



Hopping Conductivity in Single Crystals $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$

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ABSTRACT

The growth processes of Tetragonal single crystals of solid solution $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$, space group $P_{42/mmc}$, has been synthesized by Bridgman method. Conductivity and magnetoresistance of $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$ 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 $\delta = 0.026$ meV in the density of localized states, concentration and localization radius of charge carriers.

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1. INTRODUCTION

$(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$, or briefly $(\text{CdZnMn})\text{As}$, 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 $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$ 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 ($9 \times 10^6 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ 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 $(\text{Zn}_{1-x}\text{Mn}_x)_3\text{As}_2$ 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 $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$ 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 ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$ larger than 1cm^3 by modifier Bridgeman method. The single-crystal blocks of the prepared ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$ 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 ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$ single crystal composition and the most reliable result for Cd was found.

X-ray diffraction analysis was performed using DRON-UM diffractometer ($\text{FeK}\alpha$ - radiation, $\lambda = 1.93604 \text{ \AA}$, $\theta - 2\theta$ - 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 ($P4_2/nmc$ space group, $a = b = 8.963 \text{ \AA}$ and $c = 12.68 \text{ \AA}$) 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 ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$ single crystals were investigated in the 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 ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$.

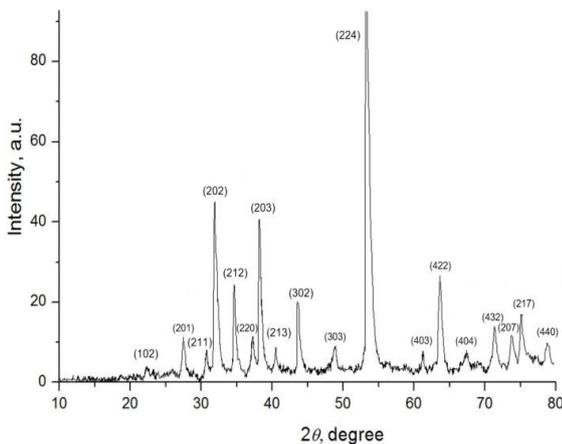


Figure 1. X-ray diffraction patterns of ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$ with Miller indexes for $P4_2/nmc$ space group and lattice parameters $a = b = 8.61(4) \text{ \AA}$ and $c = 12.25(7) \text{ \AA}$.

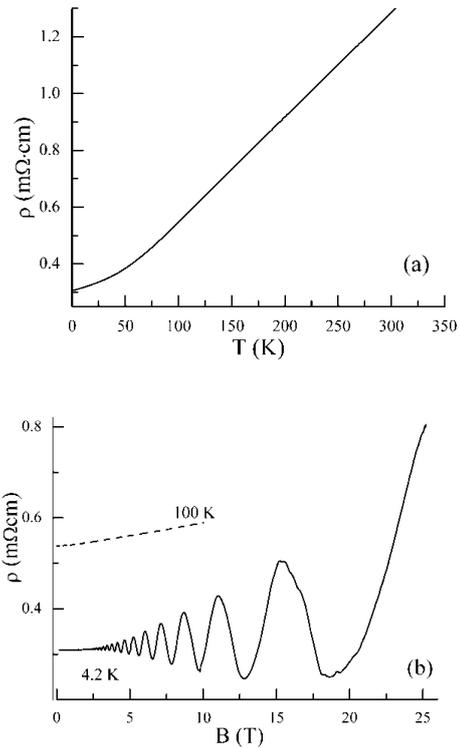


Figure 2. Temperature dependence of the resistivity (a) and magnetoresistance (b) ($T = 4.2 \text{ K} - 100 \text{ K}$) of single crystal ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$

Single crystal resistance of solid solutions of ($\text{Cd}_{0.6}\text{Zn}_{0.4}$) 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 ($\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08}$) $_3\text{As}_2$ 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_0 is characteristic temperature that depend on the mechanism of hopping conductivity: $p = 1$ which corresponds to hopping conduction over the nearest neighbors, $P = 1/4$ is Mott's 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:

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

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

Mott's 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 $\ln[E_a/(kT) + m] = \ln p + p \ln T_0 + \ln(1/T)$. 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 Mott's 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 $\ln \rho$ from T^{-1} in Equation (1) at temperatures $\sim 4,5$ 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.

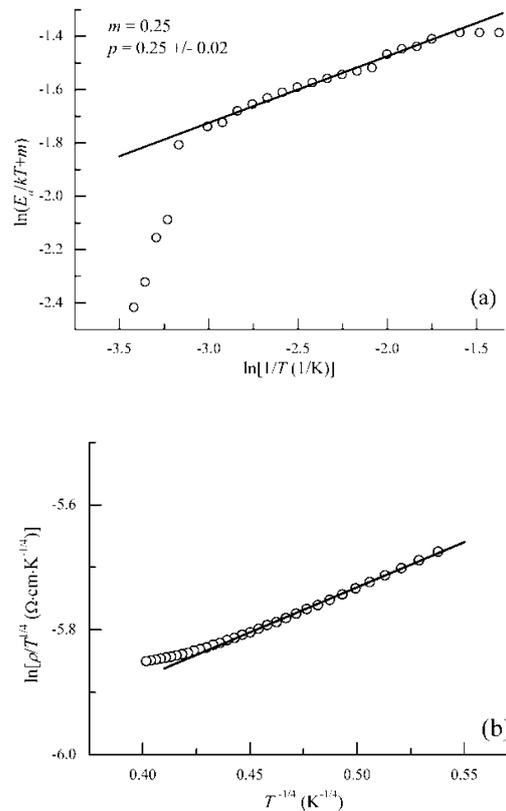


Figure 3. Dependence of $\ln(E_a/kT + m)$ on $\ln(1/T)$ for the sample $(Cd_{0.6}Zn_{0.32}Mn_{0.08})_3As_2$ (a), and a linear segment that corresponds with Mott's conduction with a variable hopping range (b)

Then, for the expression $\Delta \approx \frac{k}{2} \sqrt{T_{VSE} T_{0SE}}$, $g_0 = \frac{3\kappa^3(\Delta - \delta)^2}{\pi e^6}$, $g(\mu) = \frac{N_A}{2k(T_{VM}^3 T_{OM})^{1/4}}$, 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 Mott's conduction with a variable hopping range.

TABLE 2. Parameters of the acceptors state in $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$

N_A (10^{16} cm^{-3})	a (\AA)	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 $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$, obtained with modified Bridgeman method belonged to the tetragonal system, space group $P_{42/nmc}$, $a = b = 8.61(4) \text{ \AA}$, $c = 12.25(7) \text{ \AA}$. The temperature dependence of the electrical conductivity for the sample $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$ 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 $(\text{Cd}_{0.6}\text{Zn}_{0.4})_3\text{As}_2$, 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 $\Delta = 0.21 \text{ meV}$, rigid gap $\delta = 0.026 \text{ meV}$, the width of the localized states of the zone $W = 1.83 \text{ meV}$, localization radius of charge carriers $a = 72 \text{ \AA}$ which is consistent with literature data and confirms our conclusion about the type of hopping conduction.

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فرایندهای رشد تک‌بلور تتراگونگال محلول جامد فرایند تولید تک‌بلور $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$ با گروه فضایی P_{42}/nmc به روش Bridgman انجام شد. هدایت الکتریکی و مقاومت مغناطیسی $(\text{Cd}_{0.6}\text{Zn}_{0.32}\text{Mn}_{0.08})_3\text{As}_2$ در محدوده دمایی ۱٫۶ K تا ۳۰۰ K و در میدان مغناطیسی تا ۲۵ T اندازه‌گیری شد. انتقال از مکانیزم هدایت متغیر دامنه Mott نزدیک به دمایی هلیوم در این کار بررسی شد. عرض کولمب $D = 0.21 \text{ meV}$ و شکاف سفتی $\delta = 0.026 \text{ meV}$ در تراکم حالت‌های موضعی، غلظت و شعاع موضعی حامل‌های بار به دست آمد.

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