

Orbital Angular Momentum Correlated Charge to Spin Conversion in Metallic Antiferromagnet

Zhiqiang Zhu, Lu Cheng, Xiaoguang Xu,* Kangkang Meng, Jingyan Zhang, Xiao Deng, Tao Zhu, Hualiang Lv, Renchao Che,* Dingfu Shao, Delin Zhang, Yong Wu, Gang Zhang, and Yong Jiang*

Current-induced spin-orbit torque (SOT) allows efficient electrical manipulation on magnetization in spintronic devices. Maximizing the SOT efficiency is a key goal that is pursued via increasing the net spin generation and accumulation. However, spin transport in antiferromagnets is seriously restricted due to the strong antiferromagnetic coupling, which blocks the development of antiferromagnetic-based devices. Here, a significant enhancement of SOT efficiency in Ir₂₀Mn₈₀ (IrMn)-based heterostructure associated with the orbital effect of naturally oxidized Cu (Cu*) bottom layer is reported. Considering the weak spin-orbit coupling of Cu*, the enhancement results from an orbital current generated from charge current at the Cu*/IrMn interface that contributes to spin current in the IrMn layer due to the strong spin-orbit coupling. The SOT efficiency variation with IrMn thickness reveals the process of orbital angular momentum (OAM) transportation and conversion. Moreover, the contribution of orbital current is verified by the critical current density decreasing of SOT-driven magnetization switching in Cu*/IrMn/[Co/Pt]₃ heterostructure. This study opens a path to design high-efficient SOT-based spintronic devices combining the advantages of OAM and metallic antiferromagnets.

1. Introduction

Over the past decades of research, spintronics has offered means to utilize current-induced spin torques for data storage with nanomagnets.^[1,2] Following spin-transfer torque,^[3–5] spin-orbit torque (SOT) is a popular method to manipulate the magnetization of magnetic materials.^[6–9] High-efficient SOT-based spintronic devices require large conversion ratio of charge current to spin current, which can be realized by exploring possible materials and mechanisms. Metallic antiferromagnets (AFMs) including heavy elements (AFM*) are desirable candidates for SOT devices due to the strong spin-orbit coupling (SOC), which has been proved by the large SOT efficiencies in IrMn^[10] and PtMn.^[11] Apart from these traditional AFM*, Mn₂Au, RuO₂ and noncollinear antiferromagnetic Mn₃X (X = Ge, Sn, Ga, Ir, Rh, and Pt) also show considerable spin Hall effects (SHE),^[12–16] which

Z. Zhu, L. Cheng, X. Xu, K. Meng, J. Zhang, X. Deng, Y. Wu, Y. Jiang
School of Materials Science and Engineering
University of Science and Technology Beijing
Beijing 100083, China
E-mail: xgxu@ustb.edu.cn; yjiang@ustb.edu.cn

X. Deng, T. Zhu
Beijing National Laboratory for Condensed Matter Physics and Institute of Physics
Chinese Academy of Sciences
Beijing 100190, China
H. Lv
Shanghai Frontiers Science Research Base of Intelligent Optoelectronics and Perception
Institute of Optoelectronics
Fudan University
Shanghai 200433, China

 The ORCID identification number(s) for the author(s) of this article can be found under <https://doi.org/10.1002/adma.202418264>

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R. Che
Laboratory of Advanced Materials
Shanghai Key Lab of Molecular Catalysis and Innovative Materials
Academy for Engineering & Technology
Advanced Coatings Research Center of Ministry of Education of China
Fudan University
Shanghai 200438, China
E-mail: rcche@fudan.edu.cn

D. Shao
Key Laboratory of Materials Physics
Institute of Solid-State Physics
HFIPS
Chinese Academy of Sciences
Hefei 230031, China

D. Zhang, Y. Jiang
Institute of Quantum Materials and Devices
School of Electronic and Information Engineering
State Key Laboratory of Separation Membranes and Membrane Processes
Tiangong University
Tianjin 300387, China

G. Zhang
Yangtze Delta Region Academy of Beijing Institute of Technology (Jiaxing)
Jiaxing 314019, China

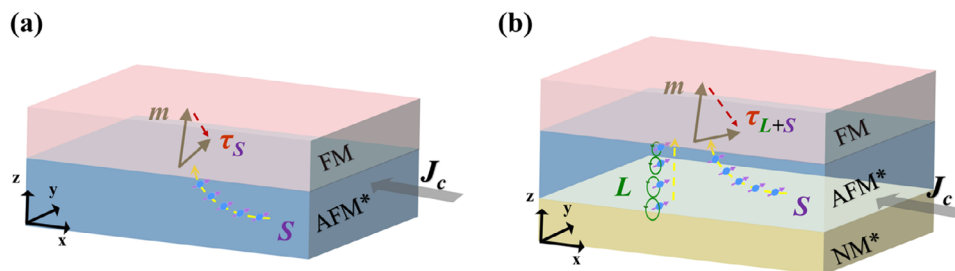


Figure 1. Schematic illustration of the SOT effect and charge to spin conversion mechanism in metallic antiferromagnets including heavy elements (AFM*) heterostructures. a) The schematic diagram of AFM* generating spin current and exerting torque on the adjacent magnetic layer. b) The schematic diagram of the mechanism for additional torque exerted by orbit currents, which is generated from some kind of normal metal (NM*) layer and transports through the AFM* layer.

enables possible applications of AFMs in SOT devices (Figure 1a). In addition, by forming the exchange bias (EB) with the ferromagnetic functional layer, SOT-driven field-free magnetization switching can also be achieved, where the interfacial exchange bias field serves as an auxiliary field.

The so-called orbital Hall effect (OHE)^[17] was first reported theoretically in p-doped silicon. Analogy to SHE,^[18–20] OHE refers to a flow of orbital angular momentum (OAM) generated perpendicular to the charge current.^[21–24] OAM was commonly believed to be quenched owing to the crystal field and raised only weakly through spin–orbit coupling (SOC) in spin-split materials. However, recent research has proved that OAM can arise widely in metals with weak SOC.^[21,23,25–27] Similar to spin angular momentum (SAM), the magnetization of magnetic materials can also be manipulated by OAM, although the nonequilibrium orbital currents only interact indirectly with magnetic moments through SOC.^[21,28–32] This torque caused by OAM is comparable in magnitude to the SOT generated by heavy metals, such as Pt.^[33] Accordingly, the effect of OAM on the adjacent magnetic layer becomes an important topic in spintronics and attracts great attentions.^[28,31,34–35] However, the interaction mechanism between OAM and AFMs is still blank. It was theoretically demonstrated that the intrinsic SHE in many materials^[21,36] is efficiently converted by OHE when spin–orbit coupling is sizable. And the relative sign between the OHE and SHE generally depends on the correlation $\langle \mathbf{L} \cdot \mathbf{S} \rangle$. Here, $\mathbf{L}$ denotes the OAM near nuclei and $\mathbf{S}$ is the operator of spin. Thus, the spin and orbit of the electron are inseparable. As shown in Figure 1b, when the OAM is generated by some kind of normal metal (NM*) layer and injected into the adjacent AFM* layer, it is supposed to become dephased through the AFM* layer and transfers to spin current during the diffusion process with SOC. The converted spin current finally exerts an additional torque on the adjacent magnetic layer. Considering OAM is a highly efficient charge to spin conversion media to drive the SOT-induced magnetization switching, it is important to clarify the transport and related mechanism of OAM in AFM* to accelerate the design of high-efficient OAM-facilitated AFM-based SOT devices.

This study focuses on the charge to spin conversion due to the OAM transport and conversion in the antiferromagnets $\text{Ir}_{20}\text{Mn}_{80}$ (IrMn) and the effects on the SOT efficiency based on the $\text{Cu}^*/\text{IrMn}/\text{Co}/\text{Pt}$ heterostructure. The partially oxidized light metal Cu (denoted by Cu^* hereafter) serves as the source of OAM, which has been widely employed among the studies in the area

of spin orbitronics.^[28,31,34,35,37] And the OAM generated by Cu^* layer was mainly attributed to the mechanism of the interfacial orbital Rashba–Edelstein effect (OREE).^[30,32,35] Moreover, the OAM is employed to facilitate the SOT-driven magnetization switching in $\text{Cu}^*/\text{IrMn}/[\text{Co}/\text{Pt}]_3$ devices. This study clarifies the orbital angular momentum correlated charge to spin conversion in metallic antiferromagnet and provides a possible way to design high-efficient SOT devices combining the advantages of AFMs and OAM.

2. Results and Discussion

In the transport measurements, the Hall bar devices are fabricated based on the multilayers with a stacking structure of $\text{Cu}^*(3)/\text{IrMn}(t)/\text{Co}(0.8)/\text{Pt}(1)$ ($t = 1–5$, thickness in nanometer). Since the transport properties of spintronic devices are sensitive to the interfacial structure, it is necessary to characterize the structure of multilayers before the electrical measurements. As shown in Figure 2a, the cross-sectional image of $\text{Cu}^*(3)/\text{IrMn}(3)/\text{Co}(0.8)/\text{Pt}(1)$ sample was observed by using the high-angle annular dark-field scanning transmission electron microscope (HAADF-STEM). The corresponding energy dispersive spectrometer (EDS) mapping images in Figure 2a show the distribution of the Cu, Ir, Mn, Co, and Pt elements and demonstrate the clear layered structure of $\text{Cu}^*/\text{IrMn}/\text{Co}/\text{Pt}$ multilayer. Moreover, to further clarify the magnetic configuration of IrMn layer, we have also characterized the samples of $\text{Cu}^*(10)/\text{IrMn}(5)/\text{Al}_2\text{O}_3(5)$ by using polarized neutron reflectivity (PNR) measurements. Figure 2b shows the splitting between the spin-up and spin-down neutrons corresponding to the magnetic contribution from the in-plane direction of stacking layers, as the PNR is only sensitive to in-plane magnetization. By fitting the PNR results, the nuclear scattering length density (nSLD) and magnetization scattering length density (mSLD) are presented in Figure 2c as a function of the neutron incidence depth. Here, the nSLD and mSLD represent the chemical and magnetization profiles, respectively. According to the PNR results, the Cu^* layer is confirmed to have an oxidation gradient from CuO to Cu_2O from top to bottom due to the shortage of oxygen atoms. The IrMn layer is proved to be antiferromagnetic with no obvious uncompensated magnetic moments at the interfaces even when the thickness is up to 5 nm. This is consistent with the absence of significant EB in subsequent magnetic hysteresis and electrical transportation measurements.

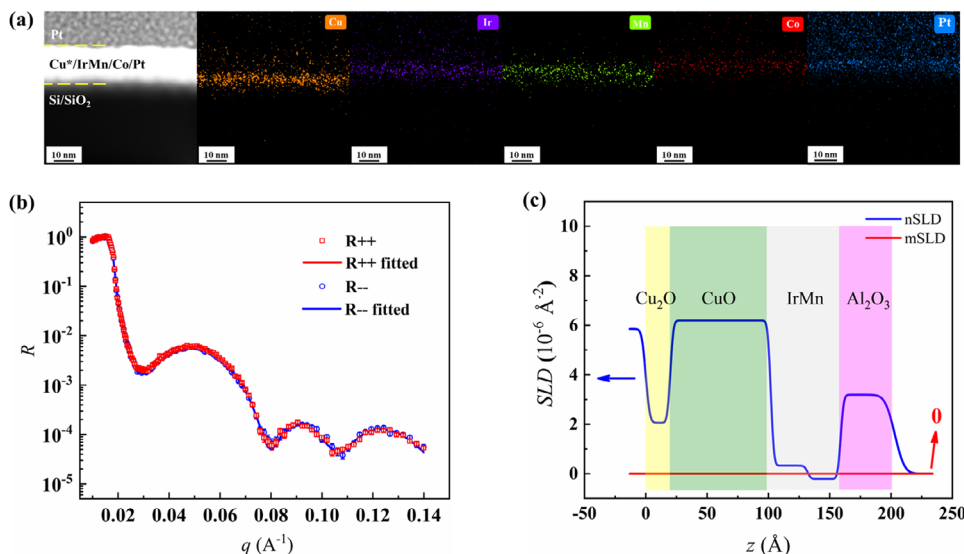


Figure 2. a) Cross-sectional HAADF-TEM image of Cu* (3)/IrMn (3)/Co (0.8)/Pt (1) multilayer and the EDS mappings corresponding to this TEM image. b) The polarized neutron reflectivity (R++ and R-) of the Cu* (10)/IrMn (5)/Al₂O₃ (5) multilayer as a function of wave factor (q). c) Nuclear scattering length density (nSLD) and magnetization profiles (mSLD) of the Cu* (10)/IrMn (5)/Al₂O₃ (5) multilayer.

Harmonic Hall measurement is a convincing method to characterize the SOT efficiency,^[38] which is applicable to quantitatively demonstrate the OAM transportation in AFM* layer and its further effect on the adjacent magnetic layer. In this study, the stacking structures of Cu*(3)/IrMn (t)/Co (0.8)/Pt (1) were employed with IrMn (t)/Co (0.8)/Pt (1) as references to decide the contribution of Cu* layer. Since the thicknesses of the Cu*, Co, and Pt layers remain unchanged, they are omitted in the subsequent description of heterostructures for simplicity. First, the harmonic Hall measurement of Cu*/IrMn (3)/Co/Pt device was presented in detail as an example, and the schematic configuration of electrical measurements is shown in **Figure 3a**. The Cu* (3) layer is chosen to generate OAM since it is insulated without shunting effect (see Note S1, Supporting Information). Besides this, the Cu* layer has also been proved to be paramagnetic with good surface roughness in Note S1 (Supporting Information). To demonstrate the presence of the orbital current induced torque on the Co layer, the H_{DL} of Cu*/IrMn (3)/Co/Pt device can be

extracted from the transverse second-harmonic resistance $R_{xy}^{2\omega}$, following the expression as:^[38]

$$R_{xy}^{2\omega}(\varphi) = R_{DL+VT} \cos(\varphi) + R_{PHE} [2\cos^3(\varphi) - \cos(\varphi)] \frac{H_{FL} + H_{oe}}{H_{ext}} \quad (1)$$

$$R_{DL+VT} = R_{AHE} \frac{H_{DL}}{H_{ext} + H_{dem} - H_{ani}} + R_{VT} \quad (2)$$

Here, the H_{oe} represents the current-induced Oersted field and the R_{VT} is the transverse resistance due to the Hall voltage $\sim (\nabla T \times m) \cdot \gamma$ which is induced by the anomalous Nernst effect or spin Seebeck effect due to a thermal gradient ∇T . H_{ext} , H_{dem} and H_{ani} are the external magnetic field, the effective demagnetization field and the anisotropy field, respectively. We measured $R_{xy}^{2\omega}$ of Cu*/IrMn (3)/Co/Pt device at various H_{ext} to separate the torque and thermal contributions to R_{DL+VT} when the AC current is fixed

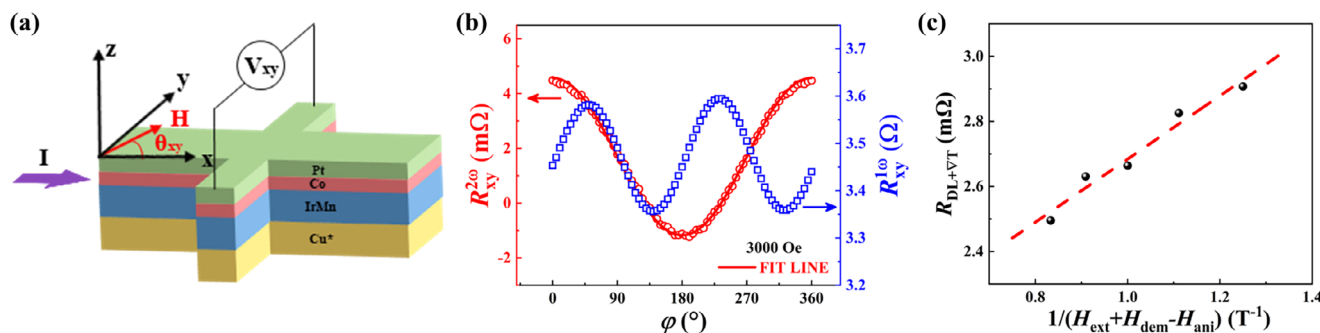


Figure 3. a) The harmonic measurements configuration. b) The $R_{xy}^{1\omega}$ and $R_{xy}^{2\omega}$ results of harmonic measurements on Cu*/IrMn (3)/Co/Pt device under the magnetic field of 3000 Oe. c) The values of R_{DL+VT} and their linear fitting versus $1/(H_{ext} + H_{dem} - H_{ani})$.

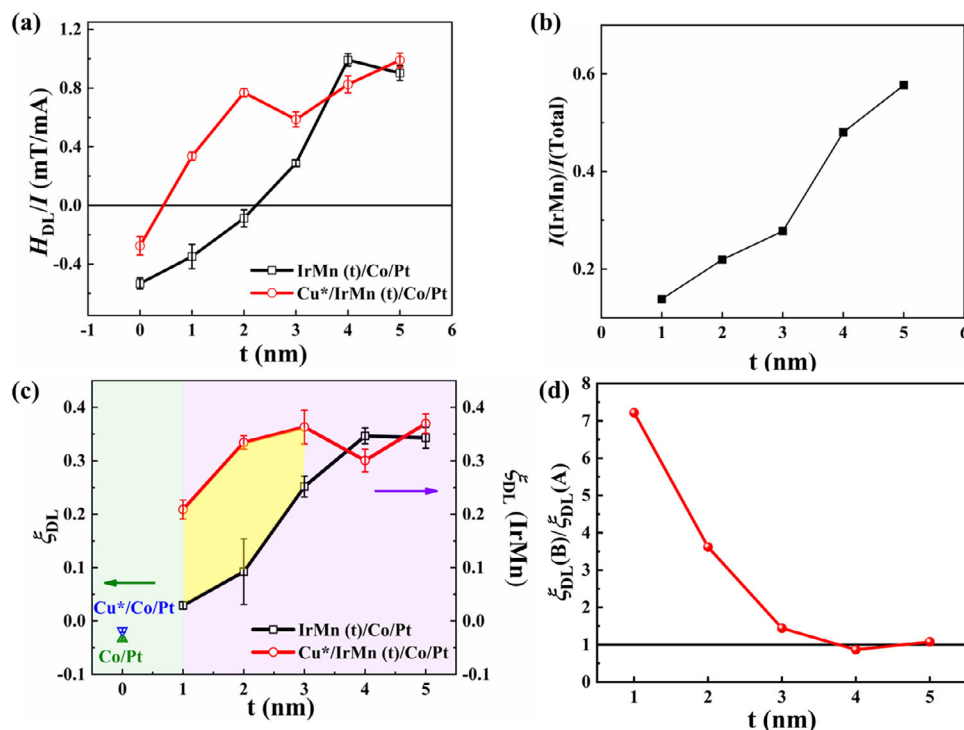


Figure 4. a) The calculated H_{DL}/I_{AC} results of harmonic measurements for IrMn (3)/Co/Pt and Cu*/IrMn (3)/Co/Pt devices. b) The proportion of the current that flows through the IrMn layer and the total current. c) The calculated magnitude of ξ_{DL} and $\xi_{DL}(\text{IrMn})$, which represents the ξ_{DL} generated by the IrMn layer. d) The $\xi_{DL}(\text{IrMn})$ ratio of Series B devices and Series A devices.

at 1 mA (peak value). Figure 3b shows the angle-dependent of $R_{xy}^{1\omega}$ and $R_{xy}^{2\omega}$ curves as $H_{\text{ext}} = 0.3$ T. More detailed results of transverse second-harmonic resistance $R_{xy}^{2\omega}$ of Cu* (3)/IrMn (3)/Co (0.8)/Pt (1) device is shown in Figure S2a (Supporting Information). The solid lines represent their fittings with $\cos(\varphi)$ and $2\cos^3(\varphi) - \cos(\varphi)$ using Equation (1), and the corresponding coefficients obtained from the fitting results are shown in Figure S2b (Supporting Information). It can be observed that the coefficient corresponding to the $\cos(\varphi)$ term ($R_{DL+\nabla T}$) is two orders of magnitude larger than the coefficient corresponding to the $2\cos^3(\varphi) - \cos(\varphi)$ term ($R_{PHE}(H_{FL} + H_{oe}/H_{\text{ext}})$). Considering the small values of $R_{PHE}(H_{FL} + H_{oe}/H_{\text{ext}})$, we can infer that the field-like effective field H_{FL} is nearly zero over the entire range of the magnetic field tested. Therefore, it is reasonable to neglect the contribution of the H_{FL} in subsequent discussion. Then we plotted and linearly fitted the $R_{DL+\nabla T}$ versus $1/(H_{\text{ext}} + H_{\text{dem}} - H_{\text{ani}})$ as Figure 3c according to Equation (2). Here, the $H_{\text{dem}} - H_{\text{ani}}$ was estimated to be 0.5 T from the anomalous Hall resistance in Figure S3b (Supporting Information).^[38] And we also omitted the data points at both low and high magnetic fields, because the magnetization is not fully saturated at low magnetic fields and the contribution of H_{DL} tends to disappear when H_{ext} is large enough to force the magnetization to align rigidly along the field direction. From the linear fitting, $R_{AHE} \cdot H_{DL}$ is obtained to be 1.04 ± 0.091 m Ω ·T. Additionally, the R_{AHE} value of Cu*/IrMn (3)/Co/Pt device is approximately estimated to be 1.772 Ω from Figure S3b (Supporting Information). Thus, the H_{DL} per unit applied current is evaluated to be 0.587 ± 0.051 mT/mA under an applied AC current of 1 mA.

Similarly, the H_{DL}/I_{AC} of IrMn (3)/Co/Pt device was estimated to be 0.288 ± 0.011 mT mA⁻¹ using Harmonic Hall measurement, which is less than two times of the value compared with that of the device with Cu* layer. As schematically illustrated in Figure 1b and described above, the significantly increased H_{DL}/I_{AC} should be attributed to the contribution of Cu* layer. In the Cu*/IrMn (3)/Co/Pt heterostructure, OAM will be converted into SAM in the IrMn layer due to its SOC, and finally exert an additional SOT on the Co layer. To further demonstrate the transport and conversion of OAM in AFM IrMn layer, we also performed transverse second-harmonic measurements on Cu*/IrMn (t)/Co/Pt and IrMn (t)/Co/Pt devices with t varying from 0 to 5 nm, which can also figure out the IrMn thickness dependence of the OAM contribution to H_{DL}/I_{AC} . As plotted in Figure 4a, for the series of IrMn (t)/Co/Pt devices (denoted as series A), an increasing value of H_{DL}/I_{AC} can be observed and a sign change occurs when t increases from 2 to 3 nm. It can be understood that the SOT is induced by the spin currents generated via SHE in both IrMn and Pt layers, which have the same sign and comparable magnitude of spin Hall angle (θ_{SH}).^[39–41] Thus, the spin current generated in IrMn layer increases with its thickness increasing and resistivity decreasing, leading to a sign changing of H_{DL}/I_{AC} . The series of Cu*/IrMn (t)/Co/Pt devices (denoted as series B) exhibit a similar trend. However, its H_{DL}/I_{AC} value is larger than that of IrMn (t)/Co/Pt until $t = 3$ nm. The sign change of H_{DL}/I_{AC} for Cu* series devices occurs when t increases from 0 to 1 nm. Moreover, the Joule heating effect can be excluded from the main contribution of the H_{DL}/I_{AC} value increasing for the Cu*/IrMn (3)/Co/Pt devices, as discussed in Note S4

(Supporting Information). For the field-like component, the H_{FL} values are simulated to be zero for all these devices with or without Cu* layer. To sum up, an increase in H_{DL}/I_{AC} for series B compared to series A can be attributed to the SAM converted from the OAM generating at the Cu*/IrMn interface, which then exerts an additional SOT on the Co layer.

To normalize the magnitude of this additional SOT, shunting effect in the IrMn/Co/Pt heterostructure is necessary to be considered in calculating the corresponding damping-like SOT efficiency (ξ_{DL}) subsequently. As shown in Figure S4a (Supporting Information), we measured the longitudinal resistances of the IrMn (t)/Co/Pt and Cu*/IrMn (t)/Co/Pt devices. When the Co/Pt layer is treated as a single entity and its resistance is assumed to remain constant in different heterostructures, the resistances of IrMn (t) layer can be calculated in Figure S4b (Supporting Information) based on the parallel resistance relationship. Thus, the proportion of the current flowing through the IrMn layer to the total current ($I(\text{IrMn})/I(\text{Total})$), together with the contribution of SOT from the IrMn layer, denoted as $H_{DL}(\text{IrMn})$, can be calculated using:

$$\frac{H_{DL}(\text{Total})}{I(\text{Total})} = \frac{H_{DL}(\text{IrMn})}{I(\text{IrMn})} - \frac{H_{DL}(\text{Co/Pt})}{I(\text{Co/Pt})} \quad (3)$$

The results of $H_{DL}(\text{Total})/I(\text{Total})$ and $I(\text{IrMn})/I(\text{Total})$ values for each heterostructure are shown in Figure 4a and b, respectively. The value of $H_{DL}(\text{Total})/I(\text{Total})$ in Co/Pt heterostructure corresponds to $H_{DL}(\text{Co/Pt})/(Co/Pt)$. And finally, we can evaluate the damping-like SOT efficiency using:^[42]

$$\xi_{DL} = \frac{2e/\hbar}{M_s t_{FM} H_{DL}/J} \quad (4)$$

where e is the electric charge, $\hbar$ is the reduced plank constant, and t_{FM} is the thickness of the ferromagnetic layer. As shown in Figure 4c, the green and blue triangles represent the magnitude of ξ_{DL} for Co/Pt and Cu*/Co/Pt heterostructures, while the black and red lines represent the magnitude of ξ_{DL} generated by the IrMn layer in IrMn (t)/Co/Pt and Cu*/IrMn (t)/Co/Pt heterostructures, respectively. The bright yellow area in Figure 4c represents a significant increase of the $\xi_{DL}(\text{IrMn})$ for Series B devices compared to that for Series A devices when $t \leq 3$ nm. However, when $t \geq 4$ nm, $\xi_{DL}(\text{IrMn})$ tends to close to each other. This significant increasing of $\xi_{DL}(\text{IrMn})$ when $t \leq 3$ nm can also be intuitively observed in Figure 4d, which represents the $\xi_{DL}(\text{IrMn})$ ratio of Series B devices to Series A devices. The conventional Rashba effect can generate spin currents, which has been demonstrated for both bulk asymmetry in the 2D layered material $\text{Fe}_{2.5}\text{Co}_{2.5}\text{GeTe}_2$ ^[43] and the more common interface asymmetry.^[44] However, considering that the spin diffusion length of IrMn layer is only ≈ 0.7 nm,^[45,46] as well as the longer orbital currents transport length comparing to spin currents,^[24,47–49] the observed different $\xi_{DL}(\text{IrMn})$ as $t \leq 3$ nm should be contributed by the transport and conversion of OAM in IrMn layer, which arises at the Cu*/IrMn interface due to OREE. Accordingly, the OAM transport length in IrMn can be estimated to be ≈ 3 nm, which is much larger than the spin diffusion length.

To further demonstrate that the additional SOT generated by orbital currents can effectively facilitate current-induced

magnetization switching directly, we fabricated perpendicular magnetic anisotropic (PMA) IrMn (t)/[Co (0.5)/Pt (1)]₃ and Cu*/IrMn (t)/[Co (0.5)/Pt (1)]₃-based SOT devices ($t = 1$ –4 nm). Current-induced magnetization switching measurements were conducted under a magnetic field of 300 Oe along the x -axis to reach full switching for each device. As shown in Figures 5a–d and S6a–d (Supporting Information), the AHE loops (orange lines) prove the stable PMA of these heterostructures. As for the current-induced magnetization switching, the critical current density (J_c) is estimated to be 2.74×10^{11} and $3.42 \times 10^{11} \text{ A m}^{-2}$ for the $t = 1$ nm devices with and without Cu* layer, respectively. Similar behaviors can also be observed for the devices of $t = 2$ and 3 nm. However, when the thickness of IrMn layer is $t = 4$ nm, J_c basically shows no difference between the devices with and without Cu* layer. Figure 5e summarizes the variation of J_c with respect to the IrMn thickness, and Figure 5f shows the absolute value of J_c differences induced by the Cu* layer, together with the J_c decreasing ratios relative to the device without Cu* layer. Both the J_c differences ($0.68 \times 10^{11} \text{ A m}^{-2}$) and the relative ratio (20%) for $t = 1$ nm devices possess the most significant improvement among all the heterostructures with different IrMn thickness, indicating the orbital effect from Cu* layer has great contribution during the charge to spin conversion process. Moreover, the trend of J_c is consistent with that of SOT efficiency variation versus the IrMn thickness obtained from the harmonic Hall measurements, further confirming the OAM transport and conversion in antiferromagnetic IrMn layer leading to a corresponding contribution to the SOT-induced magnetization switching process. Besides, regardless with or without Cu* layer, J_c decreases with the IrMn thickness increasing, corresponding to the SHE contribution from IrMn layer. When the thickness of IrMn reaches $t = 4$ nm, the Cu* layer has no contribution to the magnetization switching. Therefore, the OAM transport length in IrMn by SOT behaviors is also demonstrated to be ≈ 3 nm, consistent with harmonic Hall measurements. In previous studies, Pt/Co/IrMn (8) multilayer shows exchange bias that is beneficial to SOT switching.^[50] Considering the OAM transport length in metallic antiferromagnet is much longer than spin diffusion length, it is possible to explore antiferromagnet-based field-free SOT devices based on exchange bias and OHE in the future.

According to the study, orbit currents can transport in AFM* with a diffusion length much larger than spin currents. At the same time, the conversion from OAM to SAM occurs along with the orbit current diffusion due to the strong SOC of AFM*. In such heterostructures, spin currents will be generated by both OHE and SHE in AFM* layer. Owing to the larger orbit diffusion length, the spin accumulation at the AFM*/FM layer is much stronger than that without the orbit current contribution. Accordingly, OHE can effectively facilitate SOT-driven magnetization switching in AFM*-based devices together with SHE. Therefore, orbital angular momentum correlated charge to spin conversion enables the design of high energy efficient AFM-based SOT devices for spintronic applications.

3. Conclusion

In summary, we observed a substantially enhanced SOT efficiency at room temperature in Cu*/IrMn/Co/Pt heterostructures

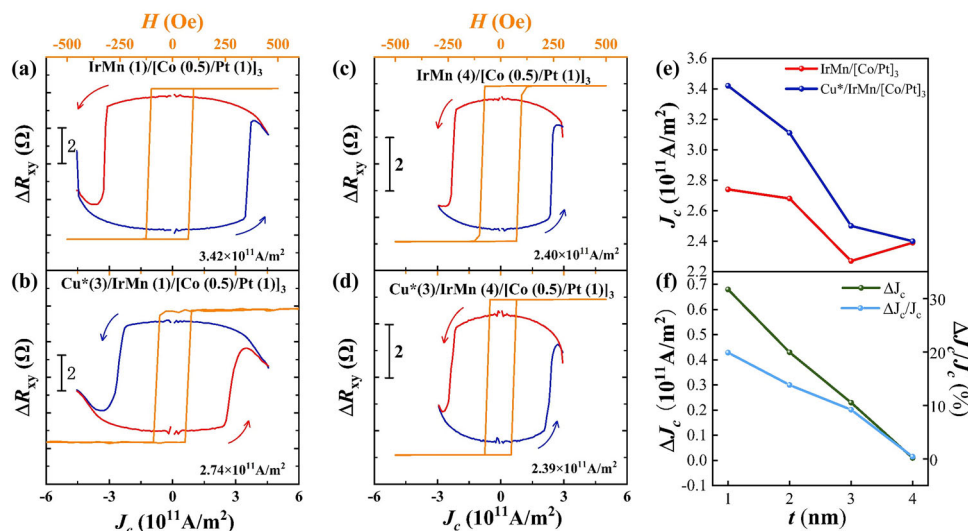


Figure 5. The AHE loops and SOT-driven magnetization switching curves of IrMn (1, 4)/[Co (0.5)/Pt (1)]₃ a,c) and Cu*/IrMn (1, 4)/[Co (0.5)/Pt (1)]₃ devices b,d). e) The variation of J_c with respect to the IrMn thickness. f) Cu* layer induced ΔJ_c and J_c changing ratio versus the IrMn thickness.

compared with the heterostructures without Cu* layer. The SOT efficiency enhancement could be attributed to the additional spin currents converted from the orbital currents, which arise due to the OREE at the Cu*/IrMn interface. The converted spin current transports across the IrMn layer, and finally accumulates at the IrMn/Co interface, together with the intrinsic SHE of IrMn, leading to a great increase of the effective spin accumulation comparing to the spin current only generated by SOC. Moreover, the critical current density decreases for the SOT-induced magnetization switching of the Cu*/IrMn/[Co/Pt]₃ heterostructure, which supports the OAM contribution to the charge to spin conversion in IrMn antiferromagnetic layer. Considering the advantages of metallic AFMs like IrMn, it would be possible to realize exchange-bias and orbital effect simultaneously. Therefore, combining the advantages of AFM and OAM would facilitate the design of AFM-based SOT devices to realize field-free magnetization switching at low current density, which inspires the potential applications of the spin-orbitronic devices with low power consumption.

4. Experimental Section

Sample Preparation: The IrMn/Co/Pt heterostructures were deposited on Si/SiO₂ substrates or pregrown Cu* layer by magnetron sputtering. The pregrown Cu* layers were grown on the Si/SiO₂ substrates using electron beam evaporation, and then stored in air for 1 day to naturally oxidize before later film growth. Both films preparation steps were carried out with a base pressure better than 1×10^{-5} Pa. All heterostructures for electric transportation measurements were patterned into Hall bars with lateral dimensions of $6 \mu\text{m} \times 14 \mu\text{m}$ by using photolithography and Ar ion milling techniques.

Characterization: The composition and morphology of the prepared heterostructures were characterized by HAADF-TEM (JEM-2100F). The magnetic configuration was measured by PNR on the Multipurpose Reflectometer beamline at the Chinese Spallation Neutron Source. The PNR measurements were conducted under an in-plane external field of 1.9 T at room temperature.

Magnetic Properties and Transport Measurements: The magnetic properties were measured using a vibrating sample magnetometer (VSM,

Quantum Design) at room temperature. And the electric transportation measurements were carried out on Physical Property Measurement System (PPMS, Quantum Design DynaCool) at room temperature. For harmonic measurements, AC currents were generated by Keithley 6221 current source at a fixed frequency of 128 Hz, while primary and secondary harmonic Hall voltage signals were captured using two lock-in amplifiers (SR380, Stanford Research Systems). The harmonic measurements configurations were shown in Figure 3a, where H , I , and M represent external magnetic field, applied current and magnetization, respectively. The AC current was applied along the x -axis when the external magnetic field rotated in the xy -plane. In the SOT-driven magnetization switching tests, pulsed DC current was applied by Keithley 6221 with a pulse width of 50 μs , separated by a 16 μs interval to minimize thermal interference on the signal. To validate the magnetization switching, Hall resistance was measured with a nanovoltmeter (Keithley 2182A) between successive pulses as the applied 200 μA DC current exerting minimal influence on the magnetization state.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

metallic antiferromagnets, orbital angular momentum, spin-logic device, spin-orbit torque

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