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Determination of Out-of-Plane Spin Polarization of Topological Surface States by Spin Hall Effect Tunneling Spectroscopy

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Determining the detailed spin texture of topological surface states is important when one wants to apply topological insulators in spintronic devices. In principle, the in-plane spin component of the surface states can be measured by a method analogous to the so-called Meservey–Tedrow technique. Herein, it is suggested that the out-of-plane spin component can be determined by spin Hall effect tunneling spectroscopy. An analytical formula that allows to extract the out-of-plane spin component from spin Hall effect tunneling spectra is derived. The formula is tested using realistic tight-binding models of Bi_2Se_3 and Sb_2Te_3. It is demonstrated that the extracted out-of-plane spin polarization is in very good agreement with the actual out-of-plane spin polarization.

1. Introduction

Topological insulators (TIs) possess surface states that are protected by the momentum space topology of the material.[1–3] An interesting feature of these surface states is spin-momentum locking, which means that momentum and spin of an electronic surface state are strictly related to each other, i.e., electrons with opposite spin propagate into opposite directions.[4–9] This feature makes TIs interesting materials for spintronic devices.[10–17] In particular, the combination of TIs with ferromagnets promises interesting device applications such as magnetoresistance devices[13,18–20] or spin–orbit torque.[15,16,21,22] It has been demonstrated that TIs can be made ferromagnetic by magnetic proximity effect[23–25] or doping with magnetic impurities.[26–29] Recently, the first intrinsic magnetic TI has been realized experimentally.[30]

In previous work, we have shown that the combination of ferromagnets with TIs provides several interesting opportunities: it is possible to construct spin current generators, detectors, and spin transistors.[14] One can create flat surface bands[31,32] and a magnetically induced Weyl semimetal state can be reached.[32]

For spintronic devices made from TIs, it is important to determine spin texture and degree of spin polarization of the surface states. Experimentally, spin and angle resolved photoemission spectroscopy (SARPES) has been used to measure the spin texture.[6,33–35] However, the values reported for the degree of spin polarization varied strongly.[6,35–37] It was pointed out that the spin of the photoelectrons can be different from the electrons in the topological surface states depending on photon energy and photon polarization.[36,38] Therefore, alternative techniques to determine the spin texture and degree of spin polarization would be valuable.

For ferromagnetic materials, there exists the so-called Meservey–Tedrow technique[39,40] to measure the spin polarization. In this technique, one uses tunneling spectroscopy from a superconducting thin film in a strong external magnetic field. We have recently demonstrated that the Meservey–Tedrow technique can be adapted to TI surface states and allows to measure the in-plane component of the surface state spin polarization.[41] However, the method is insensitive to the out-of-plane component of the spin texture.

In this work, we will show that spin Hall effect tunneling spectroscopy can be used to measure the out-of-plane spin polarization of the topological surface states and thus can complement the Meservey–Tedrow technique to give a complete measurement of the surface state spin texture by tunneling spectroscopy. Spin Hall effect tunneling spectroscopy was introduced by Liu et al.[42] as a means to measure the Spin Hall effect under finite bias voltages. This technique allows to measure the energy dependence of the Spin Hall effect near the Fermi energy of a given metal. It was shown that the charge–spin conversion efficiency of TI surface states can be determined experimentally using this technique.[43]

A schematic of a spin Hall effect tunneling spectroscopy device is shown in **Figure 1**. The main idea is to create a spin polarized current by a ferromagnet and feed it through leads 1 and 3. The spin texture of the surface states then creates a transverse voltage between leads 2 and 4 which depends on the voltage applied between leads 1 and 3. We will show in this work that the out-of-plane component of the spin in the topological surface states can be obtained from a ratio of differential conductances

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