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Transport evidence of mass-less Dirac fermions in 
$\text{(Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2 \ (x + y = 0.4)$

V S Zakhalinikii, T B Nikulicheva, E A Pilyuk, E Lähderanta, M A Shakhov, O N Ivanov, E P Kochura, A V Kochura and B A Aronzon

1 Belgorod National Research University, 85 Pobedy St, Belgorod, 308015, Russia
2 Department of Mathematics and Physics, Lappeenranta University of Technology, PO Box 20, FIN-53852 Lappeenranta, Finland
3 Ioffe Institute, 26 Politekhnicheskaya, St Petersburg, 194021, Russia
4 Belgorod State Technological University Named After V.G. Shukhov, Belgorod 308012, Russia
5 SouthWest State University, Kurak 305040, Russia
6 P. N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow 119991, Russia

E-mail: zakhvalinskii@bsu.edu.ru

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Abstract

Charge carriers parameters on a 2D-layer surface for $(\text{Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2 \ (y = 0.08)$ (the concentration $n_{2D} = 1.9 \times 10^{12} \ \text{cm}^{-2}$, the effective value of the 2D-layer $d_{2D} = n_{2D}/\tau_{2D} = 14.5 \ \text{nm}$, the wave vector $k_F = 0.1 \ \text{nm}^{-1}$, the charge carriers relaxation time due to dispersion $\tau_{D} = 1.8 \times 10^{-13} \ \text{s}$, the velocity of charge carriers on Fermi surface $v_F = h k_F/m_c = 2.65 \times 10^5 \ \text{m s}^{-1}$, the mean free path $l_F = v_F/\tau_D = 47.7 \ \text{nm}$) were determined. It was found that the dependence of the cyclotron mass $m_c/(0)/m_0$ on Fermi wave vector $k_F$ for $(\text{Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2 \ (y = 0.08)$ 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$_3$As$_2$ has been treated as ideal because of its ultrahigh mobility and chemical stability in air. It allows considering Cd$_3$As$_2$ 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 $(\text{Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2$ (CZMA) compound $(x + y = 0.4)$ [8]. SdH effect was investigated in a temperature range $T = 4.2 \div 300 \ \text{K}$ and in a transverse magnetic field $B = 0 \div 25 \ \text{T}$. 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$_3$As$_2$ single crystals [8, 9]. Magnetic field dependences of resistivity have been recently measured at various orientations between a magnetic field vector and electrical current, directed along (100) crystal plane. Magnetoresistance dependences $\Delta \rho/B$ demonstrate unusual features in $(\text{Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2 \ (x + y = 0.4; y = 0.04)$ single crystal at different orientation. An asymmetry and parity violation of magnetoresistance of magnetic diluted Dirac–Weyl semimetal $(\text{Cd}_{0.6}\text{Zn}_{0.36}\text{Mn}_{0.04})_3\text{As}_2$ was established [10].

The purpose of this investigation was to continue the study of transport properties of solid solutions diluted a magnetic semiconductor $(\text{Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2 \ (x + y = 0.4)$ containing Mn $(y = 0.04$ and 0.08).
2. Experimental details

A modified Bridgeman method was used to obtain single crystals of CZMA. All the samples had tetragonal crystal structure (s. g. P42/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 Cd3As2, table 1 [8, 11–13].

In table 1: \( n_R \) is Hall concentration of charge carriers; \( n_{SdH} \) is SdH carrier concentration; \( \mu_H \) is Hall mobility; \( P_{SdH} \) is a period of the SdH oscillations; \( m_c(0) \) and \( \alpha \) are the values of the linear law \( m_c(B) = m_c(0) + \alpha B; T_{Dp} \) 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: \( n_{2D} = 2eH_F / h = 1.9 \times 10^{12} \text{ cm}^{-2} \). Comparing this value with the concentration of charge carriers in the space \( n_{SD} = 1.3 \times 10^{18} \text{ cm}^{-3} \) found from the transport measurements the effective value of 2D-layer \( d_{2D} = n_{2D}/n_{SD} = 14.5 \text{ nm} \) can be calculated.
The wave vector can be determined if the density of charge carriers is known, that can be expressed as:

\[ n_{2D} = \frac{g k_F^2}{4\pi} \]

where \( g \)—the factor of degeneration of Landau bands. In our spin–filtered densities case we apply degeneration factor as \( g = 25 \). As a result, it was found that for CZMA \( (y = 0.04) \) the wave vector is \( k_F = 0.1 \text{ nm}^{-1} \).

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

\[ \Delta E_N = \frac{\hbar H}{2\pi m_c} \]

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

\[ T_D = \frac{\hbar}{2\pi^2 \tau_D k_B} \]

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

From the values \( k_F, m_c \) and \( T_D \) calculated for the samples \( y = 0.04 \) the velocity on Fermi surface \( v_F = \frac{\hbar k_F}{m_c} = 2.65 \times 10^5 \text{ m s}^{-1} \), the mean free path \( l_F = v_F \tau_D = 47.7 \text{ nm} \) 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 \( \text{Mn} \) concentration leads to changes in transport properties of diluted magnetic semiconductor \((\text{Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2 (x + y = 0.4) \). The results of SdH oscillation investigations in \( y = 0.04 \) samples showed the absence of a phase shift \( \beta \) and evidence of Berry phase. Thus, \((\text{Cd}_{0.6}\text{Zn}_{0.36}\text{Mn}_{0.04})_3\text{As}_2 \)

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**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 \( \text{Cd}_3\text{As}_2 \).

| \( \gamma \) | 0.04 | 0.08 | \( \text{Cd}_3\text{As}_2 \) |
|---|---|---|---|
| \( n_0, \text{cm}^{-2} \) | \( 3.4 \times 10^{17} \) | \( 1.3 \times 10^{18} \) | — |
| \( n_0/n_{\text{SdH}} \) | 0.97 | 1.04 | 1.20 \([11] \) |
| \( \mu_{\text{SdH}} \text{, cm}^2\text{V}^{-1}\text{s}^{-1} \) | 2.28 | 1.53 | 2.9 \([13] \) |
| \( P_{\text{SdH}} \text{, T}^{-1} \) | 0.061 | 0.025 | 0.020 \([13] \) |
| \( m_c(0)/m_0 \) | 0.0409 | 0.0435 | 0.043 \([13] \) |
| \( \alpha/m_0 \times 10^4, 1/T \) | 3.3 | 0 | — |
| \( T_0, \text{K} \) | 12.7 | 13.2 | 9.8 \([12] \) |
| \( T_{0p}, \text{K} \) | 4.4 | 6.4 | — |

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

| \( \gamma \) | 0.04 | 0.08 |
|---|---|---|
| \( \mu_{\text{2D}}, 10^{-4}, \text{cm}^2\text{V}^{-1}\text{s}^{-1} \) | — | 0.73 |
| \( \mu_{\text{H}}, 10^{-4}, \text{cm}^2\text{V}^{-1}\text{s}^{-1} \) | 2.28 | 1.53 |
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 $(\text{Cd}_{1-x-y}\text{Zn}_x\text{Mn}_y)_3\text{As}_2 (x + y = 0.4)$.

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ORCID iDs

V S Zakhvalinskii https://orcid.org/0000-0001-7055-8243
T B Nikulicheva https://orcid.org/0000-0001-6661-3959
O N Ivanov https://orcid.org/0000-0002-1803-5928

References

[1] Wang Z, Weng H, Wu Q, Dai X and Fang Z 2013 Phys. Rev. B 88 125427
[2] Borisenko S, Gibson Q, Evtushinsky D, Zabolotnyy V, Buchner B and Cava R J 2014 Phys. Rev. Lett. 113 027603
[3] Liu Z K et al 2014 Science 343 964
[4] Xu G, Weng H, Wang Z, Dai X and Fang Z 2011 Phys. Rev. Lett. 107 166806
[5] Armitage N P, Mele E J and Vishwanath A 2018 Rev. Mod. Phys. 90 015001
[6] Yan B and Felser C 2017 Annual Review of Condensed Matter Physics 8 337
[7] Wang S, Lin B-C, Wang A-Q, Yu D-P and Liao Z-M 2017 Advances in Physics: X 2 518
[8] Zakhvalinskii V S, Nikulicheva T, Lahderanta E, Shakhov M A, Nikitovskaya E and Taran S 2017 Journal of Physics Condensed Matter 29 455701
[9] He L P et al 2014 Phys. Rev. Lett. 113 246402
[10] Ivanov O, Zakhvalinskii V, Nikulicheva T, Yaprintsev M and Ivanichikhin S 2018 Phys. Status Solidi 12 1800386(6)
[11] Lawson B J, Hor Y S and Li L 2012 Phys. Rev. Lett. 109 226406
[12] Narayanan A et al 2015 PRL 114 117201
[13] Zhao Y et al 2015 Phys. Rev. X 5 031037(9)
[14] Shoenberg D 1984 Magnetic Oscillations in Metals (Cambridge: Cambridge Univ. Press)
[15] Lahou R, Lisunov K G, Shubnikov M L, Stamo V N and Zakhvalinskii V S 1996 Phys. Status Solidi (b) 198 135
[16] Zhang Y et al 2005 Nature (London) 438 201
[17] Novoselov K S et al 2005 Nature 438 197
[18] Lahoud E et al 2013 Phys. Rev. B 88 195107
[19] Lawson B J, Li G, Yu F, Asaba T, Tinsman C, Gao T, Wang W, Hor Y S and Li L 2014 Phys. Rev. B 90 195141