

# Studies of defects in *n*-type CdTe by charge transient spectroscopy

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(Received 23 August 1989; accepted for publication 13 November 1989)

Charge transient measurements have been used to study deep levels in *n*-type CdTe single crystals. The samples, including In-doped, undoped, and Sn-doped single crystals, were grown by the Bridgman or the travelling heater method (THM). The temperature dependence of the capture cross section was investigated under the partial filling conditions. The activation energies of capture cross section were determined. For In-doped samples, the results indicate both levels  $E_c - 0.66$  eV (Bridgman samples) and  $E_c - 0.68$  eV (THM samples) are associated with the same indium-defect complex, but levels  $E_c - 0.34$  eV (Bridgman) and  $E_c - 0.32$  eV (THM) exhibited different capture mechanisms. The unusual capture properties of the trap at  $E_c - 0.61$  eV in the undoped sample can be attributed to a doubly charged Cd interstitial. For Sn-doped samples, four levels were observed, and levels  $E_c - 0.89$  eV and  $E_c - 0.43$  eV can be related to the presence of tin.

## I. INTRODUCTION

Many electronic applications of CdTe are limited by the lack of understanding and control of deep lying levels within the forbidden energy gap. These levels are usually associated with either native defects or defect-impurity complexes. The concentration of these defects can be affected by the activity of Cd or Te during crystal growth or postgrowth annealing processes. They can also be affected by impurity dopants.<sup>1,2</sup>

Since the deep level transient spectroscopy (DLTS) technique introduced by Lang (1974),<sup>3</sup> there are many modifications to the original spectroscopy technique. Capacitance transients or current transients have usually been used to obtain the information about deep levels in semiconductors. In the present work, charge transients have been chosen to characterize deep levels in *n*-type CdTe single-crystal materials. This approach was initially used by Farmer, Lamp, and Meese,<sup>4</sup> and was referred to as charge transient spectroscopy (QTS). The charge transients are obtained from the integration of the current transient signal. A significant advantage of the QTS method over current transient spectroscopy is the very wide range of the emission rate  $e_n$  that can be covered. ( $e_n = 1/\tau_n$ , where  $\tau_n$  is the transient decay time constant.) Because in obtaining the charge, the integration removes the prefactor  $1/\tau_n$  from the output magnitude equation. The sensitivity is especially improved for deep levels with lower emission rates.

For In- and Al-doped *n*-type CdTe single crystals, the midgap group of deep levels has been discussed by several authors, and groups of levels around  $E_c - 0.2$  eV and  $E_c - 0.4$  eV have been observed.<sup>5-7</sup> Different crystal-growth conditions and sample preparation processes made it difficult to draw definitive conclusions as to the nature of the associated defects.

Trapping levels in CdTe have been studied using both crystals grown by the Bridgman technique and the THM method in this laboratory. Since the Bridgman method involves a high temperature of 1100 °C, it tends to pick up impurities from the quartz ampoule. The THM Te-solution growth method involves a lower growth temperature of 850 °C and an additional zone refining step: One expects less

impurity contamination. Four levels were observed for Sn-doped samples. The only published work we have seen on Sn-doped CdTe was by Kremer and Leigh,<sup>8</sup> whose DLTS measurement only observed one level at  $E_c - 0.9$  eV.

On the other hand, in most discussions of the thermal stimulated processes, the capture cross section  $\sigma_n$  is usually assumed to be independent of temperature. However, several authors have reported that the magnitude of the DLTS peak for certain traps increased with increasing filling pulse length and have shown unusual behaviors.<sup>2,5</sup> The present measurements have found that the capture cross sections of several trap levels are thermally activated. A partial filling pulse condition has been used to obtain their temperature dependence. It can yield additional information about the respective defect structure and, if ignored, can yield a false value in the emission activation energy. The capture cross section activation energies have been taken into account in obtaining the true depths of these trap levels within the forbidden energy gap.

## II. THE TEMPERATURE DEPENDENCE OF THE CAPTURE PROCESS

In the present work, the properties of the capture cross sections are studied by using a constant filling pulse length, which is much shorter than the saturation pulse length. A QTS spectrum can be obtained as in the conventional DLTS technique. The capture cross section thermal activation energy was obtained from the change of peak amplitude with temperature.

The transient signal at a time  $t$  and temperature  $T$ , which can be monitored as capacitance or charge due to the thermal emission of electrons from a deep level, is given by

$$X(t, T) = X(0, T) \exp[-e_n(T)t], \quad (1)$$

where  $e_n(T)$  is the electron thermal emission rate, with

$$e_n = A(T) \exp(-\Delta E_t/kT) \quad (2)$$

and

$$A(T) = U_{th} \sigma_n N_c. \quad (3)$$

$\Delta E_t$  is the activation energy of the trapping center,  $U_{th}$  is the

thermal velocity of electrons,  $\sigma_n$  is the carrier capture cross section, and  $N_c$  is the effective density of states in the conduction band. A transient time constant is defined as

$$\tau_n = 1/e_n. \quad (4)$$

The decay signal  $X(t, T)$  is processed by the QTS technique. The boxcar output yields the difference of the transient signals at gate delay times  $t_a$  and  $t_b$ , with

$$X = X(t_a, T) - X(t_b, T) \\ = X(0, T) [\exp(-t_a/\tau_n) - \exp(-t_b/\tau_n)]. \quad (5)$$

The output has a maximum at a temperature  $T_m$ , and the corresponding transient time constant is given by

$$\tau_{\max} = (t_b - t_a) / [\ln(t_b/t_a)]. \quad (6)$$

In this study the operating mode is chosen such that

$$t_b/t_a = \gamma, \quad (7)$$

and  $\gamma$  is held constant.<sup>3,9</sup> Therefore, the amplitude of a transient peak is given by

$$X_m = X(t_b, T_m) - X(t_a, T_m) = X(0, T_m) B(\gamma). \quad (8)$$

The factor  $B(\gamma)$  is invariant with the varying rate window. From Eq. (5) to Eq. (8) we have

$$B(\gamma) = \left( \frac{1}{\gamma - 1} \right) \exp\left( -\frac{\ln(\gamma)}{\gamma - 1} \right). \quad (9)$$

The change in the peak height is related to the trap filling factor  $X(0, T_m)$ , which represents the trap filling status prior to the emission transient process:

$$X(0, T_m) = X_0(t_f, T_m) = X_{\inf} [1 - \exp(-C_n t_f)], \quad (10)$$

where  $t_f$  is the width of the filling pulse, and  $C_n$  is the electron capture rate. A constant filling pulse height was used in the measurement.  $X_{\inf}$  is the maximum peak amplitude under a saturating filling condition, when the traps in the investigated region are completely filled after a filling pulse, then

$$X(0, T_m) = X_0(t_f, T_m) = X_{\inf}. \quad (11)$$

This is the case of the conventional emission DLTS technique, when the temperature dependence of the DLTS peak only appears to vary its position ( $T_m$ ) with respect to different rate windows, and does not vary its amplitude and line shape. Once the saturation condition is satisfied, the capture process during the period of time  $t_f$  does not affect the measurements in the emission process. The emission activation energies are determined by the slope of the Arrhenius plot of  $\ln(e_n/T^2)$  vs  $1/T$ .

When a partial filling condition is selected, the filling pulse width is shorter than the capture time constant. The initial condition prior to the transient decay process  $X_0(t_f, T_m)$  depends on the width of the filling pulse  $t_f$ , as indicated in Eq. (10). The output of the boxcar will have a peak with an amplitude of

$$X_{\max} = X_0(t_f, T_m) B(\gamma) = X_{\inf} [1 - \exp(-C_n t_f)] B(\gamma). \quad (12)$$

For a thermal activated capture process

$$\sigma_n = \sigma \exp(-\Delta E_\sigma/kT), \quad (13)$$

so that

$$C_n = U_{\text{th}} n_c \sigma_n = U_{\text{th}} n_c \sigma \exp(-\Delta E_\sigma/kT). \quad (14)$$

$\sigma$  is the high-temperature capture cross section of a given electron trap,  $\Delta E_\sigma$  is the capture cross section activation energy, and  $n_c$  is the electron concentration available for trap capture.

The DLTS measurements are performed with a fixed filling pulse duration  $t_f$ , under this condition the thermally activated capture process is observed through the varying amplitude of the DLTS peak as one changes  $t_a$  and keeps  $t_b/t_a$  constant.

From Eq. (12) and Eq. (14) we have

$$\ln\{1 - [X_0(t_f, T)/X_{\inf}]\} = A' \exp(-\Delta E_\sigma/kT), \quad (15)$$

where the factor  $A' = t_f U_{\text{th}} n_c \sigma$ .  $T$  is the temperature of the DLTS peak maximum. Taking into consideration the temperature dependence of the free-electron density  $n_c$  by

$$n_c = N_c \exp(-\Delta E_f/kT), \quad (16)$$

where  $\Delta E_f = E_c - E_f$ ,  $E_f$  is the position of the Fermi level. The thermal activation energy of capture cross section  $\Delta E_\sigma$  can then be determined.

For *n*-type CdTe, the thermal velocity of electrons is given by<sup>2</sup>  $U_{\text{th}} = 2.18 \times 10^6 T^{1/2} \text{ cm s}^{-1}$ , and the density of states  $N_c$  is  $1.44 \times 10^{14} T^{3/2} \text{ cm}^{-3}$ .

The capture cross section activation energy is determined by the slope of the Arrhenius plot of  $\ln(1 - X_0/X_{\inf})/T^2$  vs  $1/T$ . Then the location of the trap level within the forbidden gap is determined as  $(E_c - \Delta E_t - \Delta E_\sigma)$ .

In the QTS measurements, the transient current signal  $i(t)$  is integrated to obtain the charge transients. This charge transient signal has the form

$$Q(t, T) = Q(0, T) \exp(-t/\tau_n). \quad (17)$$

The quantity  $Q(0, T)$  represents the trap filling status prior to the thermal emission transient process. All the above discussions are valid for the case of charge transient measurements. Under saturating filling pulse conditions,  $Q(0, T)$  is given by

$$Q(0, T) = AWqN_t/2, \quad (18)$$

where  $W$  is the width of the depletion layer and  $A$  is the area of the Schottky contact. The factor  $AW$  is the volume in which the trapped electrons are emitted to give rise to the transient signal.  $N_t$  is the concentration of the traps, and  $q$  is the electron charge.

### III. EXPERIMENTAL PROCEDURES AND RESULTS

The CdTe crystals investigated were grown in this laboratory. The crystal TB was doped with tin, the crystal IB was doped with indium, and the crystal UB was undoped. They were grown by the modified vertical Bridgman method under a controlled Cd vapor pressure. The crystal IH was doped with indium, and was grown by the travelling heater method (THM).<sup>10</sup> Postgrowth Cd vapor annealing treatments were also carried out at 700 °C for 10 h or 800 °C for 15 h and followed by quenching to room temperature. Resistivity and Hall-effect measurements were made by the dc van der Pauw method with a field of 4 kG and a voltage drop of

less than 1 V across the specimen. The results showed all the samples were *n* type. The tin-doped and undoped CdTe were highly resistive as grown, and further Cd vapor annealing brought the resistivity down to the range of 1–100  $\Omega$  cm. (The free-carrier concentrations are shown in Tables I–III.)

An ohmic indium electrode was first melted onto the back of the sample, then the sample was annealed in forming gas (with 5% hydrogen and 95% nitrogen) at 250–300 °C for 20 min. Samples were etched in 10% bromine-methanol solution for 1 min then etched in 0.6M Na<sub>2</sub>SO<sub>4</sub>/2.5M NaOH solution for 2 min. A gold Schottky contact was evaporated onto the front surface immediately after chemical etching. A capacitance-voltage (*C-V*) analysis was performed in order to obtain the net donor concentration.

The QTS experimental system is essentially the same as described by Farmer and co-workers.<sup>4</sup> An operational amplifier circuit was used as the integrator to obtain a voltage signal which is proportional to the transient charge; it is followed by a sample and hold amplifier, which blanks off the unrequired part of the signal. The system has been developed to optimize the sensitivity for the study of defects with low emission rates. The main error results from the leakage current of the sample, especially under the saturating filling pulse condition. By carefully adjusting the RC feedback loop in the integrator and selecting a suitable bias voltage according to the particular *C-V* characteristics of the given diode, the error can be minimized. Under the partial filling pulse condition, this error is further reduced because of the short forward pulse used.

The QTS spectra for the tin-doped samples TB2 and TB3 are shown in Fig. 1. Four different centers were observed for TB3, with a saturating filling pulse length of  $t_f = 150$  ms, and the rate window ranges from 55.6 to 2.86 s<sup>-1</sup>. The emission activation energies were determined by the usual Arrhenius plot of  $\ln(e_n/T^2)$  vs  $1/T$ , as shown in Fig. 2. The saturated amplitudes  $X_{inf}$  were measured as a reference for amplitude normalization when a partial filling pulse was used. The results are summarized in Table I. The

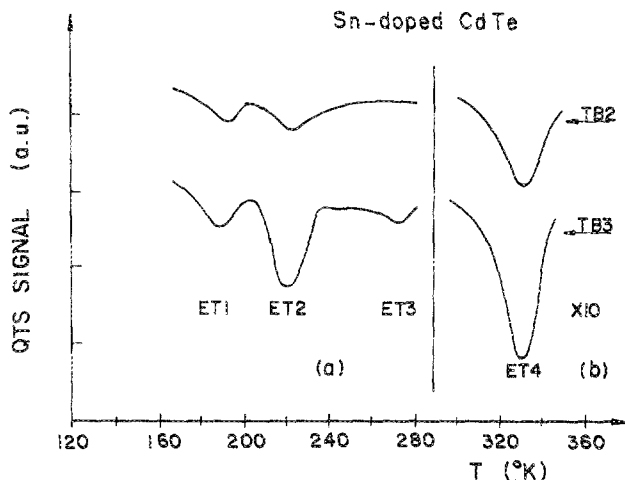


FIG. 1. QTS spectra of electron traps for Sn-doped CdTe samples TB2 and TB3 obtained with a filling pulse length of  $t_f = 150$  ms. (a) and (b) were observed with a rate window of 55.6 and 2.86 s<sup>-1</sup>, respectively.

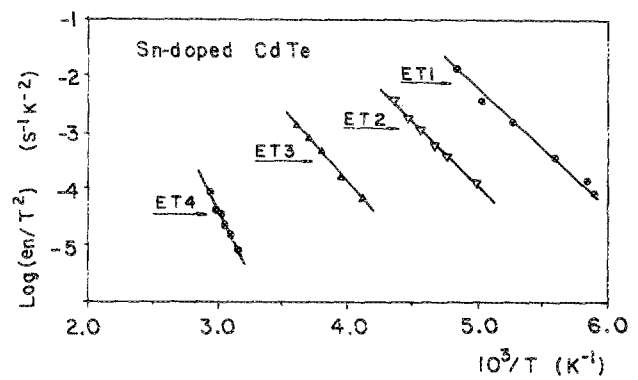


FIG. 2. Arrhenius plots of  $(e_n/T^2)$  vs  $10^3/T$  for Sn-doped sample TB3.

amplitude of the dominant peak ET4 increased two to three times after further Cd vapor annealing at 800 °C for 15 h. The density of conduction electrons increased commensurately. The amplitudes of the peak associated with ET1 and ET3 are smaller, resulting in larger errors in the activation energies. The parameters of electron traps for indium-doped samples IB2 and IH4 are shown in Table II. The undoped sample UB4 showed three peaks, and the relevant parameters are shown in Table III.

The capture characteristics were obtained from the emission QTS measurements under the partial filling condition. With a filling pulse length of  $t_f = 0.1$  ms, the decay time constant ranges from 0.06 to 8 ms. Taking into consideration the temperature dependence of conduction electron density, the activation energies of the cross section were determined and are also shown in Tables I–III. The values of  $\sigma_n$  of the temperature-dependent capture levels are the pre-exponential factor or the high-temperature limit in Eq. (13).

For the samples IB2 and IH4, the QTS spectra showed the capture cross section of levels EB5 and EH5 to be almost temperature independent, where the change in QTS peak amplitude was less than 10% over the temperature range of 300–330 K. The levels EB3, EB4, and EH4 showed a significant temperature dependence. Figure 3 shows the QTS spectra under a partial filling condition for the trapping center EB4 of the indium-doped sample IB2. Trapping center EH4 showed a nearly identical behavior in the same range of temperature, and the line shapes did not change significantly. The amplitude decreased as the peaks shifted towards higher temperature. The plot of  $\ln(1 - X_0/X_{inf})/T^2$  vs  $1/T$  as shown in Fig. 4, yields an activation energy of  $0.07 \pm 0.005$  eV for the capture cross section of defect EB4. For level EH4, an activation energy of  $0.08 \pm 0.005$  eV was found. Also, an activation energy of  $0.09 \pm 0.005$  eV was obtained for level EB3.

Figure 5 shows the QTS spectra of level EU3 for the undoped sample UH4. It showed an unusual behavior under the partial filling condition. In addition to shifting towards higher temperature and lowering of its amplitude, the line shape also changed with decreasing rate window, and another peak seemed to appear at the lower temperature side, but the amplitude was too small for analysis. For the dominant peak, an activation energy of 0.09 eV was obtained for the capture cross section.

TABLE I. Bridgman-grown Sn-doped samples. The trap parameters were obtained under saturation conditions, with a filling pulse length of  $t_f = 150$  ms.

Sample	Annealing	$n$ ( $10^{15} \text{ cm}^{-3}$ )	Trap label	Activation energy (eV)	$\sigma_n$ ( $10^{-13} \text{ cm}^2$ )	$N_t$ ( $10^{14} \text{ cm}^{-3}$ )
TB2	Cd vapor 700 °C 10 h	3.0	ET1	$0.36 \pm 0.03$	0.5	0.05–0.5
			ET2	$0.4 \pm 0.02$	0.2	0.5–1
			ET4	$0.88 \pm 0.03$	30 (0.06 eV) <sup>a</sup>	2–3
TB3	Cd vapor 800 °C 15 h	8.0	ET1	$0.38 \pm 0.03$	0.9	0.5–1
			ET2	$0.43 \pm 0.02$	0.4	1–1.5
			ET3	$0.51 \pm 0.04$	0.09	0.5–1
			ET4	$0.89 \pm 0.03$	50 (0.07 eV) <sup>a</sup>	6–8

<sup>a</sup>This is the activation energy of the capture cross section obtained under partial filling condition.

#### IV. DISCUSSION

A comparison of trap parameters between the indium-doped samples IB2 and IH4 suggests that the levels EB5 and EH5 must be due to the same defect structure. The concentration of this trapping center decreased with increasing Cd vapor pressure, similar to results described by Verity *et al.*<sup>2</sup> for EH5 and EG6 in their In-doped THM sample and their undoped Bridgman sample. The levels EB5 and EH5 are related to a commonly reported double-negatively charged state of the Cd vacancy  $V_{\text{Cd}}$ . This level is also similar to one reported for E8 by Takebe *et al.*,<sup>6</sup> who suggested that this is a recombination center, and is related to a complex center including the Cd vacancy.

Analyzing the spectra under partial filling conditions, the nearly identical temperature dependence of the capture cross section for levels EB4 and EH4 suggests that these two levels are due to similar defect structures and are likely related to an indium-defect complex. In the present work, the saturating filling pulse width  $t_f$  was of 150 ms, and an activation energy of 0.67 eV was obtained for EB4 and EH4. The studies of the capture process result in an activation energy of 0.07–0.08 eV for the capture cross section. A similar level

was identified as EG4 by Verity *et al.*<sup>2</sup> for their In-doped Bridgman sample; however, they obtained different emission activation energies of 0.62 and 0.51 eV by using 20- and 2-ms filling pulses, respectively, and assigning the level EG4 to be associated with both In and Si impurity. In the present work, EB4 and EH4 do not seem to be related to the Si impurity, because we observed it in both THM and Bridgman samples with nearly identical concentrations.

In contrast to the above, the emission activation energies of EH2 and EB3 are nearly the same, but observation under partial filling conditions showed that the capture cross section of EB3 is thermally activated, while EH2 is not. Therefore they cannot be considered as the same trapping center. For level EB3 the capture barrier or the activation energy of the capture cross section was 0.09 eV, and its true depth was 0.25 eV. This level might be similar to level E3 with an emission activation energy of 0.33 eV as reported by Takebe *et al.*<sup>6</sup> for the Al-doped Bridgman sample, but they found the electron-capture activation energy to be 0.29 eV; the true depth was then 0.04 eV. Isett and Raychaudhuri<sup>5</sup> also reported a level IR2 ( $E_i = 0.37$  eV) for their In-doped sample, and observed a temperature-dependent capture cross section, but no capture activation energy was reported.

TABLE II. Indium-doped CdTe samples. The trap parameters were obtained under saturation conditions with  $t_f = 150$  ms.

Sample	Sample preparation	$n$ ( $10^{16} \text{ cm}^{-3}$ )	Trap label	Activation energy (eV)	$\sigma_n$ ( $10^{-13} \text{ cm}^2$ )	$N_t$ ( $10^{14} \text{ cm}^{-3}$ )
IB2	Bridgman Cd vapor 700 °C 10 h	20.0	EB1	$0.23 \pm 0.02$	0.02	0.05–0.2
			EB3	$0.34 \pm 0.02$	50 (0.09 eV) <sup>b</sup>	0.5–1.5
			EB4	$0.66 \pm 0.03$	10 (0.07 eV) <sup>b</sup>	0.5–2.5
			EB5	$0.79 \pm 0.03$	4.0	8–10
IH4	THM Cd vapor 800 °C 15 h	8.0	EH2	$0.32 \pm 0.02$ (0.35) <sup>a</sup>	0.2	0.5–1.5
			EH4	$0.68 \pm 0.03$ (0.72) <sup>a</sup>	20 (0.08 eV) <sup>b</sup>	1–3
			EH5	$0.80 \pm 0.03$ (0.83) <sup>a</sup>	5.0	5–7

<sup>a</sup>These results were obtained by TSCAP for the In-doped CdTe crystals grown by THM in our laboratory.<sup>11</sup>

<sup>b</sup>These values are the activation energies of the capture cross section.



TABLE III. Undoped Bridgman-grown CdTe samples. The trap parameters were obtained under saturation condition with a filling pulse length of  $t_f = 150$  ms.

Sample	Annealing	$n$ ( $10^{15} \text{ cm}^{-3}$ )	Trap label	Activation energy (eV)	$\sigma_n$ ( $10^{-13} \text{ cm}^2$ )	$N_t$ ( $10^{14} \text{ cm}^{-3}$ )
UB3	none	6.0	EU1	$0.25 \pm 0.02$	0.02	0.5–1
			EU5	$0.78 \pm 0.02$	4.0	4–6
UB4	Cd vapor 800 °C 15 h	20.0	EU1	$0.23 \pm 0.02$	0.03	0.1–0.2
			EU3	$0.61 \pm 0.02$	40 <sup>a</sup>	0.5–2
			EU5	$0.79 \pm 0.03$	6.0	1–3

<sup>a</sup> This capture cross section showed unusual temperature dependence (see text).

The center EB1 is probably related to contamination during the Bridgman crystal growing process, because this level disappeared with further zone refining or by the THM process, and it was also observed in the undoped Bridgman sample UB4 as level EU1. A similar level EG1 for an undoped Bridgman sample was reported by Verity *et al.*<sup>2</sup> and was assigned to residual impurities. The values of the emission activation energies for traps EH2, EH4, and EH5 are in agreement with the results obtained by thermally stimulated capacitance (TSCAP) measurements for In-doped CdTe crystals grown by THM in our laboratory.<sup>11</sup> Similar to our level EH2 ( $E_c - 0.32$  eV) for the In-doped THM sample, the level IH4 was reported for In-doped THM sample by Verity *et al.*<sup>2</sup>

The level EU3 showed unusual thermal properties in the capture process which have been described in the former section. The appearance of another peak within a limited temperature range may be explained by a trapping center involving two charges. The process of capturing the first or the second electron has different temperature dependencies. Such trapping centers should have two energy levels, and their difference or correlation energy may be very small due

to lattice relaxation. In the emission QTS measurements the difference between the two emission rates may be too small to be distinguished as two peaks, as they showed the same activation energy of  $E_c - 0.61$  eV. The temperature dependence of the capture process can reveal the difference between them. The 0.09-eV activation energy of the capture cross section for the main peak in Fig. 5 suggests this level is located at  $E_c - 0.52 \pm 0.03$  eV. The capture cross section of the other trapping level is assumed to be temperature independent, and its location can then be directly obtained from its emission activation energy of  $E_c - 0.61$  eV. This phenomenon has only been seen in the undoped Bridgman-grown sample, and does not occur in other doped samples. Our samples were grown by a modified Bridgman method under a controlled Cd vapor pressure and followed by Cd vapor annealing, and this level was observed for sample UB4 only after it had been further annealed in Cd vapor, which enhances the Cd concentration. This suggests that this trapping center is related to a doubly charged Cd interstitial  $\text{Cd}_i$ . Level NA6-A8 (0.74 eV) was reported by Ido *et al.*<sup>1</sup> in In-doped samples and E7 (0.68 eV) by Takebe *et al.*<sup>6</sup> in Al-doped samples and were attributed to a donorlike complex center including the double-positively charged state of Cd interstitial  $\text{Cd}_i$ , but they did not report the temperature dependence of the capture cross section.

A theory of the activated capture cross section based on the multiphonon emission process together with lattice relaxation has been developed by Henry and Lang.<sup>12</sup> When used with the smaller effective mass of the conduction electron in CdTe, one obtains a reasonable agreement for the observed capture cross section. The dominant trapping cen-

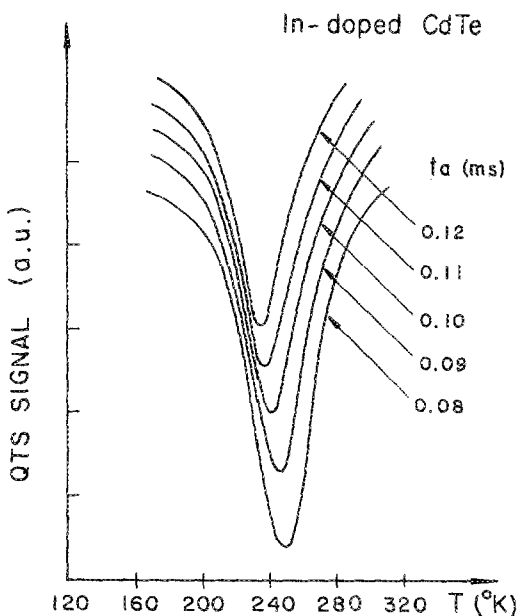


FIG. 3. QTS spectra of electron trap EB4 for In-doped CdTe sample IB2 under partial filling condition with  $t_f = 0.1$  ms; the rate windows are given by the sampling times  $t_a$  while keeping the ratio  $t_b/t_a = 3$ .

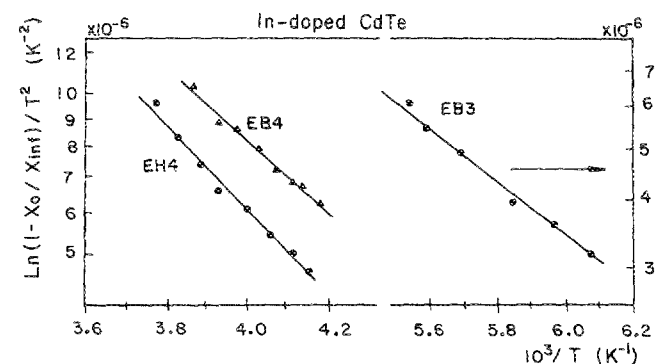


FIG. 4. Arrhenius plot of  $\ln(1 - X_0/X_{\text{inf}})/T^2$  vs  $10^3/T$  for traps EH4, EB4, and EB3 in In-doped samples.

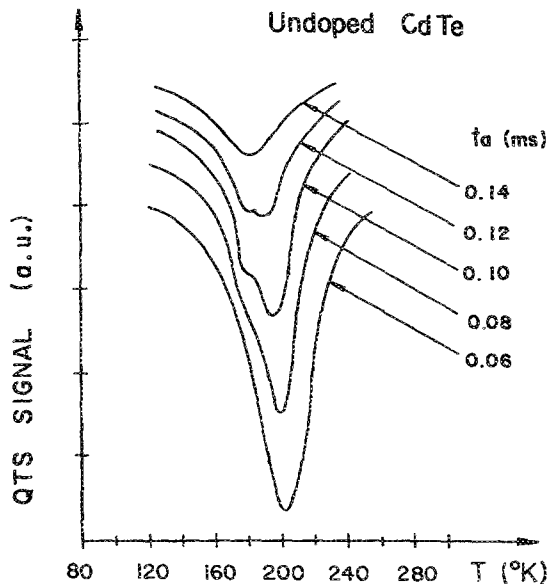


FIG. 5. The capture characteristics by emission QTS experiments for level EU3 of the undoped sample UH3, under partial filling condition with  $t_f = 0.1$  ms. The rate windows are given by the sampling times  $t_a$  while keeping the ratio  $t_b/t_a = 3$ .

ter EU5 ( $E_c - 0.79$  eV) in the undoped sample UB3 and UB4 was seen in most undoped samples, and similar to the levels EB5 and EH5 in our In-doped samples, their concentration decreased after Cd vapor annealing. The possible origins of this level have been proposed as the following: (1) Similar to an acceptor level at 0.78–0.80 eV reported in all samples studied including those reported for P-doped, Cs-doped, and undoped samples by Kremer and Leigh,<sup>8</sup> it was suggested to be a native defect involving the Cd vacancy. (2) The residual impurities introduced during the Bridgman process might exist through the formation of telluride precipitates, and Cd vapor annealing would reduce the density of this defect as observed results. (3) An impurity whose solubility or stable sites in the lattice are dependent on the Cd pressure could also show the same behavior. In the present work, because the undoped samples were grown with a controlled Cd vapor pressure, the density of Te precipitates is assumed to be very low. Another fact that has to be considered is that the further Cd vapor treatment not only reduces the concentration of the trapping center EU5, but also introduces a level EU3 which has been attributed to a Cd interstitial. Therefore, it is not suggested that the level EU5 is directly related to the doubly ionized Cd vacancy or Te interstitial, it is likely as the proposal (3). The Si, most possibly, present as an impurity, sits substitutionally on the Cd site acts as a donor. Its concentration would also decrease with increasing Cd vapor pressure. An analogous assumption has been made for level E8 in the Al-doped sample of Takebe *et al.*<sup>6</sup>

For the tin-doped samples, the largest QTS peak is associated with a very deep level ET4 at  $E_c - 0.89$  eV; this must be related to the presence of tin, as it has not been observed in other samples. The concentration of this trapping center is significantly increased after further Cd vapor anneal, with a

commensurate decrease in resistivity. This suggests that before annealing this Sn-related donor level was compensated for by other unknown acceptor centers, which can be assumed to be related to Cd vacancies. The Cd vapor anneal affects the resistivity through a decompensation process associated with the reduction of Cd vacancies. Brunthaler *et al.*<sup>13</sup> have reported their photoelectron spin resonance results for CdTe samples doped by group IV impurities. They have shown that tin can be incorporated substitutionally on the Cd site, and thus act as a double donor. Their measured energy-level position is in the range of  $E_c - 1.0$  eV to  $E_c - 0.8$  eV, which agrees with our value for ET4. Therefore we can assign our level ET4 to this donorlike trapping center. Because of its double positive charge, the capture cross section for holes should be much smaller than for electrons, therefore the hole emission rate can be ignored when applying Eq. (2) for this deep level. Kremer and Leigh<sup>8</sup> have also reported a level at  $E_c - 0.9$  eV from their DLTS measurements in Sn-doped CdTe. In the present work, a 0.07-eV activation energy of the capture cross section was obtained, thus the trapping level ET4 is located at  $E_c - 0.82$  eV. Level ET1 ( $E_c - 0.38$  eV) and ET3 ( $E_c - 0.51$  eV) are similar to level EG2 (0.34 eV) and EG4 (0.52 eV) reported by Verity *et al.*<sup>2</sup> for their undoped and In-doped Bridgman samples. We associate these two levels to a residual impurity such as Si from the Bridgman crystal growing process. Level ET2 ( $E_c - 0.43$  eV) may be assumed to be related to the presence of tin, since it was not observed in the samples other than those containing tin. Kremer and Leigh<sup>8</sup> observed levels at  $E_c - 0.4$  and  $E_c - 0.5$  eV for Sn-doped samples from photoconductivity measurements rather than by DLTS. The level ET2 has not been reported previously. The commonly observed 0.22–0.25 eV trap level only appears in our Bridgman-grown samples, both undoped and In-doped, but not in our Sn-doped Bridgman sample. The presence of tin seems to suppress this level.

## V. CONCLUSIONS

In summary, electron trapping centers of In-doped, Sn-doped, and undoped CdTe samples have been studied by the QTS technique. The results described above provide clear evidence that the observed traps are closely related to the crystal-growth process, the impurity dopant, as well as the postgrowth treatment. The levels EB4, EH4, and EH2 are associated with the indium dopant, ET2 and ET4 are related to the tin dopant, levels EB1, EU1, ET1, and ET3 are related to the impurity contamination during the Bridgman crystal-growth process, and the formation of a foreign atom-defect complex is assumed. The origin for EU5 is proposed as a substitution impurity in the Cd site. EB5 and EH5 are related to a commonly reported Cd vacancy or a defect involving a Cd vacancy.

The results based on partial filling conditions revealed the thermally activated capture process for several levels. The true depth of level EB3 is 0.25 eV, and it is possibly related to an impurity introduced in the crystal-growth process, and a multiphonon mechanism may be involved in its emission process. The level at EU3 can be accounted for by two separate levels with nearly the same emission rate and is

related to a Cd interstitial.

In conclusion, the charge transient spectroscopy is an effective method for the investigation of deep levels in CdTe. The use of the unsaturated filling condition to study the kinetics of the capture process plays an important part in characterizing such levels, especially in unravelling the nature of the traps such as EB3 or EU3.

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