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Josephson diode and spin-valve effects on the surface of altermagnet CrSb

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We experimentally investigate charge transport in In–CrSb and In–CrSb–In proximity devices, which are formed as junctions between superconducting indium leads and thick single crystal flakes of altermagnet CrSb. For double In–CrSb–In junctions, $dV/dI(B)$ curves are mirrored in respect to zero field for two magnetic field sweep directions, which is characteristic behavior of a Josephson spin valve. Also, we demonstrate Josephson diode effect by direct measurement of the critical current for two opposite directions in external magnetic field. We interpret these observations as a joint effect of the spin-polarized topological surface states and the altermagnetic spin splitting of the bulk bands in CrSb. For a single In–CrSb interface, the superconducting gap oscillates in magnetic field for both field orientations, which strongly resembles the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) behavior. FFLO is based on finite-momentum Cooper pairing, therefore, it is fully compatible with the requirements for the Josephson diode effect.

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In altermagnets, the concept of spin-momentum locking was extended to the case of weak spin-orbit coupling [1, 2]. As a result, the small net magnetization is accompanied by alternating spin splitting in the k-space [1, 3, 4]. Consequently, an altermagnet sometimes behaves as an antiferromagnet, and sometimes as a ferromagnet, depending on the crystal-field or interface-crystal relative orientations.

Spin-momentum locking is a key feature not only of altermagnets, but also of a large class of topological materials [5]. In the latter case, it is responsible for the spin polarization of the topological surface states, which are able to carry supercurrents over extremely large distances. In proximity topological devices, spin-polarized surface states lead to the different realizations of the Josephson diode effect (JDE).

The JDE is typically observable for Josephson spin-valves (JSV), where the ferromagnetic multilayer is sandwiched between two superconducting electrodes in vertical [6] or planar geometries [7]. While in conventional Josephson junctions supercurrent is modulated by magnetic flux, in a JSV it is mainly controlled by the relative orientation of magnetic layers, giving rise to the critical current asymmetry and reversal.

The JDE has recently been predicted for junctions incorporating altermagnets [8]. Experimental investigations of the Josephson current asymmetry can be conveniently performed for CrSb, which has recently been identified as a new altermagnetic metal through spin-integrated soft X-ray angular-resolved photoelectron spectroscopy (SX-ARPES) [9]. CrSb reveals both altermagnetic and topological features [10]. Topological surface states have been clearly demonstrated on the (100) cleaved side surface close to the Fermi level originating from bulk band topology in CrSb [11].

CrSb single crystal flakes are obtained by mechanical exfoliation. CrSb is a three-dimensional altermagnet, therefore, one has to select relatively thick (above 1 μm) single crystal flakes with $\approx$100 μm lateral size. The selected flake is placed on the In contact leads. The In–CrSb–In resistance is measured in a standard four-point technique.

Figure 1a shows the effect of the magnetic field for two opposite field sweep directions. While sweeping from $\pm$100 mT magnetic field, the zero-resistance regions are shifted to finite fields $\approx \mp$10–13 mT, as confirmed by the $dV/dI(I)$ curves in Fig. 1b: the differential resistance is finite at zero field value, but there is zero-resistance region at 13 mT magnetic field.

The main experimental finding is the $dV/dI(B)$ curves reversal in Fig. 1a. Indeed, for two magnetic field sweep directions, the $dV/dI(B)$ curves are mirrored in

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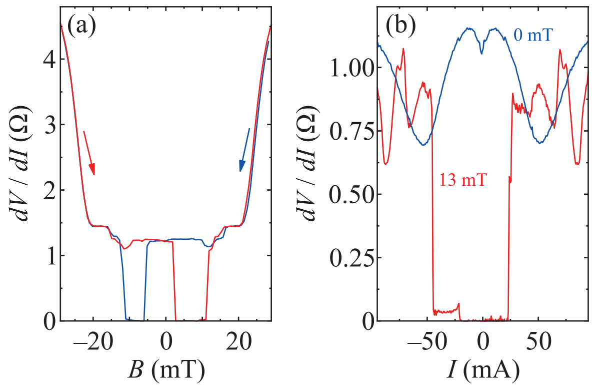

Fig. 1. (Color online) (a) – JSV effect as the $dV/dI(B)$ curves reversal for two opposite magnetic field sweep directions at 30 mK temperature. The zero-resistance region is not only shifted to finite magnetic fields, but the $dV/dI(B)$ curves are mirrored in respect to zero field, including regions with finite resistance. (b) – $dV/dI(I)$ curves after magnetization of the sample. Differential resistance is always finite at zero field now, but there is wide zero-resistance region at 13 mT magnetic field. Magnetic field is directed normally to the In–CrSb interfaces (i.e. to the CrSb flake)

respect to zero field, including regions with finite dV/dI differential resistance.

The spin-valve effect is not so strong in parallel to the In–CrSb interfaces magnetic field orientation. the $dV/dI(B)$ curves are clearly mirrored in respect to zero field (see also the regions of finite resistance), confirming the JSV behavior. Thus, the spin-valve effect is sensitive to the $\pi/2$ rotation of the magnetic field, which resembles the results for CrSb magnetization [12]. Since the JSV usually demonstrate the JDE, we show the $I_c^+(B)$ and the inverted $-I_c^-(-B)$ critical current values, which is the direct demonstration of the JDE.

As a result, double In–CrSb–In not only transfer Josephson current at millikelvin temperatures on the surface of altermagnet CrSb, but also demonstrate prominent Josephson spin-valve and diode effects in external magnetic field.

Since indium is a conventional s-wave superconductor, the observed effects should mainly be associated with the specific properties of the proximized altermagnet CrSb. The observed behavior is a known fingerprint of JSV [6]. Whereas in conventional Josephson junctions the supercurrent is primarily modulated by the magnetic flux through the junction area, in JSV it is largely defined by the relative orientation of magnetic layers, giving rise to the $I_c(B)$ asymmetry and reversal.

It seems to be important that altermagnet CrSb exhibits both altermagnetic and topological features, including topological surface states [10–12]. Due to spin-momentum locking, the topological surface states in CrSb are spin-polarized, in addition to the altermagnetic spin splitting in the bulk bands. This naturally motivates a qualitative description of the In–CrSb–In junction in terms of the JSV scenario with two distinct (surface and bulk) magnetic phases.

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