Electron Energy Relaxation in $(Cd_{1-x}Zn_x)_3As_2$ Dirac Semimetals Studied by Terahertz Laser Pulses

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Abstract— **We performed a study of a range of $(Cd_{1-x}Zn_x)_3As_2$ mixed crystals undergoing a transition from the Dirac semimetal phase to trivial semiconductor at variation of the composition x. We show that for the Dirac semimetal phase, the photoelectromagnetic effect amplitude is defined by the number of incident radiation quanta, whereas for the trivial semiconductor phase, it depends on the power in a laser pulse irrespective of its wavelength. We assume that such behavior is attributed to formation of surface electron states with a spin texture in Dirac semimetals.**

I. INTRODUCTION

RECENTLY, a topological state of matter – a Dirac semimetal – has been first predicted theoretically and then observed experimentally through the ARPES measurements in Cd_3As_2 [1 – 3]. In a Dirac semimetal, the bulk conduction and valence bands are inverted and touch each other in two points of the Brillouin zone, the Dirac points. The dispersion relation is linear in the proximity of the Dirac points in all three dimensions of the momentum space. The question concerning formation of spin-polarized surface electron states in 3D Dirac semimetals remains open. According to [1, 3], the surface states of Cd_3As_2 do not possess any spin texture. However, the authors do not exclude a possibility that the spin-polarized surface states may be formed, but the sensitivity of the method used does not allow discriminating these states.

In this paper, we present an indication for formation of spin-polarized electron states with high mobility on the surface of the Dirac semimetal solid solutions $(Cd_{1-x}Zn_x)_3As_2$ with the inverted energy spectrum.

II. RESULTS

Our experimental approach is based on measurements of the photoelectromagnetic (PEM) effect induced by terahertz laser pulses. Previously, it has been demonstrated that in the range of $(Bi_{1-x}In_x)_2Se_3$ solid solutions which exhibit a transition from the topological insulator phase with the inverted electronic energy spectrum at low x to the trivial insulator with the direct spectrum at higher indium content, there exists a substantial difference in the radiation power dependence of the PEM effect amplitude for the two phases [4]. In the trivial insulator case, the PEM effect amplitude is defined by the incident radiation power irrespectively of its wavelength, whereas for the topological insulator phase, it depends on the number of incident radiation quanta in unit time. In this paper, we apply this approach to the solid solutions of Dirac semimetals $(Cd_{1-x}Zn_x)_3As_2$ undergoing an analogous transition from the inverted to the direct spectrum in the bulk at $x > 0.08$ [5].

The samples used were single crystals of $(Cd_{1-x}Zn_x)_3As_2$ grown from the vapor phase. Since the transition from the inverted electronic spectrum to the direct one occurs in $(Cd_{1-x}Zn_x)_3As_2$ at $x \approx 0.08$, we have selected three samples for a detail study. Two of them correspond to the inverted spectrum composition region $x < 0.08$, the third one has $x = 0.25$, and the spectrum is direct.

All samples studied were of the n-type. The free electron concentration measured using the Hall effect was on the order of 10^{17} cm^{-3} and did not change in the temperature range (4.2 – 300) K. The resistivity temperature dependence is typical for degenerate semiconductors: the resistivity drop with lowering temperature T from 300 K to 20 K is followed by a further saturation at $T < 20$ K. Since the free electron concentration does not change, this resistivity variation is completely determined by the mobility temperature dependence. The low temperature mobility absolute values are very high and exceed 10^5 $cm^2/V\cdot s$.

We have studied the PEM effect induced by the action of 100 ns – long pulses of an optically pumped NH_3 terahertz laser with the wavelengths of 90 and 148 μm. The magnetic field up to 3 T was applied to induce the PEM effect at the temperature $T = 4.2$ K. The experimental details can be found elsewhere [4, 6, 7].

The PEM effect manifests itself as a voltage drop across the sample in the direction normal to the magnetic field and to the incident radiation flux. The effect originates from the Lorentz force action to the diffusive electron flux. The voltage sign is defined only by the net charge flux direction.

The PEM effect was observed in all samples at both laser wavelengths used. Kinetics of the PEM effect signal repeats the time profile of a laser pulse (see insert in the Fig.1). The effect arises only in non-zero magnetic field, its amplitude is odd in magnetic field. The magnetic field dependence of the PEM effect amplitude U_{PEM} is shown in the Fig.1. For all samples, the effect is linear in low fields $B < 1.5$ T with a tendency of saturation in higher fields. It is important to note that the PEM effect sign corresponds to the net electron flux from the sample surface to its bulk.

The effect of the radiation intensity variation on the PEM effect amplitude is shown in the Figs.2. For the direct

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spectrum sample with x = 0.25 (Fig.2a), the effect scales up as a function of the incident radiation power for both laser wavelengths used (the main panel), whereas the dependence of U_{PEM} on the number of radiation quanta is different for different laser wavelengths (insert in the Fig.2a). Instead, the inversed spectrum sample with x = 0.045 demonstrates an absolutely opposite behavior (Fig.2b): the U_{PEM} dependence on the number of incident quanta is the same for both wavelengths (the main panel), and the U_{PEM} dependence on the terahertz radiation power diverges for different wavelengths (the insert in the Fig.2b).

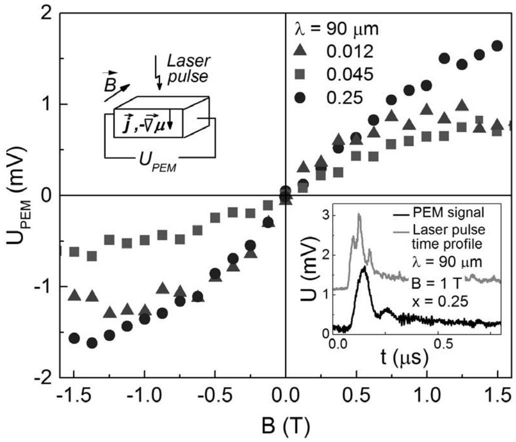

Fig.1. Dependence of the PEM effect amplitude on the magnetic field B applied for $(Cd_{1-x}Zn_x)_3As_2$ samples for alloy compositions x = 0.012; 0.045; 0.25. The laser wavelength λ = 90 μm, T = 4.2 K. The experiment geometry is shown in the upper inset. Typical shape of the laser pulse and PEM response are shown in the lower inset.

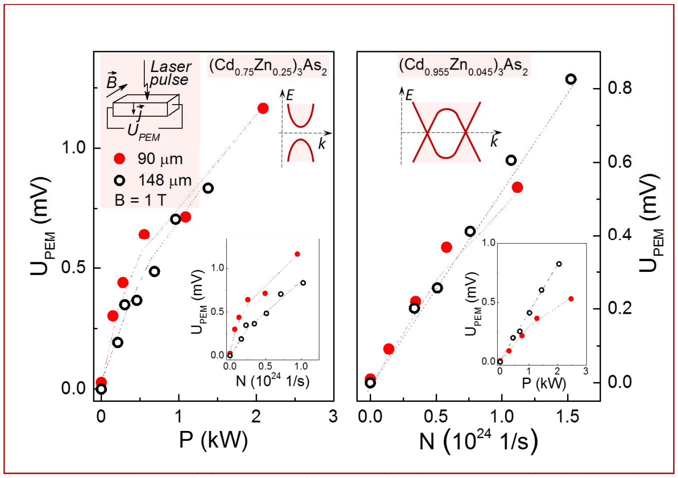

Fig.2. Dependence of the PEM effect amplitude U_{PEM} on the incident laser radiation power P and on the rate of incident quanta for the cases of a trivial insulator and a Dirac semimetal.

III. DISCUSSION

As it has been shown in [4, 6], the diffusive electron flux from the surface to the bulk of degenerate semiconductors may come out only as a result of formation of conductive surface electron states with the mobility higher than in the bulk. This kind of surface states are apparently present both in the inverse and direct gap phases of $(Cd_{1-x}Zn_x)_3As_2$ solid solutions. The effect amplitude, however, scales up differently as a function of the incident radiation flux in the two cases. It was suggested in [4] that this difference in the case of topological insulators $(Bi_{1-x}In_x)_2Se_3$ is due to the different relation between the characteristic thermalization τ_{th} and diffusion τ_{dif} times of free electrons excited by the incident terahertz radiation. In the trivial insulator case, $\tau_{th} << \tau_{dif}$, so the excited electrons first thermalize and then start to diffuse, so the effect depends on the power absorbed. In the case of a topological insulator, the reverse relation $\tau_{th} >> \tau_{dif}$ is realized, so the diffusion starts first, and then the number of diffusing electrons depends on the number of incident quanta. Thermalization of electrons excited by the incident terahertz radiation occurs mainly via the inter-electron interaction since the optical phonon energy in higher than the laser quantum energy used. Consequently, the strong enhancement of the thermalization time in topological insulators compared to the trivial insulators is likely to come out as a result of reduction of the number of electrons that interact effectively with a given one. As it was suggested in [4], this reduction may be due to appearance of locking of the spin direction to the momentum direction of surface electron states in topological insulators, so the surface electrons may effectively interact only with other electrons possessing the same spin and, respectively, momentum direction, and not with the whole Fermi sphere as in the case of trivial insulators. Therefore this enhancement of the thermalization time is a signature of appearance of the spin texture of surface electron states. The results of the present experiment demonstrate that this kind of spin texture appears not only in the topological insulators, but in the Dirac semimetals as well.

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REFERENCES

[1]. S. Borisenko, Q. Gibson, D. Evtushinsky, V. Zabolotnyy, B. Buechner, and R.J. Cava, “Experimental realization of a three-dimensional Dirac semimetal,” *Phys. Rev. Lett.*, vol. # 113, pp. 027603, 5, 2014.

[2]. Z.K. Liu, J. Jiang, B. Zhou, Z.J. Wang, Y. Zhang, H.M. Weng, D. Prabhakaran, S-K. Mo, H. Peng, P. Dudin, T. Kim, M. Hoesch, Z. Fang, X. Dai, Z.X. Shen, D.L. Feng, Z. Hussain, and Y.L. Chen, “A stable three-dimentsional topological Dirac semimetal Cd_3As_2,” *Nat. Mater.*, vol.# 13, pp. 677 – 681, 2014.

[3]. M. Neupane, S.-Y. Xu, R. Sankar, N. Alidoust, G. Bian, C. Liu, I. Belopolski, T.-R. Chang, H.-T. Jeng, H. Lin, A. Bansil, F. Chou, and M.Z. Hasan., “Observation of a three-dimensional topological Dirac semimetal phase in high-mobility Cd_3As_2 ,” *Nat. Commun.*, vol.# 5, pp. 3786, 8, 2014.

[4]. A.V. Galeeva, S.G. Egorova, V.I. Chernichkin, M.E. Tamm, L.V. Yashina, V.V. Rumyantsev, S.V. Morozov, H. Plank, S.N. Danilov, L.I. Ryabova, and D.R. Khokhlov, “Manifestation of topological surface electron states in the photoelectromagnetic effect induced by terahertz laser radiation,” *Semicond. Sci. Technol.,* vol. # 31, pp. 095010, 9, 2016.

[5]. E.K. Arushanov, A.F. Knyazev, A.N. Naterpov, and S.I. Radautsan, “Dependence of the bandgap of $Cd_{3-x}As_xAs_2$ on composition,” *Sov. Phys. Semicond.*, vol.# 17, pp. 759 – 761, 1983.

[6]. S.G. Egorova, V.I. Chernichkin, L.I. Ryabova, E.P. Skipetrov, L.V. Yashina, S.N. Danilov, S.D. Ganichev, and D.R. Khokhlov, “Detection of highly conductive surface electron states in topological crystalline insulators $Pb_{1-x}Sn_xSe$ using laser terahertz radiation,” *Sci. Rep.*, vol.#5, pp. 11540, 5, 2015.

[7]. S.G. Egorova, V.I. Chernichkin, A.O. Dudnik, V.A. Kasiyan, L. Chernyak, S.N. Danilov, L.I. Ryabova, and D.R. Khokhlov, “Discrimination of conductive surface electron states by laser terahertz radiation in PbSe – a base for $Pb_{1-x}Sn_xSe$ topological crystalline insulators,” *IEEE Trans. Terahertz Sci. Technol.,* vol.# 5, pp. 659 – 664, 2015.