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Spin-valve effect for spin-polarized surface states in topological semimetals

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We experimentally investigate magnetoresistance of a single GeTe–Ni junction between the α-GeTe topological semimetal and thick nickel film at room and liquid helium temperatures. For the magnetic field parallel to the junction plane, we demonstrate characteristic spin-valve hysteresis with mirrored differential resistance dV/dI peaks even at room temperature. In contrast, for normal magnetic fields spin-valve effect appears only at low temperatures. From the magnetic field anisotropy, observation of the similar effect for another topological semimetal Cd_3As_2, and strictly flat $dV/dI(H)$ magnetoresistance curves for the reference GeTe-Au junction, we connect the observed spin-valve effect with the spin-dependent scattering between the spin textures in the topological surface states and the ferromagnetic nickel electrode. For the topological semimetal α-GeTe, room-temperature spin-valve effect allows efficient spin-to-charge conversion even at ambient conditions.

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In topological semimetals, spin-orbit interaction lifts the spin degeneracy of the surface states leading to their in-plane spin polarization, with strongly correlated and predominantly antiparallel spin textures in the neighboring Fermi arcs [1]. Spin- and angle-resolved photoemission spectroscopy data indeed demonstrate surface Fermi arcs with nearly full spin polarization [2].

For usual ferromagnetic multilayers, the multilayer resistance depends on the mutual orientation of the layers' magnetizations due to the spin-dependent scattering, so the spin-valve resistance can be affected by external magnetic field or high current density [3, 4].

Due to the different spin polarization of the Fermi arc surface states and ferromagnetic bulk, magnetic topological materials also demonstrate spin-valve effect at relatively low current densities [5, 6]. It seems to be reasonable to investigate magnetic-field-induced magnetization dynamics for spin valves based on non-magnetic topological semimetals, which is enabled by strong spin-orbit coupling and spin-momentum locking in the surface states. Among nonmagnetic Weyl semimetals, GeTe is of special interest due to the reported giant Rashba splitting [7].

Here, we experimentally investigate magnetoresistance of a single GeTe–Ni junction between the α-GeTe topological semimetal and thick nickel film at room and liquid helium temperatures. For the magnetic field parallel to the junction plane, we demonstrate characteristic spin-valve hysteresis with mirrored differential resistance dV/dI peaks even at room temperature. In contrast, for normal magnetic fields spin-valve effect appears only at low temperatures.

We prepare several types of interface structures. The main one are the GeTe–Ni junctions between a ferromagnetic nickel film and a non-magnetic topological semimetal GeTe. For comparison, we also prepare Cd_3As_2–Ni junctions based on the non-magnetic topological Dirac semimetal Cd_3As_2 and the reference GeTe–Au junctions with a gold normal layer. We investigate magnetoresistance of a single GeTe–Ni or Cd_3As_2–Ni junction using a standard three-point technique: one Ni contact is grounded, the neighboring one is used as a voltage probe, while current flows through another contact. For the magnetoresistance measurements, magnetic field is applied by a standard electromagnet for room temperature or by superconducting solenoid for liquid helium (4.2 K) one.

The characteristic spin-valve behavior appears for both field orientations at liquid helium temperature, see Fig. 1a and b. We do not observe strong temperature dependence for the parallel to the interface magnetic field, $dV/dI(H)$ curves are of qualitatively similar behavior in Fig. 1a with $dV/dI(H)$ resistance minima at the same ± 0.5 kOe. However, two distinct resistance peaks appear also at ± 2 kOe normal magnetic field, as depicted in Fig. 1b. The $dV/dI(H)$ curves are mirrored in respect

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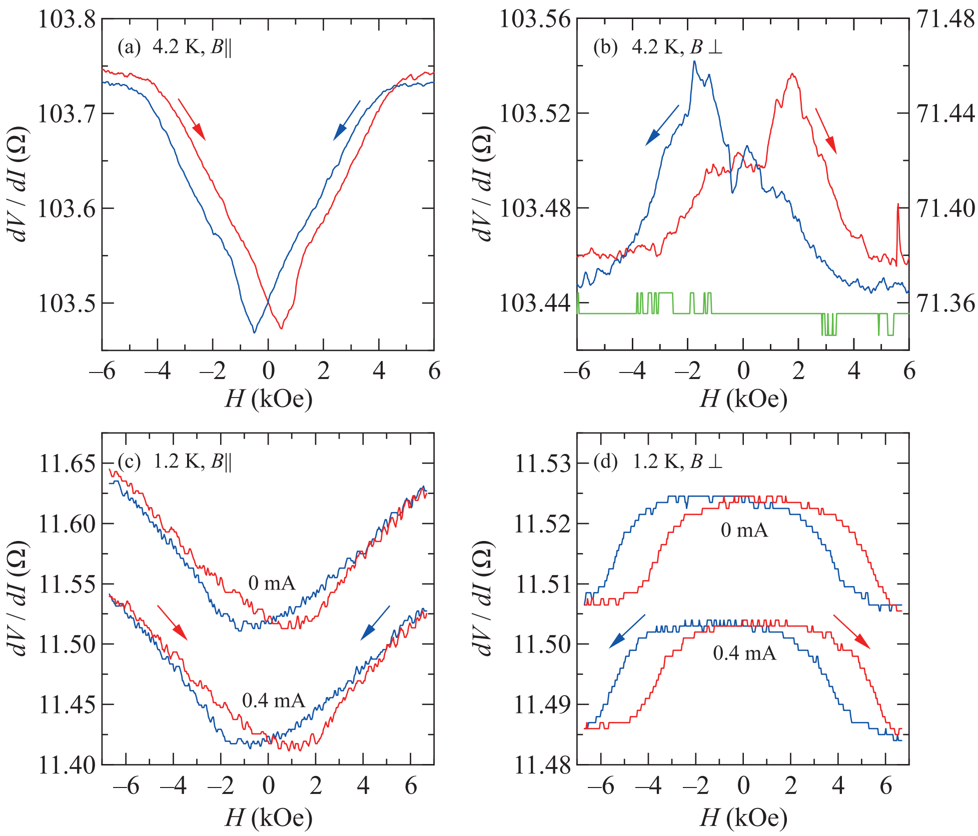

Fig. 1. (Color online) Spin-valve magnetoresistance $dV/dI(H)$ of GeTe–Ni and Cd_3As_2-Ni junctions ((a), (b) and (c), (d)), respectively) at 4.2 K liquid helium temperature. (a) – Magnetic field is parallel to the GeTe–Ni interface, there is no strong temperature dependence for this field orientation. (b) – In normal magnetic field, two distinct resistance peaks appear also in ± 2 kOe. The $dV/dI(H)$ curves are mirrored in respect to the zero field, demonstrating spin valve effect. The green curve is for the reference GeTe–Au junction of approximately similar resistance. (c), (d) – Similar spin-valve magnetoresistance for Cd_3As_2–Ni junction between nickel electrode and the Dirac semimetal Cd_3As_2. The $dV/dI(H)$ minima and maxima are at ± 1.5 kOe for both magnetic field orientations

to the zero field, the overall resistance drop is still about 0.15 %. We check, that there are no magnetoresistance or any resistance peaks for the reference GeTe–Au junction of approximately similar resistance, see the green $dV/dI(H)$ curve in Fig. 1b. We should conclude, that the observed spin-valve effect requires thick ferromagnetic Ni layer as an essential part of the structure for the non-magnetic GeTe semimetal.

The observed behavior is quite universal for the junctions “ferromagnet–non-magnetic topological semimetal”. Very similar spin-valve magnetoresistance can also be demonstrated for Dirac semimetal Cd_3As_2, see Fig. 1c and d. In this case, the $dV/dI(H)$ minima and maxima are centered at ± 1.5 kOe for both magnetic field orientations. Thus, despite the qualitative $dV/dI(H)$ behavior is quite universal for GeTe and Cd_3As_2 topological semimetals, the exact hysteresis value is defined not only by the Ni electrode, but also by the topological semimetal itself.

As a result, we observe pronounced spin-valve effect in magnetoresistance of the junction between the non-magnetic topological semimetal and ferromagnetic electrode. For GeTe topological semimetal, spin-valve hysteresis can even be demonstrated at room temperature in the parallel to the interface magnetic field.

Since nickel is a conventional ferromagnet, the observed spin-valve effect requires some magnetic ordering for the GeTe and Cd_3As_2 topological semimetals. However, both materials are nominally non-magnetic. For our single crystals, the powder X-ray diffraction analysis confirms pure single-phase GeTe, also, GeTe composition is verified by energy-dispersive X-ray spectroscopy.

There are several characteristic features of α-GeTe, which seems to be important in GeTe–Ni devices. First of all, topological surface states with nontrivial spin textures [8, 9] can play an important role. In addition, there are nontrivial spin textures with nonzero spin winding numbers in the bulk of α-GeTe, which are associated with the type-II Weyl fermions around the triple points of the electronic band structure [8]. Also, the pronounced spin-orbit splitting [8, 9] can influence on the charge transport as a whole.

On the other hand, Cd_3As_2 is not characterized by bulk spin structures, despite Cd_3As_2–Ni junctions show qualitatively similar spin-valve effects. For this reason, we should consider possible contribution from the surface-state induced spin textures [9] in GeTe and Cd_3As_2 topological semimetals.

It is important, that spin-valve effect can not be solely ascribed to the Ni film magnetization reorientation: (i) due to the high Curie temperature, the Ni film is not sensitive to temperature in 4.2–300 K range, while the spin-valve effect in normal magnetic fields strongly depends on the temperature in this range; (ii) the reorientation field range is different for the Cd_3As_2 Dirac semimetal with helical surface states in Fig. 1, despite the same Ni film.

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1. D. A. Pshenay-Severin, Y. V. Ivanov, A. A. Burkov, and A. T. Burkov, J. Phys. Condens. Matter **30**, 135501 (2018).
2. S.-Y. Xu, I. Belopolski, D. S. Sanchez et al. (Collaboration), Phys. Rev. Lett. **116**, 096801 (2016).
3. B. Dieny, V. S. Speriosu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri, Phys. Rev. B **43**, 1297 (1991).
4. R. Q. Zhang, J. Su, J. W. Cai, G. Y. Shi, F. Li, L. Y. Liao, F. Pan, and C. Song, Appl. Phys. Lett. **114**, 092404 (2019).
5. V. D. Esin, D. N. Borisenko, A. V. Timonina, N. N. Kolesnikov, and E. V. Deviatov, Phys. Rev. B **101**, 155309 (2020).
6. O. O. Shvetsov, V. D. Esin, A. V. Timonina, N. N. Kolesnikov, and E. V. Deviatov, Europhys. Lett. **127**, 57002 (2019).
7. D. Di Sante, P. Barone, R. Bertacco, and S. Picozzi, Adv. Mater. **25**, 509 (2013).
8. J. Krempaský, L. Nicolaï, M. Gmitra, H. Chen, M. Fanciulli, E. B. Guedes, M. Caputo, M. Radović, V. V. Volobuev, O. Caha, G. Springholz, J. Minár, and J. H. Dil, Phys. Rev. Lett. **126**, 206403 (2021).
9. G. Kremer, T. Jaouen, B. Salzmann, L. Nicolaï, M. Rumo, C. W. Nicholson, B. Hildebrand, J. H. Dil, J. Minár, G. Springholz, J. Krempaský, and C. Monney, Phys. Rev. Research **2**, 033115 (2020).