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Josephson spin-valve realization in the magnetic nodal-line topological semimetal Fe_3GeTe_2

O. O. Shvetsov, Yu. S. Barash, A. V. Timonina, N. N. Kolesnikov, E. V. Deviatov[1)]

Institute of Solid State Physics of the Russian Academy of Sciences, 142432 Chernogolovka, Russia

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Recently, Fe_3GeTe_2 (FGT) has attracted significant attention as a unique candidate for the ferromagnetic nodal line semimetal [1], hosting spin-polarized Fermi arc surface states [2]. FGT is an itinerant van der Waals ferromagnet characterized by an out-of-plane magnetocrystalline anisotropy both for three-dimensional single crystals and down to two-dimensional limit.

Usually, spin valves are realized as ferromagnetic multilayers [3] with different layers' thickness. Due to the different spin polarization of the Fermi arc surface states and ferromagnetic bulk, magnetic topological materials should also demonstrate spin-valve transport properties [4, 5], i.e. they can be regarded as natural realization of spin-valves.

In a Josephson spin valve (JSV), ferromagnetic multilayer is sandwiched between two superconducting electrodes [6]. In JSVs supercurrent is defined mainly by the relative orientation of the layers' magnetizations, while in conventional Josephson junctions it is modulated by magnetic flux. In the majority of devices the Josephson current is directed perpendicular to the layers, but the spin-valve effects can also occur in systems, where the supercurrent flows along the planes [7].

Due to the natural spin-valve realization, magnetic topological semimetals like FGT may be regarded as a platform for planar JSV investigations.

Non-trivial surface properties are only known for three-dimensional topological semimetal single crystals. Thus, we use thick ($1\,\mu$m) FGT flakes, which are obtained by a mechanical cleavage from the initial single crystal. One FGT flake is transferred to the substrate with the defined In leads pattern. We study electron transport between two neighbor In leads in a standard four-point technique, all the wire resistances are excluded, which is necessary for low-impedance samples.

$dV/dI(I)$ curves clearly demonstrate Josephson effect for two different samples, which are referred as S1 and S2. Qualitative behavior is similar, despite strongly different critical current I_c ($I_c = 0.17\,$mA (S1) and 0.018 mA (S2)) and normal resistance values. As expected, the zero-resistance state appears below some critical temperature, which is about 0.88 and 0.34 K for the devices.

Figure 1 demonstrates the influence of external in-plane and normal magnetic fields on sample resistance at $T = 30\,$mK. The result is qualitatively similar for both field orientations: the zero-resistance state is suppressed by the external field, $dV/dI(B)$ curves are not symmetric with respect to the zero field value. As a most important, the observed $dV/dI(B)$ asymmetry depends on the magnetic field sweep direction. Moreover, all the dV/dI features are mirrored for the opposite field sweeps.

There are also some features in Fig. 1, which are different in two magnetic field orientations. For the in-plane magnetic fields, $I_c(B)$ shows fast aperiodic fluctuations in Fig. 1a–c. On the contrary, no noticeable fluctuations can be observed for normal magnetic field orientation, see Figs. 1d–f.

This behavior can not be expected for usual SFS junctions with the homogeneous magnetization of the central ferromagnetic layer, where remagnetization can only shift the $I_c(B)$ pattern position in magnetic field. On the other hand, the observed behavior is a known fingerprint of Josephson spin valves [6].

In the case of FGT, the presence of spin-polarized topological Fermi arcs has been demonstrated by ARPES [1], while spin momentum locking was inferred to be responsible for anti-symmetric magnetoresistance in FGT/graphite/FGT heterostructures [2]. Thus, a FGT flake may be regarded as a spin valve, this scenario is independently verified by magnetoresistance of a single Au-FGT junction for the reference Hall bar sample, where typical spin-valve hysteresis is observed [3]. Moreover, Figure 1 shows asymmetric resistive features even at high currents, i.e. for the suppressed superconductiv-

[1)]e-mai: dev@issp.ac.ru

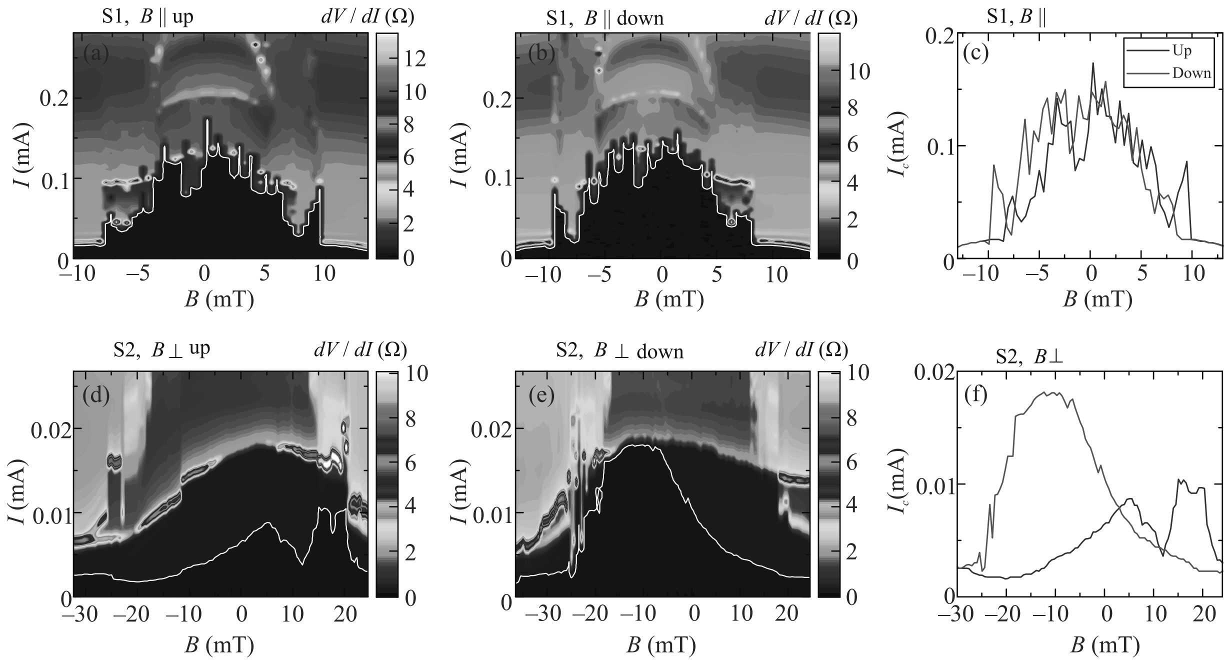

Fig. 1. (Color online) Colormaps of $dV/dI(I,B)$ for samples S1 and S2 in (a), (b) and (d), (e) respectively. The panels (a), (d) and (b), (e) differ by the magnetic field sweep direction, which is from negative to positive values in (a) and is just opposite in (b). All the data are obtained at 30 mK. To establish definite sample magnetization, every magnetic field sweep begins from high field value $B = \pm 100$ mT (the sign depends on the sweep direction). The colormaps are obtained from $dV/dI(I)$ curves at fixed magnetic field values, which are changed point-by-point in up or down directions. To establish definite sample magnetization state, every magnetic field sweep cycle begins from high field value $B = \pm 100$ mT. The $dV/dI(B)$ reversal can be clearly seen, e.g., by the asymmetric black feature at ± 9 mT in (a), (b). The reversal effect is even more pronounced in (d), (e) for normal magnetic fields. (c), (f) $I_c(B)$ dependencies for the in-plane and normal magnetic field orientations, respectively. The general $I_c(B)$ shapes are asymmetric in both cases, the asymmetry is reversed for the up (blue) and down (red) field sweeps. For the in-plane magnetic fields, $I_c(B)$ shows well-reproducible aperiodic fluctuations in (c). On the contrary, no noticeable fluctuations can be observed in (f). In normal magnetic fields, there is an interplay between maximum and minimum in $I_c(B)$ at ± 12 mT, which is well known for the Josephson spin valves [6]. The data are obtained at 30 mK

ity. These features are also reversed for two magnetic field directions, which confirms spin-valve behavior in FGT. Thus, our experimental results can be regarded as demonstration of the JSV, which is realized in the magnetic nodal-line topological semimetal FGT.

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