Towards Field-Free and Ultra-Low Power Spintronic Devices: Leveraging Altermagnetism and Orbitronics

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Current-induced spin-orbit torque (SOT) offers a promising approach for achieving energy-efficient magnetization switching in advanced spintronic devices. However, the technological advancements have been hindered by two key challenges: the requirement of an external in-plane magnetic field for deterministic switching and the need for high switching current density. To address these issues, we have been concurrently investigating two emerging mechanisms: Spin Splitting Effect (SSE) in altermagnets and Orbital Hall Effect (OHE) in light metals. In one study, we explored the potential of a newly emerged altermagnetic material (RuO_2) in combination with a heavy metal (Pt) to achieve both field-free and low-power switching concurrently. We leveraged σ_Z in RuO_2 for field-free switching (FFS) via the SSE and enhanced SOT efficiency by utilizing σ_Y in Pt through spin Hall effect (SHE). A maximized FFS of 82% was observed at an optimized t_{Pt} = 1.5 nm for an applied current density, $J = 2.56 \times 10^{11}$ A/m² (36 % lower than reported) at a crystal angle of $\Theta = 90°$ with respect to the [101] axis. In another study, we investigated Ru/Pt/Co heterostructure, where we utilized combined effects of OHE in Ru and SHE in Pt, to enhance SOT efficiency and reduce the threshold current density. We observed 1.7 times enhancement in SOT efficiently, with an additional 2.5 times improvement upon inserting a seed layer (NiW), compared to a Pt/Co reference sample. We are further interlinking both SSE and OHE to achieve ultra-low power field-free magnetization switching in a single heterostructure. This talk will provide an overview of these two phenomena and their potential use for spin-based devices.

Index Terms—**Altermagnet, spin-splitting effect, orbital Hall effect, field-free switching, spin-orbit torque.**

I. Introduction

The advancement of emerging spintronic devices relies on the ability to control their magnetization in a reliable and energy-efficient manner. Over the last decade, SOT has emerged as an efficient approach for ultra-fast magnetization switching in heavy metal (HM)/ferromagnetic (FM) heterostructures. In the SOT mechanism, a charge current is converted into a spin current in the HM layer via SHE [1]. The generated spin current then flows orthogonally to the charge current and exerts a torque on the adjacent FM layer. Over the past few years, SOT driven magnetization switching in perpendicular magnetized devices has been widely investigated, but an external in-plane magnetic field is commonly needed for deterministic switching.

Various techniques, such as utilizing interlayer coupling, exchange coupling, structural asymmetry, and tilted magnetic anisotropy, have been proposed to achieve FFS. However, these techniques are not industry friendly due to large current requirement and complex device structures. Recently, a new class of magnetic materials called altermagnets have emerged that combine the benefits of both ferromagnetic and antiferromagnetic materials. In this class of materials, RuO_2 has been found to exhibit σ_Z spin polarization, owing to its SSE. Both theoretical and experimental studies have shown that the spin-polarization tends to align with Neel vector along [001] axis, regardless of the direction of applied current. As such, by tilting the Neel vector through a specific crystal growth, the direction of spin polarization can be controlled, enable the generation of σ_Z spin current and hence the FFS. Bose et al. demonstrated that RuO_2 deposited on TiO_2 substrates of different orientation can result in perpendicular, in-plane, and canted vector with respect to the surface normal to the unit cell. Karube et al. investigated the role of σ_Z for FFS in RuO_2/Ru/Co heterostructure by utilizing tilted spin polarization. They observed FFS efficiency of 75% at $J \approx 3.5 \times 10^{11}$ A/m², achieved through the SSE in RuO_2. Therefore, further improvements in FFS efficiency are required to meet the demands of energy-efficient, next-generation spintronic devices.

Besides this, another challenge hindering the development of SOT-based perpendicular magnetized device is the large current density for magnetization switching. Two independent studies reported the highest spin Hall angle (SHA) values of 0.62 and 0.64 for tungsten (W) in W/CoFeB/MgO heterostructures as a single-layered HM material. To further enhance SOT switching efficiency, various approaches have been explored, including ion implantation, self-induced SOT from ferromagnetic materials, alloying of heavy metal materials, and multilayered HM structures. However, many of these techniques are not suitable for large-scale production. Therefore, sustained research efforts are required to make SOT-based devices more efficient and viable for commercial applications.

Recent theoretical calculations showed that the OHE in certain materials with weak SOC can have higher orbital Hall conductivity (OHC) than spin Hall conductivity (SHC) of mostly used elements in the field of spintronics. However, the orbital current generated from OHE cannot directly interact with local magnetization of magnetic materials. Instead, OHE needs an intermediate material with strong SOC to convert I_{OH} to I_{SH}. Therefore, we need two materials with weak SOC and strong SOC to fully utilize the potential of OHE. It has been demonstrated that materials with strong SOC can exhibit large

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SHE. Hence, by choosing right combination of materials to form a heterostructure, it is possible to synergistically harness both OHE and SHE to obtain giant SOT efficiency.

In this talk, we will provide an overview of these two emerging phenomena: SSE and OHE. By combining SSE from RuO_2 and SHE from Pt, we achieved 36% reduction in the switching current density, and a 82% enhancement in the FFS as switching percentage. In another study, we explored combined effects of OHE in Ru and SHE in Pt and obtained giant enhancement in SOT efficiency.

II. Results and Discussions

A. *Enhanced Field-Free switching via σ_Z Spin Polarization*

RuO_2 is an altermagnetic metallic oxide with a rutile-type crystal structure. Fig. 1 (a) shows the crystal structure of RuO_2 unit cell, where antiferromagnetically coupled Ru atoms surrounded by octahedrally coordinated oxygen atoms. We deposited RuO_2(101) layer epitaxially on a single crystal Al_2O_3 ($1\bar{1}02$) substrate using DC/RF sputtering. The crystallinity of RuO_2 (101) has been confirmed by XRD measurement (Fig. 1(b)). Later, we deposited Pt(1.2, 1.5, 1.7 and 2 nm)/Co(1 nm)/Ru(2 nm) films and investigated switching dynamics.

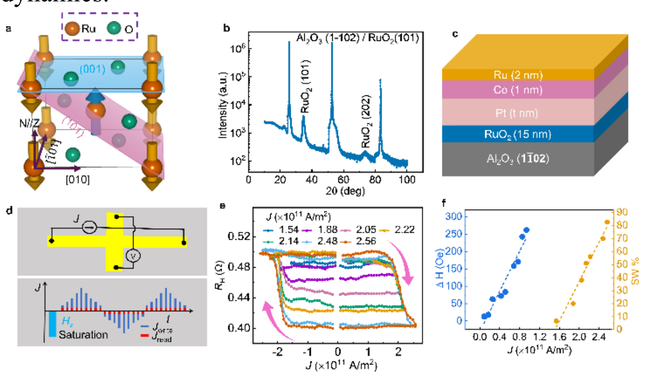

Fig. 1 (a) Crystal structure of RuO_2 unit cell. (b) Gonio scan (θ-2θ) showing crystallinity of sputtered RuO_2 film. (c) Schematic of stack structure. (d) Experimental schematic for SOT-driven switching. (e) R_H vs J switching loops at various ranges of J. (f) Variation of ΔH and SW% as a function of different applied J.

Based on the results of magnetic hysteresis loop-shift measurements, we first investigated SOT-driven switching experiments on Hall bar devices with t_{Pt} = 1.5 nm. Fig. 1(d) illustrates experimental schematic and protocol of the measurements. Initially, we saturated the device to a positive magnetization state and swept pulse currents in absence of external in-plane magnetic field, along a 90º angle with respect to RuO_2 [101] and measured the AHE signal. Fig. 1 (e) shows switching loops over the entire applied range of J values without any external in-plane field, confirming the presence of FFS. Fig. 1(f) shows SW% increases with increasing J, probably due to enhancement of both SHE and SSE. We have attained a maximum SW% of 82 at J = 2.56 × 10^{11} A/m^2, The SW% is higher compared to reported values of 70 and J is also 36% lower compared to reported values for RuO_2 only as a spin source [2].

B. *Giant SOT via leveraging both OHE and SHE*

In another study, we achieved an enhancement in the SOT efficiency and reduction in the switching current density by utilizing combined effects of SHE and OHE. We deposited sample stacks of S1: Ta(1)/Ru(4)/Pt(1.5)/Co(1.1)/Ru(2) and S2:Ta(1)/NiW(2)/Ru(4)/Pt(1.5)/Co(1.1)/Ru(2) using DC magnetron sputtering (Fig. 2(a)). Here, bottom Ru layer has strong orbital Hall conductivity and generates an I_{OH} [3]. The generated I_{OH} then converts into spin current upon traverses through an intermediate Pt layer due to its strong spin-orbit coupling as depicted in Fig. 2(b). Additionally, Pt itself generates I_S. Hence, combining both I_{OH} and I_s can lead to a giant SOT efficiency.

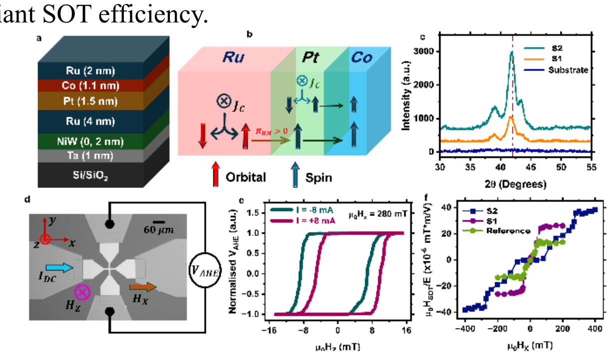

Fig. 1(a) Schematic of stack structures. (b) Schematic representation of spin and orbital torque generation in Ru/Pt/Co heterostructure. (c) XRD plot of bare substrate and samples with Ru as OHL deposited below Pt layer. (d) Schematic of loop-shift measurement setup. (e) Shift in the hysteresis loops for sample S2 by applying a DC of ±8 mA in the presence of an in-plane field of μ_0H_X. (f) Comparison of the slope μ_0H_{SOT}/E as a function of μ_0H_X.

We characterized damping-like torque efficiency ξ_{DL}^{E} using current induced loop shift measurements on Hall bar devices to quantify the effective field. For this experiment, we applied a constant DC while varying an out-of-plane magnetic field and recorded R_H vs H_z loop. As shown in Fig. 2(c), +8 mA (-8 mA) DC produces a significant shift in the hysteresis loop. This shift can be attributed to the effective field arises from both spin and orbital Hall effects. Further, we calculated H_{SOT}/E as a function of H_x, where E is the electric applied to the device. As shown in Fig. 2(e), we observed 1.9-fold enhancement by utilizing the OHE of Ru and a 2.7-fold enhancement by improved OHE of Ru using NiW seed layer.

Conclusions

We investigated both the SSE and OHE in two separate studies to address the issues of in-plane field requirement and high-power needed for switching. In one study, We leveraged σ_Z in RuO_2 to achieve FFS via SSE and enhanced SOT efficiency by utilizing σ_Y in Pt through SHE. In another study, we utilized the combined effects of OHE in Ru and SHE in Pt, to enhance SOT efficiency and reduce threshold current density.

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