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Photocapacitance study of deep levels in thin CdTe PV devices

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Abstract

Steady state photocapacitance (PHCAP) was used to survey the deep levels in the energy range 0.73 eV to 1.38 eV with respect to the valence band in CdS/CdTe PV devices. The effect of the cadmium chloride treatment process on deep level densities is shown qualitatively. Estimates of the optical transition thresholds E_p^o for three deep minority type levels $E1$, $E2$, and $E3$ are given and a discussion of possible assignment to specific defects is presented. Preliminary results using deep level optical spectroscopy (DLOS) to measure the optical cross sections for holes σ_p^o of the $E2$ and $E3$ levels are given. The thermal emission rates e_n^t for electrons at 79 K are estimated for the $E2$ and $E3$ levels.
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Keywords: CdTe; Photocapacitance; $CdCl_2$

1. Introduction

Thin film polycrystalline CdS/CdTe devices have shown great potential as a low cost PV technology [1,2]. It is of interest to understand the electronic nature of defects in such devices [3]. Such studies could also provide information on changes to defect structures due to device fabrication processes such as the $CdCl_2$ treatment [4].

To lower the manufacturing cost and minimize the use of material it is preferred to thin the CdTe absorber layer [1]. For devices with an absorber thickness of less than 2 μm the depletion layer extends nearly to the back contact. This type of nearly fully depleted structure limits the sensitivity of deep level transient spectroscopy (DLTS) [5]. Past results in collaboration with other groups (not shown) with reverse bias DLTS and forward bias injection DLTS or optical DLTS with $h\upsilon > E_g$ have not produced spectra with resolvable levels. We have shown that using thermal admittance spectroscopy (TAS) it is possible to characterize certain deep levels in thin devices [6,7]. However, TAS only allows characterization of levels that cross the Fermi level [8]. Also simulations using SCAPS software show that for cells with CdTe thickness <3 μm deep levels within 0.25 eV of the valence band may not be detectable by admittance spectroscopy [9].

It would be desirable to have techniques that could characterize both thermally and optically the defect levels above the Fermi level in fully depleted cells. Others have used steady state and transient photocapacitance (PHCAP) to characterize defect levels in CdTe [10,11]. Optical deep level transient spectroscopy (ODLTS) with sub-band gap light energy has been used by others [8,12] for other materials. Initial measurements of thermal emission rates of electrons to the conduction band e_n^t indicate that ODLTS is promising. In the present work the transient PHCAP technique deep level optical spectroscopy (DLOS) first shown by Chantre et al. [12] was used to further characterize levels found by steady state PHCAP. Due to limitations of the present measurement hardware the transient optical and thermal results are preliminary.

2. Experimental

2.1. Device fabrication

Small area (0.3 cm^2) CdS/CdTe PV devices were fabricated in vacuum with varied $CdCl_2$ treatment and without the application of a Cu containing back contact. The fabrication system was an all in-line continuous vacuum process using modified close-spaced-sublimation (CSS) or heated pocket deposition (HPD) sources as described elsewhere [2]. There was no chemical etching or any wet processing in the back contact process. The non-optimum $CdCl_2$ treatment had limited O_2 in the process ambient. The optimum $CdCl_2$ treatment had ∼2% O_2 partial pressure in a 5.3 Pa ambient. The total $CdCl_2$ treatment time in all cases was 4 min. The optimum treatment temperature was ∼400 °C. More details of the $CdCl_2$ treatment

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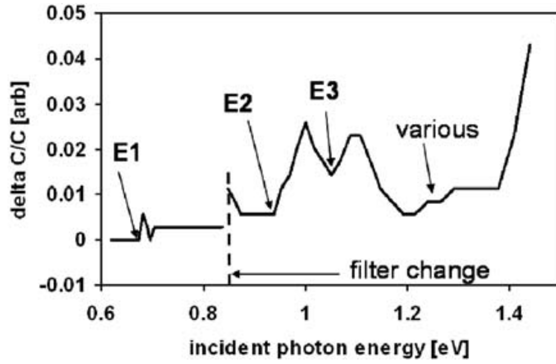

Fig. 1. Example steady state photocapacitance spectrum with positive changes in capacitance related to distinct levels. Spectrum not normalized to incident flux to allow view of level $E1$.

are given elsewhere [13]. For all cases a secondary back contact or metallization layer consisting of a layer of conductive carbon coating followed by a layer of conductive Ni coating was applied by a spray process after removal of the substrates from vacuum.

2.2. Steady state photocapacitance measurements

Steady state PHCAP was performed on seven cells for an initial survey of deep levels in the upper half of the band gap [14]. The steady state PHCAP procedure is as follows: 1) the CdTe cell was attached to a Cu cold finger and cooled in a LN_2 dewar to 79 K, 2) sub-band gap monochromatic light was applied through the glass substrate on the cell to stimulate optical emission, 3) incident light energy was varied in 0.05 eV increments from 0.62 eV to 1.46 eV [allowing 1 min to come to steady state] and 3) measure capacitance changes using a 10 kHz, 0.020 Vrms oscillating signal. A 50 watt quartz halogen light source was passed through a DMC1–06 Optometrics monochromator to provide incident light. The capacitance signal was measured using an HP 4192A impedance analyzer. For the spectra shown the measurements were performed at zero applied bias. An example steady state PHCAP spectrum is shown in Fig. 1. The incident photon flux at varying wavelength $\Phi(h\upsilon)$ was quantified using an InGaAs photodiode. The photodiode has an energy range of 0.73 eV to 1.38 eV which sets a limit on normalized PHCAP spectra. The flux was measured after the incident light passed through the glass/SnO:F superstrate. The reflection of the SnO/CdS interface was neglected. The spectrum shown in Fig. 2 was normalized using

$$C(\text{normalized}) = (C - C_{\text{dark}})/(C_{\text{dark}} {}^{*} \Phi) \quad (1)$$

where Φ is the photon flux.

2.3. Transient photocapacitance measurements

Deep level optical spectroscopy (DLOS) [12] was used to find preliminary estimates of the optical cross sections for the optical emission of holes from the E2 and E3 levels identified in the steady state PHCAP spectrum. The optical cross sections were found using

$$(\mathrm{d}C/\mathrm{d}t) = \sigma_p^{\mathrm{o}} {}^{*} \Phi^{*} N_t \quad (2)$$

where Φ is the incident photon flux. The initial setup at $t=0$ was $p(0)=N_t$. The optical emission rates e_p^{o} are on the order of 10–20× more than the thermal emission rates e_{n}^t for the $E2$ and $E3$ levels allowing the use of Eq. (2) [12]. The trap density N_t is not known quantitatively so the cross sections are presented in arbitrary units.

2.4. Optical deep level transient measurements

The thermal emission of carriers from optically filled traps was present even at 79 K. Preliminary measurements of the thermal emission time constants at 79 K using filling light at varying wavelengths for level $E2$ from 1220 nm to 1320 nm and for level $E3$ from 1100 nm to 1180 nm were performed. The thermal emission time constants were found using

$$C(t) - C(\infty) = C_{\mathrm{o}} {}^{*} \exp(-t/\tau) \quad (3)$$

and for the emission rates

$$e_{\mathrm{n}}^t = \tau^{-1}. \quad (4)$$

In the present work due to hardware limitations full optical deep level transient spectroscopy (ODLTS) spectra were not generated.

3. Results and discussion

As shown in Fig. 1 there are three distinct peaks in the steady state PHCAP spectrum. The positive changes in the capacitance signal for these three peaks are indicated for clarity. The sharp positive changes in the capacitance signal are apparent optical transitions for the emission of holes and indicate a donor type level given the p-type material and the initial trap occupancy $p(0)=N_t$ [8,15,16]. The negative changes may be optical

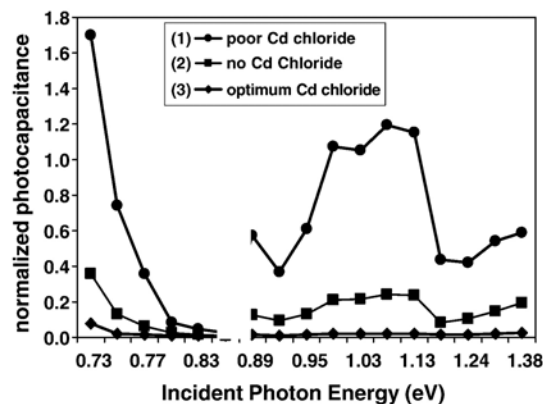

Fig. 2. Steady state photocapacitance spectrum of devices with various $CdCl_2$ treatments and no intentional Cu application. Gap in traces from 0.85 to 0.89 eV is due to filter change. Spectrum normalized to incident flux.

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