given ~4.4 eV per pair.[1] The laser beam was focused down to approximately 1 mm diameter, so that transport properties could be observed on a point by point basis across the detector surface. A high-voltage power supply was used to bias the detector creating an electric field throughout the detector. The diagram in Fig. 1a shows the experimental setup. In this diagram a negative applied bias causes electrons to drift from the cathode at the top surface to the anode, where they are collected and observed on a fast digitizing oscilloscope. The sample was placed in a sealed, shielded chamber where a continuous flow of liquid nitrogen was used to cool the sample for the temperature dependent study. The oscilloscope behaves as an integrator of collected charge, a typical voltage transient is shown in Fig. 1b. The charge collected follows an exponential behavior due to the trapping of carriers, and may be represented by the previously introduced expression.

$$V(t) = \frac{N_0 q}{C}\frac{\tau}{T_R}[1 - \exp(t/\tau)] \text{ for } t < TR \text{ Volt}$$

or

$$V(t) = V_0[1 - \exp(-t/\tau)] \text{ Volt.}$$

For $t = \tau$, the voltage expression reduces to

$$V(t) = V(\tau) \cong 0.63\ V_0 \text{ Volt.}$$

Experimental results demonstrated that in order to accurately resolve the trapping time an applied bias must be selected such that the transit time of the carriers was greater than the trapping time. For 2 mm detectors an applied bias of 12 volt was found to work well. Likewise, for 5 mm thick detectors an identical field of 60 volt/cm or 30 volt was used.

Mobility measurements were made at considerably

higher bias voltages, fields were normally of the order of 1 kV/cm. The expression for mobility is

$$\mu = \frac{d^2}{T_R V} \frac{cm^2}{Vs} \quad (4)$$

where d is the thickness of the detector, T_R is the carrier transit time, and V is the applied bias. From the expression we see that for the best estimation of mobility, the transit time must be accurately measured. This may be achieved by increasing the electric field such that $T_R << \tau$ at which point a sharp transition in the voltage transient is observed and the transit time may be accurately determined. Under high bias conditions the transit time becomes much less than the trapping time and nearly all of the carriers drift across the sample without being trapped, which allows the transit time and hence the mobility to be determined.

RESULTS AND DATA ANALYSIS

A comparison of high voltage transients is shown in Fig. 2a. As the bias voltage is increased the transit time of the carriers becomes much less than the trapping time and a sharp transition in the voltage transient occurs. This sharp transition allows for accurate estimation of the transit time and hence a good estimation of mobility. In Fig. 2b a comparison between high-voltage room temperature transients is shown for CZT and CdTe. From the voltage transients in Fig. 2b, the measured transit time for electrons was $T_R = 0.167$ μs for CZT and $T_R = 0.164$ μs for CdTe. The corresponding electron mobility was calculated to be 1198 cm²/Vs for the CZT detector and 977 cm²/Vs for the CdTe detector. The mobility of these two detectors was representative of other detectors under study. The electron mobility observed for CZT was slightly greater than in most of the CdTe detectors under study. Measurements of various CdTe and CZT detectors produced electron mobility that varied between 894–1350 cm²/Vs for CZT and 750–1262 cm²/Vs for CdTe. Average electron mobilities in the two materials was observed to be $\mu_{CZT} = 1120$ cm²/Vs and $\mu_{CdTe} = 945$ cm²/Vs.

Electron mobility in a CZT detector was measured at temperatures varying from 293 K to 138 K and was observed to change from approximately 1200 cm²/Vs at room temperature to nearly 2400 cm²/Vs at 138 K. The results for CZT are plotted in Fig. 2c along with CdTe data taken from literature for comparison.[6] The quoted data for CdTe was from Hall mobility experiments and had stronger temperature dependence than our CZT experimental data in this range. The increase in mobility at low temperature is due to decreasing scattering (increasing drift velocity) between carriers and phonons at the reduced temperatures.

Electron trapping times in typical CZT and CdTe detectors are compared in Fig. 3a. The raw voltage transients are shown in the figure along with the corresponding trapping time. For the two detectors in Fig. 3a the trapping time was 2.8 μs in CZT and 3.1 μs

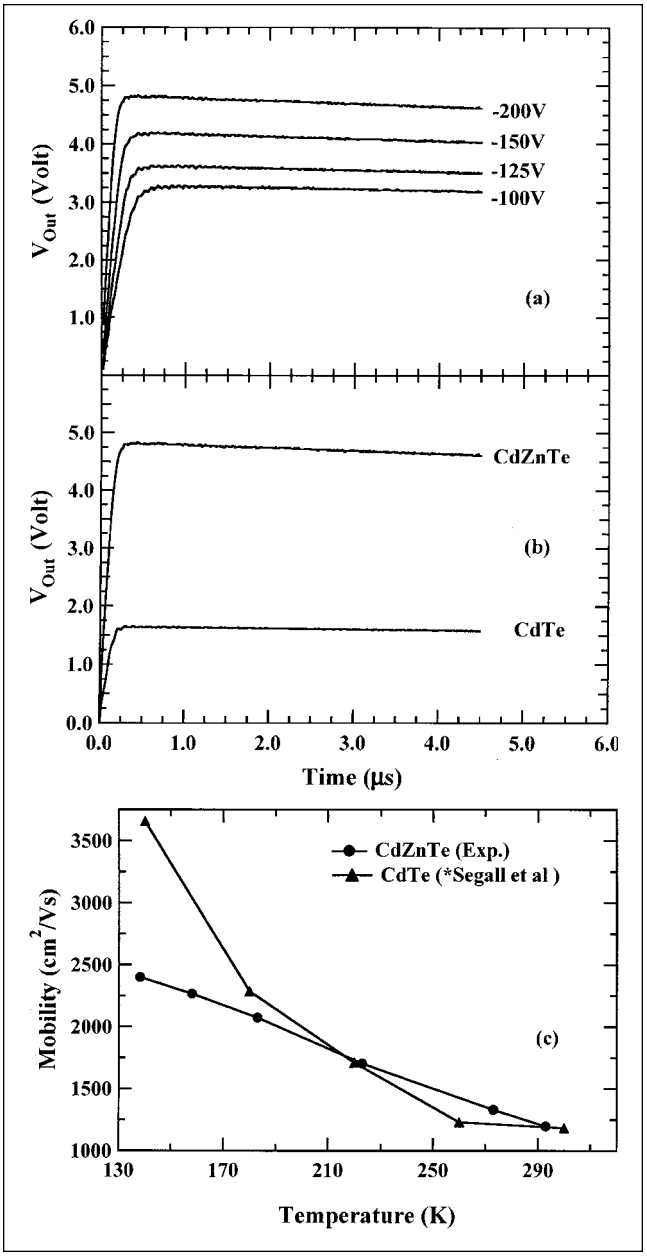

Fig. 2. (a) Comparison of high voltage transients used for determination of mobility. (b) Comparison of high voltage transients for CZT and CdTe. Transit times were measured to be 0.167 μs and 0.164 μs for CZT and CdTe respectively. (c) Comparison of electron mobility vs. temperature for CZT and CdTe.

in CdTe. These trapping times were representative of our other results for CZT and CdTe detectors. Our results yielded slightly shorter electron trapping times in the CZT detectors compared to those in CdTe. Electron trapping time in CZT varied for different detectors between 1.6–4.2 μs with an average value of 2.5 μs. Similarly, electron trapping time in CdTe varied for different detectors between 1.7–4.2 μs with an average value of 3.1 μs.

Electron trapping time and mobility were compared for detectors cut from entirely different ingots versus those cut from different locations within the same ingot. Fig. 3b displays the voltage transients for

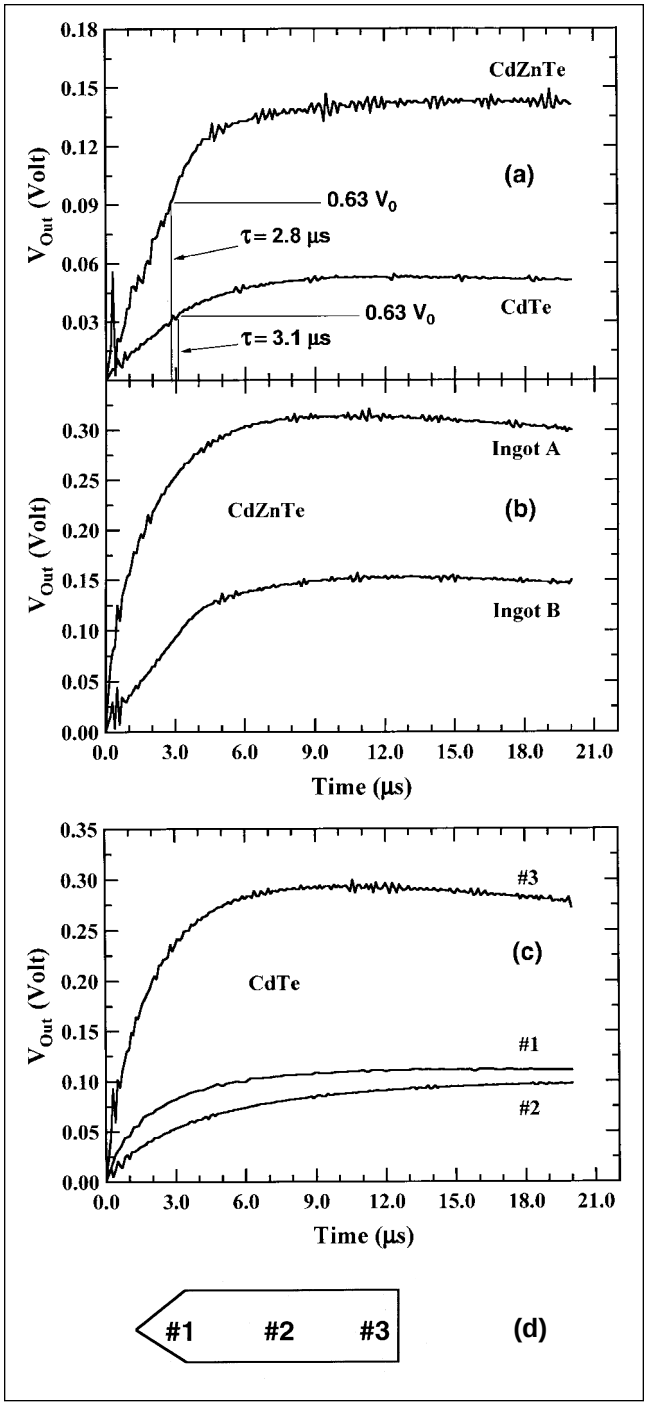

Fig. 3. (a) Typical voltage transient used for determination of electron trapping time for CZT and CdTe. (b) Comparison of voltage transients for two CZT detectors cut from different ingots. (c) Comparison of voltage transients for three CdTe detectors cut from different locations within the same ingot. (d) Relative positions in the ingot from which three CdTe detectors were cut.

two CZT detectors cut from different ingots. The electron trapping time for the detector cut from ingot A was determined to be τ=1.6 μs and the mobility was observed to be μ = 1105 cm²/Vs. The electron trapping time for the sample cut from ingot B was considerably larger, τ = 3.1 μs and the mobility was found to be μ = 1039 cm²/Vs. Figure 3c displays the corresponding

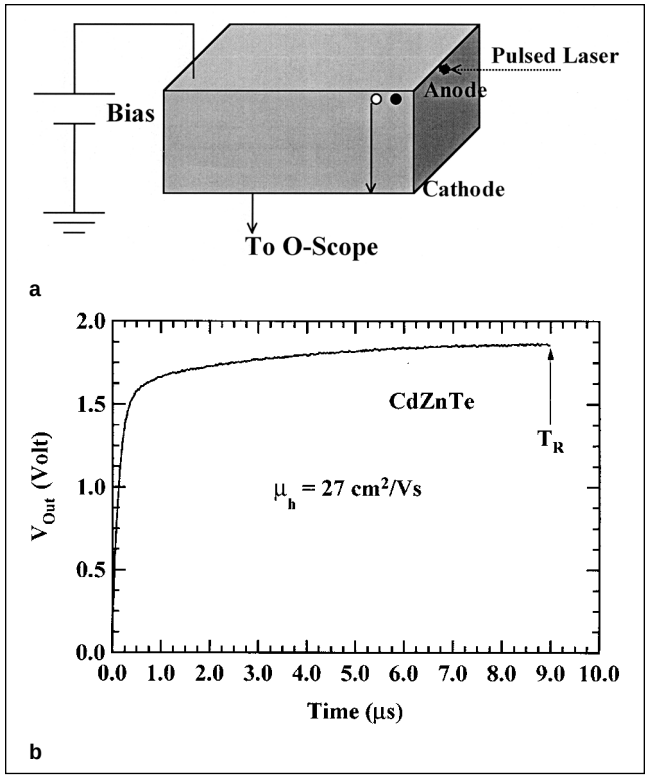

Fig. 4. (a) Experimental setup depicting hole collection for hole mobility determination. (b) Voltage transient depicting high mobility electron contribution and low mobility hole contribution.

voltage transients for three CdTe detectors cut from different positions in the same ingot. As indicated in Fig. 3d detector number 1 was cut from near the tip of the ingot and had an electron trapping time τ = 2.1 μs and mobility μ = 737 cm²/Vs. Detector number 2 cut from the center of the ingot had an electron trapping time τ = 4.0 μs and mobility μ = 1022 cm²/Vs. The detector cut from near the end of the ingot, number 3, had an electron trapping time τ= 1.7 μs and a mobility μ = 1262 cm²/Vs.

Because spatial variation of transport properties across the surface of detectors is desired, a mapping system is currently being developed. Although mapping of transport properties on a point by point basis will not be presented at this time, the spatial variation in electron trapping time was measured at five locations on a 15 × 15 × 2 mm CZT detector. Trapping time was measured near the center of the detector and at the four corners for comparison. The trapping time was observed to vary from 2.25 μs to 2.88 μs across the detector.

Two different irradiation configurations were compared, top surface irradiation through the electrical contact and irradiation from the side. The main advantage of the top-side irradiation is that transport properties may be measured on a point by point basis, hence mapping in this setup is possible. A second advantage of this configuration is that the electron-hole pairs are traversing the detector thickness somewhere in the middle of the detector (not near the edge). Here, the internal electric field is expected to be

close to uniform (i.e. without the edge effect). By using the side impact irradiation configuration, the primary benefit is the improved signal to noise ratio since the laser does not have to penetrate the electrical contact. However, there are some drawbacks to this setup. Mapping is not possible in this configuration since the electron-hole pairs are created near the edge of the detector. Also, the field near the edge of the detector is often different compared to that of the center of the detector. Voltage transients for side and top irradiation were compared in various detectors and the resulting trapping time from each were the same provided the field near the edge of the detector was nearly the same as in the center. The signal is stronger for the side impact irradiation configuration as expected.

Hole mobility was measured in both CZT and CdTe detectors using the side-impact irradiation configuration for improved signal to noise ratio. The bias was reversed to achieve hole collection at the cathode. The setup is shown in Fig. 4a. The resulting voltage transient is shown in Fig. 4b for an applied bias of 650 Volt across a 5-mm thick CZT detector. The laser irradiation in this example was from the side at a depth of 1 mm below the top surface cathode. Examining the voltage transient in Fig. 4b, one can see the high mobility electron contribution in the steep rising portion of the signal, which takes place in a fraction of a microsecond. The slow-rising portion of the transient, which extends out to 9 μs, represents the contribution due to the holes. The hole mobility for the CZT detector of Fig. 4b was determined to be about 27 cm^2/Vs. Similar measurements taken on various CZT and CdTe detectors yielded hole mobilities that ranged from 27 cm^2/Vs to 66 cm^2/Vs.

CONCLUSIONS

The mobility μ and trapping time τ were measured in CZT and CdTe using a time of flight technique. Electron mobility for CZT was observed to vary between different detectors over the range of 900–1350 cm^2/Vs at room temperature. Room temperature electron mobility for various CdTe detectors was observed between 740–1260 cm^2/Vs. Average CZT electron mobility at room temperature was found to be slightly higher than that of CdTe, μ_{CZT} = 1120 versus μ_{CdTe} = 945 cm^2/Vs. Electron mobility in CZT was observed to change with temperature between 1200 cm^2/Vs and 2400 cm^2/Vs at 293 K and 138 K, respectively. Electron trapping time for various CZT detectors at room temperature varied between 1.6–4.2 μs. Electron trapping time for CdTe detectors varied between 1.7–4.2 μs. Average trapping time calculated for the majority of the CZT detectors was slightly less than that for CdTe, τ_{CZT} = 2.5 versus τ_{CdTe} = 3.1 μs. Hole mobility in CZT and CdTe detectors was observed to be in the range of 27–66 cm^2/Vs for the detectors under study.

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