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Topological insulator based spin valve devices: Evidence for spin polarized transport of spin-momentum-locked topological surface states

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ABSTRACT

Spin-momentum helical locking is one of the most important properties of the nontrivial topological surface states (TSS) in 3D topological insulators (TIs). It underlies the iconic topological protection (suppressing elastic backscattering) of TSS and is foundational to many exotic physics (e.g., majorana fermions) and device applications (e.g., spintronics) predicted for TIs. Based on this spin-momentum locking, a current flowing on the surface of a TI would be spin-polarized in a characteristic in-plane direction perpendicular to the current, and the spin-polarization would reverse when the current direction reverses. Observing such a spin-helical current in transport measurements is a major goal in TI research and applications. We report spin-dependent transport measurements in spin valve devices fabricated from exfoliated thin flakes of Bi_2Se_3 (a prototype 3D TI) with ferromagnetic (FM) Ni contacts. Applying an in-plane magnetic (B) field to polarize the Ni contacts along their easy axis, we observe an asymmetry in the hysteretic magnetoresistance (MR) between opposite B field directions. The "polarity" of the asymmetry in MR can be reversed by reversing the direction of the DC current. The observed asymmetric MR can be understood as a spin-valve effect between the current-induced spin polarization on the TI surface (due to spin-momentum-locking of TSS) and the spin-polarized ferromagnetic contacts. Our results provide a direct transport evidence for the spin helical current in TSS.

1. Introduction

Three-dimensional (3D) topological insulators (TIs) represent an interesting new class of quantum matter hosting spin helical surface states protected by time-reversal symmetry [1–7]. The nontrivial topological surface states (TSS, depicted in Fig. 1a) located inside the bulk band gap feature a characteristic spin-momentum-locking, where charge carriers of a given momentum ($\vec{k}$) are spin polarized in-plane perpendicularly "locked" to $\vec{k}$. For electrons, the spin polarization ($\vec{S}$) is along the direction of $\vec{k} \times \vec{n}$ (σ^- helicity, governed by the left hand rule, depicted in Fig. 1b) with $\vec{n}$ being the surface normal, and holes have the opposite polarization ($-\vec{k} \times \vec{n}$, σ^+ helicity, right handed spin-momentum locking). A directional electrical current (I) carried by such spin-helical TSS would be automatically spin-polarized (noting the spin polarization for a given *current* direction is the same regardless whether the current is carried by electrons or holes, as electron momentum is opposite to the current direction), and its spin polarization reverses upon reversing the current direction (depicted in Fig. 1c,e), or going to the opposite surface (reversing $\vec{n}$). The spin-momentum locking of TSS is the basis of the topological protection (as a backscattering that reverses momentum would have to reverse the spin) and many other exotic physics predicted for TI (e.g. majorana fermions [4,8]), and the expected helical spin-polarized transport makes TI particularly promising for spintronics device applications [4,9–13]. While the existence of the spin-momentum-locked TSS in 3D TIs has been established by spin and angle resolved photoemission spectroscopy (spin ARPES) measurements [14–20], direct demonstration of the spin-helical current (current induced spin polarization) using spin-sensitive transport measurements has been lacking till very recently [21–23], even though various different theoretical proposals have been discussed [9–13]. Previously, the spin valve effect (where a current flows through two ferromagnets (FM) of parallel magnetizations with lower resistance and antiparallel magnetizations with higher resistance) and spin valve devices have been commonly used to study spin transport in various materials

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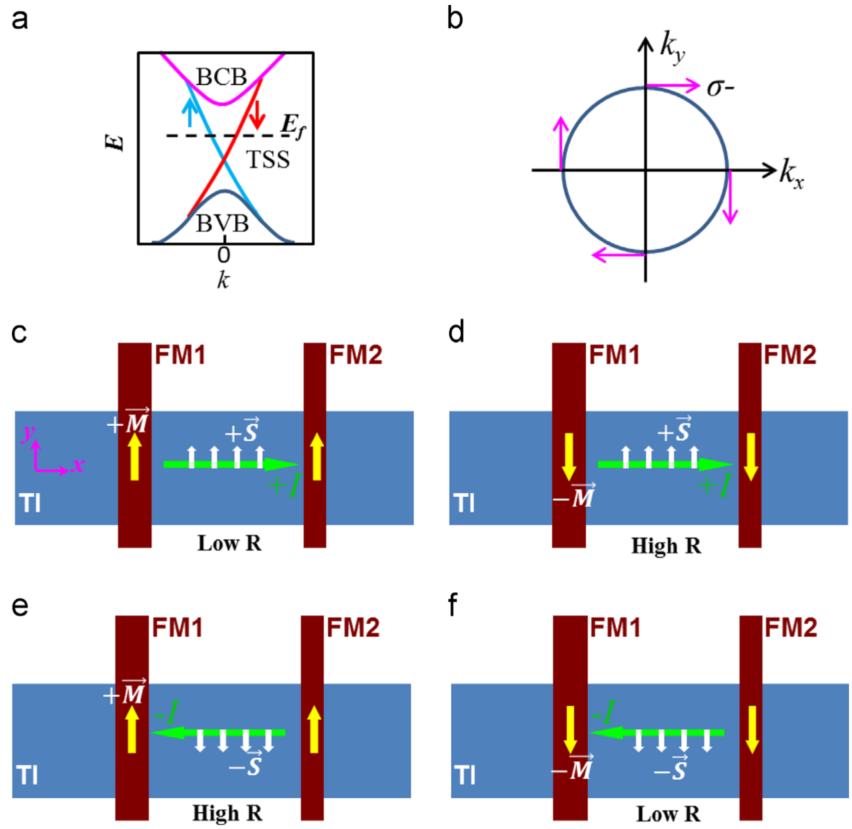

Fig. 1. (Color online) Schematic of the experimental design to probe the spin helical TSS. (a) TI band structure with the bulk conduction band (BCB), topological surface states (TSS, arrows indicating the top surface spin polarization due to spin-momentum-locking), bulk valence band (BVB). (b) Schematic of the electron Fermi surface at top surface, in the k_x–k_y plane of TSS with spin polarization showing σ^- helicity. (c–f) Schematic of a TI-based spin valve device and a TI-FM spin valve effect between the current-induced spin polarization ($\vec{S}$) of TSS (top surface) and magnetic field-induced spin polarization (magnetization, $\vec{M}$) of FM contacts. We expect a lower resistance (R) state if the TSS spin polarization is parallel to the FM magnetization (c,f) and a higher R state if they are anti-parallel (d,e). Reversing the current direction reverses TSS spin polarization and reversing the magnetic field (B, assumed to be sufficiently large) reverses the magnetization of both FM contacts. The resistance is measured between the two FM contacts.

(including metals, semiconductors, and graphene) [24–28]. Inspired by this, we have fabricated TI-based spin valve devices from exfoliated thin flakes of Bi_2Se_3 (a prototype 3D TI [29,30]) with FM (Ni) contact electrodes, and performed spin-valve measurements where the magneto resistance (MR) between two Ni contacts is monitored as a function of an in-plane magnetic (B) field applied to magnetize the Ni contacts along their easy axis (perpendicular to the current). We observe an *asymmetry* in the MR between the opposite limits of *large* positive/negative B field (where both FM contacts are magnetized along a common direction that reverses between the two limits). Furthermore, the "polarity" of this MR asymmetry reverses when the direction of the DC current is reversed. This effect (current-direction-reversible spin-valve MR asymmetry between opposite large B fields) has not been observed in previous spin-valve devices on other materials (where MR is symmetric between opposite large B fields), and can be interpreted as a spin-valve effect between the TI channel (which has a current-induced spin polarization via spin-momentum-locking of TSS) and both FM electrodes (whose common magnetization direction may be parallel or anti-parallel with the TI surface current spin polarization). Our results give a direct transport evidence for the spin helical current of TSS in a 3D TI Bi_2Se_3.

2. Experimental

The high quality bulk Bi_2Se_3 single crystal is grown by the Bridgeman method [31–33]. Thin flakes of 10–20 nm in thickness are exfoliated from the bulk crystal using the standard "scotch tape" method [31,34–35] and are placed on top of heavily doped Si substrates with 300 nm SiO_2. The FM electrodes (Ni, thickness = 40 nm, length ~3 μm, width between 200 nm and 800 nm) crossing and contacting the TI top surface are defined by standard e-beam lithography and deposited by e-beam evaporation. These Ni electrodes are contacted further outside the Bi_2Se_3 flake by Au electrodes fabricated by a second e-beam lithography and evaporation. In this work, we have selected flakes of relatively narrow width (~1 μm) and performed two-terminal spin-valve measurements (resistance between two FM electrodes) using a DC bias current I and an in-plane B field (see Fig. 1c–f for device and measurement schematics). The voltage (V) difference is measured between the FM (Ni) electrodes (labeled by Ni1 and Ni2), and the magnetoresistance (MR) is defined by $R=V/I$. Hereafter, we define $+I$ ($-I$) direction as from Ni1 to Ni2 (Ni2 to Ni1) along $+x$ ($-x$) axis and the positive (negative) in-plane B field points to the $+y$ ($-y$) axis indicated by the green and yellow arrows, respectively, as depicted in Fig. 1c. At a fixed bias current I, we sweep the B field from a sufficiently large positive value (far exceeding the coercive fields of the Ni electrodes, so that both Ni electrodes are magnetized along $+y$ direction, depicted in Fig. 1c) through zero and to a large negative value (both Ni electrodes magnetized along $-y$ direction, depicted in Fig. 1d) and then sweep back again to the starting large positive B field. We then reverse the direction of the bias current and repeat the above measurements (Fig. 1e,f). Results from two devices are presented below.

3. Results and discussions

Fig. 2 shows the results of magnetoresistance measurements in our spin valve device "A", fabricated on a 12 nm-thick exfoliated