Drift Mobility and Mobility-Lifetime Products in CdTe:Cl Grown by the Travelling Heater Method

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Abstract—We report the electron and hole charge transport properties of semi insulating CdTe:Cl grown by the Travelling Heater Method (THM). An alpha-particle Time of Flight (TOF) method was used to measure electron and hole drift mobility, with room temperature values of $880 \text{ cm}^2/\text{Vs}$ for electrons and $90 \text{ cm}^2/\text{Vs}$ for holes. The variation in mobility was also investigated as a function of temperature, with electron and hole mobilities at 190 K of $1150 \text{ cm}^2/\text{Vs}$ and $20 \text{ cm}^2/\text{Vs}$ respectively. Using a Hecht analysis the electron and hole mobility-lifetime products were also measured over the same temperature range, with values at room temperature of $8 \times 10^{-4} \text{ cm}^2/\text{V}$ and $7 \times 10^{-5} \text{ cm}^2/\text{V}$ respectively. Time-resolved ion beam induced charge (IBIC) imaging was used to produce micrometer resolution maps of electron drift mobility and signal amplitude, which showed excellent spatial uniformity.

Index Terms—Cadmium telluride, charge transport, time of flight.

I. INTRODUCTION

OPTIMIZATION of the charge transport properties of semi-insulating CdTe crystals is crucial to the successful development of large volume radiation detectors. Many efforts have been reported over several decades concerning the growth of high resistivity CdTe, using techniques such as the Travelling Heater Method (THM) or Vertical Gradient Freeze (VGF), summarized in [1]. In order to produce large volume radiation detectors with the highest energy resolution, it is critical to combine high material resistivity ($>10^9 \Omega \text{ cm}$) with high electron and hole mobility-lifetime products ($\mu\tau$).

In this paper we present a study of electron and hole charge transport in chlorine doped CdTe (CdTe:Cl) grown by THM at Eurorad (France). By independent measurement of both mobility (μ) and $\mu\tau$ for electrons and holes, the influence of these parameters on electron and hole drift length is investigated. In addition, the spatial uniformity of drift mobility in CdTe was measured using an ion beam implementation of the Time of Flight (TOF) method. This technique of time-resolved ion beam induced charge (IBIC) imaging has recently been developed at the University of Surrey's nuclear microbeam [2].

TOF drift mobility measurements on semi insulating materials have been reported by many workers, with some of the first data obtained from high resistivity CdTe reported by Zanio *et al.* [3] using alpha-particle induced pulses. Eisen *et al.* [4] performed a comparison of alpha-particle induced mobility

and lifetime measurements in THM CdTe and high pressure Bridgman (HPB) CdZnTe. Laser-induced TOF mobility measurements have also been performed in VGF CdTe [5], THM CdTe [6], and HPB CdZnTe [7]–[9]. Overall these studies show broadly similar electron mobilities in CdTe and CdZnTe, reaching $1100 \text{ cm}^2/\text{Vs}$ in the best material, whereas the hole mobility in CdZnTe is generally smaller than in CdTe (typically $90 \text{ cm}^2/\text{Vs}$). In contrast however the mobility-lifetime products, which are the primary measure of detector performance, are generally larger in HPB CdZnTe than for THM CdTe:Cl. This is particularly noticeable for electrons, where the mobility-lifetime product for high quality CdZnTe is typically $5 \times 10^{-3} \text{ cm}^2/\text{V}$ [10].

Direct measurements of the spatial uniformity of drift mobility and mobility-lifetime product have not previously been reported; however there has been considerable speculation about the role of tellurium inclusions and other extended defects in degrading the signal amplitude response in both CdTe and CdZnTe.

II. THEORY

The measurement of carrier drift mobility in semi insulating CdTe and other high resistivity semiconductor materials requires a dynamic method, such as the TOF technique. In the TOF technique free carriers are produced in the material using a suitable form of irradiation, such as a pulsed electron beam, an alpha-particle source, or a fast laser pulse. The carrier drift time t_{dr} is measured directly either from the induced current pulse, or from the charge pulse. For carriers drifting across a thickness d the drift mobility μ is given by

$$\mu = \frac{d^2}{V t_{\text{dr}}} \quad (1)$$

where V is the applied voltage across the material thickness.

In this study TOF measurements were carried out on single crystal bulk CdTe material, with devices fabricated using planar ohmic contacts in a “sandwich” configuration. An alpha-particle source is conveniently used to generate electron hole pairs at a depth of approximately $20 \mu\text{m}$ below the incident contact. Consequently the induced signal is predominantly due to single carrier transport, corresponding to electron transport when the alpha particles are incident on the cathode, and hole transport when incident on the anode.

In the thick CdTe samples used for this study typical electron and hole drift times are $1\text{--}5 \mu\text{s}$, compared to the mean electron and hole lifetimes in this material of $\sim 1 \mu\text{s}$. Consequently a significant proportion of the initially-generated charge carriers drift across the entire thickness of the device, and the measured

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pulse width (current pulse) or risetime (charge pulse) can be used directly in (1) to obtain the drift mobility.

Measurement of the amplitude of the charge pulse gives the total charge Q induced at the device contact, and hence the electron and hole mobility-lifetime products, $\mu_e\tau_e$ and $\mu_h\tau_h$. Commonly used as a figure of merit for radiation detectors, $\mu\tau$ is directly related to the mean carrier drift length λ , such that

$$\lambda = \mu\tau E \quad (2)$$

where E is the applied field strength. For single carrier charge transport, the Charge Collection Efficiency (CCE) is described by the simplified Hecht equation, which for electron transport has the form

$$\text{CCE} = \frac{Q}{Q_0} = \frac{\mu_e\tau_e V}{d^2} \left[1 - e^{-\left(\frac{d^2}{\mu_e\tau_e V}\right)} \right] \quad (3)$$

where V is the applied bias and d is the device thickness. In the Hecht formalism a uniform electric field is assumed as a function of depth. Q_0 is the charge produced by the radiation interaction, and is related to the incident energy E_α such that

$$Q_0 = \frac{E_\alpha}{W} q \quad (4)$$

and the electron hole pair (ehp) creation energy, W , is 4.4 eV/ehp.

III. EXPERIMENTAL METHOD

The drift mobility and mobility-lifetime product for electrons and holes was measured in THM-grown CdTe:Cl as a function of temperature using alpha-particle induced TOF. Two CdTe devices were used in these measurements: device 1 consisted of a 9 mm thick detector with an active surface area of approximately 50 mm², and device 2 was a 1.2 mm thick device with an active surface area of 150 mm². The samples were mounted in a temperature-controlled cryostat. An automatic temperature controller was used to vary the sample temperature in the range 190–300 K.

Alpha-particle induced pulses were recorded using a digital oscilloscope, connected to the sample via two alternative schemes. In the first method current pulses were recorded using a high gain (1 MV/A) current amplifier directly connected to the CdTe detector. The current amplifier bandwidth was 1.8 MHz. The typical pulse amplitude at the amplifier output was 30–50 mV, depending on bias voltage. Signal averaging was applied to the current pulses using the digital oscilloscope in order to improve the signal/noise ratio. A typical current pulse shape is shown in Fig. 1(a), where the fast initial transient is due to the limited time response of the measuring system.

In the second method the detector was connected to a charge sensitive integrating preamplifier (eV Products model 550). The preamplifier risetime was approximately 100 ns, and the sensitivity was 3.6 mV/fC which produced a typical pulse amplitude of 200–500 mV. The signal/noise of single charge pulses was considerably higher than for current pulses, and individual charge pulses were digitized without signal averaging (Fig. 1(b)).

Fig. 1. Alpha-particle induced pulses used in the TOF method: (a) current pulse averaged over 32 pulses, (b) single charge pulse with no averaging.

For both methods, pulses were acquired from the oscilloscope using LabView software in an event-by-event mode. Various pulse analysis algorithms were applied to each pulse to extract and histogram the required parameter. For μ measurements the carrier drift time was calculated from the pulse width (current pulses) or pulse rise time (charge pulses). For $\mu\tau$ measurements the induced charge was calculated from the amplitude of the charge pulses.

The incident deposited energy is only approximately 0.9 pJ per 5.49 MeV alpha particle, with a flux of ~ 1 kHz of alpha particles onto the sample. Consequently no space charge effects were observed in the device, which was maintained at a steady bias voltage. The measured alpha-particle pulse shapes show no evidence of polarization effects due to the high local density of electron hole pairs created by each alpha-particle interaction.

IBIC imaging was performed to investigate the uniformity of $\mu\tau$ and μ in the CdTe devices. In this method a focused proton beam with a beam diameter ~ 3 μ m was raster-scanned across the sample to produce high resolution maps of signal amplitude and carrier drift time. The sample was connected to a charge integrating preamplifier, and individual pulses were acquired using a dedicated data acquisition system. The beam current was severely reduced using collimation slits, so that the proton rate onto the sample was ~ 1 kHz.

Fig. 2. $1/t_{\text{dr}}$ plotted against voltage for electrons and holes, acquired at room temperature from device 2 (thickness 1.2 mm).

The output of the preamplifier was connected simultaneously to a spectroscopy amplifier and to a high speed waveform digitizer. The spectroscopy amplifier (shaping time $\tau_s = 2 \mu\text{s}$) was used to record the pulse amplitude. By recording a sequence of amplitude maps at different bias voltage, and by application of the single carrier Hecht equation, a map of $\mu\tau$ was produced [11].

The waveform digitizer simultaneously recorded the full pulse shape and hence the rise time of each pulse. This time-resolved IBIC data was used to extract the mean carrier drift time for each pixel, and hence produce a map of mobility. A more complete description of this implementation of time-resolved digital IBIC can be found in [2].

IV. RESULTS AND DISCUSSION

Typical examples of an alpha-particle induced current and charge pulse from device 1 are shown in Fig. 1, acquired at a bias voltage of 100 V. In both cases the pulses were produced by cathode irradiation of the device, and are due to electron transport. The current pulse has a duration of $\sim 3 \mu\text{s}$, with a steady-state amplitude of $\sim 35 \text{ mV}$, corresponding to a current induced at the device electrode of 35 nA. The sharp spike at the beginning of the pulse is caused by poor impedance matching, and has a time structure determined by the bandwidth of the current amplifier.

The charge pulses were used for the analysis of drift times and signal amplitudes in this work, due to the superior signal/noise compared to current pulses.

Room temperature electron and hole drift mobilities for device 2 are shown in Fig. 2, calculated from plots of $1/T$ versus applied voltage. For electrons, the measured drift time across the device thickness (1.2 mm) varied from $3.2 \mu\text{s}$ at $V = 7 \text{ V}$ to $0.35 \mu\text{s}$ at $V = 41 \text{ V}$, and showed good linearity with no saturation. The drift times measured for holes varied from $6.9 \mu\text{s}$

Fig. 3. Electron and hole drift mobility, as a function of temperature. The dashed lines are to aid the eye.

at $V = 15 \text{ V}$ to $3.8 \mu\text{s}$ at $V = 42 \text{ V}$. The amplitude of the hole pulses was considerably less than that of electrons, due to the shorter hole mean drift length.

The room temperature mobilities obtained from this data were $\mu_e = 880 \pm 50 \text{ cm}^2/\text{Vs}$ and $\mu_h = 90 \pm 25 \text{ cm}^2/\text{Vs}$. These room temperature mobility values are similar to those reported by Suzuki *et al.* [6] for THM-CdTe grown by Acrorad, which were measured using laser-induced TOF ($1100 \text{ cm}^2/\text{Vs}$ for electrons and $88 \text{ cm}^2/\text{Vs}$ for holes at room temperature).

The temperature variation of the electron and hole drift mobility in device 2 was measured from $T = 190 \text{ K}$ to $T = 300 \text{ K}$, as shown in Fig. 3. Reduction of the temperature from 300 K to 190 K caused an increase in electron mobility to $1150 \text{ cm}^2/\text{Vs}$, due principally to an increase in scattering mobility at low temperature. In contrast for holes, reduction in temperature over the same range causes the hole mobility to fall to $20 \text{ cm}^2/\text{Vs}$.

These mobility data follow the same trend at low temperature as that reported by Suzuki *et al.* [6] for THM-grown CdTe produced by Acrorad. In general, a temperature dependent mobility can be described by a trap-controlled mobility μ_d where

$$\mu_d = \mu_0(T) \left[1 + \frac{N_T}{N_C} \exp\left(\frac{E_T}{kT}\right) \right]^{-1} \quad (5)$$

and where $\mu_0(T)$ is a theoretically-determined temperature dependent mobility due to ionized impurity and optical phonon scattering. Suzuki *et al.* deduced a shallow donor level with an energy of 28 meV below the conduction band which influences the electron transport, and an acceptor level 140 meV above the valance band which limits the hole transport. These states have been ascribed to chlorine vacancy complexes, and the A-Centre, respectively. In our data further experimental measurements are required in the temperature range $100\text{--}190 \text{ K}$ to confirm the trap energies in the Eurorad material.

Fig. 4. Variation of electron and hole $\mu\tau$ from device 2, as a function of temperature. The dashed lines are to guide the eye.

Analysis of the charge pulse amplitudes as a function of bias voltage for electron and hole induced pulses was used to calculate $\mu_e\tau_e$ and $\mu_h\tau_h$ for device 2. At $T = 300$ K the mobility-lifetime products for electrons and holes were $\mu_e\tau_e = 8 \times 10^{-4}$ cm²/V and $\mu_h\tau_h = 7 \times 10^{-5}$ cm²/V. These values are comparable to those reported for other THM-grown CdTe [4].

The temperature dependence of $\mu_e\tau_e$ and $\mu_h\tau_h$ is shown in Fig. 4. Reducing the temperature from $T = 300$ K to $T = 240$ K produces no significant change in $\mu_e\tau_e$; however at $T = 190$ K $\mu_e\tau_e$ increases to 1.1×10^{-3} cm²/V reflecting the increase in mobility. The electron mean lifetime remains approximately constant over this temperature range, with a value of approximately 0.7–0.8 μ s. Similarly, the dependence of $\mu_h\tau_h$ with temperature shows a decrease to 3.6×10^{-5} cm²/V at $T = 190$ K, corresponding to the underlying decrease in hole mobility.

IBIC was used in both regular and time-resolved modes to study the spatial uniformity of the electron signal amplitude, drift time and mobility. All the IBIC measurements were carried out on device 1 (thickness 9 mm) using a 2 MeV scanning proton beam. The device measured was at room temperature, and the proton beam was scanned over the cathode electrode. A bias of -150 V was applied to the cathode, with the anode connected to ground. The resulting charge pulses were due to electron transport through the device.

Fig. 5 shows an IBIC map of signal amplitude. The total size of the image is 2 mm by 2 mm. The data shows one corner of the device electrode, with regions to the left and bottom of the image corresponding to exposed CdTe where no metal contact is present and no charge transport is observed. The data show good signal amplitude uniformity, which confirms the high uniformity of the electron drift length in this sample. The absence of any regions of reduced signal amplitude on length scales of >1 μ m confirms the lack of extended trapping centers in this material, for example due to tellurium inclusions.

Fig. 5. IBIC map of room temperature signal amplitude in device 2, acquired with a bias of 150 V.

Fig. 6. (a) Time-resolved IBIC map of room temperature electron drift mobility in device 1 (thickness 9 mm), acquired with a bias of 150 V, (b) horizontal cross section at pixel $Y = 35$.

From analysis of the risetime of individual pulses a map of electron drift time was obtained at room temperature. The minimum measurable drift time for the IBIC system is determined by the preamplifier rise time, which is approximately 30 ns. In this device, at a bias of 150 V, the typical electron drift time is 5 μ s. Within the electrode region, good uniformity was observed in the electron drift time. The measured drift time increased significantly at the edge of the electrode, due to a decrease in electric field strength in this region.

Using (1) the drift time data was rescaled to produce a map of electron drift mobility, shown in Fig. 6(a). The data show a good uniformity in μ_e , with a typical value of 900 cm²/Vs, as shown

in Fig. 6(b). The apparent reduction in mobility at the electrode edges is nonphysical, and reflects the longer drift times in this region due to reduced field strength. Away from the electrode edges, the mobility map shows no regions of reduced electron mobility, which is consistent with the uniform signal amplitude shown in Fig. 5.

The IBIC images demonstrate the excellent uniformity of charge transport in this THM-grown CdTe material. No evidence was observed for extended trapping sites in this sample. Such trapping sites have been observed in CdZnTe, caused by the presence of tellurium inclusions with diameters in the range 1–10 μm [12]. Using infrared microscopy, tellurium inclusions have also been observed around the wafer edges of THM-grown CdTe [13], [14], and further measurements are required to identify the nature and extent of charge trapping around such inclusions.

V. CONCLUSION

We have investigated the temperature dependence of drift mobility and mobility-lifetime product for electrons and holes in two samples of THM CdTe:Cl material grown by Eurorad. At room temperature the measured electron and hole mobility is 880 cm^2/Vs and 90 cm^2/Vs . The trend in mobility as the temperature is reduced from 300 K to 190 K is very similar to that reported in Acrorad grown THM CdTe:Cl, and is consistent with a transition from an impurity-limited mobility at room temperature to a trap-controlled mobility at lower temperatures.

Mobility-lifetime products were also measured, with values at room temperature for electrons and holes of $8 \times 10^{-4} \text{ cm}^2/\text{V}$ and $7 \times 10^{-5} \text{ cm}^2/\text{V}$ respectively. The spatial uniformity of electron mobility and mobility-lifetime product was investigated using time-resolved IBIC, and demonstrated the excellent uniformity of charge transport in this material.

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