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DEEP LEVELS IN $Cd_{0.99}Mn_{0.01}Te$:Ga

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Two types of samples were studied. In the material with higher donor concentration four electron traps labelled by us as $E1$ to $E4$ were found. For the traps $E2$ and $E3$ energies obtained from Arrhenius plots are equal to 0.24 eV and 0.36 eV, respectively. Electric field enhanced electron emission from the levels $E1$ and $E4$ was observed and described in terms of Frenkel–Poole mechanism. Capture process from the traps $E2$ was found to be thermally activated with energetic barriers equal to 0.20 eV for $E2$.

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1. Experiment and samples

Deep level transient spectroscopy (DLTS) since its invention [1] has been a well-known powerful method of studying deep levels in semiconductors. This method has been used by us to study semiconducting compound $Cd_{0.99}Mn_{0.01}Te$ of shallow donor concentration $N_D = (1\text{–}5) \times 10^{16}$ cm^{-3}. The Schottky contact was prepared by vacuum evaporation of gold 1 mm^2 layer on chemically cleaned surface of CdMnTe sample. The soldered indium served as an ohmic contact. The material comes from Prof. W. Giriat from IVIC Venezuela. Our DLS-82E system is based on 1 MHz capacitance bridge and lock-in integrator.

The DLTS signal temperature scans were taken within 80–420 K temperature range. The DLTS measurements performed on our samples revealed the presence of several deep levels, marked by us from $E1$ to $E4$. The DLTS measurements were taken for different values of reverse bias and depolarization pulse heights. In that manner different values of electric field were realised. Exemplary temperature dependence of DLTS signal is shown in Fig. 1.

2. Results and discussion

The electron emission rate e_n obtained from DLTS data divided by temperature square plotted as a function of reciprocal temperature — which is the so-called Arrhenius plot — provides the value of energy activation of the trap E_T and its apparent capture cross-section σ_n. From the Arrhenius plots shown in Fig. 2 we calculated E_T and σ_n by the least squares method. For the $E2$ trap

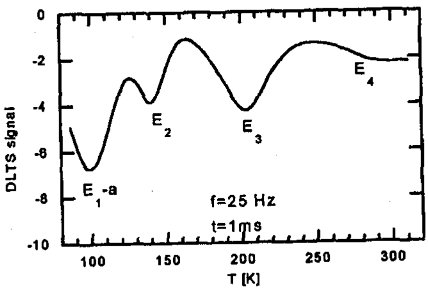

Fig. 1. Exemplary DLTS signal (in arbitrary units) of $Cd_{0.99}Mn_{0.01}Te$:Ga samples. Filling pulse width 1 ms.

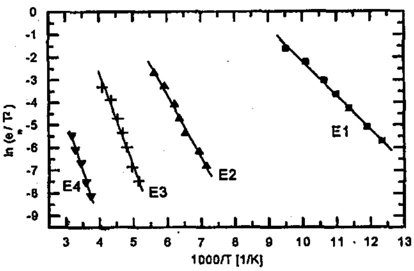

Fig. 2. Arrhenius plots corresponding to the traps $E1-E4$. The plots for the traps $E1$ and $E4$ are at relative high electric field 1.2×10^5 V/cm.

for which there was no influence of electric field on emission rate we obtained $E_{\mathrm{T2}} = (0.24 \pm 0.02)$ eV and $\sigma_{\mathrm{n2}} = 3.3 \times 10^{-12}$ cm^2. Three of the traps: $E1$, $E3$, and $E4$ have shown electric field enhanced emission rate. Arrhenius plots are given also for them yielding trap energies $E_{\mathrm{T1}} = 0.13$ eV, $E_{\mathrm{T1}} = 0.36$ eV, and $E_{\mathrm{T4}} = 0.4$ eV at the relative high electric field equal to 1.2×10^5 V/cm.

Electric field dependence of electron emission rates from the traps was investigated. Detailed description of the isothermal differential DLTS (DDLTS) mode of operation of our DLS-82E system used for this study is given in [2]. Usually the influence of electric field on emission rate can be explained in the terms of Frenkel–Poole effect [3]. Due to the electric field superimposed on a defect potential a lowering of effective emission barrier occurs. The thermionic electron emission from the trap is easier now but it is possible only if a defect center acquires a net charge upon carrier emission which means that the trap has to be donor-like in n-type material and acceptor-like in p-type material. The lowering of effective emission barrier as compared to zero electric field E_{T0} in the presence of electric field of intensity F is equal to

$$\Delta E_{\mathrm{PF}} = \alpha(F)^{1/2}, \tag{1}$$

where

$$\alpha = e(Ze/\pi/\varepsilon)^{1/2}, \tag{2}$$

and where e is electron charge, Z is a charge state after emission and ε is semi-

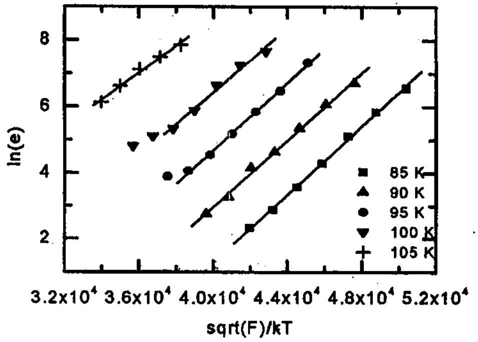

Fig. 3. Emission rate as a function of electric field for the trap $E1$ at several temperatures. Solid lines were calculated by the least squares method. Slopes of the lines: $\alpha_1 = (4–5) \times 10^{-4}$ $((\mathrm{eV})^2\mathrm{cm/V})^{1/2}$.

conductor dielectric constant. According to the model the semilogarithmic plot of emission rate e_n versus square root of electric field divided by kT product gives a straight line of slope α. The theoretical value of α calculated for $Z = 1$ for the $\mathrm{Cd_{0.99}Mn_{0.01}Te}$ material should be equal to 2.2×10^4 $((\mathrm{eV})^2\mathrm{cm/V})^{1/2}$. For example in Fig. 3 the $\ln e_n = f(F/(kT))$ for the traps $E1$ is shown for several temperatures. For each of the traps the slope of the lines is temperature independent. However, only in the case of the trap $E4$ the experimental value is close to the theoretical one: $\alpha_4 = (3–3.5) \times 10^{-4}$ $((\mathrm{eV})^2\mathrm{cm/V})^{1/2}$. For the trap $E3$ it is around 1×10^{-4} $((\mathrm{eV})^2\mathrm{cm/V})^{1/2}$ which is twice less than the theoretical value. On the other hand, we have too high value of $\alpha_1 = (4–5) \times 10^{-4}$ $((\mathrm{eV})^2\mathrm{cm/V})^{1/2}$. Too low value of α_3 trap can be attributed to higher localization of impurity potential for $E3$ trap. In turn, too high value of $\alpha_1 = (4–5) \times 10^{-4}$ $((\mathrm{eV})^2\mathrm{cm/V})^{1/2}$ can be explained either by contribution of phonons in emission process or by doubly charged defect center resulting according to Eq. (2) in 1.4 times higher value of α. Experimentally obtained values of α and energy activation at zero electric field E_{T0} are given in Table. Due to the weak electric field dependence of emission rate for the trap $E3$ the value of $E_{\mathrm{T03}} = 0.38$ eV is close to $E_{\mathrm{T3}} = 0.36$ eV obtained from Arrhenius plot in Fig. 2. Corresponding capture cross-section obtained from the same Arrhenius plot is $\sigma_{n3} = 5.5 \times 10^{-15}$ cm^{-2}.

The DLTS measurements were taken also for different time duration of filling pulses. In this way different level of filling the traps was realized. No influence of the trap filling degree on electron emission from the trap was observed. As the value of activation energy is independent of the width of filling pulse we could assume that we deal with point defects. However, for the traps $E2$ a significant decrease in DLTS signal with decreasing lock-in frequencies was observed. We were able to explain this behaviour assuming strong temperature dependence of capture cross-section. In order to study the capture cross-section we applied the method proposed by Henry and Lang [4]. For the levels $E2$ the capture cross-section was found to depend exponentially on inverse of temperature according to relationship

$$\sigma_n = \sigma_{n\infty} \exp(-E_B/kT) \tag{3}$$

TABLE

Experimentally obtained values of α and energy activation at zero electric field E_{T0}.

Trap label	α from experiment $[((\mathrm{eV})^2\mathrm{cm/V})^{1/2}]$	E_{T0} [eV] energy activation extrapolated to zero electric field
$E1$	4.5×10^{-4}	0.28
$E3$	1×10^{-4}	0.39
$E4$	3.3×10^{-4}	0.51

with E_{B} equal to 0.20 eV. Such a strong temperature dependence of a capture cross-section can be explained with the help of the so-called large relaxation model (LLR) [5]. According to the model electron emission from the trap level accompanies relaxation of the lattice surrounding related defect and energy activation is necessary for the carriers to be captured again at the level. As thermal activation energy for the levels $E2$ obtained from Arrhenius plots is equal to 0.24 eV the distance of these levels from the bottom of conduction band is equal only to 0.04 eV.

Energetic barriers for capture were also observed in CdTe [6] and related CdZnTe [7] and CdMnTe [8, 9] compounds. In indium doped CdTe [6] the level labelled as $ET2a$ of energy 0.34 eV with energy barrier for capture equal to 0.28 eV results in true distance of the level from the bottom of conduction band as 0.06 eV. In Refs. [8, 9] the level of energy 0.25 eV with thermal energy barrier for capture equal to 0.11 eV was found in gallium doped $\mathrm{Cd_{0.97}Mn_{0.03}Te}$. These data are close to the data obtained by us for the level $E2$.

References

[1] D.V. Lang, *J. Appl. Phys.* **45**, 3023 (1974).

[2] J. Szatkowski, E. Płaczek-Popko, K. Sierański, O.P. Hansen, *Mater. Sci. Forum* **258-263**, 1653 (1997).

[3] J. Frenkel, *Phys. Rev.* **54**, 647 (1938).

[4] C.H. Henry, D.V. Lang, *Phys. Rev. B* **15**, 989 (1977).

[5] E.F. Schubert, *Doping in III–V Semiconductors*, Cambridge University Press, AT&T, 1993, p.71.

[6] G.M. Khattak, C.G. Scott, *J. Phys., Condens. Matter* **3**, 8619 (1991).

[7] K. Khachaturyan, M. Kamińska, E.R. Weber, P. Becla, R.A. Street, *Phys. Rev. B* **40**, 6304 (1989).

[8] T. Wojtowicz, G. Karczewski, N.G. Semaltianos, S. Koleśnik, I. Miotkowski, M. Dobrowolska, J.K. Furdyna, *Mater. Sci. Forum* **143-147**, 1203 (1994).

[9] N.G. Semaltianos, G. Karczewski, B. Hu, T. Wojtowicz, J.K. Furdyna, *Phys. Rev. B* **51**, 17499 (1995).