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PAPER

Transport evidence of mass-less Dirac fermions in $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ (x + y = 0.4)

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Abstract

Charge carriers parameters on a 2D-layer surface for $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ ($y = 0.08$) (the concentration $n_{2D} = 1.9 \times 10^{12}$ cm^{-2}, the effective value of the 2D-layer $d_{2D} = n_{2D}/n_{3D} = 14.5$ nm, the wave vector $k_F = 0.1$ nm^{-1}, the charge carriers relaxation time due to dispersion $\tau_D = 1.8 \times 10^{-13}$ s, the velocity of charge carriers on Fermi surface $v_F = \hbar k_F/m_c = 2.6^5 \times 10^5$ m s^{-1}, the mean free path $l_F = v_F \tau_D = 47.7$ nm) were determined. It was found that the dependence of the cyclotron mass $m_c(0)/m_0$ on Fermi wave vector k_F for $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ ($y = 0.08$) is in compliance with a theoretical linear dependence, that describes mass-less Dirac fermions.

1. Introduction

Among topological Dirac and Weyl semimetal (TDSs and TWSs) materials Cd_3As_2 has been treated as ideal because of its ultrahigh mobility and chemical stability in air. It allows considering Cd_3As_2 as a promising candidate for finding new topological phases [1–4]. The existence of nontrivial topological characteristics of 3D and 2D electronic states are of wide interest [5–7].

Earlier we discussed the results of studying Shubnikov-de Haas (SdH) oscillations in $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ (CZMA) compound ($x + y = 0.4$) [8]. SdH effect was investigated in a temperature range $T = 4.2 \div 300$ K and in a transverse magnetic field $B = 0 \div 25$ T. The values of the cyclotron mass m_c, the effective g-factor g^* and Dingle temperature T_D were determined. For a sample with a composition $y = 0.04$, $x = 0.36$ a strong dependence of the cyclotron mass on a magnetic field was observed. Our results of Fast Fourier Transform (FFT) analysis based on studying Shubnikov—de Haas oscillations indicate the presence of topological properties. For other composition ($y = 0.08$, $x = 0.32$) the magnitude of the phase shift was $\beta = 0.44$ being close to $\beta = 0.5$, which also suggests that single CZMA crystals with $y = 0.08$ demonstrate properties of Dirac semimetals and indicates the presence of Berry phase and 3D Dirac fermions in Cd_3As_2 single crystals [8, 9]. Magnetic field dependences of resistivity have been recently measured at various orientations between a magnetic field vector and electrical current, $\vec{J}$ directed along (100) crystal plane. Magnetoresistance dependences $\frac{\Delta\rho}{\rho}(B)$ demonstrate unusual features in $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ ($x + y = 0.4$; $y = 0.04$) single crystal at different orientation. An asymmetry and parity violation of magnetoresistance of magnetic diluted Dirac–Weyl semimetal $(Cd_{0.6}Zn_{0.36}Mn_{0.04})_3As_2$ was established [10].

The purpose of this investigation was to continue the study of transport properties of solid solutions diluted a magnetic semiconductor $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ ($x + y = 0.4$) containing Mn ($y = 0.04$ and 0.08).

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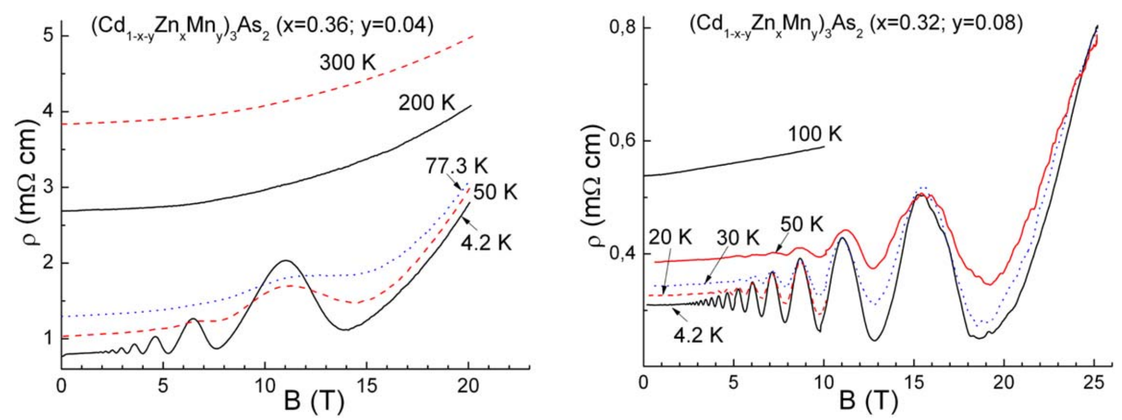

Figure 1. SdH oscillations observed at 4.2–50 K in CZMA ($x + y = 0.4$) at $y = 0.04$ (on the left) and $y = 0.08$ (on the right) [8].

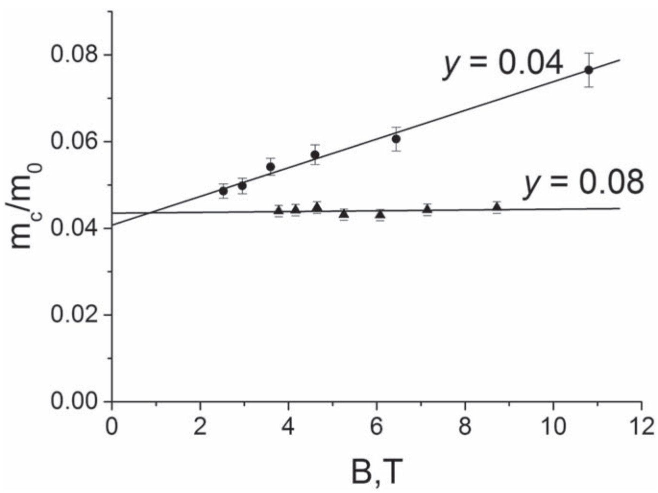

Figure 2. Field dependence of cyclotron mass for($Cd_{1-x-y}Zn_xMn_y)_3As_2$samples(x $+$ $y = 0.4$) at $y = 0.04$ and$y = 0.08$ [8].

2. Experimental details

A modified Bridgeman method was used to obtain single crystals of CZMA. All the samples had tetragonal crystal structure (s. g. $P4_2$/nmc). Well-resolved single-period SdH oscillations were observed well in the all investigated CZMA ($x + y = 0.4$) specimens at temperatures between $T = 4.2$ and 50 K (figure 1, see [8]).

It has been recently found that the cyclotron mass is independent on a magnetic field, B, for CZMA monocrystals ($y = 0.08$ and $y = 0.04$) (figure 2, [8]). And an anomalous dependence of the cyclotron mass on a magnetic field was observed that obeys a linear law:

$$m_c(B) = m_c(0) + \alpha B.$$

Our further studies of CZMA ($x + y = 0.4$) were prolonged on the basis of the results obtained in [8]. The parameters found from SdH oscillations and Hall Effect for CZMA samples ($x + y = 0.4; y = 0.04, y = 0.08$) are presented in comparison with Cd_3As_2, table 1 [8, 11–13].

In table 1: n_R is Hall concentration of charge carriers; n_{SdH} is SdH carrier concentration; μ_H is Hall mobility; P_{SdH} is a period of the SdH oscillations; $m_C(0)$ and α are the values of the linear law $m_C(B) = m_C(0) + \alpha B$; $T_{D\mu}$ characterizes broadening of Landau levels due to scattering of electrons by lattice defects.

|Frequencies H_F for samples $x = 0.36; y = 0.04$ and $x = 0.32; y = 0.08$ obtained by simple Fast Fourier Transform (FFT) analysis of SdH oscillations are occurred to be equal (about 40 T) [8].

The concentration of charge carriers, n_{2D}, in 2D-layer CZMA ($y = 0.08$) can be found analyzing SdH oscillations with the help of Lifshitz-Onsager relation [14], where the frequency $H_F = 40$ T directly relates to the cross-sectional area of 2D Fermi surface: $n_{2D} = 2eH_F/h = 1.9 \times 10^{12}$ cm^{-2}. Comparing this value with the concentration of charge carriers in the space $n_{3D} = 1.3 \times 10^{18}$ cm^{-3} found from the transport measurements the effective value of 2D-layer $d_{2D} = n_{2D}/n_{3D} = 14.5$ nm can be calculated.

Table 1. Parameters found from SdH oscillations and Hall Effect for CZMA samples (x + y = 0.4; y = 0.04, y = 0.08) in comparison with Cd_3As_2.

Y	0.04	0.08	Cd_3As_2
n_R, cm^{-3}	$3.4 \cdot 10^{17}$	$1.3 \cdot 10^{18}$	—
n_R/n_{SdH}	0.97	1.04	1.2 [11]
$\mu_H \cdot 10^{-4}$, $cm^2V^{-1}s^{-1}$	2.28	1.53	2.9 [13]
P_{SdH}, T^{-1}	0.061	0.025	0.02 [13]
$m_C(0)/m_0$	0.0409	0.0435	0.043 [13]
$\alpha/m_0 \times 10^3$, 1/T	3.3	0	—
T_D, K	12.7	13.2	9.8 [12]
$T_{D\mu}$, K	4.4	6.4	—

Table 2. Effective 2D-mobility and Hall 3D-mobility in the CZMA samples (y = 0.04 and y = 0.08).

y	0.04	0.08
$\mu_{2D} \cdot 10^{-4}$, cm^2 V^{-1} s^{-1}	—	0.73
$\mu_H \cdot 10^{-4}$, cm^2 V^{-1} s^{-1}	2.28	1.53

The wave vector can be determined if the density of charge carriers is known, that can be expressed as: $n_{2D} = gk_F^2/4\pi$, where g—the factor of degeneration of Landau bands. In our spin-filtered densities case we apply degeneration factor as $g = 25$ [15]. As a result, it was found that for CZMA (y = 0.04) the wave vector is $k_F = 0.1\ nm^{-1}$.

According to Lifshitz-Kosevich theory [14] the temperature dependence of SdH oscillation amplitude can be expressed as:

$$\Delta R(H,\ T) \propto \frac{2\pi^2 k_B T/\Delta E_N(H)}{\sinh[2\pi^2 k_B T/\Delta E_N(H)]} \times \exp[-2\pi^2 k_B T_D/\Delta E_N(H)]$$

where T_D and ΔE_N are adjustable parameters, and H corresponds to a magnetic field at the minimum (maximum) of longitudinal magnetoresistance. The value ΔE_N is an energy gap between N and (N + 1) Landau band:

$$\Delta E_N = \frac{heH}{2\pi\ m_c},$$

where m_c—is an effective cyclotron mass. The parameter T_D is Dingle temperature

$$T_D = \frac{h}{2\pi^2 \tau_D k_B},$$

where τ_D—a is relaxation time for charge carriers due to diffraction, for samples y = 0.04 and y = 0.08 $\tau_D = 1.9 \times 10^{-13}$ s, $\tau_D = 1.8 \times 10$–13 s, respectively.

From the values k_F, m_c and τ_D calculated for the samples $y = 0.04$ the velocity on Fermi surface $v_F = \hbar k_F/m_c = 2.65 \times 10^5\ m\ s^{-1}$, the mean free path $l_F = v_F \tau_D = 47.7$ nm were calculated.

In the table 2 effective 2D-mobility and Hall 3D-mobility are presented.

A linear dispersion law is an important feature of quantum transport (figure 3). This kind of dependence was also observed for Dirac fermions in graphene [16, 17]. The dispersion law for the carriers (electrons): $E = \hbar v_F k$, where v_F—Fermi velocity, k—a wave vector. The relation with effective mass:

$$m_c = E/(v_F)^2 = \hbar k/v_F.$$

From the data in figure 3 it can be seen that the values obtained experimentally [11, 18, 19] and the values obtained for CZMA (y = 0.04) (marked with symbols) are in a good accordance with the theoretical linear dependence, that describes mass-less Dirac fermions (the continuous line).

In agreement with [8] rising Mn concentration leads to changes in transport properties of diluted magnetic semiconductor $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ (x + y = 0.4). The results of SdH oscillation investigations in y = 0.04 samples showed the absence of a phase shift β and evidence of Berry phase. Thus, $(Cd_{0.6}Zn_{0.36}Mn_{0.04})_3As_2$

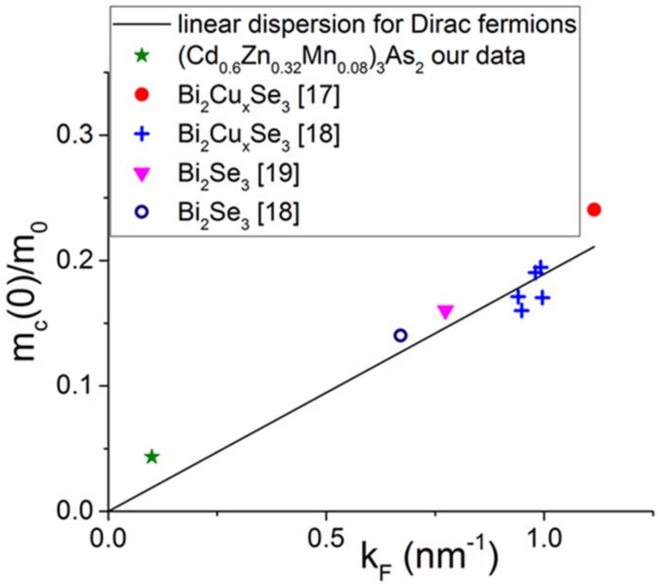

Figure 3. The dependence of the reduced cyclotron mass $m_c(0)/m_0$ on Fermi wave vector k_F, obtained from transport experiment with mono crystals Bi_2Se_3 with different doping levels [11, 18, 19] and completed with our result for CZMA (y = 0.04).

samples are not topological insulators but they demonstrate an anomalous dependence of charge carriers' cyclotron mass on a magnetic field.

Thus, we have shown the presence of a relation between manganese concentration and topological properties in CZMA diluted magnetic semiconductor and the presence of mass-less Dirac fermions in $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ $(x + y = 0.4)$.

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