Large Spin Torque in Topological Insulator/Ferromagnetic Metal Bilayers

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While there are several proposals on spintronic applications of the surface state’s helical spin texture in three-dimensional (3D) topological insulators (TI), none has been realized yet. Motivated by recent measurements of spin-transfer torque in heavy metal (HM)/ferromagnetic-metal (FM) structures [1–3], we propose measuring spin-transfer torque in a TI/FM bilayer with in-plane magnetic moment and in-plane current. Based on ARPES experiments on TI/FM bilayers and transport measurements on thin TI films, we focus on the role of two types of surface states: the topological Dirac surface state and an additional two-dimensional electron gas (2DEG) with Rashba spin-orbit coupling. We find that each surface state contributes to both an out-of-plane (field-like) and an in-plane torque. However, the torques due to the topological Dirac surface state and the Rashba-split 2DEG turn out to be in opposite directions. This will allow for the experimental assessment of the dominant source of spin-torque. Finally, we estimate the spin-torque efficiency in TI/FM bilayers to be comparable to that of the HM/FM system opening up exciting prospect for applications.

Introduction – Theoretical proposals for harnessing the helical spin texture of topological surface states of strong 3D TIs [4] so far have focused on TI/ferromagnetic insulator (FI) hybrid structures [5–7]. In these (ideal) TI/FI bilayers, the topological surface state is well defined at the interface between the two insulators and carries all current running through the system. However, room-temperature FIs are scarce. Though YIG is a rare room-temperature FI, it is not suitable for nanoscale fabrication. Furthermore, for certain applications, such as a three-terminal device (magnetic memory), a metallic magnetic material allows for a straightforward (resistive) readout [2, 3]. Finally, the applicability of the ferromagnetic-resonance technique for measuring the spin-torque efficiency [1–3] makes a TI/FM bilayer an attractive system. Hence, we propose the experimental investigation of spin torque due to a current running through a TI/FM bilayer [see Fig. 1(a)] and analyze here the role of the topological surface state and its helical spin texture.

Current-driven manipulation of nanoscale magnetic devices holds great promise for next generation memory devices. One such mechanism relies on a current through a (non-magnetic) material leading to a torque on an adjacent ferromagnetic metal through the spin-Hall effect. The figure of merit for such a device is the spin-Hall angle: a dimensionless ratio of spin-current density perpendicular to charge-current density. This quantity measures the efficiency of spin-torque generation driven by charge current. Such spin-Hall-effect based magnetization switching has recently been demonstrated for Ta- and W-based devices with switching currents \( I < 1 \) mA [2, 3]. However, for practical applications, even higher spin-torque efficiencies (lower switching currents) would be desirable. In this work, we propose using TIs for the torque generation, utilizing the surface state’s spin-momentum locking and predict a substantial spin-torque efficiency.

We need to address two issues in order to establish a simplest theoretical model that captures salient realistic aspects of TI/FM bilayers: (1) the influence of the FM on the TI surface band structure, and (2) the possibility of TI bulk conduction. The first issue arises as the topological surface state is not necessarily protected when the TI is in contact with a metal [8]. However, ARPES results on TIs with thin FM layers on top show a bandstructure as sketched in Fig. 1(b): the topological surface state survives and additional (Rashba-split) surface bands are
formed due to band bending [9–12]. The second issue has to do with the chemical potential of most topological insulators, including Bi$_2$Se$_3$ the to date best studied material [13–16], lying in the conduction band. However, recent experiments showed that surface states dominate the transport for thin Bi$_2$Se$_3$ films of high-quality [17]. Based on these observations we will focus on the topological (Dirac) state with its linear dispersion [thick solid line in Fig. 1(b) and (c)] and the Rashba-split 2DEG (dashed lines in Fig. 1).

To study the spin torque on the FM moments, we proceed in the following in two steps: First, we consider the TI without a ferromagnet, and briefly discuss the non-equilibrium spin density $\langle \vec{S} \rangle_{\text{neq}}$ in the presence of a current in the TI surface (inverse spin-galvanic effect). In a second step, we use this spin density as a boundary condition and analyze the diffusion of the spin density into the ferromagnetic metal and the resulting torque on the FM moments. This two step approach is justified, as long as the chemical potential $\mu_D \gg \Delta_{ex}$, with $\Delta_{ex}$ the exchange coupling of the surface-state spins with the FM moments [situation in Fig. 1(b)]. Note that the presence of spin diffusion makes the TI/FM bilayer different from a TI/FI structure. For the case of a TI/FI bilayer, the spin density merely acts as an effective field coupling to the magnetic moments of the ferromagnet which leads to a torque of the form $\vec{T} = \Delta_{ex} \vec{m} \times \langle \vec{S} \rangle_{\text{neq}}$, with $\vec{m}$ the magnetization direction in the ferromagnet. This thus adds to the torque from the Oersted field (field-like torque) [6]. We will show in the following, that there is an additional perpendicular torque due to the spin diffusion (Slonczewski-like torque [18]).

Dirac state – A TI surface state is described by the Dirac Hamiltonian

$$\mathcal{H}^D_k = v_F (\hat{z} \times \hat{\sigma}) \cdot \vec{k} - \mu_D$$

with $\hat{\sigma}$ the Pauli matrices acting in spin space and $\hat{z}$ is the unit vector in $z$ direction. This leads to the characteristic linear dispersion and spin helicity around the Fermi surface, see Fig. 1(c). The velocity operator $\vec{v} = \partial_k \mathcal{H}^D_k$ is directly proportional to the spin operator $\vec{S} = (\hbar/2) \hat{\sigma}$ and reads

$$\vec{v} = \frac{2}{\hbar} v_F (\hat{z} \times \vec{S}).$$

(2)

While the TI has a vanishing equilibrium spin expectation, any current running through the system leads to a finite spin density independent of the microscopic details of the transport. We consider a current density $j_x = e n \langle \vec{v} \rangle_{\text{neq}}$ in $x$ direction with $e$ the electron’s charge and $n$ the electron density, which yields a spin density

$$\langle S_y \rangle^D_{\text{neq}} = -\frac{\hbar}{2 e v_F} j_x.$$  

(3)

If the magnetic moments of a FI couple to the surface-state spins through $\mathcal{H}_{ex} = -\Delta_{ex} \vec{m} \cdot \vec{S}$ as discussed in

Yokoyama et al. [6], the spin polarization on the TI surface leads to a spin torque of the form $\vec{T} = \Delta_{ex} \vec{m} \times \langle \vec{S} \rangle_{\text{neq}}$. This leads to a field-like torque, which for an in-plane magnetization is out-of-plane. In the next section, we show how spin diffusion into the FM additionally leads to an in-plane torque (Slonczewski-like torque), in a way similar to the spin-current injection in HM / FM bilayers [1–3].

Spin diffusion – Given the spin polarization at the TI surface, Eq. (3), as an input, we consider the diffusion of these spins into the ferromagnetic metal and the torque they thereby exert. The diffusion (in $z$ direction) leads to a steady-state (itinerant) spin density through [19]

$$0 = -\vec{\nabla} \cdot \vec{J}_i - \frac{1}{\tau_f} \langle \vec{S} \times \vec{m} \rangle_i - \frac{1}{\tau_\sigma} \langle \vec{m} \times (\vec{S} \times \vec{m}) \rangle_i - \frac{\vec{S}_i}{\tau_{sf}},$$

(4)

where the spin current (for the $i$th spin component) is given by

$$\vec{J}_i = -D \vec{\nabla} S_i,$$

(5)

with $D$ the diffusion coefficient. The second term in Eq. (4) describes the precession of the spins around the moments of the FM with $\tau_f$ the spin precession time. The third term captures the relaxation of the spin component perpendicular to $\vec{m}$ with $\tau_\sigma$ the spin decoherence time, and the last term is the spin diffusion with time scale $\tau_{sf}$. In the following, we use $\lambda_{sf} = 5nm$ [20] and values for $\lambda_1$ and $\lambda_\phi$ of the order 1nm ($\lambda^2 = D \tau_i$).

We solve equations (4) and (5) requiring no spin current through the outer boundary of the FM, $\vec{J}(d) = 0$, where $d$ is the thickness of the ferromagnetic layer. For the TI/FM interface, we assume that due to the exchange interaction, the itinerant spins of the FM right at the interface align with the spin density of the TI interface, i.e., $\vec{S}(0) = \gamma \langle \vec{S} \rangle_{\text{neq}}$ with $\gamma$ of order one [21]. With these
boundary conditions, the spin distribution in \( z \) direction is given by

\[
\hat{S}(z) = S_{\perp}(z) + iS_z(z) = S_0 \frac{\cosh[k(z-d)]}{\cosh(kd)}
\]

with

\[
k = \sqrt{\lambda_{\parallel}^{-2} - i\lambda_{\perp}^{-2}}.
\]

and \( \lambda_{\parallel}^{-2} = \lambda_{sf}^{-2} + \lambda_{\perp}^{-2} \). \( S_{\perp}(z) \) is the in-plane spin density and \( S_0 \) is the initial spin density \( (d = 0) \), both perpendicular to \( \vec{m} \). Figure 2 shows the in-plane spin density \( S_{\perp} \) perpendicular to the magnetization (solid line) and \( S_z \) along the \( z \) axis (dashed line) for \( d = 8 \text{nm} \). Note that this thickness \( d = 8 \text{nm} \gg 1/k' \) with \( k = k' + ik'' \). Using Eq. (6), we can thus approximate

\[
\hat{S}(z) \approx S_0 e^{-kz} = S_0 \cos k'' z e^{-k' z} + iS_0 \sin k'' z e^{-k' z},
\]

i.e., both components oscillate and decrease exponentially, see Figure 2.

Figure 3(a) shows the torque as a function of the FM layer thickness \( d \). The torque is given by the spatial change of the spin current compensated by the spin relaxation,

\[
\hat{T} = \int_0^d dz \left[ -\partial_z \hat{J}(z) - \frac{1}{\tau_{\text{sf}}} \hat{S}(z) \right].
\]

Given the spin distribution in \( z \) direction of Eq. (6), we find

\[
\hat{T} = S_0 \left( \frac{1}{\lambda_{\phi}^2} - i \frac{D \sinh(kd)}{k} \right) \cosh(kd)
\]

\[
\rightarrow S_0 \left( \frac{1}{\lambda_{\phi}^2} - i \frac{\sqrt{2}}{2} \right) \frac{J_x}{\lambda_{\phi}^2}.
\]

For the limit in the last line, we used \( d \rightarrow \infty \). As expected from the fast decay of the spin density in Figure 2, the torque is ‘deposited’ within only a few nanometers. The total torque exerted on the ferromagnet as a function of the thickness \( d \) thus stays constant with layer thickness.

For the geometry described in Fig. 1(a), the spin polarization perpendicular to the magnetization of the FM is \( \sqrt{2}/2 \) of the total polarization \( (S_y)_{\text{neq}} \), and we find for the thick-FM limit \( (d \gg 1/k') \)

\[
\hat{T} = -\frac{\hbar}{2} \left( \frac{1}{\lambda_{\phi}^2} - i \frac{\sqrt{2}}{2} \right) \frac{J_x}{\lambda_{\phi}^2}.
\]

In analogy to the spin-Hall angle \( \theta_{\text{SH}} = (2eJ_S)/(hJ_C) \), which describes the spin-Hall current per charge current, we define the spin-torque efficiency

\[
\hat{\theta} = \frac{\hat{T}}{J_x \hbar} = -\frac{\sqrt{2}}{2} \frac{D}{v_F} \left( \frac{1}{\lambda_{\phi}^2} - i \frac{\sqrt{2}}{2} \right).
\]

Figure 3(b) shows the ratio of out-of-plane to in-plane spin-torque efficiency as a function of \( \lambda_{\parallel}/\lambda_{\phi} \), and we find for \( \lambda_{\parallel} \sim \lambda_{\phi} \), the two are roughly of the same size.

Using \( \lambda_{\parallel} = \lambda_{\phi} = 1 \text{nm} \), \( \lambda_{sf} = 5 \text{nm} \), \( v_F = 5 \times 10^5 \text{m/s}^{-1} \), and a typical diffusion coefficient \( D = 1 - 10 \text{cm}^2 \text{s}^{-1} \), we find for the in-plane and out-of-plane-torque efficiency \( |\theta_{\perp}| = 0.15 - 1.5 \) and \( |\theta_z| = 0.065 - 0.65 \).

**Rashba-split 2DEG**—The real TI/FM interface not only hosts a topological Dirac state as considered above, but also a Rashba-split 2DEG with a dispersion

\[
\mathcal{H}_k^\text{R} = \frac{k^2}{2m} + \alpha(\hat{\gamma} \times \hat{\sigma}) \cdot \mathbf{k} - \mu_R.
\]

Figure 1(b) shows schematically the combined bandstructure with chemical potentials \( \mu_D > \mu_R > 0 \). Note that according to experiment, both \( v_F \) and \( \alpha \) are positive, such that an alternating spin structure with the spins clockwise on the TI surface state as denoted in Fig. 1(c) is obtained [11]. The spin-torque due to Rashba SOC in the presence of a current has been studied both theoretically [22–24] and experimentally [25], and we use here the result for the non-equilibrium spin density in the strong-spin-orbit-coupling case [23],

\[
(S_y)_{\text{neq}}^\text{R} = \frac{\hbar}{2e} \frac{\alpha J_x}{2E_F^R}.
\]

Together with the Dirac surface state, the total spin polarization yields

\[
(S_y)_{\text{neq}} = (S_y)_{\text{neq}}^\text{D} + (S_y)_{\text{neq}}^\text{R} = \frac{\hbar}{2e} \frac{J_y^D}{v_F} - \frac{\alpha J_x^R}{2E_F^R}.
\]
Note that the contribution of the Dirac and the Rashba surface state are of opposite sign. Using a rough estimate for the current ratio for the two states \( J_D / j_s \approx 0.6 \) [17], \( m\alpha = 2(k_F - k_F') \approx 0.02\AA^{-1} \) and \( E_F \approx 0.2eV \) from ARPES[11], we find \((2E_F)(m\alpha) \approx 5 \times 10^{5}m/s \approx v_F \). Both contributions are roughly of the same magnitude, and potentially cancel each other out.

However, in as long as spin torque is measured, the dominant source between topological Dirac surface state and the Rashba-split 2DEG can be assessed through a direct measurement: The field-like torque coming from the spin polarization will either increase or decrease the field-like torque coming from the Oersted field. For \( v_F, \alpha > 0 \) [11] and assuming a coupling through ferromagnetic exchange, the topological surface state adds to the torque generated by the Oersted field, while the Rashba surface states will weaken the torque. This thus allows for the identification of the TI surface state that dominates the generation of torque.

**Conclusions** — In this work, we analyzed TI / FM bilayers and their potential for magnetic-memory applications based on large spin-torque generation. We propose measuring the spin-torque efficiency of the TI surface states through ferromagnetic resonance as recently done for heavy metal/FM bilayers [1–3, 26]. Considering itinerant spins that diffuse into the FM, we predict both, an out-of-plane (field-like) torque, as well as an in-plane (Slonczewski-like) torque in such TI/FM bilayers. This is in contrast to what is expected of TI/FI bilayer (only field-like torque) and what is found in heavy metal/FM bilayers (primarily Slonczewski-like torque)[1–3, 26]. In our model, both components of the torque originate from the combination of the inverse spin-galvanic effect of the TI surface and spin diffusion into the FM. For metallic TIs, an additional in-plane torque could arise from the bulk spin-Hall effect. As transport is dominated by the surface states for thin TIs[17], we still expect the two components of the torque to be of comparable magnitude [see Figure 3(b)]. For realistic parameters, we predict a spin-torque efficiency of the order of \( |\alpha| \approx 0.1 \). This is comparable to or larger than the largest value of spin-torque efficiency observed to date [1–3, 26]. Therefore, our predictions point to an exciting prospect for TI/FM bilayers in magnetic memory applications.

Finally, we comment on limits of the applicability of our approach to extremely thin FM layers and future directions. As the total spin torque stays constant independent of FM layer thickness for \( d \geq 2nm \), thin FM layers are preferable for device applications. However, our calculation treating the FM layer in z direction to be in the diffusive regime relies on a FM layer that is thicker than its diffusion length. For a device with an FM layer thinner than the diffusion length, the device should be modeled using a quantum Boltzmann approach [27, 28]. This will be a subject of future investigation. However, for the first experimental demonstration of the principle and the potential of the TI/FM bilayer, our simple model can guide ferromagnetic resonance measurements which do not require such thin FM layers.

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