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Hopping Conductivity in Single Crystals $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$

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ABSTRACT

The growth processes of Tetragonal single crystals of solid solution $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$, space group $P_{42/nmc,}$ has been synthesized by Bridgman method. Conductivity and magnetoresistance of $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ were measured in the range 1.6K to 300K and in magnetic field up to 25 T. Crossover from Mott variable-range-hopping conductivity mechanism close to helium temperatures. In this work, we found the width of the coulomb D = 0.21 meV and a rigid gap δ = 0.026 meV in the density of localized states, concentration and localization radius of charge carriers.

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1. INTRODUCTION

$(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$, or briefly (CdZnMn)As, is a zinc blende compound belonging to the group A_2B_5 diluted magnetic semiconductors (DMS). According to the forecast in modern electronics firm solutions $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ are now a subject of a great number of investigations as a material. Their fields of application are receivers and sources of IR spectral range, thermal elements, Hall sensors and high-performance IR radiation sources [1]. At the same time, it is subject of scientific research for its properties. Increasing interest in Cd_3As_2 is mainly due to its solid solutions and is related to the fact that according to theoretical [2] and experimental [3-7] researches, cadmium arsenide is a Dirac semimetal with nontrivial physical properties, i.e. electrical stimulated superconductivity with non-Cuppers mechanism [5], the highest carrier mobility amongst bulk semiconductors and semimetal materials (9×10^6 $cm^2V^{-1}s^{-1}$ at 5 K) [6]. It is leading to construct the prototype metal- Cd_3As_2 - metal broadband ultrafast photo detector with potential detection range within far-infrared region [7]. Diluted magnetic semiconductors (DMS) group A_2B_5 have the lowest cation-cation distance in crystal structure among widely-spread DMS (0.29 nm for $(Zn_{1-x}Mn_x)_3As_2$ in contrast with 0.38 nm among other DMS). That kind of structural features leads to sp-d (sp-f) exchange interaction between the band carriers and localized magnetic moments of atoms and d-d (f-f) between magnetic impurity atoms that are much stronger in A_2B_5 semiconductors than in others DMS [8]. In addition, the combination of topological properties and magnetic exchange interaction in DMS can stimulate the chiral anomaly phenomena. It has been stimulated our examination of electrical and transport properties of $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ single crystals. Especially, at low temperatures the manifestation of topological states can be clearly observed.

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2. EXPERIMENTAL

We obtained single crystal blocks $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ larger than $1cm^3$ by modifier Bridgeman method. The single-crystal blocks of the prepared $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ were characterized by scanning electron microscopy

(QUANTA 600) and energy dispersive X-ray spectroscopy (EDX). Through energy dispersive X-ray spectroscopy (EDX) the matching with $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ single crystal composition and the most reliable result for Cd was found.

X-ray diffraction analysis was performed using DRON-UM diffractometer (FeKα - radiation, λ = 1.93604 Å, θ - 2θ - method). Determination of Miller indexes and specification of basis unit cell parameters were carried out on the basis of crystal structure data α"- Cd_3As_2 (P42/nmc space group, a = b = 8.963 Å and c = 12.68 Å) with help of ICSD Database [9] and program for exploring manipulating crystal structures and calculating powder patterns Powder Cell (Figure 1).

The electrical and magnetotransport properties of $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ single crystals were investigated in th range 1.6 - 300 K using the standard six-point geometry in pulsed magnetic fields up to 25 T. The samples had high conductivity and linear current–voltage characteristics in the range of the measurements.

3. RESULTS AND DISCUSSIONS

Figure 2 shows the results of an experimental investigation of temperature dependence of the resistivity and magneto-resistance of single crystals of $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$.

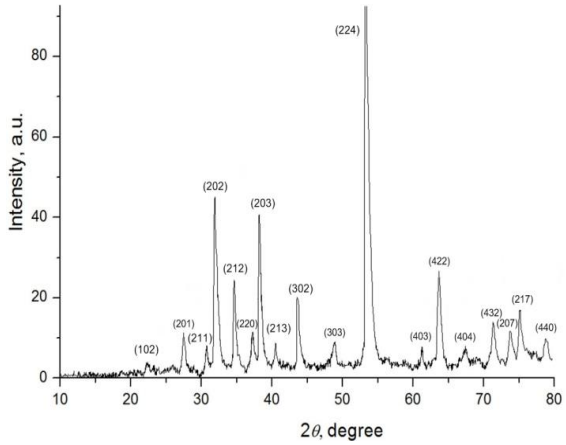

Figure 1. X-ray diffraction patterns of $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ with Millers indexes for $P4_2/nmc$ space group and lattice parameters $a = b = 8.61(4)$ Å and $c = 12.25(7)$ Å.

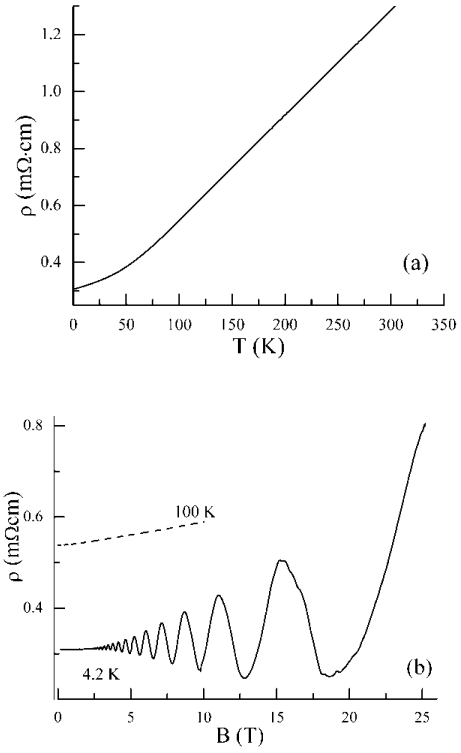

Figure 2. Temperature dependence of the resistivity (a) and magnetoresistance (b) (T = 4.2 K - 100 K) of single crystal $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$

Single crystal resistance of solid solutions of $(Cd_{0.6}Zn_{0.4})As_2$, decreases with increasing temperature in the range 1.6 to 300 K. Mn doping leads to increasing resistance, while temperature increasing in the range 1.6 to 300 K (Figure 2). In order to determine the conductivity mechanism of $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ in low temperature range, analysis was carried out that clarified temperature dependence of conduction [10]:

$$\rho(T) = \rho_0 \exp[E_A/(kT)] \quad (1)$$

where ρ_0 is pre-exponential factor, E_A activation energy, and k Boltzmann constant.

Hopping conductivity can be also described in accordance with the universal law [11]:

$$\rho(T) = DT^m \exp(T_0/T)^p \quad (2)$$

where D is constant and T_o jscharacteristic temperature that depend on the mechanism of hopping conductivity: p = 1 which corresponds to hopping conduction over the nearest neighbors, P = 1/4 is Motts conductivity with a variable hopping range , and P = 1/2 is Shklovsky-Efros hopping conductivity over the nearest neighbors.

The value T_0 in Equation (2) depending on the conductivity type may be written as:

$$T_{0M} = \frac{\beta_M}{kg(\mu)a^3}, \quad T_{0SE} = \frac{\beta_{SE}e^2}{\kappa ka} \tag{3}$$

Here g (μ) is density of localized states near the Fermi level μ, a radius of the charge carrier localization, κ dielectric constant, and β_M= 21, β_{SE}= 2.8 [11].

Motts conduction with a variable hopping range occurs when the density of localized states near the Fermi level is finite and constant [12]. The presence of the Coulomb gap leads to Shklovsky - Efros hopping conduction over the nearest neighbors [11]. comprising a smooth parabolic Coulomb gap Δ and a rigid gap δ can be equal to four different values: I) $g(\varepsilon) = 0$ for $\mu - \delta < \varepsilon < \mu + \delta$; II) $g(\varepsilon) = \alpha(\kappa^3/e^6)(\varepsilon - \mu + \delta)^2$ for $\mu - \Delta < \varepsilon < \mu - \delta$; III) $g(\varepsilon) = \alpha(\kappa^3/e^6)(\varepsilon - \mu - \delta)^2$ for $\mu + \delta < \varepsilon < \mu + \Delta$; IV) $g(\varepsilon) = g_0$ for $\varepsilon < \mu - \Delta$ and $\varepsilon > \mu + \Delta$, where g_0 – the value of the density of localized states out of gap, $\alpha = 3/\pi$. The function $g(\varepsilon)$ is symmetrical around the Fermi level, and at $\delta = 0$ coincides with the density of localized states, that contains only the Coulomb gap [11].

The mechanism of hopping conduction is characterized by the value of the parameter p in Equation (2), but there is one more very important temperature dependent multiplier, set by degree of dependence on m. Therefore, it is necessary to simultaneously determine the two independent parameters m and p.

Taking into account that the local activation energy, $E_a \equiv d\ln\rho / d(kT)^{-1}$ [11], Equation (2) can be rewritten as $\ln[E_a/(kT) + m] = \ln p + p\ln T_0 p + \ln(1/T)$. It can be seen that the left side of the equation is a linear function of ln(1/T) for a given value of m, and the value of parameter p can be determined from the slope of the graph $\ln[E_a/(kT) + m]$ from ln(1/T) (Figure 3a).

The analysis of the type of hopping conduction can be carried out as follows:

Assuming m = 1/4 in Equation (4) the value $p \approx 1/4$ can be obtained. It is typical for Motts conduction with a variable hopping range.

Figure 3b shows There is plot for the dependence $\ln(\rho/T^{1/4})$ on $T^{-1/4}$ for the sample $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$. In accordance with Equation (2), this also allows to make an assumption about the variable hopping range conduction. The values D and T_{0M} can be found from linear segments of Figure 3a; they are presented in Table 1.

TABLE 1. Hopping conductivity parameters of $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$

ρ_0 (Ohm·cm)	E_a (meV)	D (Ohm·cm·K–1/2)	T_0 (K)
0.0123	0.325	0.0026	2616.5

E_A activation energy can be determined from the linear segment of the plot ln ρ from T^{-1} in Equation (1) at temperatures ~ 4,5 K, at condition that coefficient ρ_0 weakly depend on T [8]. The values ρ_0 and E_A are presented in Table 1.

The data obtained at B = 0 and in weak fields, discussed above gives an opportunity to determine various microscopic parameters, allowing to check the findings on the mechanism of hopping conduction [13].

In the sample $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ the effect of the Coulomb gap is minimal, because Mott conduction type is implemented only when B = 0. That is the reason why density of localized states near acceptor band can be approximated by a rectangular shape, the width of the Coulomb gap in the density of localized states near the Fermi level $W \approx kT_{vM}^{3/4}T_0^{1/4}$ [11]. From the equation $g(\mu) \approx N_A/(2W)$ density of localized states for the given type of conduction ($g(\mu) \equiv g$), and from Equation (3) can be obtained a. The value of κ can be found from the equation $E_A = F(K)e^2\kappa^{-1}N_A^{1/3}$ [10], where $F(K)$ – some universal compensation function.

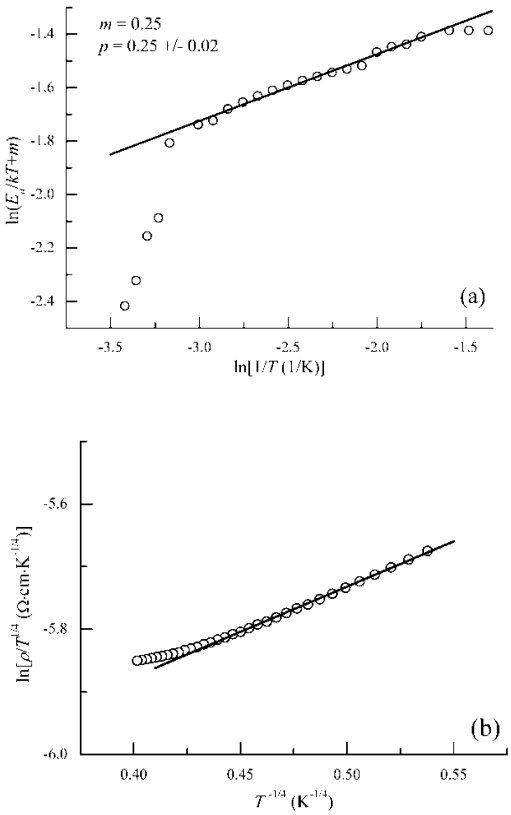

Figure 3. Dependence of ln(E_a/kT + m) on ln(1/T) for the sample $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ (a), and a linear segment that corresponds with Motts conduction with a variable hopping range (b)

Then, for the expression $\Delta \approx \frac{k}{2}\sqrt{T_{VSE}T_{0SE}}$, $g_0 = \frac{3\kappa^3(\Delta-\delta)^2}{\pi e^6}$, $g(\mu) = \frac{N_A}{2k(T_{VM}^3 T_{0M})^{1/4}}$, the values Δ and δ can be found. The calculated values Δ, δ, κ, a, W and g for the sample are shown in Table 2.

$$E_A = F(K)e^2\kappa^{-1}N_A^{1/3} \quad (8)$$

where $F(K)$ is some universal compensation function ($F(K) = 0.43$) [10].
The relationship between Δ and W values corresponds with the relevant mechanism of conduction at $B = 0$. The relation $\Delta/W \sim 0, 1$ is favorable for the Motts conduction with a variable hopping range.

TABLE 2. Parameters of the acceptors state in $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$

N_A (10^{16} cm^{-3})	a (Å)	κ	Δ (meV)	W (meV)	g (10^{16} cm^{-3} meV^{-1})	δ (meV)
144.0	72	215	0.21	1.83	39.34	0.026

4. CONCLUSION

In summary, it has been shown that the single crystals $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$, obtained with modified Bridgeman method belonged to the tetragonal system, space group $P_{42/nmc}$, $a = b = 8.61(4)$ Å, $c = 12.25(7)$ Å. The temperature dependence of the electrical conductivity for the sample $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ in temperature range 1.6 – 300 K and magnetoresistance in magnetic fields up to 25 T. When, B=0 and T is in the range 4.5–20 K, it is dominating hopping mechanism of charge transfer with variable range conductivity, in contrast to the solid solutions $(Cd_{0.6}Zn_{0.4})_3As_2$, demonstrating in the same temperature range Shklovsky-Efros hopping conductivity with a variable range mechanism [9]. From the analysis of temperature dependence of resistance, the values of microscopic parameters were found: the width of Coulomb gap Δ = 0.21 meV, rigid gap δ = 0.026 meV, the width of the localized states of the zone W=1.83 meV, localization radius of charge carriers a = 72 (Å) which is consistent with literature data and confirms our conclusion about the type of hopping conduction.

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چکیده

فرایندهای رشد تک‌بلور تتراگونگال محلول جامد فرایند تولید تک‌بلور $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ با گروه فضایی P_{42}/nmc به روش Bridgman انجام شد. هدایت الکتریکی و مقاومت مغناطیسی $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ در محدوده دمای ۱٫۶ تا ۳۰۰ K و در میدان مغناطیسی تا ۲۵ T اندازه گیری شد. انتقال از مکانیزم هدایت متغیر دامنه Mott نزدیک به دمای هلیوم در این کار بررسی شد. عرض کولمب $D = 0.21$ meV و شکاف سفتی $\delta = 0.026$ meV در تراکم حالت‌های موضعی، غلظت و شعاع موضعی حامل‌های بار به دست آمد.

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