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$Cd_{1-x}Mn_xTe$ alloys

Stretched-exponential photoionization of the DX-related centers in indium- and gallium-doped Cd$_{1-x}$Mn$_x$Te alloys

J Trzmiel[1]**, E Placzek-Popko**[1]**, J M Wrobel**[2]**, K Weron**[1] **and P Becla**[3]

[1] Institute of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
[2] Department of Physics, University of Missouri-KC, Kansas City, MO 64110, USA
[3] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Abstract
The kinetics of photoconductivity build-up in indium- and gallium-doped Cd$_{1-x}$Mn$_x$Te mixed crystals was studied at 80 K. The photoconductivity transients are non-exponential, due to the presence of metastable DX centers, formed by both elements in these semiconductors. It has been shown for the first time that the kinetics of the observed photoconductivity transients can be properly described solely by the Kohlrausch–Williams–Watts (KWW) function. This statement has been verified by the careful analysis of the derivatives of the transients. It has been found that they obey short-time power-law behavior, regardless of the donor type and the content of manganese. This asymptotic property can be explained exclusively by the KWW approach. Such an approach results from a broad distribution of relaxation rates related to the DX centers. It is reasonable to assume that, in Cd$_{1-x}$Mn$_x$Te alloys, the broad distribution arises from the differences in local atomic configurations in the vicinity of the DX centers.

1. Introduction

Non-exponential build-up and decay of photoconductivity and photocapacitance in semiconductors with metastable defects, the so-called DX centers, have been reported a number of times. The decay kinetics of both photoconductivity and photocapacitance [1–12] in these materials may be well described by the stretched-exponential function, known also as the Kohlrausch–Williams–Watts function.

In most cases, the phototransients of the build-up in materials possessing the DX centers have usually been explained in terms of a double-exponential function resulting from the two-step photoionization model of DX centers. It is assumed that the photoionization of DX centers proceeds in two steps resulting in the non-exponential kinetics of photoconductivity growth [4, 11, 13–17]. As a consequence the kinetics is modeled with the formula

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

with one of the exponentially decaying terms assigned to the ionization of the two-electron ground state of the DX center to an intermediate one-electron state whereas the other one

is 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 [16, 17]

$$A_1/A_2 = 1/[1 - 2\tau_2/\tau_1].$$

In this paper, we present a study of photoconductivity build-up in indium- and gallium-doped Cd$_{1-x}$Mn$_x$Te alloys. Both anions form DX centers in these semiconductors and result in non-exponential kinetics of phototransients as well as in persistent photoconductivity of the material [16–23]. Analyses of the observed normalized transients suggest that the non-exponentiality may be explained by a double-exponential or a KWW function. However, the transient derivatives show a short-time linear dependence on time. This behavior cannot be explained within the double-exponential model but it is an immanent characteristic of the derivatives of stretched-exponential functions. Therefore the authors of this paper suggest that the KWW function is more suitable to describe the photoconductivity build-up in the studied semiconductors.

The fact that the KWW function is more suitable is not the only benefit of the analyses. Within the double-exponential approach it is assumed that the considered system
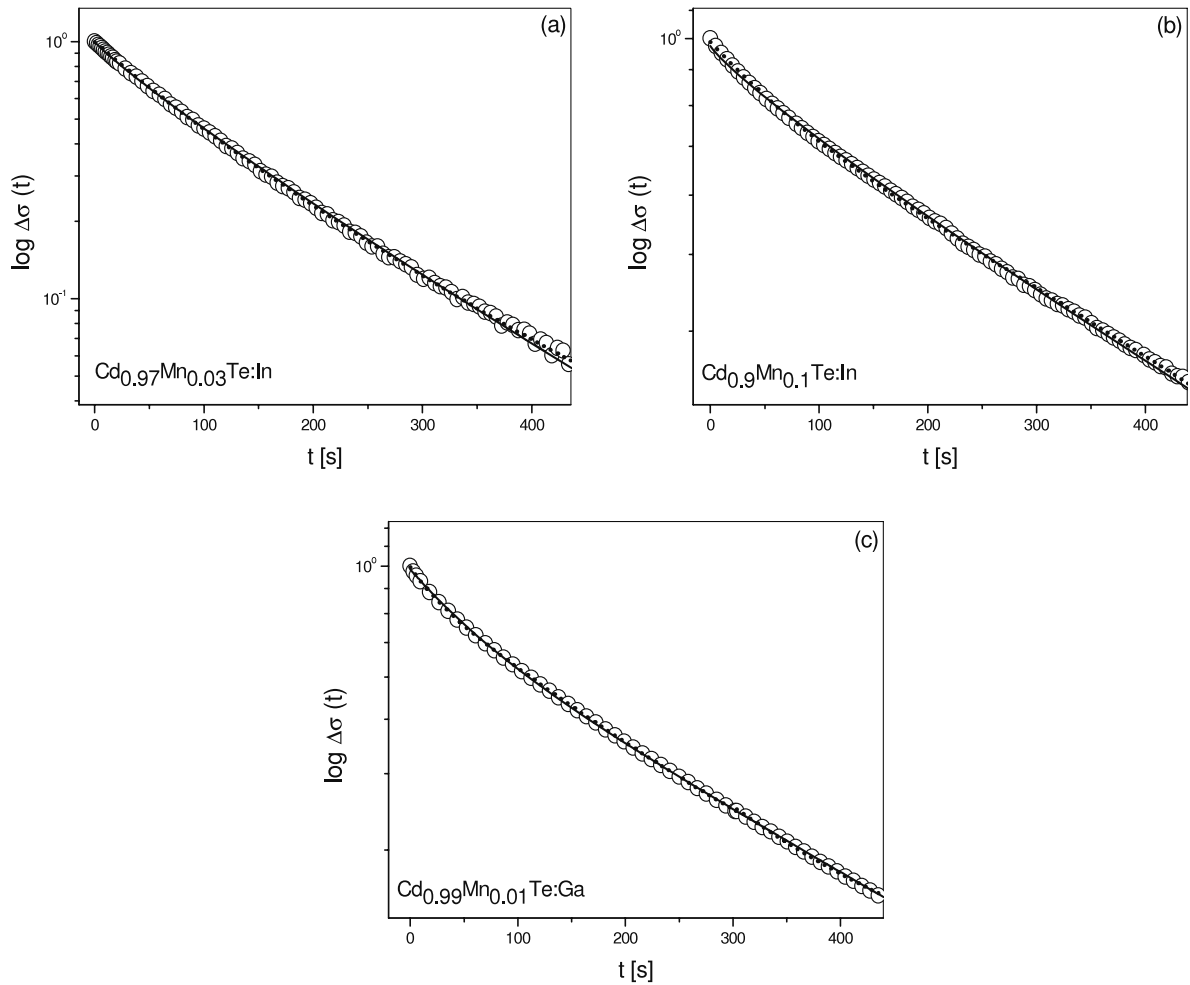
Figure 1. The transient of the normalized relative photoconductivity for indium- and gallium-doped $Cd_{1-x}Mn_x$Te at 77 K for 1.24 eV photon energy, observed under the same illumination conditions. The solid lines are the best fits of the stretched-exponential function to the measured data. Dotted lines correspond to the best fits of the double-exponential function.

is purely deterministic. All the relaxing entities possess the same properties and therefore the whole system can be represented by a single one. In the case of a complex system, here the $Cd_{1-x}Mn_x$Te alloy, the influence of randomness cannot be neglected. Therefore the considered medium should rather be represented by an effective object which cannot be assigned to any single relaxation contribution. It can be proven that the statistical properties of the individual relaxation rates determine the measured effective response of the system [24–26]. The KWW function is a consequence of a broad distribution of the relaxation rates.

2. Experimental details

Single crystals of $Cd_{0.93}Mn_{0.07}$Te:In, $Cd_{0.9}Mn_{0.1}$Te:In and $Cd_{0.99}Mn_{0.01}$Te:Ga, grown by the Bridgman method, were used for this study. Prior to the measurements, the sample wafers were annealed in cadmium vapors in order to reduce the number of cadmium vacancies. The wafers were mechanically polished and subsequently etched in 2% Br_2 in methanol solution. Capacitance–voltage measurements, performed with a 1 MHz capacitance bridge, yielded the room temperature,

net donor concentration of the order of 10^{15} cm^{-3} in the $Cd_{0.93}Mn_{0.07}$Te:In sample and of the order of 10^{16} cm^{-3} in both the $Cd_{0.9}Mn_{0.1}$Te:In and $Cd_{0.99}Mn_{0.01}$Te:Ga samples.

For the photoconductivity measurements, ohmic contacts were made by indium soldering of gold wires to fresh surfaces of the wafers. The four-point probe method was utilized. In the experiment, the measurement of potential difference across the sample was carried out at 10 μA current supplied from a Keithley constant-current source. A tungsten lamp served as a light source for illumination of the sample and a shutter with a 0.2 s time constant was used to turn the light on and off. The light passed through a monochromator and with the help of fiber optics the monochromatic beam was focused on the sample immersed in liquid nitrogen. A thermopile was used to measure the light intensity.

All photoconductivity transients were recorded at 77 K after exposing the samples to monochromatic light with photon energy equal to 1.24 eV. This energy is less than the bandgap in the investigated materials. The measurements were carried out at various light intensities. Prior to each measurement, the investigated sample had to be warmed up to a temperature at which persistent photoconductivity was
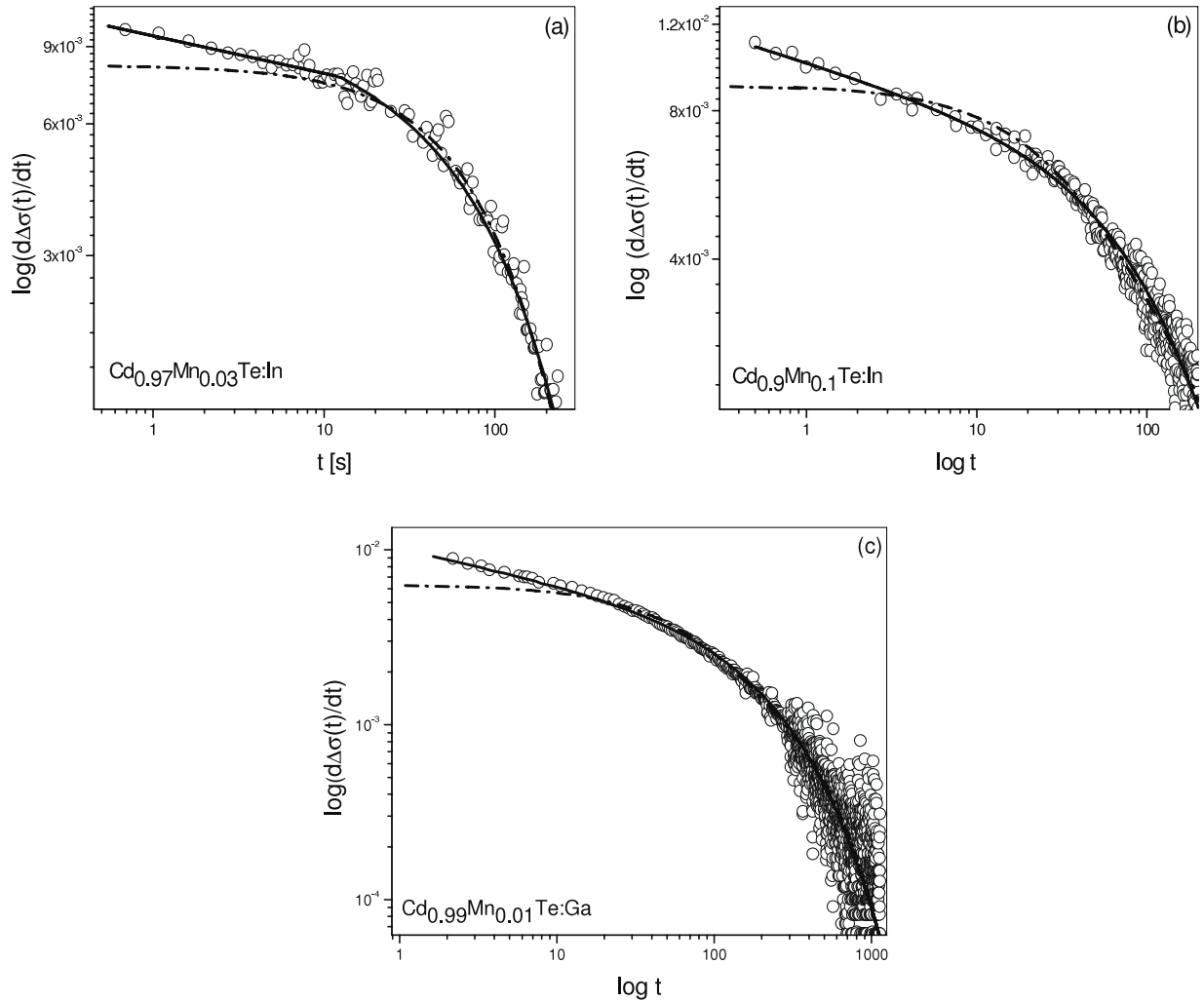
Figure 2. The relaxation response corresponding to the data presented in figure 1 with the best fit of the stretched-exponential function (solid line) and the double-exponential function (dashed lines) to the phototransients.

suppressed. Subsequently, the sample was cooled down in darkness to the liquid nitrogen temperature. Under illumination, the measurement was carried until conductivity was saturated. Typically the build-up of conductivity lasted several minutes.

3. Results and discussion

In figure 1, the kinetics of photoconductivity build-up at 77 K, obtained for the $Cd_{0.93}Mn_{0.07}Te$:In, $Cd_{0.9}Mn_{0.1}Te$:In and $Cd_{0.99}Mn_{0.01}Te$:Ga samples, is shown. In the figure, the normalized relative change $\Delta\sigma(t)$ in the conductivity due to illumination

$$\Delta\sigma(t) = \frac{\sigma(t_{sat}) - \sigma(t)}{\sigma(t_{sat}) - \sigma(t_{on})} \qquad (2)$$

is presented in a semi-logarithmic scale. Here $\sigma(t_{on})$ represents the value of conductivity at the instant of turning the light on and $\sigma(t_{sat})$ is the saturated conductivity under illumination. The observed transients of the normalized relative photoconductivity are non-exponential and may be described in terms of both the double-exponential function,

given by equation (1), and the stretched-exponential function:

$$\Phi_{KWW}(t) = e^{-\left(\frac{t}{\tau}\right)^{\alpha}}. \qquad (3)$$

In the above relation, $0 < \alpha < 1$ is the stretching exponent and τ is a time constant of the transient. The solid lines in figure 1 represent the best fits of the KWW functions to the experimental data. Dotted lines in figure 1 correspond to the best fits of the double-exponential functions. It can be noted that the fittings are indistinguishable.

It has been reported that, in materials which follow the stretched-exponential relaxation pattern, the relaxation response (defined as the growth rate of the normalized relative conductivity $f(t) = -\frac{d\Delta\sigma(t)}{dt}$) exhibits the power-law time dependence [4]. In order to ascertain if this is true in the current experiment, the relaxation response corresponding to the data presented in figure 1 was calculated. The result is shown in figure 2 in double-logarithmic scales. The analyses show that, for all samples, the kinetics of the photoconductivity build-up follows the short-time power law, that is $f(t) \rightarrow t^{\alpha-1}$ as $t \rightarrow 0$. Figure 2 also shows that the stretched-exponential response function (solid line) coincides with the

experimental points over the whole investigated time range while the double-exponential fit (dotted line) significantly deviates from the experimental points for short times. The double-exponential function, commonly used to describe the non-exponential relaxation phenomena [16, 17, 21–23, 27, 28], is not appropriate in the case of the considered kinetics. The power-law property of the transients observed in this experiment can be justified solely by means of the stretched-exponential approach.

The results presented in figure 2 have been observed for all the $Cd_{1-x}Mn_xTe$ samples under study regardless of the donor type, manganese content or light intensity. Hence the photoconductivity build-up observed in the studied gallium- and indium-doped $Cd_{1-x}Mn_xTe$ alloys is consistent with the stretched-exponential relaxation pattern. The physical processes responsible for such behavior are not clear but this type of response has been observed in many complex condensed-matter systems. It is generally accepted that various charge states of DX centers in $Cd_{1-x}Mn_xTe$ are associated with large lattice relaxation [16, 17, 22, 23]. Different local atomic configurations yield a broad distribution of the activation energies and result in a broad distribution of relaxation rates. Therefore, the stretched-exponential response of the systems investigated here could be justified by the differences in the local atomic configurations of DX centers. An additional argument to support this conclusion is that the preliminary observations of photoconductivity build-up in gallium-doped CdTe implied that the short-time power law for the normalized photoconductivity rate is not applicable [29]. It was possible to describe the CdTe data by a double-exponential function resulting from a two-step photoionization of DX centers.

4. Conclusions

The kinetics of low temperature photoconductivity build-up in $Cd_{0.97}Mn_{0.03}Te$:In, $Cd_{0.9}Mn_{0.1}Te$:In and $Cd_{0.99}Mn_{0.01}Te$:Ga semiconducting alloys were studied. In these materials, the dopants form metastable DX centers, resulting in persistent photoconductivity. In order to describe the photoconductivity build-up in materials with DX centers, usually the double-exponential function is used. This function originates from the assumption that photoionization of DX centers proceeds in two steps and each of the exponents is related to a single step. Analyses of the observed normalized transients suggest that the non-exponentiality may be explained not only by a double-exponential function but also by the stretched-exponential function. However, the transient derivatives show a short-time power-law property, regardless of the donor type, manganese content and light intensity. This behavior can be solely

explained within the stretched-exponential model. On the other hand, this relaxation pattern is the effect of a broad distribution of relaxation rates. Such a distribution may result from a different local atomic configuration of DX centers in the $Cd_{1-x}Mn_xTe$ alloy.

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