Efficient Orbital Torque in Polycrystalline Ferromagnetic-Metal/Ru/Al_2O_3 Stacks

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Introduction

The efficient current-induced spin torque is significant for developing spintronic memory and logic devices. In the last decade, there has been much interest in spin-orbit torque, which utilizes the spin-orbit coupling (SOC) in the heavy metal (and/or Rashba interface) to generate spin current and resultant torque effects in the adjacent ferromagnetic layer [1-2]. Recently, great interest has emerged on the torque effect based on orbital angular momentum injection and the SOC in the ferromagnet called orbital torque (OT) [3-6]. While spin current carries at most $\hbar/2$ angular momentum with each electronic state, the angular momentum carried with a state in an orbital current is not limited. Also, the orbital current generation does not require SOC. Hence, strong orbital current generation exists in a wide variety of materials, making the OT an attractive candidate for the operation mechanism of practical spintronic devices.

Industrial on-silicon production requires the development of OT devices based on polycrystalline stacks. Experimentally, OT was observed in polycrystalline stacks prepared by room temperature evaporation or sputtering [3-5]. However, the commonly used orbital transport layers are Pt and Cu. The large SOC of Pt [5] would hinder the orbital transport. The Cu with a filled *d*-shell [4] cannot support orbital transport theoretically, and it is shown that the orbital transport in Cu is related to the oxidation of Cu, which would lead to a complex non-uniform layer structure, seriously complicating the analysis of OT in polycrystalline stacks. It is highly warranted to obtain efficient long-range orbital transport in a uniform polycrystalline layer, which remains elusive.

Experiment

The current-induced torque effect in polycrystalline ferromagnetic metal (FM)/Ru/Al_2O_3 stacks is experimentally studied [Fig. 1]. FM(t_F)/Ru(t_{Ru})/Al_2O_3(2), FM(t_F)/Ru(t_{Ru}) and FM(t_F)/Pt(1)/Ru(t_{Ru})/Al_2O_3(2) multilayers (thickness in nm) were grown on a Si/SiO_2 substrate at room temperature, where FM = $Co_{40}Fe_{40}B_{20}$ (CoFeB) or $Ni_{81}Fe_{19}$ (NiFe). Ru is chosen because of its electronic distribution of $4d^75s^1$ and a small bulk-originated spin-orbit torque. The unfilled *d* shell ensures that the orbital current generation is allowed by the orbital hybridization, and the orbital current propagation is not limited by the absence of *d* electrons at the Fermi level. The weak SOC prevents the SOC-related orbital relaxation, and the interference from the conventional spin Hall torque. The current-induced torque effect is studied by spin-torque ferromagnetic resonance (ST-FMR).

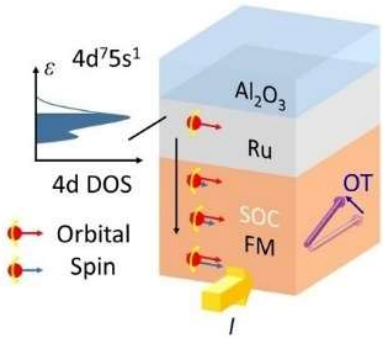

Fig. 1 OT in FM/Ru/Al_2O_3

Results and Discussion

A large symmetric component S is observed in the ST-FMR spectrum for the CoFeB(7)/Ru(6)/Al_2O_3(2) stack [Fig. 2], demonstrating a large current-induced torque effect. A large torque efficiency j_s/j_c (the ratio between the spin current density and the charge current density) = ξ_{FMR} ~0.15 is obtained. If the CoFe is replaced by NiFe or the Al_2O_3 capping layer is removed, the torque efficiency dramatically decreases. The strong torque efficiency dependence on the FM materials is attributed to the relatively larger SOC of the CoFeB than that of the NiFe. these results also reveal that the Ru/Al_2O_3 interface is essential to the OT generation.

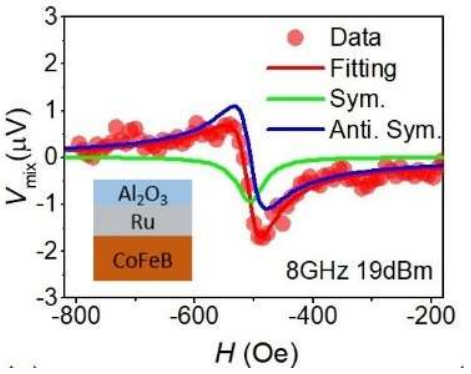

Fig. 2 ST-FMR result of CoFeB(7)/Ru(6)/Al_2O_3(2)

The torque efficiency of CoFeB(t_F)/Ru(6)/Al_2O_3(2) with various CoFeB film thicknesses (t_F = 4.8–17.8 nm) are presented in Fig. 3. $|\xi_{FMR}|$ increases with the CoFeB layer thickness and reaches a saturation value ~ 0.3 at t_F = 12.6 nm. These results well match with the long propagation length of the orbital current in FM. In controlled sample with FM = NiFe, no FM thickness dependence was observed. Fig. 4 shows the measured ξ_{FMR} as a function of Ru thickness in CoFeB(7)/Ru(t_{Ru})/Al_2O_3(2) samples (t_F = 1.2–9.2 nm). When Ru is thin, the absolute value of ξ_{FMR} enhances with increasing Ru thickness. When t_{Ru} = 7 nm, $|\xi_{FMR}|$ reaches a maximum of 0.18; further increase in t_{Ru} makes decrease of $|\xi_{FMR}|$. These results can be well interpreted by the orbital Rashba effect at the Ru/Al_2O_3 interface, with a competition between the quality enhancement of the Ru/Al_2O_3 interface and the orbital relaxation with increasing Ru thickness.

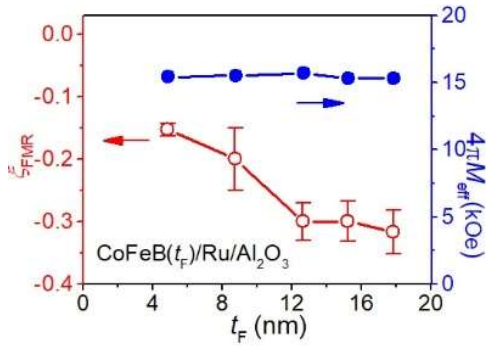

Fig. 3 CoFeB thickness dependence of the torque efficiency.

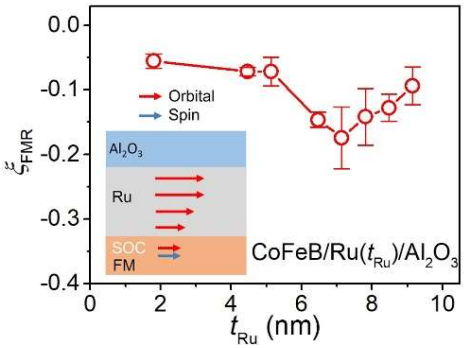

Fig. 4 Ru thickness dependence of the torque efficiency.

Finally, the orbital Rashba effect and the orbital transport were modeled using tight-binding method and quantum evolution equation. The tight-binding model was developed considering the d_{xz}, d_{yz}, d_{xy} orbits in the Ru 4d states, which hybridized with the p_x, p_y orbits in the O 2p states. As typical two-dimensional lattices, both square lattice and diamond lattice were studied [Fig. 5]. It is found that the diamond lattice can generate larger orbital Rashba effect due to richer orbital hybridization. The calculated effective orbital Hall conductance is at the order of 10^3 to 10^4 ($\hbar/2e$) $\Omega^{-1}\cdot cm^{-1}$, comparable to the experimental value 6×10^3 ($\hbar/2e$) $\Omega^{-1}\cdot cm^{-1}$ for CoFeB(12.6)/Ru(6)/Al_2O_3(2). The quantum evolution

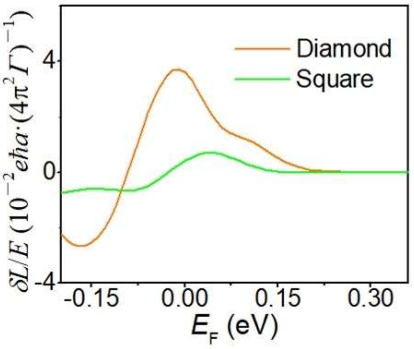

Fig. 5 Orbital Rashba effect calculated based on tight-binding model.

equation $|\psi(t+\delta t)\rangle = exp(-i\frac{\hat{H}}{\hbar}\delta t)|\psi(t)\rangle$ on a one-dimensional (1D) atom chain was studied with a Hamiltonian consists of the crystal field Δ and hopping terms. The wave function distributes on d_{yz} and d_{xy} orbitals on each atom, whose superposition forms orbital angular momentum along the y-axis. In single crystals, the crystal field Δ drives orbital procession and makes orbital angular momentum dephasing. However, it is found that long range orbital transport can be achieved even with a sizable crystal field in random crystal field case, which mimics the polycrystalline sample [Fig. 6]. This effect is due to the random precession of the orbital angular momentum compensates the precession on different atoms. This result indicates that polycrystalline structures are more favorable in terms of the orbital transport than the single crystalline structures for a certain material.

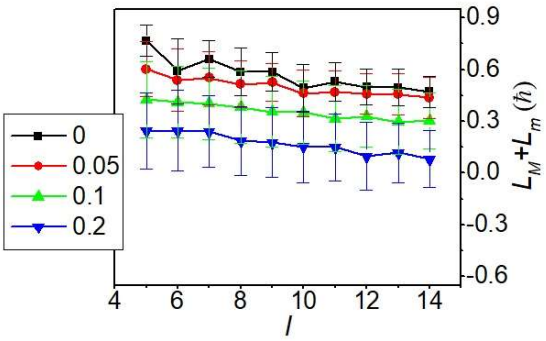

Fig. 6 Orbital transport calculated by one-dimensional (1D) quantum evolution equation. $L_M + L_m$ represent the orbital transport efficiency, l is the atom number of the 1D chain, Δ from 0 to 0.2 eV is the crystal field.

Conclusion

The OT effect is demonstrated in the polycrystalline FM/Ru/Al_2O_3 stack, which is mediated by the efficient long-range orbital transport in the uniform polycrystalline Ru layer. The FM thickness and Ru thickness dependence indicate the orbital Rashba effect is a main underlying mechanism for the torque generation. The orbital Rashba effect is studied with the tight-binding model and orbital transport is modeled by quantum evolution simulation, and the experimental results are reproduced by the numerical calculation. Our results show that transition-metal-based materials with small SOC, simple crystal structure, and itinerant *d* electrons can provide a suitable platform for studying orbital transport and developing devices.

Reference

[1] L. Liu, et al, Science **336**, 555 (2012).
[2] C. Song, et al, Prog. Mater. Sci. **118**, 100761 (2021).
[3] X. Chen, et al., Nat. Commun. **9**, 2569 (2018).
[4] J. Kim, et al., Phys. Rev. B **103,** L020407 (2021).
[5] S. Ding et al., Phys. Rev. Lett. **125**, 177201 (2020).
[6] D. Go, et al., Phys. Rev. Lett. **121**, 086602 (2018).

Publication

L. Y. Liao*, F. H. Xue*, L. Han, J. Kim, R. Q. Zhang, L. Li, J. M. Liu, X. F. Kou, C. Song, F. Pan, and Y. Otani, Efficient orbital torque in polycrystalline ferromagnetic-metal/Ru/Al_2O_3 stacks: Theory and experiment, Phys. Rev. B 105, 104434 (2022).