Spin wave effects in transport between a ferromagnet and a Weyl semimetal surface

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We experimentally investigate spin-polarized transport between a ferromagnetic Ni electrode and a surface of Weyl semimetal, realized in a thick WTe$_2$ single crystal. For highly-transparent Ni-WTe$_2$ planar junctions, we observe non-Ohmic $dV/dI(I)$ behavior with an overall increase of differential resistance $dV/dI$ with current bias, which is accomplished by current-induced switchings. This behavior is inconsistent with trivial interface scattering, but it is well known for spin-polarized transport with magnon emission. Thus, we interpret the experimental results in terms of spin wave excitation in spin textures in the WTe$_2$ topological surface states, which is supported by the obtained magnetic field and temperature $dV/dI(I)$ dependencies.

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A strong area of interest in condensed matter physics is topological materials [1–4], which combines many nontrivial effects, table top test ground for high-energy physics theories and huge potential for applications, for example in spintronics or quantum computing. Recently new classes of topological materials with gapless bulk spectra called Dirac and Weyl semimetals have been proposed [5]. Similarly to topological insulators, Weyl semimetals have topologically protected Fermi arc surface states, which are connecting projections of Weyl nodes on the surface Brillouin zone [3].

WTe$_2$ is one of the realizations of type-II Weyl semimetal [6], where energy spectrum is tilted in momentum-energy space [7]. WTe$_2$ demonstrates giant nonsaturating magnetoresistance [8, 9]. Now it is connected with complex spin textures in WTe$_2$ [10–12]. Spin- and angle-resolved photoemission spectroscopy (SARPES) data indeed demonstrate spin-polarized surface Fermi arcs, and spin polarized Fermi pockets in bulk spectrum [13, 14], see Fig. 1.

Intriguing spin properties of Weyl semimetals make it attractive material for spin investigations. Giant intrinsic Spin Hall Effect was recently predicted in TaAs based Weyl semimetals [15], while SARPES measurements demonstrated nearly full spin polarization of Fermi arcs in TaAs [16, 17]. Currently there are two main spin transport approaches: illumination with polarized light and spin injection from ferromagnetic contact [15]. In the latter case one can additionally expect back action of the semimetal on the ferromagnet in the form of spin-torque, which could lead even to remagnetization of ferromagnetic contact [19]. The generation of both out-of-plane and in-plane spin-torque has been demonstrated recently in few layers WTe$_2$ at room temperature with ST-FMR and second harmonic Hall measurements [20]. On the other hand, current-induced excitation of spin waves, or magnons, is possible at large electrical current densities for normal-ferromagnet junctions [21, 22]. Thus, it is reasonable to study spin-polarized transport between a ferromagnet and a Weyl semimetal surface.

Here, we experimentally investigate spin-polarized transport between a ferromagnetic Ni electrode and a surface of Weyl semimetal, realized in a thick WTe$_2$ single crystal. For highly-transparent Ni-WTe$_2$ planar junctions, we observe non-Ohmic $dV/dI(I)$ behavior with an overall increase of differential resistance $dV/dI$ with current bias, which is accomplished by current-induced switchings. This behavior is inconsistent with trivial interface scattering, but it is well known for spin-polarized transport with magnon emission. Thus, we interpret the experimental results in terms of spin wave excitation in spin textures in the WTe$_2$ topological surface states, which is supported by the obtained magnetic field and temperature $dV/dI(I)$ dependencies.

FIG. 1. (Color online) Sketch of Fermi arcs in (001) WTe$_2$ surface Brillouin zone, and spin polarized Fermi pockets in bulk WTe$_2$ spectrum [13, 14]. Arrows indicate spin projections, which are defined by the Weyl surface states dispersion due to spin-momentum locking [10–12].
FIG. 2. (Color online) (a) Sketch of the sample with nickel contacts to the bottom surface of a WTe$_2$ crystal (not to the scale). 50 nm thick ferromagnetic nickel leads are formed on the insulating SiO$_2$ substrate. A WTe$_2$ single crystal is transferred on top of the leads with $\approx 10$ $\mu$m overlap, forming planar Ni-WTe$_2$ junctions. Charge transport is investigated in a standard three-point technique: the studied contact ($F2$) is grounded and two other contacts ($F1$ and $F3$) are used for applying current and measuring WTe$_2$ potential. The main WTe$_2$ crystallographic directions are denoted by arrows. (b) Large positive magnetoresistance $\rho(B) - \rho(B = 0)/\rho(B = 0)$ for our WTe$_2$ samples at 1.2 K in normal magnetic field (the blue curve). It goes to zero in parallel one (the red curve), as it has been shown for WTe$_2$ Weyl semimetal $^5$. The current is parallel to the $a$ axis of WTe$_2$.

confirms $Pmn2_1$ orthorhombic single crystal WTe$_2$ with lattice parameters $a = 3.4875$ Å, $b = 6.2672$ Å, and $c = 14.0630$ Å.

A sample sketch is presented in Fig. 2 (a). 50 nm thick nickel film is thermally evaporated on the insulating SiO$_2$ substrate mounted on the in-plane magnetized sample holder. 10 $\mu$m wide ferromagnetic leads are formed by photolithography and lift-off technique. The WTe$_2$ crystal (with dimensions $500$ $\mu$m $\times 100$ $\mu$m $\times 0.5$ $\mu$m) is transferred on top of the leads with $\approx 10 \times 10$ $\mu$m$^2$ overlap and weakly pressed to form planar Ni-WTe$_2$ junctions.

We investigate transport properties of single Ni-WTe$_2$ junction by a three-point technique, see Fig. 2 (a): a studied contact $F2$ is grounded, two other contacts $F1$ and $F3$ are employed to apply current and measure voltage respectively. To obtain $dV/dI(I)$ characteristics we sweep dc-current modulated by low ($<$ 2 $\mu$A, $f = 2$ kHz) ac current. We measure dc and ac voltage simultaneously using voltmeter and lock-in amplifier correspondingly. Measured ac signal is independent of frequency in 1-5 kHz range, which is defined by applied ac filters.

In a three-point technique, the measured potential $V$ reflects in-series connected resistances of the Ni-WTe$_2$ junction, some part of the WTe$_2$ crystal, and the Ni lead with the grounding wire. To exclude the latter term, additional connection to the grounded $F2$ lead is used, as depicted in Fig. 2. From $dV/dI(I)$ independence on the particular choice of current and voltage probes to the WTe$_2$ crystal, we verify that the Ni-WTe$_2$ junction resistance dominates in the obtained $dV/dI(I)$ curves.

We check by standard magnetoresistance measurements that our WTe$_2$ samples demonstrate large, non-saturating positive magnetoresistance $\rho(B) - \rho(B = 0)/\rho(B = 0)$ in normal magnetic field, which goes to zero in parallel one, as it has been shown for WTe$_2$ Weyl semimetal $^5$. To extract features specific to WTe$_2$ Weyl semimetal surface states, the measurements are performed in a dilution refrigerator at temperatures from 30 mK to 1.2 K with different orientations of the magnetic field to the junction plane.

Despite of equally prepared Ni-WTe$_2$ junctions, there are serious device-to-device fluctuations of the junction resistance. Fig. 3 provides typical examples of low-temperature $dV/dI(I)$ characteristics for the two limiting cases.

For the transparent interface with low Ni-WTe$_2$ junction resistance, $dV/dI$ is rising at low biases with saturation at higher ones, as it has been shown for WTe$_2$ Weyl semimetal $^5$. This behavior is inconsistent with trivial impurity or roughness scattering at the interface, which can generally be described as tunneling through a potential barrier. On the other hand, an overall symmetric increase in $dV/dI$ is a familiar effect for electron scattering by emission of phonons and magnons $^27$.

In contrast, $dV/dI(I)$ demonstrates clear tunnel behavior for low-transparency junctions, see Fig. 3 (b): $dV/dI(I)$ is slightly asymmetric, the differential resistance $dV/dI$ is diminishing with bias.

For both realizations of Ni-WTe$_2$ junctions, we observe current-induced switchings of $dV/dI$ at high currents. They appear as sharp $dV/dI$ peaks or dips in Fig. 3 (a) and (b), respectively. These $dV/dI$ features
are well reproducible in different cooling cycles. They are symmetric with respect to the current sign. There is no noticeable hysteresis with the current sweep direction for experimental no. 0.5 K. At higher temperatures, \( dV/dI \) dips and peaks amplitudes and overall \( dV/dI(I) \) non-linearity are diminishing, until their complete disappearance above 1 K. The curves are obtained in zero magnetic field.

We should connect the obtained results with spin-dependent transport between a ferromagnetic Ni lead and WTe\(_2\) surface states:

(i) A ferromagnetic lead is essential, since neither current-induced \( dV/dI \) switchings nor an overall symmetric increase in \( dV/dI \) can be observed for normal or superconducting leads to a single WTe\(_2\) crystal for different junction transparencies 28, 29.

(ii) Both current-induced \( dV/dI \) switchings and overall \( dV/dI(I) \) behavior can be controlled by magnetic field, see Fig. 5.

(iii) Strong temperature dependence in the 30 mK-1.2 K range can only originate from WTe\(_2\) surface states, since transport properties of Ni layer and well compensated WTe\(_2\) bulk carriers are invariant in this temperature range.

Spin effects can be anticipated in WTe\(_2\) surface states due to the presence of spin textures in the WTe\(_2\) Fermi arcs 10, 11, 13, 14, see Fig. 1. In principle, a junction between a ferromagnetic Ni layer and a WTe\(_2\) surface can be regarded as a spin valve device. The spin valves are the sandwich structures, where spin-dependent scattering affects the magnetic moments of the spin-polarized layers, while their mutual orientation defines the differential resistance 27. \( dV/dI \) switchings have been reported for spin valves 27, but they are necessarily asymmetric with respect to the bias sign, and also accomplished by well-defined hysteresis 27, which is obviously not the case in Figs. 3 and 5.

Inelastic transport with magnon emission 24 is a more realistic variant, since the switchings are governed 22 by magnetic field in Fig. 5.

Let us start from the low-transparent junction in Figs. 3(b) and 3(b). Trivial tunneling is the main effect, which results in a standard non-linear \( dV/dI(I) \) curve with \( dV/dI \) diminishing with bias increase. In tunneling events, hot electrons appear above the Fermi level. They thermalize by scattering with lattice defects, phonons, or other electrons. This process is accomplished by spin polarization of the ferromagnetic lead and spin textures in the WTe\(_2\) surface state. In this case, hot electrons should additionally rotate their spins to be absorbed. Conservation of total spin results in excitation of a magnon, which opens an additional inelastic channel. Thus, the current is enhanced, which is observed as sharp dips in differential resistance \( dV/dI \), as it has also been previously reported for the vacuum-separated metallic contacts 24.

Spin-wave effects are even clearer for highly-transparent junctions, see Fig. 3(a), because of negligible interface barrier. For example, the current-induced switchings can not be connected with the potentially inhomogeneous interface in this case.

The crucial point is that the low-temperature zero-bias resistance is smaller than the value, obtained at high bi-
asesses, temperatures, or magnetic fields, see Figs. 3 (a), 4 (a), and 5. At zero bias, one can expect that spin polarization of some carriers at the WTe$_2$ surface is aligned parallel to one in the ferromagnet due to the complicated spin texture of the topological Fermi arc surface state, see Fig. 1. This allows a direct transport channel even for spin-polarized carriers, which is reflected in low junction resistance at zero bias. When increasing the current through the surface state, spin-momentum locking [10, 11, 13, 14] produces preferable spin polarization. It suppresses transport due to the requirement on spin rotation in transport events, which is reflected as the overall $dV/dI$ increase for both signs of the current. This picture is consistent with the magnetic-field and temperature dependences of $dV/dI(I)$: spin alignment at zero bias disappears when high magnetic field or temperature destroys spin textures of the topological surface state, so the zero-bias differential resistance is at the normal (saturated) value, see Figs. 4 and 5.

Similarly to the transparent metallic junctions [21, 22], the onset of the current-driven magnon excitations appears as $dV/dI$ peaks in Fig. 3. In low magnetic fields, the peaks positions are shifted [22] to lower currents, see Fig. 5 because an external field simplifies spin-wave excitation in the WTe$_2$ surface state. We wish to emphasize, that the magnon excitation occurs in the WTe$_2$ surface state, since transport properties of Ni layer and well compensated WTe$_2$ bulk carriers [9] are invariant below 1 K. Thus, our results can be regarded as direct manifestation of spin textures in WTe$_2$ surface states in transport experiment.

As a conclusion, we experimentally investigate spin-polarized transport between a ferromagnetic Ni electrode and a surface of Weyl semimetal, realized in a thick WTe$_2$ single crystal. For highly-transparent Ni-WTe$_2$ planar junctions, we observe non-Ohmic $dV/dI(I)$ behavior with an overall increase of differential resistance $dV/dI$ with current bias, which is accomplished by current-induced switchings. This behavior is inconsistent with trivial interface scattering, but it is well known for spin-polarized transport with magnon emission. Thus, we interpret the experimental results in terms of spin wave excitation in spin textures in the WTe$_2$ topological surface states, which is supported by the obtained magnetic field and temperature $dV/dI(I)$ dependencies.

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FIG. 5. (Color online) Evolution of $dV/dI(I)$ curves with magnetic field, which is applied along a, b and c WTe$_2$ crystal axes, respectively. Qualitative effect is similar: the level of $dV/dI(I)$ high-current saturation is constant; the zero-bias nonlinearity is suppressed; the positions of $dV/dI$ current-induced switchings are shifting to smaller currents. The effect is stronger in normal field, while there is no difference for two in-plane orientations. Color scale on the left reflects differential resistance levels in (a), color scale on the right refers to (b) and (c). The curves are obtained at 30 mK for the transparent Ni-WTe$_2$ junction from Fig. 3 (a). The gradual evolution of switchings’ positions also proves excellent reproducibility of these $dV/dI$ features.

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