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Berry Phase in single crystals of the dilute magnetic semiconductor $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$

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Berry Phase in single crystals of the dilute magnetic semiconductor $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$

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Abstract. Investigations of transverse magnetoresistance have been performed on single crystals of diluted magnetic semiconductor $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ (CZMA). Based on analysis of the Shubnikov-de Haas (SdH) oscillations, observed in the temperature range $T = 4.2 \div 30$ K and at transverse magnetic field $B = 0 \div 11$ T, the phase shift, β, indicating the presence of the Berry phase was determined.

1. Introduction

The unusual properties of cadmium arsenide, such as the abnormally high mobility of charge carriers, have long attracted the attention of researchers [1]. An extensive research activity on Cd_3As_2 and its solid solutions started because of the appearance of theoretical studies [2], predicting the possibility of topological properties in Cd_3As_2, and then being confirmed by experiments using angle-resolved photoemission spectroscopy (ARPES) [3]. The existence of the Dirac semimetal phase in Cd_3As_2 was experimentally confirmed using ARPES [3-5]. The properties of 3D Dirac topological semimetals in Cd_3As_2 caused an increasing interest, including the study of transport properties and the band structure of this compound [6-10]. A number of works has been devoted to the location of the 3D Dirac cones in the Brillouin zone and to refining the band structure of Cd_3As_2 [11-13]. Of particular interest is the study of the evolution of the band structure and topological properties of ternary and quaternary solid solutions based on Cd_3As_2 [14].

For single crystals of solid solutions $(Cd_{1-x}Zn_x)_3As_2$, based on the study of SdH oscillations and temperature dependences of the transverse magnetoresistance, a phase transition from Dirac semimetal (DS) to semiconductor with increasing Zn concentration above $x = 0.38$ was experimentally observed. By changing the concentration of Zn, the behavior of the temperature dependence of the resistivity changed from a metal with compositions $x = 0$–0.31 to a semiconductor behavior with $x = 0.38$–0.58 [15]. As known from the work [16], the transverse magnetoresistance was studied on non-oriented single crystals of the semimagnetic quaternary solid solution system $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ ($x + y = 0.4$; $y = 0.04$ and 0.08). The effect of Mn content on the topological properties of CZMA was shown, based on analysis of SdH oscillations. In the CZMA sample with Mn concentration $y = 0.04$, a strong magnetic field dependence of the cyclotron effective mass was observed. Moreover, a phase shift close to $\beta = 0.5$ indicated the presence of the Berry phase and 3D Dirac fermions in the single crystal of CZMA with $y = 0.08$. However, an anomalous external magnetic field dependence of the cyclotron effective mass, $m_c(B) = m_c(0) + \alpha B$, was not observed. Other compositions of quaternary solid solutions of the diluted magnetic semiconductor $(Cd_{1-x-y}Zn_xMn_y)_3As_2$ also showed unusual properties. In studies of the SdH effect in single crystals of CZMA ($x + y = 0.3$), an anomalous external magnetic field dependence of the cyclotron effective mass of the charge carriers was observed for samples with a high Mn content [17, 18].

The purpose of this study was to investigate the topological properties of the diluted magnetic semiconductor $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$.

2. Experimental details

The modified Bridgeman method was used to obtain single of $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ (CZMA), grown from stoichiometric amounts of Cd_3As_2, Zn_3As_2 and Mn_3As_2 by slow cooling, 5 °C/h, of a melt at the presence of a temperature gradient near the melting point (840°C). The composition and homogeneity of the samples were analyzed by X-ray powder diffraction and energy-dispersive X-ray spectroscopy (EDX) methods. The X-ray experiment was carried out on a diffractometer DRON-UM (FeKα - radiation, λ = 1.93604 Å, Θ- 2Θ - method). All the investigated samples $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ demonstrated a tetragonal crystal structure (space group $P4_2/nmc$) (ICDO Card № 03-065-857) [19]. The electrodes were attached to a rectangular prism of size 1x1x5 mm^3 by soldering. Magnetoresistance measurements were made in a transverse magnetic field configuration at 0 ÷ 11 T applying six-probe method. For experiments the sample probe was inserted in a He exchange gas Dewar, where the temperature can be adjusted with an accuracy of 0.5%.

3. Results and discussion

Well-resolved single-period SdH oscillations are observed in all investigated CZMA specimens at temperatures between $4.2 \leq T \leq 30$ K. Figure 1 shows the SdH oscillations obtained at T = 4.2 K.

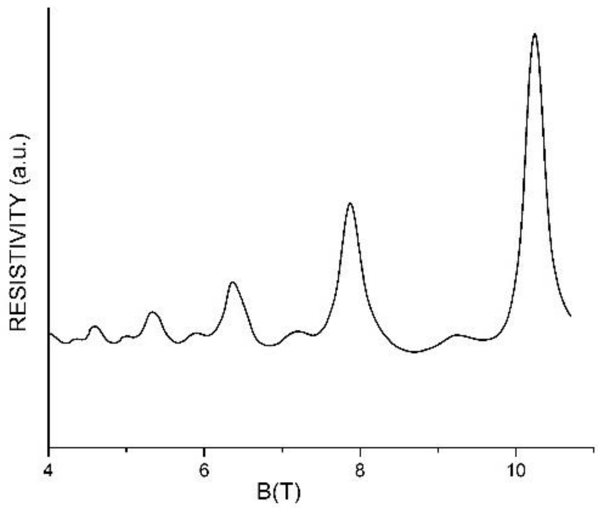

Figure 1. Oscillations of the transverse magnetoresistance obtained at T = 4.2 K for single crystals of $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$.

Clear linear dependence of the inverse magnetic field, $1/B_{max}$, of the maxima of the SdH oscillations on their quantum number was observed and the SdH period, P_{SdH}, did not depend on the magnetic field (Figure 2). Based on the above results of the SdH oscillations, a linear dependence of the Landau number that depends inversely on B was plotted. Fast Furrier analysis (FFA) of SdH oscillations are presented in Figure 3 for the CZMA. Well-defined peaks appear for frequencies F_1 = 26 T, and F_2 = 52 T. Note that the resolution of our FFA analysis is sufficient to calculate the number of periodic oscillations. The results of FFA analysis of the SdH oscillations in CZMA were presented by us for the first time since, in work [17], based on the study of the same series of samples in the mid-90s, the topological properties of Cd_3As_2 were not yet discovered and investigated.

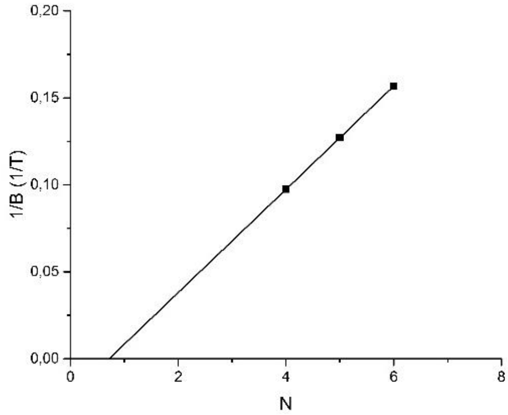

Figure 2. Landau level index plot *N*for single crystals of $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$.

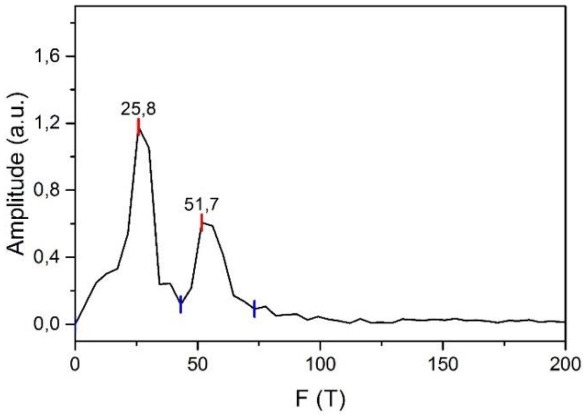

Figure 3. Results of FFT analysis of the SdH oscillations for $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$.

Around the Dirac point in momentum space, the wave function of an electron acquires a geometric Berry phase equal to π. In materials with the spin – orbit interaction and parabolic dispersion law, the Berry phase should be zero [20]. It is possible to experimentally evaluate the Berry phase from the analysis of the SdH oscillations. As follows from the work [6], the Berry phase was observed in any orientation of magnetic field and, therefore, it can be observed in the study of the oscillations of transverse magnetoresistance. The phase shift β for Dirac fermions is equal 0.5, but some deviations are possible too, such as $\beta \approx 0.45$ and 0.7 in topologic insulators $Bi_{2-x}Cu_xSe_3$ [21].

The Berry phase can be investigated in magnetic fields in which a semi-classical description of magnetic oscillations can be applied [3, 4]:

$$\rho \propto \cos\left[2\pi\left(\frac{B_F}{B}+\frac{1}{2}+\beta\right)\right],$$

where$B_F$is the SdH oscillation frequency, $\beta$is the Berry phase shift in the range $0 < \beta < 1$. A phase shift $\beta = 0$ (or equivalently, $\beta = 1$) corresponds a trivial case. The deviation from this value indicates a new physics with $\beta = 0.5$ that implies the existence of Dirac particles. The phase shift β for Dirac fermions is 0.5, but deviations are possible too, such as $\beta \approx 0.45$ or 0.7 for the topological isolator $Bi_{2-x}Cu_xSe_3$ [21]. Experimentally, this phase shift in the semi-classical mode can be obtained from the analysis of the SdH fan diagram, in which the sequence of the nth minimum$1/B_n$ in $\rho(B, T)$, is plotted against the Landau index N (Figure 4).

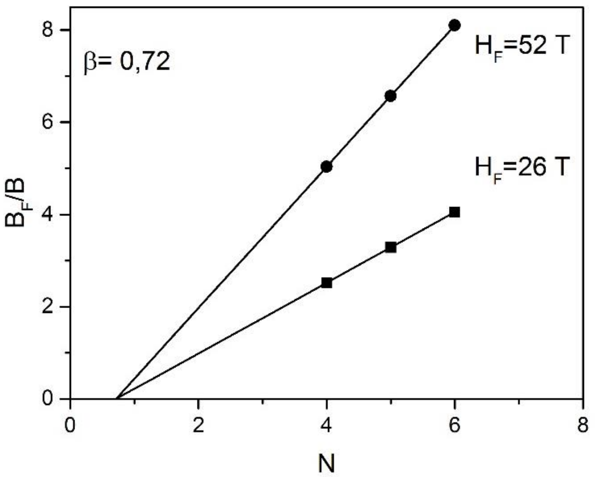

Figure 4. Landau index *N* plotted against $1/B$ for crystals of $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$.

The resulting β is close to 0.5 (Figure 4), suggesting the existence of Dirac fermions in single crystals of $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$. The existence of the Berry phase was not discussed in works [5, 6] devoted to $Cd_{1-x-y}Zn_xMn_y)_3As_2$ ($x + y = 0.3$), since the topological properties of Cd_3As_2 were not yet discovered. Finally, as mentioned above, according to the theory, the phase shift β for Dirac fermions should be equal to 0.5, however some deviations are possible.

The Berry phase can be determined by the so-called fan diagram, which is a function of Landau level index N against $1/B_{\max}$. Furthermore, different studies use either the minima or maxima of the SdH oscillations. The nonzero shift of the Berry phase observed in the SdH fan diagrams (Figures. 3, 4) is associated with the vanishing mass at the Dirac point. As shown below in Table 1, the values of cyclotron masses m_c for the single crystals determined in [17], are also close to those obtained in [16] at zero magnetic field, for CZMA ($x + y = 0.4$) with $y = 0.04$ and 0.08.In order to analyze the topological properties of CZMA solid solutions $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$, we partially used the results and experimental dependences of the SdH oscillations that we reported earlier in [17]. The parameters found from the SdH oscillations of $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ crystals [17] are given in Table 1.

Table 1. Parameters found from SdH oscillations single crystals of $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ [17].

$n_H\times10^{18}$ (cm^{-3})	$\mu_H\times10^4$ (cm^2 V^{-1} s^{-1})	$m_c(0)/m_0$	$\alpha/m_0\times10^3$ (1/T)	T_D (K)	$T_{D\mu}$(K)
1.0	3.5	0.032	–	24	3.6

Where n_H is the Hall concentration, μ_H is the Hall mobility, m_c is cyclotron effective mass, m_0 is the electron mass, T_D is the Dingle temperature, $m_c(0)$ and α are coefficients of the linear law $m_c(B) = m_c(0) + \alpha B$, $T_{D\mu}$determines the Landau level broadening due to electron scattering on lattice defects.

A study of solid solutions based on diluted magnetic semiconductor was carried out in this paper, and is focused on the detection of the topological properties. Fan diagrams were plotted for $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ based on the results of the fast Fourier transform (Figure 4). For $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$the phase shift β indicate the presence of the Berry phase.

4. Conclusion

In this paper we studied the topological properties in single crystals of diluted magnetic semiconductor $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ obtained by the Bridgman method. Thus, our results are based on the analysis and observation of the SdH effect in diluted magnetic semiconductors CZMA [17]. In the presence of a magnetic field, the analysis of the SdH oscillations revealed the existence of a nontrivial Berry phase. Our results of the study of quantum transfer in solid solutions based on 3D Cd_3As_2 complement the previous ARPES and STM experiments [22]. Having a unique electronic structure, unusually high mobility and a large linear magnetoresistance at room temperature, the semimetal 3D Dirac Cd_3As_2 and its solid solutions give rise to new possibilities for future applications in electronics.

The dependence of B_F/B_N on N for $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ shows a phase shift $\beta \approx 0.72$. A good interpretation of the results of the study of topological properties in solid solutions of CZMA based on the observation of oscillations of the transverse resistivity is complicated, since the simultaneous contribution of 2D and 3D components to the transport properties. The presence of a nonzero phase shift $\beta \neq 0$ indicates the presence of a Berry phase and confirms the presence of the topological properties in a $(Cd_{0.7}Zn_{0.28}Mn_{0.02})_3As_2$ single crystal.

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