Spin-dependent transport through the Weyl semimetal surface

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We experimentally compare two types of interface structures with magnetic and non-magnetic Weyl semimetals. They are the junctions between a gold normal layer and magnetic Weyl semimetal Ti2MnAl, and a ferromagnetic nickel layer and non-magnetic Weyl semimetal WTe2, respectively. Due to the ferromagnetic side of the junction, we investigate spin-polarized transport through the Weyl semimetal surface. For both structures, we demonstrate similar current-voltage characteristics, with hysteresis at low currents and sharp peaks in differential resistance at high ones. Despite this behavior resembles the known current-induced magnetization dynamics in ferromagnetic structures, evolution of the resistance peaks with magnetic field is unusual. We connect the observed effects with current-induced spin dynamics in Weyl topological surface states.

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I. INTRODUCTION

Recent interest to topological semimetals is connected with their peculiar properties, which originates from gapless spectrum with band touching in some distinct points. In Weyl semimetals (WSM) every touching point splits into two Weyl nodes with opposite chiralities due to the time reversal or inversion symmetries breaking. The projections of two Weyl nodes on the surface Brillouin zone are connected by a Fermi arc, which represents the topologically protected surface states. Most of experimentally investigated WSMs, were non-centrosymmetric crystals with broken inversion symmetry. For example, spin-and angle-resolved photoemission spectroscopy data indeed demonstrate spin-polarized surface Fermi arc for a WTe2 Weyl semimetal. In contrast, there are only a few candidates of magnetically ordered materials for the realization of WSMs.

Ti2MnAl is one of the newly predicted magnetic WSM. The bulk Ti2MnAl is a spin gapless semiconductor, where the valence and conduction bands touch each other in the spin up-channel and there is a large gap in the spin down band structures. Therefore, the bulk Ti2MnAl has 100% spin polarized carriers.

It is well known, that the magnetically ordered materials allows complicated magnetization dynamics. For example, current-induced excitation of spin waves, or magnons, was demonstrated as sharp $dV/dI$ differential resistance peaks in ferromagnetic multilayers at large electrical current densities. In these structures, spin-dependent scattering may even reverse the magnetic moments of the layers, which results in $dV/dI$ switchings at low currents, accomplished by well-defined hysteresis.

Bulk magnons were also demonstrated for magnetic WSM at low current densities due to the coupling between two magnetic moments mediated by Weyl fermions. Also, in a bilayer consisting of a magnetic WSM and a normal metal, a charge current can be induced in the WSM by spin current injection at the interface. On the other hand, there are spin-polarized surface Fermi arcs on a WSM surface. Similarly to the case of topological insulators, one can expect current-induced magnetization dynamics also for surface magnetic materials.

Here, we experimentally compare two types of interface structures with magnetic and non-magnetic Weyl semimetals. They are the junctions between a gold normal layer and magnetic Weyl semimetal Ti2MnAl, and a ferromagnetic nickel layer and non-magnetic Weyl semimetal WTe2, respectively. Due to the ferromagnetic side of the junction, we investigate spin-polarized transport through the Weyl semimetal surface. For both structures, we demonstrate similar current-voltage characteristics, with hysteresis at low currents and sharp peaks in differential resistance at high ones. Despite this behavior resembles the known current-induced magnetization dynamics in ferromagnetic structures, evolution of the resistance peaks with magnetic field is unusual. We connect the observed effects with current-induced spin dynamics in Weyl topological surface states.

II. SAMPLES AND TECHNIQUE

Ti2MnAl was obtained as a bulk ingot by levitation melting in high-frequency (60-70 kHz) induction furnace. A mixture of Mn and Al powders was placed into the cylindrical titanium capsule and melted in a suspended condition for 20 minutes in argon medium at 0.2 MPa pressure and at 2080 K temperature. After switching the heater off the resulting globule of the melt was dropped to a cooled copper crystallizer, where it was quenched at 278 K. The ingot cleaved mechanically for further processing as shown in Fig. (a) and (b). We check by standard magnetoresistance measurements that our Ti2MnAl is characterized by low positive magnetoresistance, see Fig. (c), which has been demonstrated for this material.

WTe2 compound was synthesized from elements by reaction of metal with tellurium vapor in the sealed sil-
X-ray diffraction (Oxford diffraction Gemini-A, MoKα) is verified by energy-dispersive X-ray spectroscopy. The genides like NbS$_3$$_2$$_2$2 successfully applied in two-stage iodine transport are confirmed by lattice parameters. The WTe$_2$ crystals were grown by the two-stage iodine transport$^{22}$, that previously was successfully applied$^{23,33}$ for growth of other metal chalcogenides like NbS$_2$ and CrNb$_2$S$_6$. The WTe$_2$ composition is verified by energy-dispersive X-ray spectroscopy. The X-ray diffraction (Oxford diffraction Gemini-A, MoKα) confirms $Pmnm_2$ orthorhombic single crystal WTe$_2$ with lattice parameters $a = 3.4875$ Å, $b = 6.2672$ Å, and $c = 14.0630$ Å. We check that our WTe$_2$ crystals demonstrate large (about 3000%), non-saturating positive magnetoresistance up to 14 T field, as it has been shown$^{24,34}$ for WTe$_2$ and is expected$^{25-27}$ for non-magnetic type-II Weyl semimetals$^{28}$.

We prepare two types of interface structures. One of them is the junction between a gold normal layer and a magnetic Weyl semimetal Ti$_2$MnAl, see Fig. 1 (b). The other one is the junction$^{38}$ between a ferromagnetic nickel layer and a non-magnetic Weyl semimetal WTe$_2$. In both cases, 50 nm thick metallic film (nickel or gold) is thermally evaporated on the insulating SiO$_2$ substrate. For nickel evaporation, the substrate is mounted on the in-plane magnetized sample holder. 10 µm wide metallic leads are formed by photolithography and lift-off technique. Small (about 100 µm size and 1 µm thick) WTe$_2$ flakes can be easily obtained from layered WTe$_2$ single crystals. For Ti$_2$MnAl, flakes are obtained by a mechanical cleaving method, see Fig. 1 (a). Then we select the most plane-parallel Ti$_2$MnAl flakes with clean surface, where no surface defects could be resolved with optical microscope. A single flake (WTe$_2$ or Ti$_2$MnAl) is transferred on top of the metallic leads with $\approx 10 \times 10$ µm$^2$ overlap and pressed slightly with another oxidized silicon substrate. A special metallic frame allows us to keep the substrates parallel and apply a weak pressure to the sample. No external pressure is needed for a flake to hold on to a substrate with metallic leads afterward. This procedure provides transparent Ni-WTe$_2$ or Au-Ti$_2$MnAl junctions, stable in different cooling cycles, which has been also demonstrated before$^{35-38}$.

We investigate transport properties of a single Ni-WTe$_2$ or Au-Ti$_2$MnAl junction by a three-point technique, see Fig. 1 (b): a studied contact is grounded, two other contacts are employed to apply current $I$ and measure voltage $V$, respectively. To obtain $dV/dI(I)$ characteristics, the dc current $I$ is additionally modulated by a low ac component ($\approx 2 \mu$A, $f = 2$ kHz). We measure both dc ($V$) and ac (which is proportional to $dV/dI$) components of the voltage drop with a dc voltmeter and a lock-in, respectively. Measured ac signal is independent of frequency in 1-5 kHz range, which is defined by applied ac filters. In the connection scheme in Fig. 1 (b), all the wire resistances are excluded, which is necessary for low-impedance samples. The measurements are performed in a dilution refrigerator for the temperature interval 30 mK–1.2 K for two different orientations of the magnetic field to the interface.
III. EXPERIMENTAL RESULTS

Fig. 2 provides typical examples of low-temperature $dV/dI(I)$ characteristics for Au-Ti$_2$MnAl (in the main field) and Ni-WTe$_2$ (in the right inset) junctions. Despite different materials, we observe similar qualitative behavior for both types of the interfaces: $dV/dI(I)$ curves are non-linear, there are $dV/dI$ peaks at high currents, and sharp symmetric switchings of differential resistance at low, $\approx \pm 25\mu$A bias. The peaks’ positions are independent of the current sweep direction, while $dV/dI$ switchings at $\approx \pm 25\mu$A demonstrates well-defined hysteresis.

We should connect the observed $dV/dI$ features with interface effects. In a three-point technique, the measured potential $V$ reflects in-series connected resistances of the Ni-WTe$_2$ or Au-Ti$_2$MnAl interface and some part of the crystal flake. From $dV/dI(I)$ independence of the particular choice of current and voltage probes in Fig. 1(b), we verify that the interface resistance dominates in the obtained $dV/dI(I)$ curves. Also, we do not observe any $dV/dI$ features in bulk properties of Ti$_2$MnAl, which is demonstrated by four-point measurements in the left inset to Fig. 2.

The obtained $dV/dI$ features can be suppressed by temperature or magnetic field above 1 K or 0.5 T, respectively, see Fig. 3. The positions of both the peaks and resistance switchings are moving to zero current with temperature increase until complete disappearance at 1.2 K, as depicted in Fig. 3(a). Evolution of $dV/dI(I)$ curves with magnetic field is different: the width of the low-current region ($\approx 50\mu$A) is nearly independent of the magnetic field, while the $dV/dI$ switching amplitude is gradually diminishing with the field. In contrast, $dV/dI$ peaks’ positions move to zero in a complicated manner.

The detailed behavior of $dV/dI$ peaks’ positions is shown in Fig. 1 for Au-Ti$_2$MnAl junction for parallel (a) and normal (b) to the interface magnetic fields. For both field orientations, the positions of the peaks are shifting non-monotonously to smaller currents, so the peaks disappear above some value of magnetic field. This value is significantly smaller for the normal field orientation ($\approx 0.2$ T, see Fig. 1(b)), in comparison with $\approx 0.6$ T for the parallel one (a).

To our surprise, not only $dV/dI(I)$ curves are similar for Ni-WTe$_2$ and Au-Ti$_2$MnAl interfaces in Fig. 2, but also $dV/dI$ features show analogous behavior. For Ni-WTe$_2$, $dV/dI$ peaks’ positions are shifting to zero current with magnetic field, the suppression is twice faster in normal field, see Fig. 5.

IV. DISCUSSION

As a result, both Au-Ti$_2$MnAl and Ni-WTe$_2$ junctions demonstrate similar $dV/dI(I)$ characteristics, with hysteresis at low currents and sharp peaks at high ones. Moreover, we observe qualitatively similar evolution of the peaks’ positions with magnetic field for both structures in Figs. 4 and 5. For this reason, the obtained results should have the same origin for these structures. From the experimental point of view, the obtained $dV/dI(I)$ curves are similar to ones for ferromagnetic multilayers.$^{15,21}$

Weyl surface state is the only common characterization of Au-Ti$_2$MnAl and Ni-WTe$_2$ interfaces, since the materials are completely different for the metallic contacts and the semimetals itself: for Au-Ti$_2$MnAl junction we study transport through a magnetically-ordered WSM and a normal metal, while Ni-WTe$_2$ one represents the junction between a non-magnetic WSM and a ferromagnet. Also, strong temperature dependence in the 30 mK–1.2 K range can only originate from the surface, since transport properties of Ni or Au layers and bulk WSM$^{14,35}$ are invariant in this temperature range.

For Au-Ti$_2$MnAl and Ni-WTe$_2$, one side of the junction has significant net spin polarization of carriers (Ni or Ti$_2$MnAl, respectively). We should conclude, that similar $dV/dI(I)$ curves are produced by spin-polarized transport through the Weyl surface state at the interface. In some sense, our experiment resembles ones on ferromagnetic multilayers, where spin-dependent scattering affects the magnetic moments of the spin-polarized layers, while their mutual orientation defines the differential resistance.$^{15-21}$ It might be natural$^{20,29}$, that we observe similar $dV/dI(I)$ characteristics.

Let us start from $dV/dI$ switchings at low currents in Fig. 2. At zero bias, one can expect that spin polarization of some carriers at the WSM surface is aligned parallel to one in the ferromagnet due to the complicated spin texture.$^{20,31}$ on the Weyl surface.$^{2,3,25,26}$ This
allows a direct transport channel even for spin-polarized carriers, which is reflected in low junction resistance at zero bias. While increasing the current through the junction, spin-momentum locking produces a preferable spin polarization in the surface state, which is reflected as sharp $dV/dI$ increase for both signs of the current. As usual, current-induced switchings are accompanied by hysteresis in Fig. 2. Spin alignment disappears at zero bias, when high magnetic field or temperature destroys the spin textures in the topological surface state, see Fig. 3 (a) and (b).

Similarly to the ferromagnetic multilayer, we should identify $dV/dI$ peaks in Fig. 2 as the onset of the current-driven magnon excitations. However, evolution of the peaks’ positions with magnetic field is unusual: the peaks are moving to lower currents in Figs. 4 and 5, which is opposite to the known bulk magnon behavior. Since the peaks disappear simultaneously with $dV/dI$ switchings in Fig. 3 (a) and (b), we should also connect the magnon excitation with spin textures in the topological surface states. However, we have no complete description of the magnon dynamics in Weyl topological surface states, in contrast to the case of topological insulators.

V. CONCLUSION

As a conclusion, we experimentally compare two types of interface structures with magnetic and non-magnetic Weyl semimetals. They are the junctions between a gold normal layer and magnetic Weyl semimetal Ti$_2$MnAl, and a ferromagnetic nickel layer and non-magnetic Weyl semimetal WTe$_2$, respectively. Due to the ferromagnetic side of the junction, we investigate spin-polarized transport through the Weyl semimetal surface. For both structures, we demonstrate similar current-voltage characteristics, with hysteresis at low currents and sharp peaks in differential resistance at high ones. Despite this behavior resembles the known current-induced magnetization dynamics in ferromagnetic structures, evolution of the resistance peaks with magnetic field is unusual. We connect the observed effects with current-induced spin dynamics in Weyl topological surface states.

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