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14. ABSTRACT

In the original proposal, we proposed to study the current-induced spin-orbit torque (SOT) in the uniformly Cr-doped magnetic topological insulator (TI) sandwiched between two different dielectric materials to reveal the origin of the giant SOT. During the research period, we have successfully grown Cr-doped TIs on GaAs substrate with high quality and cap it with Al2O3 layer. The magnetism in the Cr-doped TI is very robust, and it can even reach the quantum anomalous Hall phase at low temperature (see X. Kou et al., Nature Communications 6:8474 (2015)). Then we probed the current-induced SOT in this structure. By depositing an Au gate electrode on top of the

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as of 15-Nov-2018

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Major Goals: Recently, the state-of-the-art spin-transfer-torque memory device technology has been focused on heavy metals (e.g., Pt, Ta) with strong spin-orbit coupling (SOC), which can be used to generate spin-orbit torque (SOT) when passing an in-plane charge current to control the magnetization dynamics in an adjacent ferromagnet layer (e.g., Co, CoFeB). The use of SOT has a great potential to resolve the energy dissipation bottleneck of scaled Nanoelectronics. Topological insulators (TIs), in which the SOC is large enough to invert the band structure, are expected to be the most promising candidates to exploit the SOT when coupled to magnetic materials. However, the relevant knowledge remains quite lacking at this stage. Our previous work on magnetization switching through giant SOT in the TI/Cr-doped TI bilayer heterostructure has equipped us to further explore the mechanism of SOT generated by TIs, which will contribute to the potential application of TIs in novel spintronic nanoelectronics such as ultralow power-dissipation memory and logic devices.

In this project, we have grown the Cr-doped magnetic TI structures to explore the origin of the giant SOT. We aim to answer what mechanism causes the TIs to have a SOT efficiency three orders of magnitude larger than heavy metals. Moreover, we have studied the gate voltage controllability of the SOT in magnetic TI structures, which has great potential applications for gate-controlled, non-volatile spintronic devices. We have also explored the possibility to switch the magnetic moment by scanning the gate voltage in the magnetic TI structure. Our study reveals that TIs generate the giant SOT through the novel mechanism of spin-momentum locked Dirac fermions on the surface and the SOT generated by TIs has very good gate controllability as compared with that generated by heavy metals.

Accomplishments: see attached report

Training Opportunities: Nothing to Report

Results Dissemination: Nothing to Report

Honors and Awards: 1) Yabin Fan has been awarded the FAME Research Center 4th Annual Review Outstanding Poster Award, (Feb. 16, 2016)
2) Yabin Fan has been awarded the Chinese Government Award for Outstanding Self-financed Students Abroad, (Feb. 13, 2015)
3) Xufeng Kou has received the UCLA Electrical Engineering 2015 Outstanding Doctoral Student Award

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Statement of the problem studied

Recently, the state-of-the-art spin-transfer-torque memory device technology has been focused on heavy metals (*e.g.*, Pt, Ta) with strong spin-orbit coupling (SOC), which can be used to generate spin-orbit torque (SOT) when passing an in-plane charge current to control the magnetization dynamics in an adjacent ferromagnet layer (*e.g.*, Co, CoFeB). The use of SOT has a great potential to resolve the energy dissipation bottleneck of scaled Nanoelectronics. Topological insulators (TIs), in which the SOC is large enough to invert the band structure, are expected to be the most promising candidates to exploit the SOT when coupled to magnetic materials. However, the relevant knowledge remains quite lacking at this stage. Our previous work on magnetization switching through giant SOT in the TI/Cr-doped TI bilayer heterostructure has equipped us to further explore the mechanism of SOT generated by TIs, which will contribute to the potential application of TIs in novel spintronic nanoelectronics such as ultralow power-dissipation memory and logic devices.

In this project, we have grown the Cr-doped magnetic TI structures to explore the origin of the giant SOT. We aim to answer what mechanism causes the TIs to have a SOT efficiency three orders of magnitude larger than heavy metals. Moreover, we have studied the gate voltage controllability of the SOT in magnetic TI structures, which has great potential applications for gate-controlled, non-volatile spintronic devices. We have also explored the possibility to switch the magnetic moment by scanning the gate voltage in the magnetic TI structure. Our study reveals that TIs generate the giant SOT through the novel mechanism of spin-momentum locked Dirac fermions on the surface and the SOT generated by TIs has very good gate controllability as compared with that generated by heavy metals.

Summary of the most important results

TIs are a new class of materials which have inverted band structure in the bulk due to the strong SOC [1] and nontrivial topological Dirac fermions on the surface which are protected by the bulk topology order [2-4]. These surface Dirac fermions have the unique spin-momentum locking property, that is, the electron spin is tightly locked perpendicular to the momentum in the **k**-space. When passing a lateral current through the TI material, the spin-momentum locked Dirac fermions will generate a robust spin-polarized current on the surface, which can apply very efficient SOTs to the adjacent magnetic materials. Due to the very strong SOC, together with the topological protection of the surface states from the bulk topology order [2-4], the SOTs generated by TIs are expected to be very large, and that basically leads to our research on SOTs in TI-based magnetic structures.

In our previous work, we have realized the SOT-induced magnetization switching in the TI/Cr-doped TI bilayer heterostructure [5]. The SOT efficiency was measured to be three orders of magnitude larger than those reported in heavy metal/ferromagnet heterostructures [6]. To reveal the mechanism of the giant SOT, we have optimized our magnetic TI growth technique and recently we obtained very high quality uniformly Cr-doped magnetic TI film by molecular beam epitaxy (MBE), which has very robust magnetism and can even reach the quantum anomalous Hall phase at low temperature [7]. Thus, the high-quality magnetic TI film enables us to explore the mechanism of the SOT and its gate-voltage controllability.

In our experiment, a top-gated Hall bar structure made of Au(electrode)/ Al_2O_3(20nm)/$Cr_{0.16}(Bi_{0.50}Sb_{0.42})_2Te_3$(7nm)/GaAs(substrate) has been prepared [8], as shown in Fig. 1(a). The top gate voltage can effectively tune the carrier density at the Al_2O_3/Cr-doped TI interface, and consequently control the net current-induced SOT in the Cr-doped TI layer. As extracted from the second harmonic measurement, the effective spin-orbit field, which is a measure of the SOT, is plotted as a function of the gate voltage V_g in Fig. 1(b). We can clearly see that the SOT strength can be modulated by a factor of 4 within the accessible gate voltage range, which is almost two orders of magnitude larger than that reported in heavy metal/ferromagnet heterostructures [9]. For potential applications, we further investigated the gate voltage effect on the SOT-induced magnetization switching behaviors of the Cr-doped TI film. As shown in Fig. 1(c), we can observe that the gate voltage can dramatically change the switching phase diagram of the magnetic Cr-doped TI when both the in-plane magnetic field and the longitudinal current are applied. This indicates it is possible to switch the magnetic TI layer by scanning the gate voltage when a constant charge current I_dc is applied through the film and an in-plane magnetic field B_y is applied along the current direction. Indeed, in the experiment, we can first prepare the magnetization of the Cr-doped TI layer to be 'down' state at $V_\mathrm{g} = -10\mathrm{V}$ at the X: ($I_\mathrm{dc} = 20\mu\mathrm{A}$, $B_\mathrm{y} = 0.1\mathrm{T}$) point, as illustrated in Fig. 1(d). When we scan the gate voltage V_g from -10V to +3V, we successfully observed that the magnetization is switched from 'down" state to 'up' state (see Fig. 1(d)). Correspondingly, if we prepare the magnetization to be 'up' state at $V_\mathrm{g} = -10\mathrm{V}$ at the Y: ($I_\mathrm{dc} = 20\mu\mathrm{A}$, $B_\mathrm{y} = -0.1\mathrm{T}$) point, we can also switch the magnetization from 'up' state to 'down' state by scanning V_g from -10V to +3V (see Fig. 1(d)). The gate-voltage enabled switching points towards device applications such as electric-field controlled magnetic memories that are compatible with modern field-effect semiconductor technologies. In our work, we have compared the gate control of SOT with the net spin-polarized surface current conducting through the Cr-doped TI film, and the intrinsic spin-torque ratio ϑ_ST from the surface current is determined to be 116, demonstrating the interfacial Dirac fermion origin of the giant SOT.

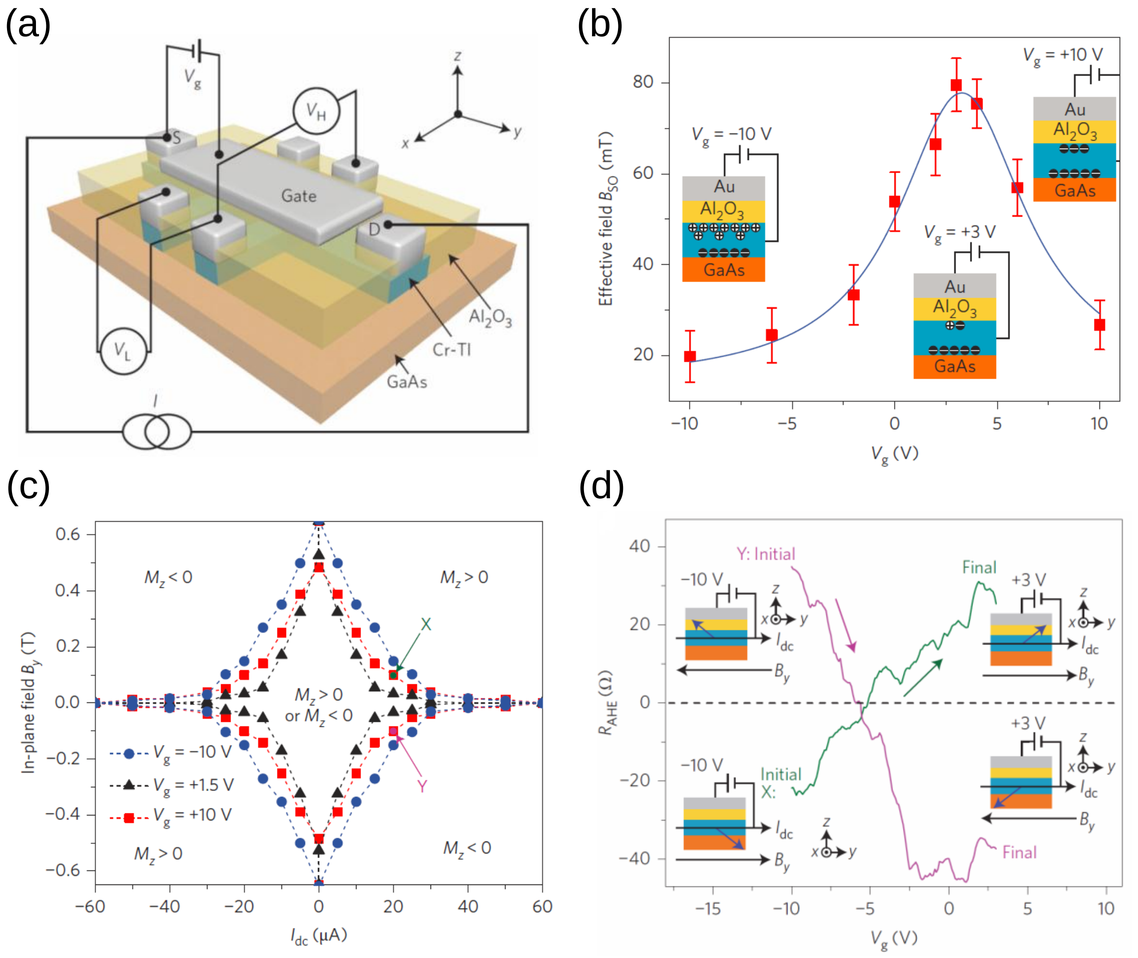

Figure 1. (a), 3D schematic of the Hall bar structure made from the Al_2O_3(20nm)/Cr-doped TI(7nm)/GaAs(substrate) stack with a top gate electrode (light gray). Standard four-point measurement setup is displayed. A gate voltage of V_g can be applied between the top gate and the source contact. (b), Effective spin-orbit field as a function of V_g as measured from experiment. Error bars represent standard errors and blue curves show the Lorentz fitting. Insets show the schemes of surface carrier distributions in the Cr-doped TI layer under $V_g = -10$ V, $V_g = +3$ V, and $V_g = +10$ V. (c), Magnetization switching phase diagrams under $V_g = -10$ V, +1.5 V and +10 V in the presence of both in-plane magnetic field B_y and longitudinal current I_{dc}. The dashed lines and symbols (extracted from experiments) represent the boundaries between different states. (d), Magnetization switching induced by scanning V_g in the presence of constant B_y and I_{dc} for X: ($I_{dc} = 20\mu A$, $B_y = 0.1T$) and Y: ($I_{dc} = 20\mu A$, $B_y = -0.1T$). Insets show the corresponding initial and final magnetization configurations. All the measurements were performed at 1.9K. Figures are adapted from our published work (Y. Fan *et al.*, *Nature Nanotechnology* **11**, 352-359 (2016))

The giant SOT and efficient current-induced magnetization switching exhibited by the magnetic TI materials may lead to innovative spintronic applications such as ultralow power-dissipation memory and logic devices. Our work [5, 8] suggests that the current-induced SOT is very efficient in magnetic TI materials. The corresponding spin-torque ratios are almost three orders of magnitude larger than those reported in heavy metal/ferromagnet heterostructures. The gate electric-field control [8] provides another approach besides the lateral current to harness the giant SOT in magnetic TI materials, which promises potential applications in energy-efficient gate-controlled SOT devices. Since efficient in generating SOT, TIs may also serve as good materials for energy-efficient SOT oscillator applications when coupled with magnetic moment. When combined with CMOS logic circuitry, TI-based SOT devices may also offer efficient non-volatile spin logic circuits. Because TIs are van der Waals materials, they are easy to grow by MBE on a large range of different substrates. Therefore, the feasibility of combining TIs with various magnetic materials and their rich applications will spur further research in the topological spintronics field based on TIs.

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