

Highly Energy-Efficient Spin Current Generation in SrIrO_3 by Manipulating the Octahedral Rotation

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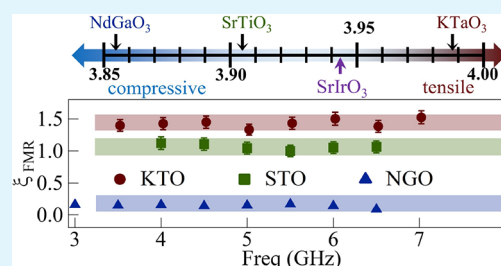
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Supporting Information

ABSTRACT: Materials with strong spin–orbit coupling (SOC) have been continuously attracting intensive attention due to their promising application in energy-efficient, high-density, and nonvolatile spintronic devices. Particularly, transition-metal perovskite oxides with strong SOC have been demonstrated to exhibit efficient charge–spin interconversion. In this study, we systematically investigated the impact of epitaxial strain on the spin–orbit torque (SOT) efficiency in the $\text{SrIrO}_3(\text{SIO})/\text{Ni}_{81}\text{Fe}_{19}(\text{Py})$ bilayer. The results reveal that the SOT efficiency is strongly related to the octahedral rotation around the in-plane axes of the single-crystal SIO. By modulating the epitaxial strain using different substrates, the SOT efficiency can be remarkably improved from 0.15 to 1.45. This 10-fold enhancement of SOT efficiency suggests that modulating the epitaxial strain is an efficient approach to control the SOT efficiency in complex oxide-based heterostructures. Our work may have the potential to advance the application of complex oxides in energy-efficient spintronic devices.

KEYWORDS: transition-metal perovskite oxides, octahedral rotation, reciprocal space mapping, spin Hall effect, spin–orbit torque, spin-torque ferromagnetic resonance



INTRODUCTION

Current-induced spin–orbit torques (SOTs) are regarded as an energy-efficient and scalable method for manipulating the magnetization in spintronic devices.^{1–5} Achieving a high interconversion between charge current and spin current is one of the crucial factors in realizing low-current, low-power SOT-induced magnetization switching.^{6–8} Typically, the origin of SOT can be attributed to either the spin Hall effect (SHE)^{7,9} or the Rashba effect^{10,11} in materials with strong spin–orbit coupling (SOC). Traditionally, materials utilized for producing SOT were predominantly heavy metals (HMs), such as Pt,^{12,13} Ta,³ and W.^{14,15} However, the SOT efficiencies of HMs typically remain below 0.5. Subsequently, topological insulators^{6,16} with spin–momentum locked surface states and two-dimensional (2D) materials¹⁷ with reduced dimensions have been demonstrated having larger SOT efficiencies. Nevertheless, challenges persist due to the high resistivity of these materials, causing current shunting and compatibility issues with magnetic materials. Large SOT efficiency has also been found in antiferromagnets, such as Mn_3Sn ^{18,19} and IrMn .²⁰ To date, the exploration of new SOT materials and the modulation of SOT efficiency persist as crucial pursuits for practical applications.^{21,22}

Recently, transition-metal perovskite oxides, such as SrIrO_3 (SIO)^{23–25} and SrRuO_3 (SRO)^{26–28} have been reported to exhibit strong SOC. The octahedral behavior in perovskite

materials plays a critical role in determining the properties of transition metal oxides.^{29–32} The spin Berry curvature of the bands is a crucial factor in determining the spin Hall conductivity. The manipulation of SOT efficiency can be achieved through octahedral rotation, as the crystal field splitting and structural symmetry breaking induced by octahedral rotation can profoundly impact the spin Berry curvature.^{32–35}

Among the transition-metal perovskite oxides, SIO holds a distinctive position.^{36–38} Due to the heavy element Ir, SOC in SIO is significantly stronger than that in commonly used 3d elements.^{39,40} Furthermore, SIO is identified as a Dirac semimetal with a Dirac cone crossing the Fermi level, potentially leading to substantial SOT efficiency.^{41–45} However, only a limited number of studies have delved into SOT efficiency in the SIO film.^{5,25,39} Previous investigations have reported the thickness-dependent SOT efficiency in SIO,^{23,46} attributed to octahedral rotation. Theories and experiments on

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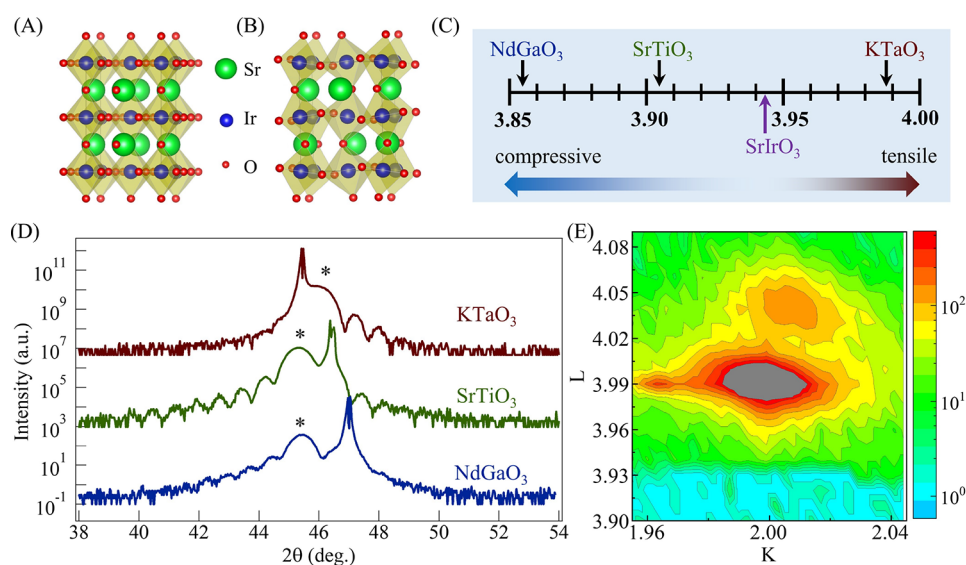


Figure 1. Schematic of the crystal structure and basic properties. (A) Ideal SIO perovskite unit cell with oxygen octahedra surrounding the Ir site. The crystal structure belongs to the crystallographic space group $Pm\bar{3}m$. (B) Schematic illustration of the effect of epitaxial strain on the lattice structure of SIO, which would result in the octahedral rotation. (C) Lattice parameters of the bulk SIO and different substrates. NGO, STO exert compressive strain on the SIO films, and KTO exerts tensile strain. (D) X-ray diffraction pattern of SIO films grown on different substrates along the (001)_c direction. SIO film peaks are labeled with “*”. (E) RSM around (024) of SIO film on the KTO substrate.

SRO²⁷ have established a strong correlation between SOT efficiency and octahedral rotation around its in-plane axes. Nevertheless, direct evidence between the octahedral rotation and the SOT efficiency in SIO is currently lacking.

In this study, we deposited SIO films with varying octahedral rotations by manipulating the epitaxial strain. Subsequently, the modulation of SOT efficiency by epitaxial strain-induced octahedral rotation in SIO films was investigated by using spin-torque ferromagnetic resonance (ST-FMR). Our findings reveal that a substantial SOT efficiency (~ 1.45) can be achieved in the SIO film grown on a KTaO₃ (KTO) substrate, where the octahedra is rotated around the in-plane axes of SIO. In contrast, the SOT efficiency of SIO film grown on the NdGaO₃ (NGO) substrate decreases to 0.15, as no in-plane octahedral rotation is formed under significant compressive strain. These results highlight an effective approach to control the SOT efficiency of SIO films.

RESULTS AND DISCUSSION

The ideal perovskite SIO possesses a cubic structure, falling within the crystallographic space group $Pm\bar{3}m$, as illustrated in Figure 1A. The ideal perovskite SIO can be stabilized with a tolerance factor in the range:⁴⁷ $0.89 \leq t_f = \frac{r_{Sr} + r_o}{\sqrt{2}(r_{Ir} + r_o)} \leq 1.05$, wherein r_{Sr} , r_{Ir} , and r_o represent the ionic radii of ions Sr, Ir, and O, respectively. Through the engineered strain, t_f may fall out of range, leading to the observed octahedral rotation depicted in Figure 1B. In this study, three distinct single-crystal substrates SrTiO₃ (STO) (001)_c, KTaO₃ (KTO) (001)_c, and NdGaO₃ (NGO) (001)_c (where “c” in the subscript denotes pseudocubic lattice) were employed. The lattice constants are depicted in Figure 1C. The applied strain on the SIO film varies, ranging from a tensile strain of 1.1% on KTO to a compressive strain of -1.0% on STO and -2.0% on NGO. This variation alters the tilting angle and rotation of the IrO₆ octahedra. Bilayers of SIO (20 nm)/Ni₈₁Fe₁₉ (Py) (10 nm) are prepared using pulsed laser deposition and DC magnetron sputtering as detailed in the Methods Section.

Figure 1D presents θ - 2θ scans of X-ray diffraction (XRD) of the SIO films grown on KTO, STO, and NGO substrates, respectively. For all three samples, only the (002)_c peaks of the SIO film and the substrate are observed, indicating a single phase (002)_c epitaxy of the single-crystal SIO films on all substrates. The Laue oscillations, observed alongside the (002)_c peaks of the SIO films, suggest a well-defined interface between the SIO films and the substrates. Furthermore, the SIO (002)_c peak is positioned to the right side of the KTO (001)_c peak and to the left side of the STO (001)_c and NGO (001)_c peak. This positioning demonstrates the tensile and compressive strain states in the SIO films on the KTO and STO/NGO substrates, respectively.

The crystal structure of the SIO film underwent further examination through reciprocal space mapping (RSM) using high-resolution XRD around the (024)/(013) substrate Bragg reflections. Figure 1E illustrates a typical RSM measured in an SIO film deposited on a KTO substrate around the (024) plane as an example. The RSM results of SIO films deposited on different substrates can be found in the Supporting Information (Figures S1 and S2), indicating that all of the SIO films are nearly fully strained on the substrates. Based on the reciprocal space vectors, we extracted the lattice constants of SIO films. For SIO/KTO, $a = b = 3.976$ Å, $c = 3.940$ Å; for SIO/STO, $a = b = 3.916$ Å, $c = 3.985$ Å; for SIO/NGO, $a = b = 3.870$ Å, $c = 3.990$ Å. Note that, due to the existence of a tolerance factor, estimating the states of octahedra in SIO films with different strains is challenging.

According to Glazer,⁴⁸ the peaks of the type $1/2(o,o,i)$ (where o stands for an odd integer and i stands for an integer) occur when the octahedra is rotated around out-of-plane axis, while the half-integer reflections of the type $1/2(i,i,o)$ would appear when the octahedra is rotated around in-plane axes. Thus, utilizing the half-integer measurements allows for the demonstration of octahedral behavior in compressively and tensely strained SIO films. Of note, the half-integer peaks originating from the film are usually weak and wide, which is a

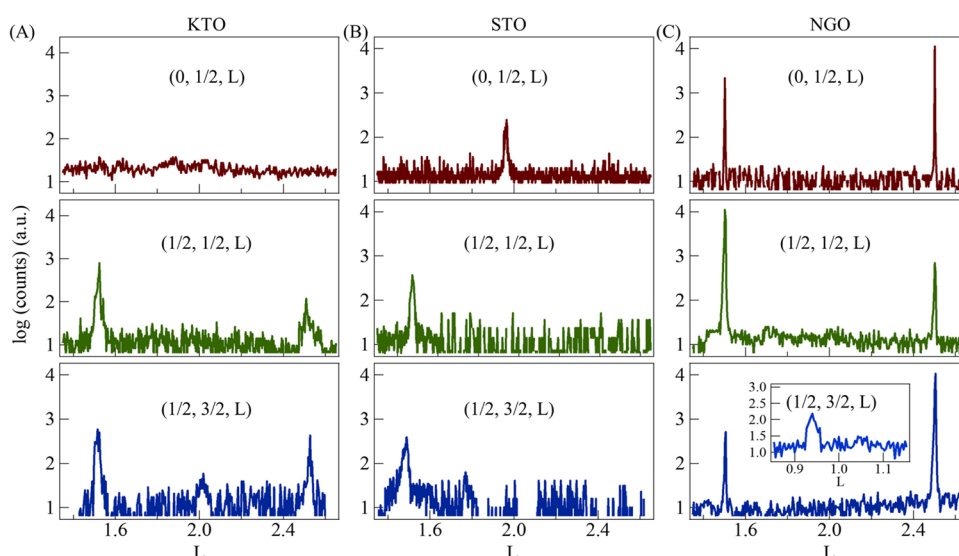


Figure 2. Half-integer measurements. (A–C) Results of half-integer L scans of $(0, 1/2, L)$, $(1/2, 1/2, L)$, and $(1/2, 3/2, L)$ measured in SIO films grown on KTO, STO, and NGO substrates, respectively. The octahedral rotation in SIO films deposited on KTO, STO, and NGO substrates are $a^-a^-c^+$, $a^-b^+c^-$, and $a^0a^0c^+$.

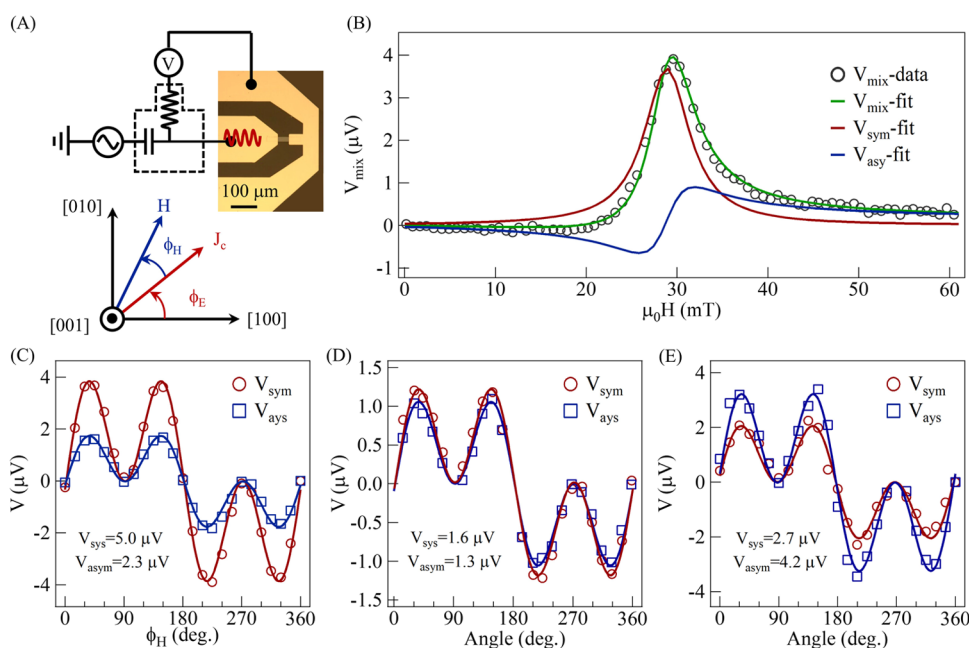


Figure 3. Measurement of SOT efficiency. (A) Schematic of the ST-FMR measurement setup and optical photograph of the device. A microwave signal was sent into the coplanar waveguide. The mixing voltage was measured by using a lock-in amplifier. (B) Typical ST-FMR spectrum measured at $\Phi_H = 45^\circ$ and $\Phi_E = 0^\circ$ in KTO/SIO/Py with a frequency of 5.5 GHz. Black circles denote the measured mixing voltage data. The green line is the fitting curve by using eq S1 in the Supporting Information and the red (blue) line represents the symmetric V_{sym} (antisymmetric V_{asym}) component. (C–E) Angular dependence of V_{sym} and V_{asym} measured in the SIO (20 nm)/Py (10 nm) bilayers grown on KTO, STO, and NGO substrate. All curves show $\cos \Phi_H \sin 2\Phi_H$ dependence.

consequence of the small atomic form factor of oxygen ions and the small crystal gain in films.⁴⁹

Half-integer L scans, specifically $(0, 1/2, L)$, $(1/2, 1/2, L)$, and $(1/2, 3/2, L)$, were conducted to characterize octahedral rotations. The octahedral rotations around the i ($i = a, b$, or c) axis can be denoted as “ i^+ ”, “ i^- ”, or “ i^0 ”, wherein “+”, “−”, and “0” represent the in-phase, out-of-phase, and zero octahedral rotation, respectively. The results of half-integer reflections for SIO films on KTO, STO, and NGO substrates are illustrated in Figure 2A–C, respectively. The half-integer reflection peaks measured in SIO/NGO (as shown in Figure 2C) exhibit

notable differences from the others. The width of peaks measured in SIO/NGO is narrower than that measured in other SIO films, and the peak positions precisely align with $3/2$ and $5/2$. Considering the relatively large amplitude of the half-integer peak, it can be concluded that these peaks should originate from the NGO substrate rather than the SIO film. The absence of the $(0, 1/2, L)$ peak in the SIO film deposited on NGO implies the lack of out-of-phase octahedral rotation around the a -axis, i.e., “ a^+ ”, while the octahedral rotation “ a^- ” and “ b^- ” can be excluded as no film peak is observed during the $(1/2, 1/2, L)$ scan. The presence of the $(1/2, 3/2, 1)$ peak

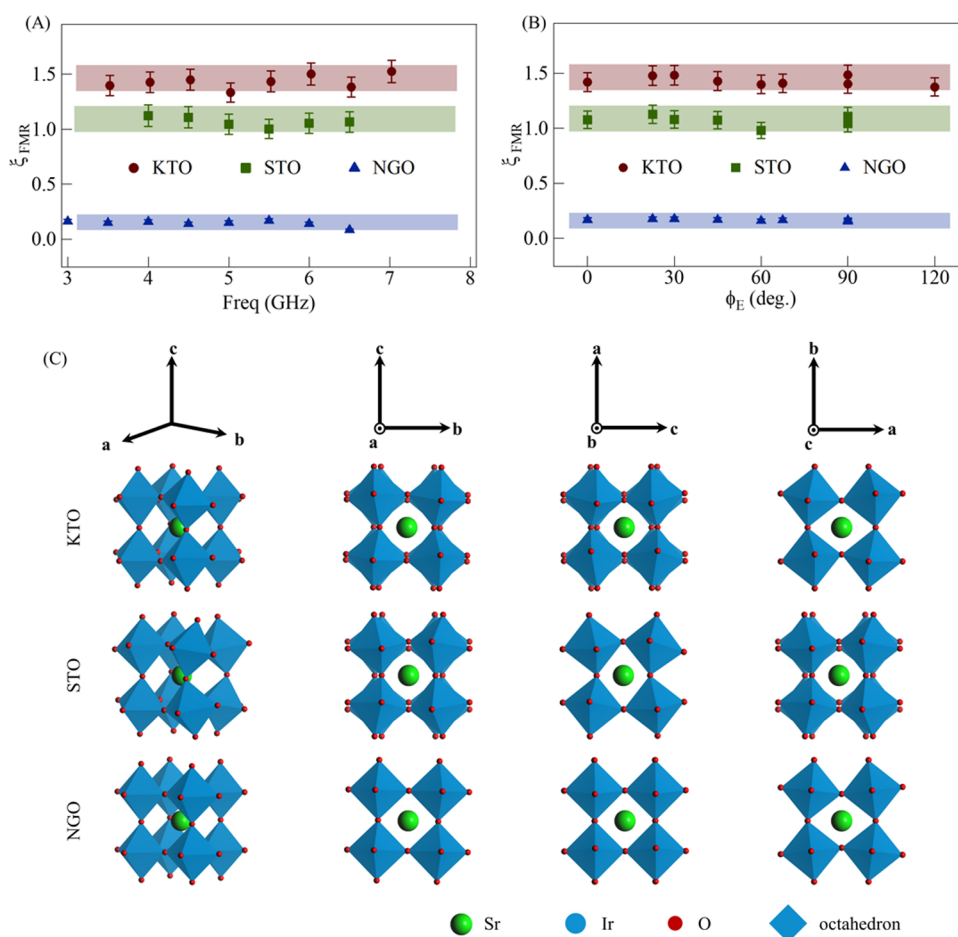


Figure 4. Giant manipulation of SOT efficiency by octahedral rotation. (A) Frequency-dependent ξ_{FMR} measured in SIO/Py bilayers on KTO, STO, and NGO substrates and the average values of ξ_{FMR} are 1.45, 1.05, and 0.15, respectively. (B) ξ_{FMR} as a function of Φ_E measured in SIO/Py bilayers on KTO, STO, and NGO substrates. The ξ_{FMR} is independent of the crystalline direction. (C) Sketches of octahedral rotation in SIO films deposited on KTO, STO, and NGO substrates from different view directions. Coordinates are defined with reference to the pseudocubic lattice of SIO.

during the (1/2, 3/2, L) scan, as shown in the inset of Figure 2C, indicates the occurrence of “ c^+ ” rotation. Considering all of the information presented in Figure 2C, the octahedral rotation for the compressively strained SIO film on NGO is identified as $a^0a^0c^+$.

In comparison, for the SIO film with less compressive strain on the STO substrate, the presence of the (0, 1/2, 2) peak during the (0, 1/2, L) scan (as shown in Figure 2B) suggests the octahedral rotation “ b^+ ” and rotation “ b^- ” can be ruled out. The rotation “ a^- ” is suggested from the presence of the (1/2, 1/2, and 3/2) peak in the absence of rotation “ b^- ”. The presence of the (1/2, 3/2, 3/2) peak and the absence of the (1/2, 3/2, 2) peak indicate the existence of the “ c^- ” rotation. Therefore, the octahedral rotation pattern for the SIO film on the STO substrate is identified as $a^-b^+c^-$. Regarding the SIO film grown on the KTO substrate, the rotation a^+ can be excluded due to the absence of the half-integer peak during the (0, 1/2, L) scan, as shown in Figure 2A. The out-of-phase octahedral rotation around the in-plane axes (“ a^- ” and “ b^- ”) is anticipated due to the presence of a half-integer peak during the (1/2, 1/2, L) scan. The results of the (1/2, 3/2, L) scan also suggest the possible rotation “ b^- ” and rotation “ c^- ”. Due to the perovskite structure of the KTO substrate (with $a = b = c$, $\alpha = \beta = \gamma = 90^\circ$), the “ a^- ” and “ b^- ” rotations are identical in this system. However, it is challenging to determine whether

the peak (1/2, 1/2, and 3/2) arises from “ a^- ” only or results from the combination of “ a^- ” and “ b^- ”. Similarly, the peak (1/2, 3/2, 3/2) may arise solely from “ b^- ”, or may result from the combination of “ b^- ” and “ c^- ”. Considering the weak peak observed at (1/2, 3/2, and 2), it can be concluded that the rotation “ c^+ ” is present, and the possibility of rotation “ c^- ” can be excluded. Considering the allowed space group and the consistency of half-integer peaks with previous studies,^{27,49} the octahedral rotation of SIO on KTO is determined to be $a^-a^-c^+$. The key parameters are summarized in a table, including the lattice constants of KTO, STO, and NGO substrates, lattice constants of SIO films deposited on different substrates, half-integer L scan numbers, and octahedral rotation status (refer to the Supporting Information (Table S1)). It is evident that the octahedral patterns of SIO films on KTO, STO, and NGO substrates are distinctly different from each other. By contrasting the SOT efficiency of SIO films on different substrates, the contribution of octahedral rotation to SOT efficiency can be ascertained.

The films were subsequently fabricated into spin-torque ferromagnetic resonance (ST-FMR) devices, and all of the SOT efficiencies in this study were determined using the standard ST-FMR technique at room temperature.^{50–52} The schematic of the measurement setup and an optical photograph of the device are presented in Figure 3A (refer to the

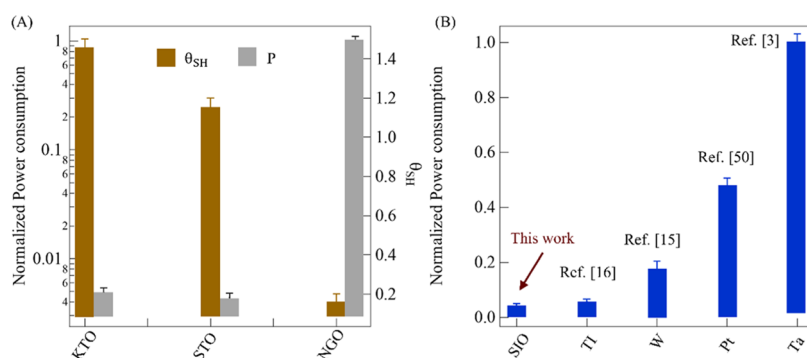


Figure 5. Analysis of switching power consumption. (A) Spin Hall angle and normalized switching power consumption in SIO films deposited on KTO, STO, and NGO substrates. The SIO on the STO substrate is of lower power consumption than SIO on the KTO substrate. (B) Normalized switching power consumption in the SIO film, Ta, Pt, W, and topological insulators. The power consumption of SIO is only 9% of that of Pt and comparable to that of the topological insulator.

Methods Section for details). By feeding a signal generated from a microwave generator into the coplanar waveguide (CPW), a *rf* current along the *x*-axis will emerge in the SIO/Py bilayer. The *rf* current results in two types of torque: the *rf* magnetic field torque due to the Oersted effect and the spin torque arising from the spin current in SIO. Both torques contribute to the precession of the magnetic moment in the Py film. When combined with the anisotropy magnetoresistance effect, rectifying voltage V_{mix} as a function of additional magnetic field H can be measured. The voltage can be described using the equation $V_{\text{mix}}(H) = V_{\text{sym}}(H) + V_{\text{asym}}(H)$, wherein the V_{sym} (V_{asym}) represents the amplitude of the symmetric (antisymmetric) component (refer to the [Supporting Information](#)). The V_{sym} component is primarily attributed to the damping-like spin torque, while the V_{asym} component originates from the field-like spin torque and the Oersted field. Thus, the damping-like SOT efficiency (ξ_{FMR}) can be expressed as follows:

$$\xi_{\text{FMR}} = \frac{V_{\text{sym}}}{V_{\text{asym}}} \frac{e}{\hbar} \mu_0 M_0 t_{\text{Py}} t_{\text{SIO}} \sqrt{1 + \frac{4\pi M_{\text{eff}}}{H_r}} \quad (1)$$

where e , $\hbar$, μ_0 , t_{Py} , t_{SIO} , and H_r are the electron charge, reduced Planck constant, permeability of vacuum, thickness of the Py film, thickness of the SIO film, and resonant field, respectively. The saturation magnetization and effective in-plane magnetization of the Py layer are denoted as M_0 and M_{eff} , respectively.

Figure 3B shows a typical ST-FMR spectrum measured at a microwave frequency of 5.5 GHz, with $\Phi_H = 45^\circ$ and $\Phi_E = 0^\circ$ in KTO/SIO/Py, where Φ_H (Φ_E) is the angle between the direction of the applied magnetic field (the [100] crystal direction of SIO films) and the direction of the microwave current. By fitting the spectrum, we can determine the V_{sym} and V_{asym} . Referring to our previous research,⁵² the direction of the spin polarization can be characterized by the angular-dependent V_{sym} and V_{asym} . Figure 3C–E illustrates the angular-dependent V_{sym} and V_{asym} of SIO (20 nm)/Py (10 nm) bilayers deposited on KTO, STO and NGO substrates. These dependencies are obtained by fitting the ST-FMR spectra measured at different Φ_H . As shown in Figure 3C–E, all $V_{\text{sym}}(\Phi_H)$ and $V_{\text{asym}}(\Phi_H)$ exhibit a $\cos \Phi_H \sin 2\Phi_H$ dependence, indicating that the direction of the spin polarization is in-plane and perpendicular to the direction of the microwave current.⁵² ξ_{FMR} can also be calculated using eq 1. The substantial variation in the $V_{\text{sym}}/V_{\text{asym}}$ ratio highlights

the significant difference in the SOT efficiency ξ_{FMR} of SIO on different substrates.

Figure 4A summarizes the frequency dependence of ξ_{FMR} in SIO/Py bilayers on KTO, STO, and NGO substrates with average values of ξ_{FMR} are 1.45, 1.05, and 0.15, respectively. The insensitivity of ξ_{FMR} to the applied frequency verifies the reliability of our measurement. We also investigated the dependences of the ξ_{FMR} on the crystallographic orientation of SIO. As shown in Figure 4B, the ξ_{FMR} values in SIO films on all three substrates are independent of Φ_E , i.e., the microwave current direction relative to the crystallographic orientation. This crystal independence may originate from twinned crystal domains.²⁷ Additionally, we observe that by changing the substrates, the electric properties of SIO films can be modulated. The measured longitudinal electrical resistivities of SIO films on the three substrates are $\rho_{xx}^{\text{STO}} = 585 \mu\Omega\cdot\text{cm} < \rho_{xx}^{\text{KTO}} = 1047 \mu\Omega\cdot\text{cm} < \rho_{xx}^{\text{NGO}} = 2267 \mu\Omega\cdot\text{cm}$ (as shown in Figure S4). The electrical resistivity of SIO films is neither positively nor negatively correlated with the SOT efficiency, eliminating the effect of electrical resistivity on the ξ_{FMR} variation across the three substrates.

Figure 4C illustrates the octahedral rotation in SIO films deposited on KTO, STO, and NGO substrates based on the results of half-integer L scans. Combining the octahedral rotation with the SOT efficiency, we observed that SOT efficiency is at a minimum when the SIO film is deposited on NGO. In this case, the octahedra does not rotate around the in-plane axes (a^0a^0) but rotates around the out-of-plane axis (c^+), suggesting that the octahedral rotation c^+ contributes little to the SOT efficiency. In contrast, the SIO film deposited on KTO exhibits measurable in-plane octahedral rotation (a^-a^-) and shows the maximum SOT efficiency, indicating that the SOT efficiency in the SIO film can be effectively modulated by the octahedral rotation around the in-plane axis. The results obtained from the SIO film on the STO substrate show that the in-plane octahedral rotation a^- contributes more than b^+ to SOT efficiency. The physical pictures of how octahedral rotation modulates SOT efficiency will be discussed. Based on previous theoretical calculations,^{24,32,53} octahedral rotation-induced distortions of octahedral crystal fields will break up the e_g and t_{2g} manifolds into further sub-bands, which increases the total bandwidth of both manifolds. Consequently, this enhancement raises the likelihood of the overlap or mixings between *d*-orbitals through the SOC interaction, which is anticipated to increase the spin Berry curvature in the intrinsic

SHE regime.²⁷ Moreover, nontrivial topological properties, stemming from the Dirac semimetal nature of SIO,^{54,55} may also contribute to a large spin Hall conductivity.⁵⁶ The modification of the spin Hall conductivity induced by octahedral rotation results in a dramatic enhancement of the SOT efficiency. Further theoretical investigations are essential to uncovering the dominant origin.

In pursuit of realistic applications, achieving low switching power consumption is the ultimate goal of SOT-induced magnetization switching. While the SOT efficiencies of SIO on KTO and STO are significantly higher than those of heavy metals ($|l_{\text{Pt}}| = 0.05\text{--}0.15$ for Pt^{12,13} and $|l_{\text{W}}| = 0.20\text{--}0.40$ for W^{14,15}), it remains uncertain whether the utilization of the SIO will result in energy efficiency superiority, given the considerably higher resistivity of SIO film compared to heavy metals. The switching power consumption P can be described by $P \propto \rho_{\text{SOT source}} j_{\text{SW}}^2$, where $\rho_{\text{SOT source}}$ is the resistivity of the SOT source and j_{SW} is the switching current density with $j_{\text{SW}} \propto \theta_{\text{SH}}^{-1}$ (θ_{SH} is the spin Hall angle). Therefore, the switching power consumption can be assessed using the following formula as

$$P \propto \rho_{\text{SOT source}} \theta_{\text{SH}}^{-2} \quad (2)$$

Figure 5A displays the normalized switching power consumption in SIO films deposited on different substrates calculated using eq 2 and the effective spin Hall angle. It is evident that, despite the SOT efficiency of SIO film on KTO being larger than that on STO, the SIO on STO exhibits greater power efficiency. Figure 5B shows the normalized switching power consumption in SIO films relative to topological insulators (TIs) and heavy metals. The power consumption of SIO is only 4% of that of Ta,³ 9% of that of Pt,⁵⁰ 25% of that of W,¹⁵ and comparable to that of topological insulator (BiSb)₂Te₃.¹⁶ These results suggest that the SIO is a promising material candidate for designing energy-efficient spintronic devices.

CONCLUSIONS

In summary, we conducted a systematic investigation of the SOT efficiency in epitaxial SrIrO₃ films by manipulating strain through changing substrates. The SOT efficiencies were determined through ST-FMR measurement. An extraordinarily large SOT efficiency (~ 1.45) and effective modulation of SOT efficiency were revealed. Additionally, through an analysis of octahedral rotation, we uncovered a robust correlation between the SOT efficiency in SIO and the rotation of octahedra around its in-plane axes. These findings underscore the significant potential offered by SIO for the design of next-generation multifunctional spintronic devices, particularly for energy-efficient magnetic storage and logic devices.

METHODS

Thin Film Deposition. The SrIrO₃ thin films were epitaxially grown on KTO, STO, and NGO substrates by pulsed laser deposition (PLD) at 750 °C and under an oxygen pressure of 100 mTorr. The laser fluence was 1.3 J cm⁻² and the laser frequency was 2 Hz. The distance between the target and substrate was 50 mm. After the deposition, the SIO films were annealed at 600 °C for half an hour under an oxygen pressure of 5 mTorr. They were transferred to an interconnected sputtering chamber after cooling to room temperature without breaking the vacuum. Then, the Py layers were deposited at room temperature at the Ar pressure of 5 mTorr by using DC magnetron sputtering with a base pressure better than 5×10^{-8} Torr.

All samples were passivated by a 2 nm SiO₂ layer by using RF magnetron sputtering.

Structural Characterization. All of the structural characterization measurements including the X-ray diffraction, reciprocal space mapping, and half-integer measurements were performed at room temperature at the Singapore Synchrotron Light Source with an X-ray wavelength of 1.541 Å.

Device Fabrication. The SIO/Py bilayers were patterned into 10 $\mu\text{m} \times 40 \mu\text{m}$ microstrips for the ST-FMR measurement by using photolithography and ion beam etching technology. The coplanar waveguides (CPWs) with a width of 120 μm and a distance of 40 μm between the signal line and ground line were patterned by photolithography. The device is fabricated via an Ultraviolet Maskless Lithography machine (TuoTuo Technology). The Ti(5 nm)/Cu(80 nm) bilayers were deposited by using a thermal evaporator as the CPW electrodes.

ST-FMR measurement. A Rohde & Schwarz SMB 100A signal generator was used to provide the modulated microwave for ST-FMR measurement. The microwave has a frequency of 3–9 GHz, a modulation frequency of 317.3 Hz, and a nominal power of 18 dBm. The rectifying voltage was collected using a Zurich Instrument MFLI lock-in amplifier.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsami.3c15514>.

Measurements of the reciprocal space mapping (RSM); the table of SIO and different substrate structure parameters; the theory of ST-FMR and the detailed ST-FMR measurements; and measurement of electrical resistivity (PDF)

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Author Contributions

[†]Q.Z., S.S., and Z.Z. contributed equally to this work. J.C. and Q.Z. conceived the idea and designed the experiments. J.C. supervised the project. S.S. and H.Z. fabricated the thin film and the device. H.Z. and Q.Z. contributed to the ST-FMR measurements. S.S. and H.Z. performed X-ray diffraction measurements. Z.Z., D.-F.S., L.L., and T.Z. contributed to SOT efficiency analysis. J.C. and Q.Z. wrote the manuscript with inputs from all authors.

Notes

The authors declare no competing financial interest.

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