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

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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 [1]. WTe_2 is one of the realizations of Weyl semimetal [2]. Spin- and angle-resolved photoemission spectroscopy data indeed demonstrate spin-polarized surface Fermi arcs, and spin polarized Fermi pockets in bulk spectrum [3, 4].

Intriguing spin properties of Weyl semimetals make it attractive material for spin investigations. 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 [5]. On the other hand, current-induced excitation of spin waves, or magnons, is possible at large electrical current densities for normal-ferromagnet junctions [6–9]. Thus, it is reasonable to study spin-polarized transport between a ferromagnet and a Weyl semimetal surface.

WTe_2 compound was synthesized from elements by reaction of metal with tellurium vapor in the sealed silica ampule. The WTe_2 crystal (with dimensions $500\,\mu\text{m} \times 100\,\mu\text{m} \times 0.5\,\mu\text{m}$) is transferred on top of the 50 nm thick ferromagnetic nickel leads with $\approx 10 \times 10\,\mu\text{m}^2$ 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. 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.

For the transparent interface with low Ni-WTe_2 junction resistance, dV/dI is rising at low biases with saturation at higher ones, see Fig. 1. 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 [10].

For any transparency of Ni-WTe_2 junctions, we observe complex dV/dI peaks or dips structures at high currents. These dV/dI features are well reproducible in different cooling cycles (see also Fig. 1 below). They are symmetric with respect to the current sign. There is no noticeable hysteresis with the current sweep direction for experimental $dV/dI(I)$ curves.

The observed $dV/dI(I)$ non-linearity as well as dV/dI peaks or dips structures are sensitive to the magnetic field and temperature. The effect of temperature is weak below 0.5 K. At higher temperatures, $dV/dI(I)$ non-linearity is diminishing. Above 1 K, the differential resistance is almost constant, so $dV/dI(I)$s are of standard Ohmic behavior.

Figure 1 demonstrates evolution of $dV/dI(I)$ curves with magnetic field, which is applied along a, b and c WTe_2 crystal axes, respectively. The effect of magnetic field is sophisticated: in high fields, the zero-bias nonlinearity is suppressed, while the level of $dV/dI(I)$ high-current saturation is unchanged, so that $dV/dI(I)$ curve is of clear Ohmic behavior above some magnetic field. In lower fields, the positions of dV/dI peaks are shifting to smaller currents.

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 dV/dI peaks 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.

(ii) Both dV/dI peaks and overall $dV/dI(I)$ behavior can be controlled by magnetic field, see Fig. 1.

(iii) Strong temperature dependence in the 30 mK–1.2 K range can only originate from WTe_2 surface state,

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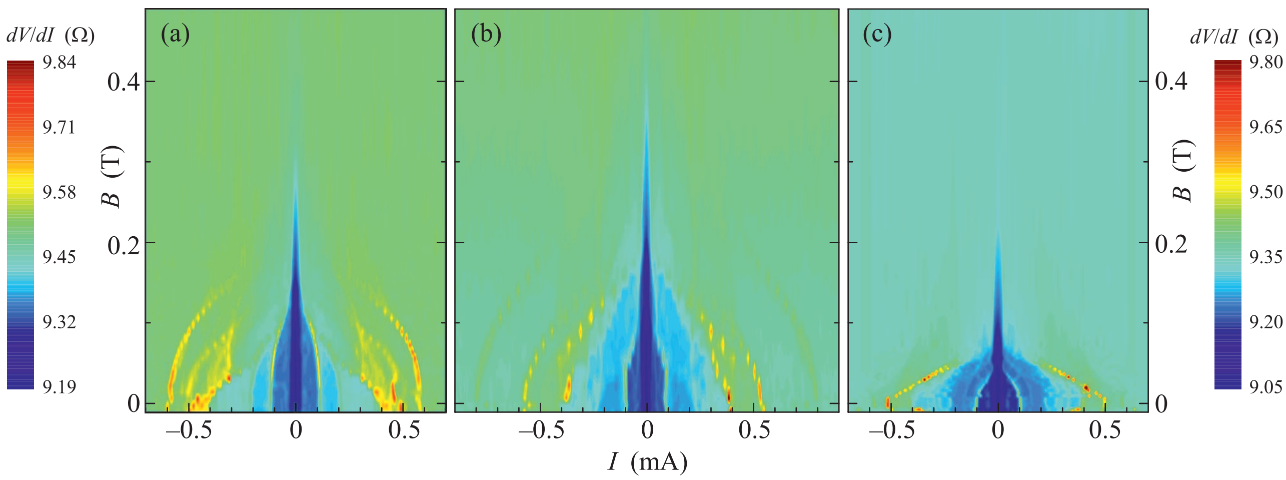

Fig. 1. (Color online) Evolution of $dV/dI(I)$ curves with magnetic field, which is applied along a, b and c WTe_2 crystal axes, respectively. Qualitative effect is similar: the level of $dV/dI(I)$ high-current saturation is constant; the zero-bias nonlinearity is suppressed; the positions of dV/dI peaks 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. The gradual evolution of peaks' positions also proves excellent reproducibility of these dV/dI features

since transport properties of Ni layer and well compensated WTe_2 bulk carriers are invariant in this temperature range.

(iv) Fermi arc surface states contribution can be reliably identified in charge transport between WTe_2 surface and a single non-magnetic contact.

Spin effects can be anticipated in WTe_2 surface states due to the presence of spin textures in the WTe_2 Fermi arcs. Inelastic transport with magnon emission [9] is the most realistic variant, since the switchings are governed [7] by magnetic field in Fig. 1.

The crucial point is that the low-temperature zero-bias resistance is smaller than the value, obtained at high biases, temperatures, or magnetic fields, see Fig. 1. 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. 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 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.

Similarly to the transparent metallic junctions [6, 7], the onset of the current-driven magnon excitations appears as dV/dI peaks. In low magnetic fields, the peaks positions are shifted [7] to lower currents, see Fig. 1, because an external field simplifies spin-wave excitation in the WTe_2 surface state.

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