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Deep-level transient spectroscopy study of hole traps in p-type CdTe

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Abstract. The presence of hole traps in p-type CdTe has been studied by deep-level transient spectroscopy. Two hole traps labelled H1 and H2 with activation enthalpies of 0.26 eV and 0.61 eV have been detected. Both traps act as donor point defects with entropies of 2.4×10^{-4} eV K^{-1} for H1 and 8.5×10^{-4} eV K^{-1} for H2. The capture cross-sections are found to be temperature independent; $\sigma_{pH1} \simeq 3\times10^{-18}$ cm^2 and $\sigma_{pH2} \simeq 1.2\times10^{-17}$ cm^2.

The concentration of defects H1 has its maximum (equal to about 1×10^{13} cm^{-3}) close to the surface whereas the defects H2 seem to be located at around 0.5 μm distance from the surface (with a concentration of 2×10^{12} cm^{-3}).

1. Introduction

Cadmium telluride (CdTe) has potential application in photodetectors and nuclear detectors and solar cells. It often serves as a substrate for the growth of semiconducting $Cd_xHg_{1-x}Te$ alloys that are important for infrared technology. Deep levels in CdTe are often of great importance for the performance of these devices. The identification of the electrically active defects and their microscopic arrangement with the crystal lattice is of fundamental importance for understanding and controlling the electronic properties of CdTe. Deep levels in CdTe have been widely investigated by means of different methods [1–11].

One of the most widely used methods for deep-level diagnostics in semiconductors is deep-level transient spectroscopy (DLTS). With the help of this method, one can measure a deep-level energy position, the concentration of the defects and the capture cross section [12]. Although many papers have reported the results of DLTS measurements in n-type CdTe (see the review article in [1]), only a few have considered p-type material [5–8].

Many different, electrically active deep centres in p-type CdTe have been detected by means of the DLTS technique. Three groups are predominant in many cases: one group of levels is around midgap and the two others are in the lower half of the band gap at $E_v + 0.3$–0.45 eV and around $E_v + 0.15$ eV [6–8]. Neither the origin nor the identity of the associated defects are precisely known at present.

The purpose of this work was to study the properties of the deep levels in p-CdTe. The DLTS method was applied to p-CdTe single crystals using In Schottky barriers.

2. Experiment

The CdTe crystals obtained by the Bridgman method were nominally undoped and were p type with a net acceptor concentration of about 1×10^{15} cm^{-3} at room temperature. Wafers

1 mm thick were mechanically and chemically polished in a 5% Br_2–methanol solution to remove surface damage. To generate the Schottky contact, indium was evaporated on one side of the wafer usually of 1 mm^2 surface and annealed at a temperature above 500 K for a few seconds. To provide an ohmic contact, gold was evaporated on the back side of the sample.

From I–U characteristics the barrier height V_B of the device was measured as 0.7 eV and the ideality factor was found to be 1.5. From C–V measurements performed at room temperature, $V_b = 0.8$ eV and the concentration N_A of shallow acceptors was 2×10^{15} cm^{-3}. C–V measurements were made with a 1 MHz capacitance meter. The discrepancy between V_b obtained from both experiments may be due to the presence of the thin oxide layer always left after chemical etching of the surface.

The DLTS measurements were performed with a lock-in type spectrometer DLS82-E, manufactured by Semitrap (Hungary) [13].

3. Results

3.1. General feature

Figure 1(a) shows a deep-level transient spectrum of the In p-CdTe Schottky diode within the 120–350 K temperature range. The working mode of differential DLTS consisting of two filling pulses U_{p1} and U_{p2} of different heights was used. Two different traps labelled H1 and H2 by us are observed. As the diode under study is the Schottky barrier type, only majority traps are detected in DLTS measurements; so the H1 and H2 traps are hole traps. The DLTS activation energies E_{DLTS} of H1 and H2 traps are evaluated from the usual $\ln(e_p/T_m^2)$ versus T_m^{-1} plot where e_p is the hole thermal emission rate and T_m is the temperature corresponding to the maximum DLTS signal. The Arrhenius plots are shown in figure 1(b) and the E_{DLTS} values obtained are 0.26 ± 0.01 eV for H1 and 0.61 ± 0.01 eV for H2 above the top of the valence band.

Depth profiles of deep centres were measured using two filling pulses with equal widths and different amplitudes [14] at constant temperature corresponding to the maximum DLTS signal at a given rate window. The results of these measurements are shown in figure 2 for both H1 and H2 traps. The concentration of defects H1 has its maximum close to the surface whereas defects H2 seem to be located at around 0.5 μm distance from the surface.

The concentration of these defects does not exceed $(1 \pm 0.3) \times 10^{13}$ cm^{-3} for H1 and $(2 \pm 0.5) \times 10^{12}$ cm^{-3} for H2.

The electric field dependence of the hole emission rate was also measured. The measurements were performed using two filling pulses of different heights. The width ΔU of the spatial window which equals $U_1 - U_2$ was chosen to be small enough to be sure that the electric field was kept constant within the window. We chose a fixed reverse bias and, while changing the local position of the spatial window by changing U_1, we changed the electric field strength. For given electric field and constant window rate (lock-in frequency) the temperature scan of the DLTS signal was recorded. No shift in the DLTS peak as a function of electric field was observed for H1 nor for H2.

3.2. Capture characteristics

The hole emission rate for an exponential transient follows the well known relation [15]

$$e_p = v_p N_v \sigma_p' \exp(-\Delta H/kT) \tag{1}$$

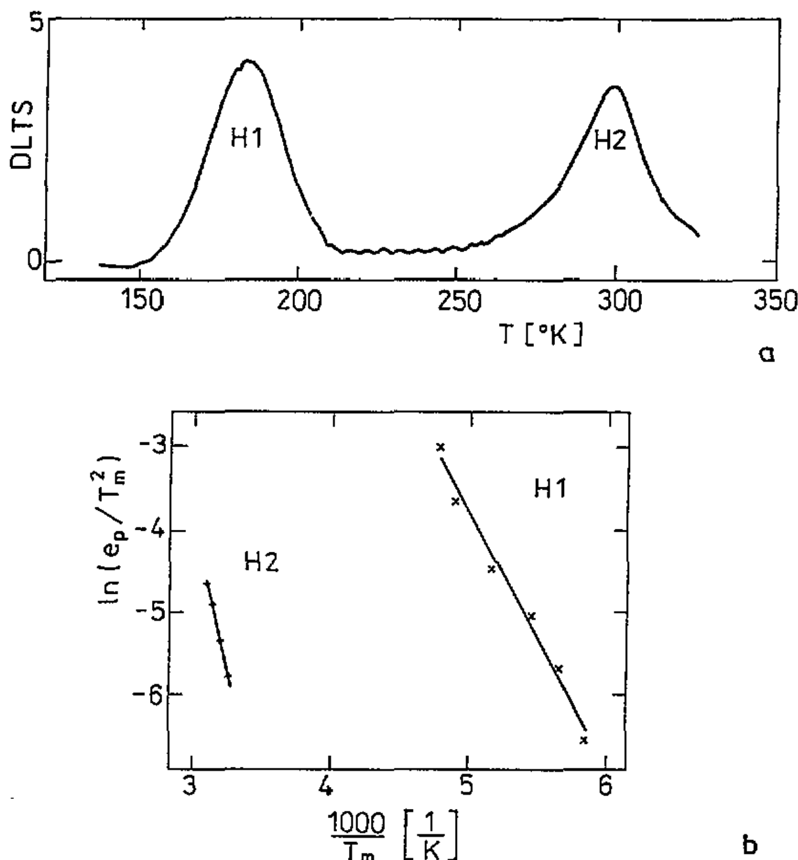

Figure 1. (*a*) The DLTS spectrum in p-CdTe: $U_R = -2$ V, $U_{p1} = 2$ V, $U_{p2} = 1.5$ V, $t_{1p} = t_{2p} = 200$ μs, $f = 100$ s^{-1}; (*b*) the Arrhenius plots of the hole thermal emission rate for both $H1$ and $H2$.

where

$$\sigma'_p = \sigma_p \exp(\Delta S/k) \tag{2}$$

N_v is the effective density of states in the valence band, ΔH is the enthalpy of ionization, σ_p is the hole capture cross section, v_p is the mean thermal velocity of holes of concentration p and ΔS is ionization entropy.

Usually the value of the capture cross section σ'_p is obtained from the Arrhenius plot. This value is equal to the capture cross section σ_p if the entropy ΔS of ionization is equal to zero. The values of σ'_p obtained from Arrhenius plots for both traps are $\sigma'_{pH1} = (6 \pm 3) \times 10^{-17}$ cm^2 for H1 and $\sigma'_{pH2} = (2 \pm 1) \times 10^{-14}$ cm^2 for H2. In general, $\Delta S \neq 0$ and σ_p should be estimated from independent measurements. If the values of captured cross sections can be measured independently, the value of ionization entropy ΔS can be evaluated from equation (2).

In order to evaluate the values of ΔS for the traps under study, capture cross section measurements were performed. The so-called isothermal frequency DLTS scan technique was applied. In this method instead of changing the temperature at a constant window rate (temperature scan DLTS) the frequency of the lock-in is changed at a constant temperature

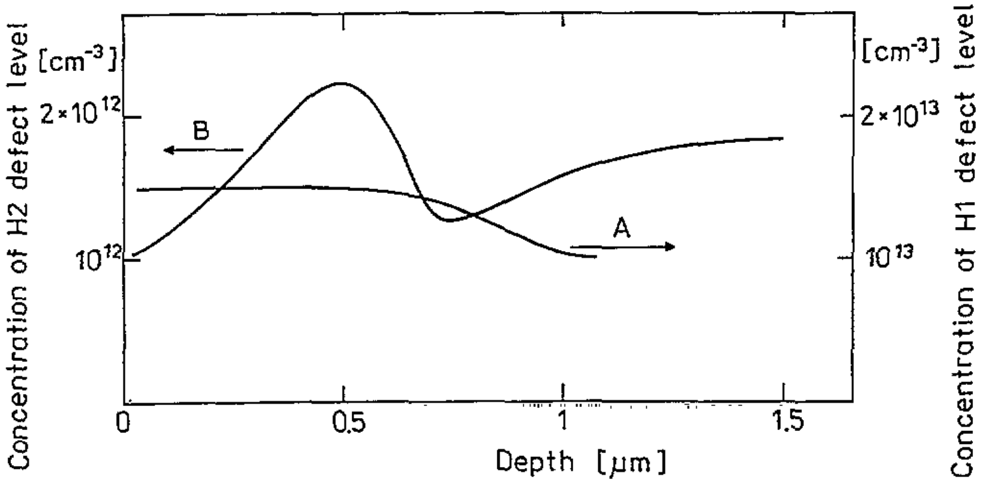

Figure 2. Depth profile scans of the $H1$ (curve A) and the $H2$ defect centres (curve B): (A) $U_R = -2$ V, $U_{p1} - U_{p2} = 0.2$ V, $t_1 = t_2 = 0.2$ ms, $f = 100$ s^{-1}; (B) $U_R = -4$ V, $U_{p1} - U_{p2} = 0.3$ V, $t_1 = t_2 = 3$ ms, $f = 2.5$ s^{-1}. The depth resolution corresponding to the difference in the filling pulse heights is equal to $\simeq 0.2$ μm at the surface and decreases with increasing depth up to $\simeq 0.1$ μm.

[16]. The capture cross section is then obtained from the increase in the DLTS signal peak amplitude ΔC on the frequency scan as a function of increasing width t_f of the excitation pulse. Following this procedure the capture cross section can be extracted from the relation [17]

$$\ln[\Delta C_0 - \Delta C(t_f)] = -c_p t_f + \ln(\Delta C_0) \tag{3}$$

where

$$c_p = \sigma_p v_p p \tag{4}$$

is the capture rate of holes, $\Delta C(t_f)$ is the observed amplitude of the DLTS signal corresponding to a given width of filling pulse and ΔC_0 is the saturation amplitude of the DLTS signal corresponding to the width of the filling pulse for which the amplitude of the DLTS signal becomes independent of t_f.

Figure 3 presents plots of $\ln[(\Delta C(t_f) - \Delta C_0]$ versus the filling pulse duration time t_f for both H1 and H2 traps. The hole capture rates c_p were calculated from the slope of the lines in figure 3. The resultant capture cross sections are $\sigma_{pH1} = (3 \pm 0.5) \times 10^{-18}$ cm^2 for H1 traps and $\sigma_{pH2} = (1.2 \pm 0.2) \times 10^{-17}$ cm^2 for H2 traps.

The comparison between the values of σ_p' obtained from Arrhenius plots and the values of capture cross section σ_p from the latter measurements yield values of ΔS equal to $(2.4 \pm 0.2) \times 10^{-4}$ eV K^{-1} for H1 and $(8.5 \pm 0.5) \times 10^{-4}$ eV K^{-1} for H2 defect centres.

The measurements of capture cross section were carried out at several temperatures within the temperature ranges 150–200 K for H1 and 250–300 K for H2. No temperature dependence of H1 and H2 capture cross sections was observed. This means that the value of activation energies E_{DLTS} obtained from Arrhenius plots are true activation energies and the values of capture cross sections σ_p are the values of σ_p at $1/T = 0$.

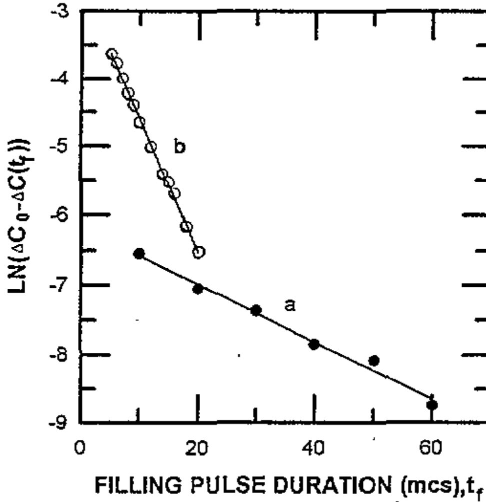

Figure 3. The results of capture cross section measurements plotted as $\ln[\Delta C(t_f) - \Delta C_0]$ versus t_f, where t_f is the length of the capture pulse, $\Delta C(t_f)$ is the maximum of DLTS signal at given t_f and ΔC_0 is the maximum of DLTS signal at saturation. (*a*) Level H1, (*b*) Level H2. For both measurements $U_R = -2$ V, $U_p = 2$ V, $t_1 = 100$ μs.

4. Discussion and conclusion

DLTS studies of deep centres in p-type CdTe yield two hole traps with trap activation enthalpies of 0.26 ± 0.01 eV for traps H1 and 0.61 ± 0.01 eV for traps H2 above the top of the valence band. The concentrations of these defects are about 10^{13} cm^{-3} and 2×10^{12} cm^{-3} for H1 and H2, respectively, and they do not change significantly within the depleted region of the contact. This means that these defects are not due to the applied method of the junction preparation. Capture cross section measurements show that both deep centres act as point defects. The values of hole capture cross sections $\sigma_p(1/T = 0)$ are $(3\pm0.5)\times10^{-18}$ cm^2 and $(1.2\pm0.2)\times10^{-17}$ cm^2 for H1 and H2, respectively. Entropies of the defects are found to be $(2.4\pm0.2)\times10^{-4}$ eV K^{-1} for H1 and $(8.5\pm0.5)\times10^{-4}$ eV K^{-1} for H2. No electric field dependence was observed for both traps, which implies a donor character of the traps.

The deep centre labelled by us as H2 with enthalpy $E_v + 0.61$ eV seems to belong to the midgap band [7]. The enthalpy of the second level labelled H1, $E_v + 0.26$ eV, is close to the enthalpy of the acceptor trap $E_v + 0.23$ eV, obtained in [8], but there are fundamental differences between these two levels. The properties of the trap detected by us, contrary to that reported in [8], are independent of electric field, which indicates its donor rather than acceptor character as was suggested in [8]. Also the captured cross section of the H1 trap is temperature independent and its value is about one order lower than the trap mentioned above in [8]. So we can conclude that these are two different traps of different origins.

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