Non-Exponential Photoionization of the DX Centers in Gallium Doped CdTe and $Cd_{0.99}Mn_{0.01}Te$

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The low temperature non-exponential transients of photoconductivity build-up in gallium doped $Cd_{0.99}Mn_{0.01}Te$ and CdTe alloys possessing DX centers were studied. It was found that the two-exponential model commonly used to explain the persistent photoconductivity growth in semiconductors with DX centers describes properly solely the photokinetics obtained for CdTe:Ga. In the case of $Cd_{0.99}Mn_{0.01}Te$:Ga the stretched-exponential approach is more appropriate, for it explains the short-time power-law exhibited by the experimental data.

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1. Introduction

Persistent photoconductivity effect (PPC) observed in CdTe and CdTe based $Cd_{1-x}Mn_xTe$ semiconducting alloys are attributed to the presence of metastable defects, DX centers, related to gallium (Ga) dopants present in these materials. It has been widely accepted that DX centers are formed when Ga dopants undergo a large lattice relaxation (LLR) and convert from their substitutional position (shallow state) to the broken bond configuration (ground, deep state) [1]. This transition will be completed solely if enough amount of energy, called the barrier for capture, is supplied to the system. At low temperatures usually the DX centers are in their ground state. Once photoionized, the DX centers make transition into the shallow states. The barrier prevents electrons from recapture at the ground state. As a consequence, the electrons remain in the shallow states resulting in the observed PPC.

Usually in the materials with DX centers, it is assumed that the ground state is occupied by two electrons. The photoionization of such a state proceeds in two steps resulting in the non-exponential kinetics of photoconductivity growth [2–8]. In consequence, the kinetics are modelled with formula

$$\Phi_{2\exp}(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} \tag{1}$$

with one of the exponentially decaying term assigned to the ionization of the two-electron ground state of the DX center to an intermediate one-electron state whereas the other one — to the photoionization of an electron from this state into the conduction band. Time constants τ_1, τ_2 are related to the amplitudes A_1, A_2 by the equation [9, 10]:

$$A_1/A_2 = 1/(1 - 2\tau_2/\tau_1). \tag{2}$$

It will be discussed in the paper that the double-exponential model describes fairly well the photoconductivity growth kinetics obtained for CdTe:Ga. In the case of the phototransient responses measured for $Cd_{0.99}Mn_{0.01}$Te:Ga the stretched-exponential Kohlrausch–Williams–Watts function

$$\Phi_{KWW}(t) = e^{-(t/\tau)^\alpha}, \qquad 0 < \alpha < 1 \tag{3}$$

is more appropriate, for the experimental data exhibit the short-time power-law dependence completely recovered solely by this function [11]. It was discussed in [11–14] that the stretched-exponential function may be derived assuming the stochastic nature of the investigated material and its local random characteristic.

2. Experimental details

Photoconductivity measurements were performed on the samples of gallium doped CdTe and $Cd_{0.99}Mn_{0.01}$Te crystals processed by the Bridgman method. The wafers were annealed in cadmium vapors, mechanically polished and etched in 2% Br_2 in methanol solution. The room temperature, net donor concentration was found to be on the order of 10^{17} cm^{-3} in the CdTe:Ga and on the order of 10^{15} cm^{-3} in the $Cd_{0.99}Mn_{0.01}$Te:Ga samples.

Ohmic contacts were produced by soldering indium onto the fresh frontside surface. The four-point probe method was applied. Keithley constant current source was used and the voltage drop across the sample measured at constant current equal to 10 μA. All photoconductivity transients were recorded at 77 K after exposing the samples to monochromatic light of photon energy equal to 1.24 eV. Prior to each measurement, the investigated sample had to be warmed up to a temperature at which persistent photoeffect was suppressed. Subsequently, the sample was cooled down in darkness to the liquid nitrogen. Under illumination, the measurement was carried out until conductivity was saturated.

3. Results and discussion

A typical kinetics of photoconductivity growth and decay for the CdTe:Ga and $Cd_{0.99}Mn_{0.01}$Te:Ga samples at 77 K, is shown in Fig. 1. Higher conductivity persists after switching off the light for the energy barrier prevents recapture of electrons from the conduction band on the DX centers ground state. The effect is better visible for the $Cd_{0.99}Mn_{0.01}$Te samples. The significant drop in conductivity for CdTe samples is presumably due to a smaller barrier for capture for this material.

In Fig. 2 the growth rate $f(t)$ of the normalized relative conductivity $\Delta\sigma(t)$ given by a following formula:
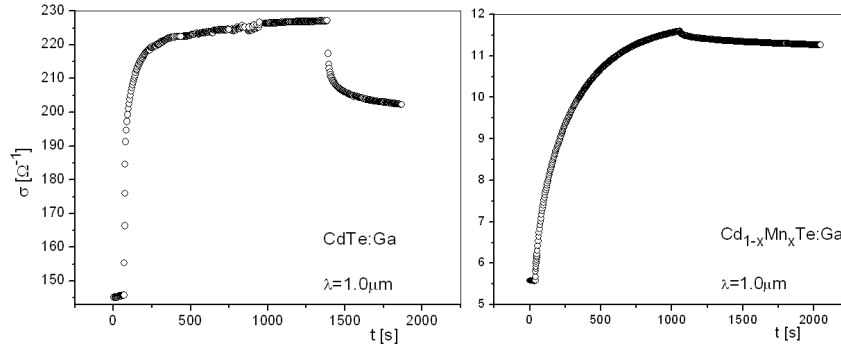
Fig. 1. Conductivity growth and decay for CdTe:Ga and $Cd_{0.99}Mn_{0.01}Te$:Ga measured at 77 K. The samples were illuminated with photons of energy equal to 1.24 eV of the same light intensity.
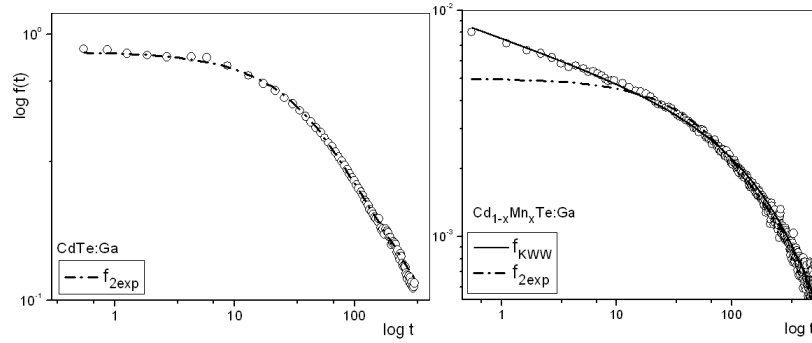

Fig. 2. The PPC build-up response data calculated according to Eq. (4). Dash-dotted and solid lines are the best fits to the experimental data of the two-exponential $\Phi_{2\,exp}$ and the stretched-exponential function Φ_{KWW}, respectively.

$$f(t) = -\frac{d\Delta\sigma(t)}{dt} = -\frac{d}{dt}\left[\frac{\sigma(t_{sat}) - \sigma(t)}{\sigma(t_{sat}) - \sigma(t_{on})}\right] \qquad (4)$$

is plotted in a double-logarithmic scale. $\sigma(t_{on})$ in the above relation represents the value of conductivity at the instant of turning the light on and $\sigma(t_{sat})$ is the saturated conductivity under illumination. The data correspond to those given in Fig. 1 and are fitted by means of the double-exponential Φ_{2exp} (dash-dotted line) and the stretched-exponential Φ_{KWW} (solid line) function, respectively. The double-exponential function recovers very well the experimental data solely for CdTe:Ga. In the case of $Cd_{0.99}Mn_{0.01}Te$:Ga the data exhibit the short-time power-law dependence, $f(t) \to t^{\alpha-1}$. This asymptotic property of the phototransients for $Cd_{0.99}Mn_{0.01}Te$:Ga was observed regardless of the photon flux intensity.

According to the stochastic approach discussed in [12–14] the short-time power-law property is a consequence of the statistical properties of the DX centers relaxation rates.

It can be proved that the power-law response observed for $Cd_{0.99}Mn_{0.01}Te:Ga$ is a consequence of a heavy-tailed distribution of the centers relaxation rates. The fact that PPC kinetics for CdTe:Ga can be properly described by means of the double-exponential function indicates that in this compound the dispersion of the DX centers relaxation rates is negligible. It means that in this case the distribution of relaxation rates is given by the δ Dirac function [12–14]. The obtained results indicate that various atoms configuration in the vicinity of the DX centers in the studied CdTe:Ga and $Cd_{0.99}Mn_{0.01}Te:Ga$ yield differences in the centers relaxation times distribution.

4. Conclusions

The photoconductivity growth kinetics in gallium doped CdTe and $Cd_{0.99}Mn_{0.01}Te$ crystals possessing DX centers were studied at 77 K. It was found that for both materials the phototransients are non-exponential. The double-exponential model commonly applied to describe the non-exponential PPC growth data is suitable solely for CdTe:Ga. In the case of $Cd_{0.99}Mn_{0.01}Te:Ga$ the stretched-exponential approach is more appropriate as it explains the short-time power-law exhibited by the experimental data. The stretched-exponential response of the studied $Cd_{0.99}Mn_{0.01}Te:Ga$ yields heavy-tailed distribution of the DX centers relaxation rates in this material. It can be assumed that different relaxation rate distribution in $Cd_{0.99}Mn_{0.01}Te:Ga$ as compared to CdTe:Ga is a consequence of various random configuration of atoms in the crystal lattice in the vicinity of the DX centers.

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