



Anisotropic spin-orbit torque generation in epitaxial SrIrO_3 by symmetry design

T. Nan^{a,1}, T. J. Anderson^{a,1}, J. Gibbons^b, K. Hwang^c, N. Campbell^d, H. Zhou^e, Y. Q. Dong^e, G. Y. Kim^f, D. F. Shao^g, T. R. Paudel^h, N. Reynolds^b, X. J. Wang^h, N. X. Sun^h, E. Y. Tsymlar^g, S. Y. Choi^f, M. S. Rzchowski^d, Yong Baek Kim^{c,i,j}, D. C. Ralph^{b,k}, and C. B. Eom^{a,2}

^aDepartment of Materials Science and Engineering, University of Wisconsin–Madison, Madison, WI 53706; ^bLaboratory of Atomic and Solid State Physics, Cornell University, Ithaca, NY 14853; ^cDepartment of Physics and Centre for Quantum Materials, University of Toronto, Toronto, ON M5S 1A7, Canada; ^dDepartment of Physics, University of Wisconsin–Madison, Madison, WI 53706; ^eAdvanced Photon Source, Argonne National Laboratory, Argonne, IL 60439; ^fDepartment of Materials Science and Engineering, Pohang University of Science and Technology, Pohang 37673, Korea; ^gDepartment of Physics and Astronomy & Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, NE 68588; ^hDepartment of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115; ⁱCanadian Institute for Advanced Research/Quantum Materials Program, Toronto, ON M5G 1Z8, Canada; ^jSchool of Physics, Korea Institute for Advanced Study, Seoul 130-722, Korea; and ^kKavli Institute at Cornell for Nanoscale Science, Ithaca, NY 14853

Edited by Qi Li, Pennsylvania State University, State College, PA, and accepted by Editorial Board Member Tobin J. Marks June 24, 2019 (received for review July 30, 2018)

Spin-orbit coupling (SOC), the interaction between the electron spin and the orbital angular momentum, can unlock rich phenomena at interfaces, in particular interconverting spin and charge currents. Conventional heavy metals have been extensively explored due to their strong SOC of conduction electrons. However, spin-orbit effects in classes of materials such as epitaxial 5d-electron transition-metal complex oxides, which also host strong SOC, remain largely unreported. In addition to strong SOC, these complex oxides can also provide the additional tuning knob of epitaxy to control the electronic structure and the engineering of spin-to-charge conversion by crystalline symmetry. Here, we demonstrate room-temperature generation of spin-orbit torque on a ferromagnet with extremely high efficiency via the spin-Hall effect in epitaxial metastable perovskite SrIrO_3 . We first predict a large intrinsic spin-Hall conductivity in orthorhombic bulk SrIrO_3 arising from the Berry curvature in the electronic band structure. By manipulating the intricate interplay between SOC and crystalline symmetry, we control the spin-Hall torque ratio by engineering the tilt of the corner-sharing oxygen octahedra in perovskite SrIrO_3 through epitaxial strain. This allows the presence of an anisotropic spin-Hall effect due to a characteristic structural anisotropy in SrIrO_3 with orthorhombic symmetry. Our experimental findings demonstrate the heteroepitaxial symmetry design approach to engineer spin-orbit effects. We therefore anticipate that these epitaxial 5d transition-metal oxide thin films can be an ideal building block for low-power spintronics.

spin-Hall effect | spin-orbit torque | epitaxial thin films | SrIrO_3

Current-induced spin torque originating from spin-orbit effects offers an energy-efficient scheme for the electrical manipulation of magnetic devices (1–4). A large spin-torque efficiency, arising from either the spin-Hall effect (5–7) or the Rashba–Edelstein effect (8), is highly desirable for enabling broad applications in spintronics. Great effort has been focused therein on semiconductors (9, 10), heavy metals (11–18), oxides (19, 20), and, more recently, topological insulators with a spin-momentum locked surface state (21–24). In the case of 5d-electron transition-metal oxides, the delicate interplay between strong spin-orbit coupling and electron-electron correlation is believed to lead to nontrivial quantum phases (25–30), e.g., topological semimetals (31), quantum spin-Hall materials (32), and topological Mott insulators (27). The interplay between crystal structure and strong spin-orbit coupling (SOC) of conduction electrons can produce a large Berry curvature that gives rise to an intrinsic spin-Hall effect (33). Furthermore, due to the sensitive dependence of the electronic structure on crystalline symmetry, the efficiency of the spin/charge-current conversion can be possibly modulated through heteroepitaxy. However, such material systems remain largely unexplored in the field of spin orbitronics.

We first motivate our work with theoretical calculations that show a large intrinsic spin-Hall effect in the orthorhombic bulk semimetal SrIrO_3 (Fig. 1A). Large spin-Hall conductivity [$\text{SHC} \sim 2 \times 10^4 (\hbar/2e) (\Omega \text{ m})^{-1}$] is obtained over the extended region around the Fermi energy including the charge-neutral point from the linear response theory for the bulk orthorhombic perovskite structure (Fig. 1C). The spin-Hall effect arises due to the Berry curvature of the electronic band structure, mainly from the nearly degenerate energy bands (Fig. 1B). The momentum-resolved SHC (see *SI Appendix* for details) revealed that the high intensities of SHC appear around the k points where the Fermi level crosses the nearly degenerate bands. Such a characteristic band structure is unique and occurs as a combined effect of SOC and the IrO_6 octahedral tilting/rotation in the bulk system, which is closely related to the nonsymmorphic symmetry of the bulk crystal structure (34, 35). Due to the extended nature of the SrIrO_3 5d orbitals, the electronic structure of SrIrO_3 is sensitive to changes in lattice symmetry. We reiterate

Significance

Modern spintronics operate based on the spin-to-charge interconversion, where charge current flowing through materials and interfaces with the strong spin-orbit interaction generates spin current via the spin-Hall effect. Here, we report the discovery of a class of intrinsic spin-Hall materials: 5d transition-metal complex oxides. In these materials, a delicate interplay between spin-orbit coupling and electron correlation exists, which can lead to nontrivial spin-related quantum transport phenomena. In particular, we find that epitaxial perovskite SrIrO_3 thin films generate room-temperature spin currents via the spin-Hall effect more efficiently than those previously reported for elemental heavy metals. Furthermore, the efficiency can be modified by epitaxially tailoring the anisotropic SrIrO_3 crystalline symmetry, thus demonstrating a path toward engineering efficient room-temperature spintronics.

Author contributions: T.N. and C.B.E. designed research; T.N., T.J.A., J.G., K.H., N.C., H.Z., Y.Q.D., G.Y.K., D.F.S., T.R.P., N.R., X.J.W., N.X.S., S.Y.C., M.S.R., Y.B.K., D.C.R., and C.B.E. performed research; T.N., T.J.A., J.G., N.C., H.Z., D.F.S., T.R.P., N.R., E.Y.T., and S.Y.C. analyzed data; and T.N., T.J.A., J.G., K.H., D.F.S., T.R.P., E.Y.T., S.Y.C., M.S.R., Y.B.K., D.C.R., and C.B.E. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission. Q.L. is a guest editor invited by the Editorial Board.

Published under the PNAS license.

¹T.N. and T.J.A. contributed equally to this work.

²To whom correspondence may be addressed. Email: ceom@wisc.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1812822116/-DCSupplemental.

Published online July 26, 2019.

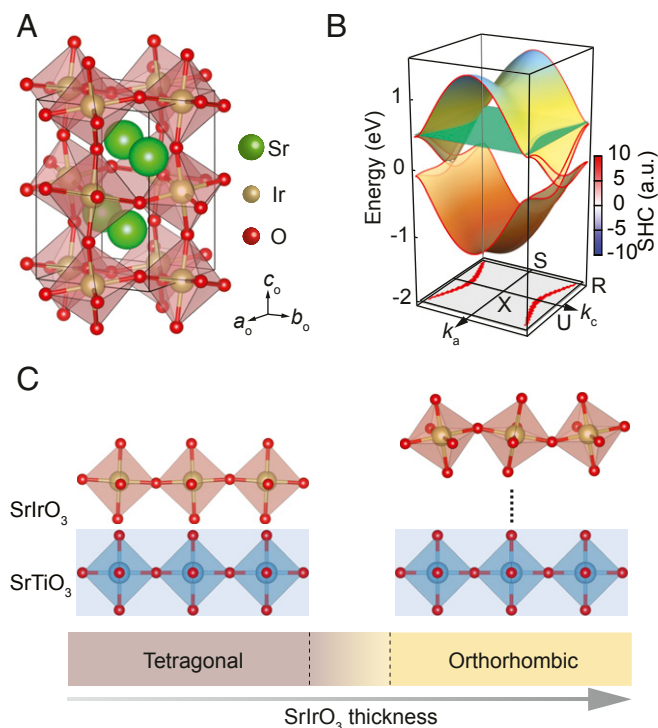


Fig. 1. The mechanism of the spin-Hall effect in SrIrO₃. (A) Orthorhombic perovskite crystal structure of bulk SrIrO₃, where x , y , and z correspond to the $[100]_o$, $[010]_o$, and $[001]_o$ directions, respectively. (B) Electron band structure of bulk SrIrO₃ along the path U-R-S-U-X-S of the Brillouin zone, where the gray boxes highlight the nearly degenerate energy bands responsible for the large bulk SHC. (C) Calculated bulk SrIrO₃ SHC σ_{xy}^S , where the charge current, spin current, and spin polarization direction are along y , z , and x , respectively. (D) Schematic illustrations of the lattice symmetry of SrIrO₃ when grown on cubic nontilted SrTiO₃, where a partial suppression of the IrO₆ octahedral tilt exists up to a certain thickness before a tilted octahedral pattern is established in thicker films.

that the large spin-Hall effect occurs only when the film has the orthorhombic structure due to its origins from the underlying bulk band structure. This suggests an approach to engineer the spin-Hall effect by precise control of oxygen octahedral tilting, which allows fine-tuning of the electronic band structure.

We illustrate our crystalline symmetry design principles for engineering a large spin-Hall effect in Fig. 1D, in which the SrIrO₃ crystalline symmetry is manipulated by utilizing a lattice symmetry-mismatched SrIrO₃/SrTiO₃ heterointerface and atomic layer-by-layer control of the SrIrO₃ layer thickness. The crystalline symmetry of perovskite oxides is directly related to the connectivity of corner-sharing octahedra that can be manipulated by epitaxial strains or interfacial couplings (36). In the case of SrIrO₃ films near the SrIrO₃/SrTiO₃ interface, the IrO₆ octahedral tilting follows the nontilted SrTiO₃ substrate due to the structural imprint of the cubic symmetry of SrTiO₃. Such a nearly complete suppression of IrO₆ octahedral tilting in ultrathin SrIrO₃ films gives rise to a tetragonal symmetry, whereas the degree of tilting in increasingly thicker films approaches that of bulk SrIrO₃. Experimentally, our synchrotron X-ray diffraction of variable thickness films directly confirmed such a structural symmetry transition in SrIrO₃, while our measurements of the spin-Hall effect in SrIrO₃ showed an enhancement, coincident with this transition to orthorhombic symmetry. We also observed a large anisotropy in the spin-Hall effect enabled by the structural anisotropy of the orthorhombic state. These results demonstrate that oxide perovskites not only possess a large spin-Hall effect at room temperature, but also enable further tuning of spin-orbit effects by symmetry design.

Epitaxial SrIrO₃ thin films were grown on (001) SrTiO₃ substrates by pulsed laser deposition with in situ high-pressure reflection high-energy electron diffraction (RHEED) (see [SI Appendix](#) for details). Ferromagnetic Permalloy Ni₈₁Fe₁₉ (Py) polycrystalline thin films were then sputtered in situ on SrIrO₃, preserving critical interface transparency for spin-current transmission and efficient spin-orbit torque (SOT) generation (37, 38). A 1-nm Al₂O₃ layer was added to prevent oxidation of Py. A control sample with an ex situ Py/SrIrO₃ interface showed a 4× smaller efficiency for spin-torque generation due to the reduced spin-current transmissivity at the interface. Atomic force microscopy images of the 1-nm Al₂O₃/3.5-nm Py/8-nm (20-unit-cell) SrIrO₃ surface reveal an atomically smooth surface (see [SI Appendix](#) for details). In Fig. 2, we show the cross-sectional filtered STEM-HAADF image of a 20-unit-cell (uc) SrIrO₃ film on (001) SrTiO₃ capped with 2.5-nm Py. From the image, we determined that the high-quality SrIrO₃ film shares the same pseudocubic epitaxial arrangement as the SrTiO₃ substrate, with sharp interfaces between both SrTiO₃/SrIrO₃ and SrIrO₃/Py and no evidence of oxidized Py at the interface (see [SI Appendix](#) for details). We confirmed by X-ray diffraction that the SrIrO₃ film grows along $[110]_o$ (subscript o for orthorhombic notation) out-of-plane, and with $[110]_o$ and $[001]_o$ in-plane along the $[100]$ and $[010]$ directions of SrTiO₃, respectively (see [SI Appendix](#) for details). For simplicity, we use pseudocubic indices a , b , and c to represent orthorhombic $[110]_o$, $[001]_o$, and $[110]_o$ orientations, respectively.

The spin-Hall effect in SrIrO₃ was probed by measuring the SOT produced in the adjacent Py layer with spin-torque ferromagnetic resonance (ST-FMR) (12, 21, 38), as illustrated in the schematics (Fig. 3A). When an alternating charge current flows in SrIrO₃, the spin-Hall effect induces a spin current that flows into Py. This spin current exerts torque on the Py and excites the magnetic moment into precession, generating an alternating change of the resistance due to the anisotropic magnetoresistance in Py. We measure a dc voltage signal V_{mix} across the device bar that arises from the mixing between the alternating current and changes in the device resistance. The ST-FMR spectrum can be obtained by sweeping external in-plane magnetic fields through the Py resonance condition (see [SI Appendix](#) for details), from which the resonance lineshape has been used

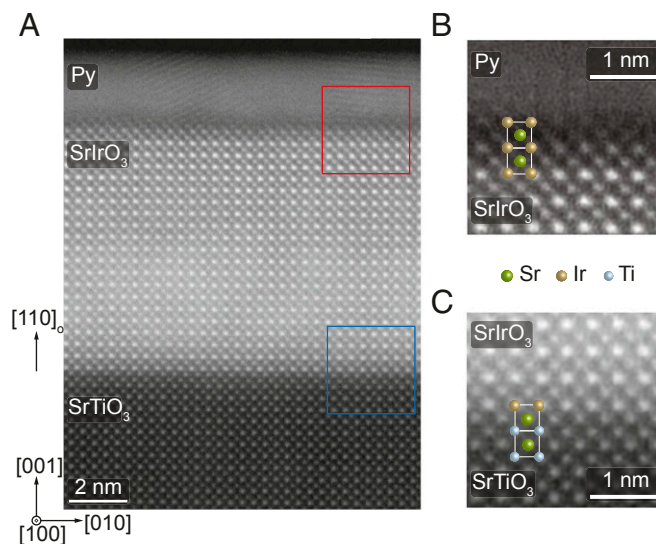
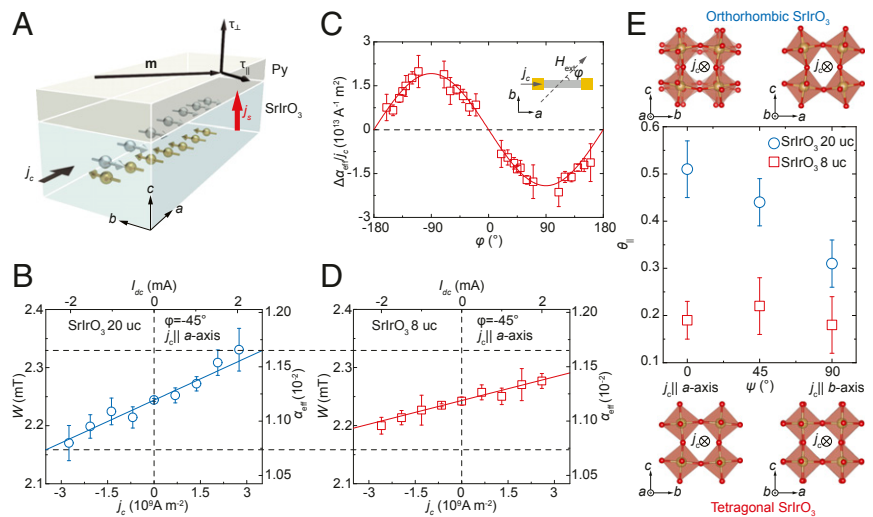


Fig. 2. The structural characterization of the Py/SrIrO₃/SrTiO₃ system. (A) STEM image of Py/SrIrO₃ heterostructure on (001) SrTiO₃ substrate. The image contrast is approximately proportional to the atomic number Z , where brighter colors represent heavier elements. (B and C) Expanded image of the top Py/SrIrO₃ interface B, and the bottom SrIrO₃/SrTiO₃ interface C, showing the high-quality SrIrO₃ film with atomically sharp interfaces. The stacking of the atomic constituents is highlighted in the blown-up images by the superimposed filled dots of different colors (Sr in green, Ir in yellow, and Ti in blue).

Fig. 3. ST-FMR measurements. (A) Schematic of the Py/SrIrO₃ bilayer on SrTiO₃(001) and the current-induced torque geometries. Incoming charge current (j_c) generates a spin current (j_s) along the out-of-plane $[110]_o$ direction or c axis. The pseudocubic indices a , b , and c correspond to orthorhombic $[1\bar{1}0]_o$, $[001]_o$, and $[110]_o$ directions, respectively. (B) Resonance linewidth W and effective magnetic damping α_{eff} as functions of dc charge current I_{dc} and current density j_c in SrIrO₃ for a 3.5-nm Py/8-nm (20-uc) SrIrO₃ microstripe (20 $\mu\text{m} \times 40 \mu\text{m}$). The current is applied along the $[110]_o$ direction (a axis) and the external magnetic field is oriented at an angle $\varphi = -45^\circ$ with respect to the current axis. The applied microwave frequency and power are 5.5 GHz and 15 dBm, respectively. The solid line represents a linear fitting. (C) Current modulation of Py effective damping as a function of external magnetic-field angle for the 3.5-nm Py/8-nm (20-uc) SrIrO₃ sample. The solid line shows the fit to $\sin(\varphi)$. Resonance linewidth W and effective magnetic damping α_{eff} as functions of dc and current density. (D) Change of W and α_{eff} due to j_c in a 3.5-nm Py/3.2-nm (8-uc) SrIrO₃ sample. (E) In-plane crystallographic orientation dependence of the ST ratio $\theta_{\parallel}$ for Py/SrIrO₃ bilayers (with Py thickness fixed at 3.5 nm) with two different SrIrO₃ film thicknesses. ψ is the angle between the $[110]_o$ direction (a axis) and the applied current axis. The top and bottom schematics illustrate the planar crystalline geometry of SrIrO₃ viewed along a and b axes for orthorhombic and tetragonal symmetries, respectively.



to evaluate the efficiency of the torque. This would require a precise calibration of the microwave current in the bilayer. However, we find that the impedance of the SrTiO₃ substrates decreases at microwave frequencies to become comparable to the bilayer, thus leading to microwave current shunting through substrates. This may affect the result based on ST-FMR lineshape analysis (see *Materials and Methods* for details).

We evaluated the ST ratio, which describes the efficiency of in-plane component of torque $\tau_{\parallel}$ generation relative to the charge-current density in SrIrO₃ via spin-Hall effect ($\theta_{\parallel} = (\hbar/2e)j_s/j_c$, where j_s is the spin current density absorbed by the Py, and j_c is the applied charge-current density in SrIrO₃), in SrIrO₃ by measuring the dc-induced changes in the ST-FMR lineshape (dc-tuned ST-FMR) (11, 12, 38). The injection of the dc exerts an additional dc ST on the adjacent Py, which modifies the Py resonance linewidth W (and effective Gilbert damping α_{eff}), as this torque component adds to or subtracts from the Gilbert damping torque depending on the relative orientation between the current and magnetic field (11). This linewidth modification due to the applied dc should be unaffected by microwave frequency current shunting through SrTiO₃ substrates, and the anomalous Nernst effect in Py due to unintentional thermal gradients. A quantitative analysis of the ST ratio $\theta_{\parallel}$ for 3.5-nm Py/8-nm (20-uc) SrIrO₃ bilayers is shown in Fig. 3B, where W and α_{eff} scale linearly with the applied dc. The current is applied parallel to the a axis and the in-plane magnetic field is swept at an angle $\varphi = -45^\circ$, with respect to the current axis. The magnitude of the in-plane torque is proportional to the change of the effective Gilbert damping α_{eff} over the current density j_c in SrIrO₃. By averaging measurements at different frequencies (see *SI Appendix* for the frequency dependence of $\theta_{\parallel}$), we find that the ST ratio, $\theta_{\parallel} = 0.51 \pm 0.07$ for 3.5-nm Py/8-nm (20-uc) SrIrO₃, comparable to the highest values reported for heavy-metal systems (7, 39), and 4 $\times$ as large as that of a 4-nm Py/4-nm Pt control sample ($\theta_{\parallel} = 0.12 \pm 0.03$). The sign for $\theta_{\parallel}$ is consistent with our first-principle calculations for bulk SrIrO₃ and experimental results on the heavy-metal Pt. We examine the symmetry of the in-plane current-induced torque by performing Py magnetization angular dependence dc-tuned ST-FMR. Fig. 3C shows the current-induced change in the effective damping $\Delta\alpha_{\text{eff}}/j_c$ (slope of the linear fit in Fig. 3B) as a function of in-plane magnetic field angle φ , which fits to $\sin\varphi$. This is consistent with the symmetry of the conventional current-induced torque that has been observed previous in polycrystalline heavy-metal/ferromagnet bilayer systems (15).

As a comparison, a significantly smaller ST ratio $\theta_{\parallel}$ was observed in the 3.5-nm Py/3.2-nm (8-uc) SrIrO₃ bilayer sample as

shown in Fig. 3D where the current-induced change in the effective damping is smaller. We attribute the large difference of $\theta_{\parallel}$ in 8- and 20-uc SrIrO₃ samples to their structural transition with thickness (from tetragonal to orthorhombic) due to the structural imprint of nontilted SrTiO₃ substrates as illustrated in Fig. 1C. This agrees with our theory prediction of large spin-Hall effect in SrIrO₃ with an orthorhombic structure (the dependence of the ST ratio on SrIrO₃ film thickness will be discussed next).

Interestingly, we also observed a significant dependence of the ST ratio on crystallographic orientation in the thicker SrIrO₃ sample (3.5-nm Py/8-nm SrIrO₃) as shown in Fig. 3E (blue circle), where the $\theta_{\parallel}$ was extracted from devices with the charge current applied along various in-plane crystal orientations (from a to b axis) while keeping the magnetic field angle $\varphi = -45^\circ$. Owing to the anisotropic structural characteristics of the orthorhombic symmetry, the IrO₆ octahedral rotation is out of phase along the a axis (Fig. 3E, Top Left), whereas it is in phase along the b axis (Fig. 3E, Top Right), which gives rise to a different oxygen octahedral configuration when the charge current is applied along the a or b axis, and, therefore, the anisotropic $\theta_{\parallel}$. This contrasts the nearly isotropic $\theta_{\parallel}$ observed in the thinner SrIrO₃ sample (3.5-nm Py/8-nm SrIrO₃, red square), which was found to exhibit almost total suppression of the octahedral tilt along both the a and b axes (Fig. 3E, Bottom) compared with the thicker film (*SI Appendix*). Such dependence on crystallographic orientation of the ST ratio in tetragonal and orthorhombic SrIrO₃ demonstrates the strong correlation between the spin-Hall effect and the crystalline symmetry.

The dependence of the ST ratio on the thickness of the SrIrO₃ layer and on the direction of current relative to the crystal axes was also confirmed by another independent characterization technique, in which the ST-induced magnetization rotation in Py was measured by the polar magnetooptic-Kerr effect (MOKE) (40). In a 5.5-nm Py/10-nm SrIrO₃ sample with the current applied along the a axis, the ST ratio was measured to be 0.15 ± 0.01 , which is 2 to 3 $\times$ as large as a Py/Pt control sample measured by the MOKE (0.065 ± 0.01 ; see *SI Appendix* for details). This is qualitatively consistent with our dc-tuned ST-FMR results, although the absolute value of the ST ratio is smaller. Nevertheless, the MOKE measurements confirm the large lattice symmetry dependence ($\theta_{\parallel} = 0.15 \pm 0.01$ in the 25-uc SrIrO₃ sample, and 0.013 ± 0.01 in the 8-uc SrIrO₃ sample) and the anisotropic ST ratio ($\theta_{\parallel} = 0.15 \pm 0.01$ with $j_c \parallel a$ axis, and 0.05 ± 0.005 with $j_c \parallel b$ axis in the 25-uc SrIrO₃ sample), which are qualitatively

consistent with the trends obtained in our dc-tuned ST-FMR measurements.

To analyze the effect of lattice symmetry on spin-Hall effect in detail, we studied the dependence of the ST ratio on varying thicknesses of SrIrO₃ films. From synchrotron X-ray measurements, we robustly established the previously discussed suppression of IrO₆ octahedral tilt for ultrathin SrIrO₃ films, which modifies the symmetry of SrIrO₃ from orthorhombic to tetragonal (see *SI Appendix* for details) (41–43). As shown in Fig. 4A, this transition is characterized by the orthorhombicity factor defined as a_o/b_o (orthorhombic indices), which illustrates a tetragonal-to-orthorhombic SrIrO₃ structural transition around 4.8 nm (12 uc). We then measured the ST ratio on the same series of SrIrO₃/Py bilayer samples (with fixed Py thickness). Accordingly, as shown in Fig. 4B, $\theta_{||}$ increases sharply and saturates at the thickness of 6.4 nm (16 uc) from a nearly constant value when the thickness is below 10 uc. The ST ratio is also expected to increase and saturate when the thickness of the spin-Hall source material exceeds the spin-diffusion length based on the standard spin-diffusion theory (44). However, the abrupt change of $\theta_{||}$ occurs at the SrIrO₃ structural transition thickness, which cannot be explained simply by the diffusive spin transport, as we determined a short spin-diffusion length of ~ 1.4 nm (3.5 uc) for tetragonal SrIrO₃ from the thickness dependence of the overlayer Py Gilbert damping enhancement (Fig. 4C; see *Materials and Methods* for the estimation of spin-diffusion length, spin mixing conductance, and intrinsic spin-Hall angle). This strong dependence of $\theta_{||}$ on lattice symmetry rather than on spin diffusion illustrates a direct connection between the degree of IrO₆ octahedral tilt and the ST efficiency.

To gain more insight into the crystalline symmetry dependence of spin-Hall effect, we performed additional SHC calculations on tetragonal and orthorhombic phases of SrIrO₃ with density-functional theory calculated band structures (see *SI Appendix* for details). Qualitatively consistent with our experimental results, the orthorhombic phase of SrIrO₃ shows a larger SHC, which can be attributed to its narrow t_{2g} bands with more band crossings protected by symmetry, which is determined by the IrO₆ octahedral tilting.

In summary, we have proposed and developed a material for SOT applications in a transition-metal perovskite with SOC $5d$ electrons, in which the interplay between SOC and the crystal structure produces a large ST ratio. Furthermore, the extended nature of $5d$ orbitals allows a sensitive response of the electronic band structure to an externally manipulated lattice structure, as manifested in the strong dependency of the spin-Hall effect on the degree of IrO₆ octahedral tilting in epitaxially strained SrIrO₃. Such intricate coupling between the electronic and lattice degrees of freedom can thus open up an avenue to engineer spin-orbit effects by tailoring the lattice symmetry through heteroepitaxy. This material acts as an ideal building block for oxide spintronics, since a broad range of ferromagnetic perovskites can be integrated in an epitaxial heterostructure with atomically sharp interfaces for efficient spin-current transmission. Therefore, we anticipate that the use of $5d$ transition-metal perovskites could lead to substantial advances in spintronics.

Materials and Methods

Sample Growth, Fabrication, and Characterization. SrIrO₃ films were epitaxially synthesized on (001) SrTiO₃ substrates using pulsed laser deposition (PLD). During the growth, layer-by-layer deposition was observed by in situ RHEED. Before the growth, the SrTiO₃ (001) substrates were chemically etched and annealed to ensure TiO₂ surface termination. The substrates were first immersed in buffered hydrofluoric acid for 60 s before being annealed at 900 °C for 6 h in an O₂-rich environment. After annealing, the substrates were etched again in buffered hydrofluoric acid to remove any leftover SrO on the surface. The PLD growth was conducted at a substrate temperature of 600 °C and an oxygen partial pressure of 75 mTorr. The laser fluence at the SrIrO₃ target surface was ~ 1 J/cm² and the pulse repetition was 10 Hz. The working distance between target and substrate was ~ 58 mm. After the SrIrO₃ growth, the sample was cooled down in an oxygen-rich atmosphere. The chamber was reevacuated at room temperature and Py

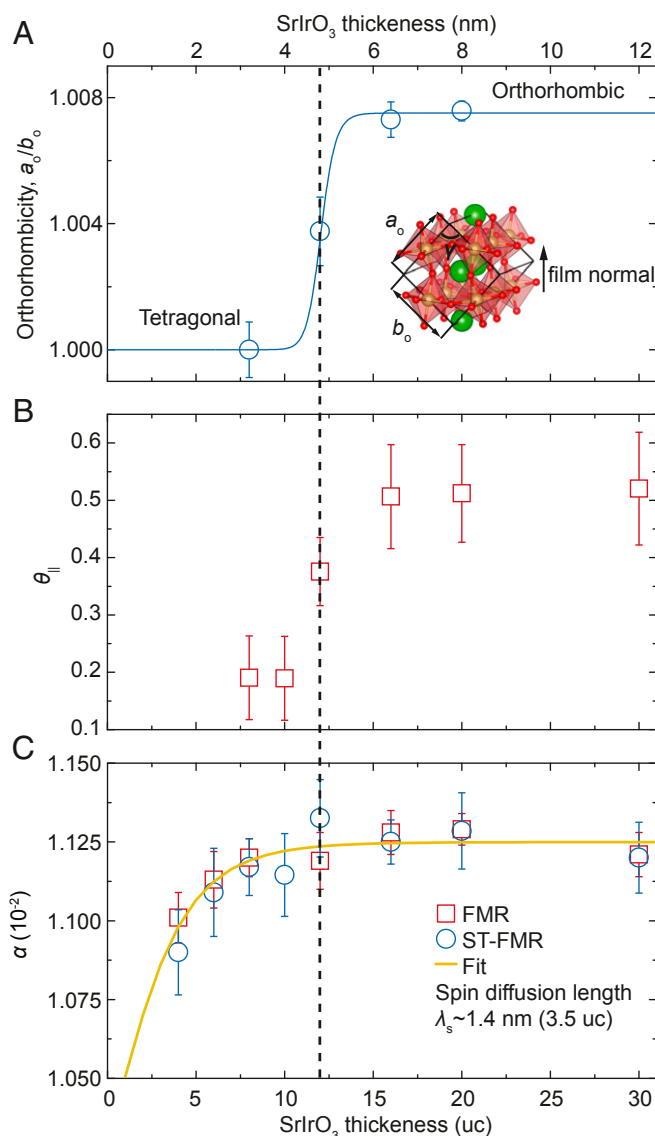


Fig. 4. Control of ST ratio with lattice symmetry stabilization. (A) Thickness dependence of orthorhombicity factor, defined as a_o/b_o , of SrIrO₃ thin films. The solid line is a guide to illustrate the SrIrO₃ crystalline symmetry transition. (Inset) Schematic of the SrIrO₃ orthorhombic uc with the tilted IrO₆ octahedra, where the arrow indicates the thin-film growth direction (c axis or $[110]_o$). γ is the angle between a_o - and b_o axis. (B) SrIrO₃ thickness dependence of spin-orbit ratio $\theta_{||}$ for Py/SrIrO₃ bilayers (with Py thickness fixed at 3.5 nm). (C) SrIrO₃ thickness dependence of Gilbert damping parameter α determined by the broadband FMR (red) and ST-FMR (blue) measurements for Py/SrIrO₃ bilayers (with Py thickness fixed at 3.5 nm). The solid line represents the fit to the diffusive spin-pumping model, which gives a spin-diffusion length $\lambda_s \sim 1.4$ nm for SrIrO₃.

was sputter deposited at an Ar pressure of 3 mTorr with a background pressure $< 2 \times 10^{-8}$ Torr, followed by a 1-nm Al passivation layer. The Py film is shown to be polycrystalline, which we confirmed by the observation of RHEED diffraction rings after deposition. The atomically flat Py surface on top of SrIrO₃ was verified using atomic force microscopy (see *SI Appendix* for details). We confirmed the thickness, epitaxial arrangement, and coherence of the SrIrO₃ films using X-ray reflectivity, X-ray diffraction, and reciprocal space mappings (see *SI Appendix* for details). The coherent SrIrO₃ films assembled on the cubic SrTiO₃ substrate with the orthorhombic SrIrO₃ $[1-10]_o$, $[001]_o$, and $[110]_o$ directions along the cubic SrTiO₃ $[100]$, $[010]$, and $[001]$ directions, respectively, and the misfit epitaxial strain from the SrTiO₃ induced a monoclinic distortion of the SrIrO₃ unit cell, which is consistent with similar orthorhombic perovskites grown on cubic substrates (see *SI Appendix* for details) (45). The thickness of Py films was measured by using X-ray reflectivity.

We patterned the Py/SrIrO₃ sample by using photolithography followed by ion-beam milling. Then 200-nm Pt/5-nm Ti electrodes were sputter deposited and defined by a lift-off procedure. Devices for ST-FMR were patterned into microstrips (20–50 μm wide and 40–100 μm long) with ground-signal-ground electrodes. Devices for electrical transport measurements were patterned into 100-μm-wide and 500-μm-long Hall bars.

Scanning Transmission Electron Microscope Measurements. Transmission electron microscope (TEM) specimens were prepared by a focused ion multibeam system (JIB-4610F, JEOL). To protect the Py/SrIrO₃ films, an amorphous carbon layer was deposited on the top surface before the ion-beam milling. A Ga⁺ ion beam with an acceleration voltage of 30 kV was used to fabricate the thin TEM lamella. To minimize the surface damage induced by the Ga⁺ ion-beam milling, the sample was further milled by an Ar⁺ ion beam (PIPS II, Gatan) with an acceleration voltage of 100 meV for 4 min. HAADF-STEM images were taken by using a STEM (JEM-2100F, JEOL) at 200 kV with a spherical aberration corrector (CEOS GmbH). The optimum size of the electron probe was ~0.9 Å. The collection semiangles of the HAADF detector were adjusted from 70 to 200 mrad to collect large-angle elastic scattering electrons for clear Z-sensitive images. The obtained raw images were processed with a band-pass Wiener filter with a local window to reduce a background noise (HREM Research Inc.).

ST-FMR Measurements. During ST-FMR measurements, a microwave current at a fixed frequency (4.5–7 GHz) is applied through the ac port of a bias-T to a radiofrequency (rf) ground-signal-ground probe tip. The microwave power output (8–14 dBm) is also fixed. The in-plane magnetic fields are generated by a rotary electromagnet which allows for magnetic-field angle dependence of ST-FMR measurements. Magnetic fields are swept from 0 to 0.12 T for driving the Py through its resonance condition. The resonance lineshape can be fitted to a sum of symmetric and antisymmetric Lorentzian components, where the antidamping (in plane, $\tau_{||}$) and field-like torque (out of plane, $\tau_{\perp}$) components are proportional to the amplitudes of the symmetric and antisymmetric lineshape, respectively. By performing the lineshape analysis, the ST ratio can be determined. However, we find through rf transmission measurements that although bare SrTiO₃ is nonconductive at low frequencies, after processing, it has a finite impedance at microwave frequencies, and as a consequence rf current is shunted through the SrTiO₃ substrate during ST-FMR measurements. This shunting may cause potential additional contributions to the Oersted field and modify the size of the antisymmetric component of the lineshape. Additionally, the unknown current shunted through the SrTiO₃ poses a challenge for determining the rf current flowing through our SrIrO₃ layer based on rf transmission calibration. Hence, it is difficult to determine the size of the spin-Hall effect in SrIrO₃ from rf lineshape analysis alone. For this reason, we rely on dc-tuned ST-FMR measurements, for which the linewidth modification due to the applied dc should be unaffected by microwave frequency current shunting, and polar MOKE measurements, for which rf current is unnecessary. Both of these measurement methods should be unaffected by the high-frequency conductivity of the SrTiO₃ substrate.

In dc-tuned ST-FMR, we modulate the rf current amplitude and measure the mixing voltage signal by using a lock-in amplifier through the dc port of the bias-T. The modulation frequency is 437 Hz. The resonance lineshape is fitted to a sum of symmetric and antisymmetric Lorentzian components, from which the resonance linewidth is extracted. We quantify the $\theta_{||}$ by linear fitting the current-dependent resonance linewidth or α_{eff} as $|\theta_{||}| = \frac{2|e|}{h} \frac{(H_{\text{FMR}} + M_{\text{eff}}/2)\mu_0 M_s t_{\text{FM}}}{|\sin\theta_{\text{py}}|} \left| \frac{\Delta\alpha_{\text{eff}}}{\Delta j_c} \right|$, where α_{eff} is the effective magnetic damping of Py that is related to W as $\alpha_{\text{eff}} = \frac{\gamma}{2\pi f} W + W_0$ (W_0 is the inhomogeneous linewidth broadening); and γ , μ_0 , M_{eff} , M_s , and t_{FM} are the gyromagnetic ratio, the permeability in vacuum, the effective magnetization, the saturation magnetization, and the thickness of Py, respectively. We determined the Gilbert damping parameter and the effective magnetization by the frequency dependence of the resonance linewidth and resonance field, respectively (SI Appendix). The charge-current density j_c is carefully calibrated by measuring the 4-point resistance for each layer with a parallel resistor model (see SI Appendix for details).

MOKE Measurements. Polar MOKE measurements of $\theta_{||}$ were performed using a 630-nm diode laser, a Glan-Taylor polarizer with an extinction coefficient of $10^5:1$, and a 10 $\times$ infinity corrected microscope objective to focus 2 mW of optical power down to a 10-μm spot. An excitation current through the device of 7–10 mA at 5,667 Hz was used to lock in to the response of the magnetization due to the antidamping ST. The laser spot was scanned across the middle of the device at external fields of 0.08 T parallel and antiparallel

to the current flow direction in the device. The linear polarization incident on the sample was 45° rotated from the external field direction to suppress quadratic MOKE effects. $\theta_{||}$ is quantified as by using the ratio of the integrated absolute value of the signal across the device that is even under the external magnetic-field reversal (A_{sum}) and odd under magnetic-field reversal (A_{diff}) according to $\theta_{||} = \frac{A_{\text{diff}}}{A_{\text{sum}}} \frac{e}{h} \frac{\mu_0 M_s t_{\text{tot}} \ln(4)}{X}$ (see SI Appendix for details), where t_{tot} is the total thickness of the SrIrO₃/Py bilayer and X is fraction of current flowing through the SrIrO₃ as determined via the parallel resistor model described in SI Appendix.

Synchrotron X-Ray Thin-Film Diffraction. Synchrotron X-ray diffraction measurements were carried out to precisely characterize the structural and lattice symmetry evolution as a function of thickness of SrIrO₃ thin films epitaxially grown on a (001) SrTiO₃ substrate. The thin-film diffraction measurements were performed on a 5-circle diffractometer with χ -circle geometry, using an X-ray energy of 20 keV (wavelength $\lambda = 0.6197$ Å) at sector 12-ID-D of the Advanced Photon Source, Argonne National Laboratory. The X-ray beam at the beamline 12-ID-D has a total flux of 4.0×10^{12} photons per second and was vertically focused by beryllium compound refractive lenses down to a beam profile of ~50 μm. The L scans along respective truncation rods {10L} were obtained by subtracting the diffuse background contributions using the 2D images acquired with a pixel 2D array area detector (Dectris PILATUS-1mm Si 100 K). The separation of respective {103} film peak positions in reciprocal space can be used to extract the out-of-plane tilt angle of the SrIrO₃ film with respect to the cubic SrTiO₃ lattice, so that we can obtain the degree of orthorhombic distortion ($a/b > 1$) for each SrIrO₃ thin film as a function of thickness (see SI Appendix for details).

Estimation of the Spin-Diffusion Length, Spin-Mixing Conductance, and Intrinsic Spin-Hall Angle in Py/SrIrO₃. To estimate the spin-diffusion length in our SrIrO₃ thin film, we characterize the Gilbert damping parameter α of Py in Py/SrIrO₃ bilayers with various SrIrO₃ thicknesses by using both ST-FMR (on patterned samples) and broadband FMR measurements (on 5-mm $\times$ 5-mm samples). In broadband FMR measurements, the microwave magnetic field is produced by a coplanar waveguide, and the resonance spectrum is obtained by sweeping external magnetic fields through the Py resonance condition with a fixed microwave frequency. We measure the field derivative of the FMR absorption intensity with field modulation at low frequency (<1 kHz). In both techniques, we perform frequency-dependent measurements, from which the resonance linewidth of Py is obtained at each frequency. The Gilbert damping parameter α is then calculated as $W = W_0 + \frac{2\alpha\omega}{|\gamma|}$, where W_0 is the inhomogeneous linewidth broadening. We observed the enhancement of α with increasing SrIrO₃ thickness due to the spin-pumping effect as shown in Fig. 4C. The data can be fitted to a diffusive spin-transport model

as (46) $\alpha = \alpha_0 + \frac{g_{\text{op}} \mu_B h}{2e^2 M_s t_{\text{SIO}}} \left[\frac{1}{G_{\perp}} + 2\rho(t)\lambda_s \coth\left(\frac{t}{\lambda_s}\right) \right]^{-1}$, where g_{op} is the Landé g factor, α_0 is the Gilbert damping with zero SrIrO₃ thickness, $G_{\perp}$ is the interfacial spin-mixing conductance per unit area, t is the thickness of SrIrO₃, $\rho(t)$ is the thickness-dependent resistivity of SrIrO₃, and λ_s is the spin-diffusion length in SrIrO₃. In this fitting, we take into account the thickness dependence of the SrIrO₃ resistivity which increases in ultrathin films due to scattering mechanisms (see SI Appendix for details), which gives a spin-mixing conductance $G_{\perp}$ of $1.8 \times 10^{14} \Omega^{-1} \cdot \text{m}^{-2}$ and a spin diffusion length of 1.4 nm. These are consistent with that reported in the LaSrMnO₃/SrRuO₃ system (47). The value of the spin-diffusion length corresponds to the tetragonal phase of SrIrO₃, since the damping parameter is largely saturated already for thicknesses less than the point of transition to the orthogonal phase at 4.8 nm (12 uc).

The ST exerted on the Py originates from the spin current that is transmitted through the interface and absorbed by Py. Therefore, the measurement of the ST ratio provides the lower bound of the intrinsic spin-Hall effect, in which the ST ratio $\theta_{||}$ can be expressed as $\theta_{||} \equiv T\theta_{\text{SH}}$, where T is the spin-current transmissivity; θ_{SH} is the intrinsic spin-Hall angle. The reduction of the spin current through the interface can be either due to spin backflow (48, 49) or spin-memory-loss mechanisms associated with spin-dependent interfacial scattering. If spin backflow is dominant, then based on the drift-diffusion approximation for a SrIrO₃ layer thicker than the spin-diffusion length, one should have $T \equiv \frac{2G_{\perp}}{2G_{\perp} + \sigma/\lambda}$, where $G_{\perp}$, σ , and λ are the spin-mixing conductance, conductivity, and spin-diffusion length of the SrIrO₃, respectively. For the 3.5-nm Py/8-nm SrIrO₃ sample, $G_{\perp} = 1.8 \times 10^{14} \Omega^{-1} \cdot \text{m}^{-2}$, $\lambda = 1.4$ nm, and $\sigma = 2.5 \times 10^5 \Omega^{-1} \cdot \text{m}^{-1}$. We then obtain $T = 0.67$, and $\theta_{\text{SH}} = 0.76 \pm 0.1$. Spin-memory loss would contribute an additional reduction in the spin transmissivity, leading to an even larger estimate for the intrinsic spin-Hall angle in SrIrO₃.

Theoretical Calculations. For the spin-Hall conductivity calculations, we employed a $j_{\text{eff}} = 1/2$ tight-binding model constructed for the orthorhombic perovskite bulk SrIrO_3 (34, 35). The model incorporates various spin-dependent hopping channels for Ir electrons generated by oxygen octahedron tilting in the bulk structure. The model Hamiltonian H consists of 4 doubly degenerate electron bands on account of the 4 Ir sites in each unit cell.

$$H = \sum_{\mathbf{k}} \psi_{\mathbf{k}}^\dagger H_{\mathbf{k}} \psi_{\mathbf{k}}.$$

Here, $\psi = (\psi_{1\uparrow}, \psi_{2\uparrow}, \psi_{3\uparrow}, \psi_{4\uparrow}, \psi_{1\downarrow}, \psi_{2\downarrow}, \psi_{3\downarrow}, \psi_{4\downarrow})^T$ are electron operators with the subscripts meaning the sublattice (1,2,3,4) and $j_{\text{eff}} = 1/2$ pseudospin ($\uparrow, \downarrow$). The explicit form of $H_{\mathbf{k}}$ and the values of the hopping parameters can be found in refs. 24 and 25. The electron band structure of the model is displayed in Fig. 1B. Then, the SHC tensor $\sigma_{\mu\nu}^{\rho}$ is calculated by the Kubo formula (7, 50):

$$\sigma_{\mu\nu}^{\rho} = \sum_{\mathbf{k}} \Omega_{\mu\nu}^{\rho}(\mathbf{k}),$$

where

$$\Omega_{\mu\nu}^{\rho}(\mathbf{k}) = \frac{2eh}{V} \sum_{\epsilon_{\mathbf{n}\mathbf{k}} < \epsilon_F < \epsilon_{\mathbf{m}\mathbf{k}}} \text{Im} \left[\frac{(\mathbf{m}\mathbf{k} | \mathcal{J}_{\mu}^{\rho} | \mathbf{n}\mathbf{k})(\mathbf{n}\mathbf{k} | J_{\nu} | \mathbf{m}\mathbf{k})}{(\epsilon_{\mathbf{m}\mathbf{k}} - \epsilon_{\mathbf{n}\mathbf{k}})^2} \right].$$

Here, $J_{\nu} = (\sum_{\mathbf{k}} \psi_{\mathbf{k}}^\dagger \frac{\partial H_{\mathbf{k}}}{\partial \mathbf{k}} \psi_{\mathbf{k}})$ is charge current, and $\mathcal{J}_{\mu}^{\rho} = (\frac{1}{4} \{\sigma^{\rho}, J_{\mu}\})$ is spin current with the $j_{\text{eff}} = 1/2$ spin represented by the Pauli matrix σ^{ρ} . In the above

expression, V is the volume of the system, ϵ_F is the Fermi level, and $|\mathbf{m}\mathbf{k}\rangle$ represents a Bloch state of H with energy $\epsilon_{\mathbf{m}\mathbf{k}}$. The momentum-resolved SHC represented by $\Omega_{\mu\nu}^{\rho}(\mathbf{k})$ enables us to trace the electron states responsible for the large spin-Hall effect. More details of the theoretical calculation of SHC in SrIrO_3 can be found in a recent theoretical paper (51) by 2 authors from the current work.

ACKNOWLEDGMENTS. This work was supported by the National Science Foundation under Designing Materials to Revolutionize and Engineer our Future Grant DMR-1629270, Air Force Office of Scientific Research FA9550-15-1-0334 and the Army Research Office through Grant W911NF-17-1-0462. Transport measurement at the University of Wisconsin–Madison was supported by the US Department of Energy (DOE), Office of Science, Office of Basic Energy Sciences under Award DE-FG02-06ER46327. Work at Northeastern University is funded by the NSF TANMS ERC Award 1160504. This research used resources of the Advanced Photon Source, a US DOE Office of Science User Facility operated for the DOE Office of Science by Argonne National Laboratory under Contract DE-AC02-06CH11357. Work at Cornell was supported by the National Science Foundation (DMR-1708499) and Western Digital, and made use of the Cornell Center for Materials Research Shared Facilities which are supported by the NSF Materials Research Science and Engineering Centers program (DMR-1719875). K.H. and Y.B.K. are supported by the Natural Sciences and Engineering Research Council of Canada, Canadian Institute for Advanced Research, and Center for Quantum Materials at the University of Toronto. We acknowledge P. J. Ryan, D. D. Fong, and J. Irwin for discussions, S. Emori for comments on the manuscript, and Y. J. Ma, D. T. Harris, L. Guo, and J. Schad for technical assistance with experiments. T.N. acknowledges L. C. Sun for assistance in graphic design.

1. A. Brataas, A. D. Kent, H. Ohno, Current-induced torques in magnetic materials. *Nat. Mater.* **11**, 372–381 (2012).
2. T. Jungwirth, X. Marti, P. Wadley, J. Wunderlich, Antiferromagnetic spintronics. *Nat. Nanotechnol.* **11**, 231–241 (2016).
3. Y. Otani, M. Shiraishi, A. Oiwa, E. Saitoh, S. Murakami, Spin conversion on the nanoscale. *Nat. Phys.* **13**, 829–832 (2017).
4. P. Gambardella, I. M. Miron, Current-induced spin-orbit torques. *Philos. Trans. A Math. Phys. Eng. Sci.* **369**, 3175–3197 (2011).
5. M. I. Dyakonov, V. I. Perel, Current-induced spin orientation of electrons in semiconductors. *Phys. Lett. A* **35**, 459–460 (1971).
6. J. E. Hirsch, Spin Hall effect. *Phys. Rev. Lett.* **83**, 1834–1837 (1999).
7. J. Sinova, S. O. Valenzuela, J. Wunderlich, C. H. Back, T. Jungwirth, Spin Hall effects. *Rev. Mod. Phys.* **87**, 1213–1260 (2015).
8. V. M. Edelstein, Spin polarization of conduction electrons induced by electric current in two-dimensional asymmetric electron systems. *Solid State Commun.* **73**, 233–235 (1990).
9. Y. K. Kato, R. C. Myers, A. C. Gossard, D. D. Awschalom, Observation of the spin Hall effect in semiconductors. *Science* **306**, 1910–1913 (2004).
10. C. Brüne et al., Evidence for the ballistic intrinsic spin Hall effect in HgTe nanostructures. *Nat. Phys.* **6**, 448–454 (2010).
11. K. Ando et al., Electric manipulation of spin relaxation using the spin Hall effect. *Phys. Rev. Lett.* **101**, 036601 (2008).
12. L. Liu, T. Moriyama, D. C. Ralph, R. A. Buhrman, Spin-torque ferromagnetic resonance induced by the spin Hall effect. *Phys. Rev. Lett.* **106**, 036601 (2011).
13. L. Liu et al., Spin-torque switching with the giant spin Hall effect of tantalum. *Science* **336**, 555–558 (2012).
14. J. Kim et al., Layer thickness dependence of the current-induced effective field vector in Ta/CoFeB/MgO. *Nat. Mater.* **12**, 240–245 (2013).
15. K. Garello et al., Symmetry and magnitude of spin-orbit torques in ferromagnetic heterostructures. *Nat. Nanotechnol.* **8**, 587–593 (2013).
16. S. Emori, U. Bauer, S.-M. Ahn, E. Martinez, G. S. D. Beach, Current-driven dynamics of chiral ferromagnetic domain walls. *Nat. Mater.* **12**, 611–616 (2013).
17. X. Fan et al., Observation of the nonlocal spin-orbital effective field. *Nat. Commun.* **4**, 1799 (2013).
18. W. Zhang et al., Spin Hall effects in metallic antiferromagnets. *Phys. Rev. Lett.* **113**, 196602 (2014).
19. K. Fujiwara et al., 5d iridium oxide as a material for spin-current detection. *Nat. Commun.* **4**, 2893 (2013).
20. E. Lesne et al., Highly efficient and tunable spin-to-charge conversion through Rashba coupling at oxide interfaces. *Nat. Mater.* **15**, 1261–1266 (2016).
21. A. R. Mellnik et al., Spin-transfer torque generated by a topological insulator. *Nature* **511**, 449–451 (2014).
22. Y. Fan et al., Magnetization switching through giant spin-orbit torque in a magnetically doped topological insulator heterostructure. *Nat. Mater.* **13**, 699–704 (2014).
23. J. C. Rojas-Sánchez et al., Spin to charge conversion at room temperature by spin pumping into a new type of topological insulator: α -Sn films. *Phys. Rev. Lett.* **116**, 096602 (2016).
24. C. H. Li et al., Electrical detection of charge-current-induced spin polarization due to spin-momentum locking in Bi_2Se_3 . *Nat. Nanotechnol.* **9**, 218–224 (2014).
25. W. Witzak-Krempa, G. Chen, Y. B. Kim, L. Balents, Correlated quantum phenomena in the strong spin-orbit regime. *Annu. Rev. Condens. Matter Phys.* **5**, 57–82 (2014).
26. C. Fang, L. Lu, J. Liu, L. Fu, Topological semimetals with helical surface states. *Nat. Phys.* **12**, 936–941 (2016).

27. D. Pesin, L. Balents, Mott physics and band topology in materials with strong spin-orbit interaction. *Nat. Phys.* **6**, 376–381 (2010).
28. T. Kondo et al., Quadratic Fermi node in a 3D strongly correlated semimetal. *Nat. Commun.* **6**, 10042 (2015).
29. J. Matsuno et al., Engineering a spin-orbital magnetic insulator by tailoring superlattices. *Phys. Rev. Lett.* **114**, 247209 (2015).
30. Y. F. Nie et al., Interplay of spin-orbit interactions, dimensionality, and octahedral rotations in semimetallic SrIrO_3 . *Phys. Rev. Lett.* **114**, 016401 (2015).
31. X. Wan, A. M. Turner, A. Vishwanath, S. Y. Savrasov, Topological semimetal and Fermi-arc surface states in the electronic structure of pyrochlore iridates. *Phys. Rev. B* **83**, 205101 (2011).
32. A. Shitade et al., Quantum spin Hall effect in a transition metal oxide Na_2IrO_3 . *Phys. Rev. Lett.* **102**, 256403 (2009).
33. D. Xiao, M. C. Chang, Q. Niu, Berry phase effects on electronic properties. *Rev. Mod. Phys.* **82**, 1959–2007 (2010).
34. J. M. Carter, V. V. Shankar, M. A. Zeb, H. Y. Kee, Semimetal and topological insulator in perovskite iridates. *Phys. Rev. B* **85**, 115105 (2012).
35. Y. Chen, Y.-M. Lu, H.-Y. Kee, Topological crystalline metal in orthorhombic perovskite iridates. *Nat. Commun.* **6**, 6593 (2015).
36. H. Y. Hwang et al., Emergent phenomena at oxide interfaces. *Nat. Mater.* **11**, 103–113 (2012).
37. W. Zhang, W. Han, X. Jiang, S.-H. Yang, S. S. P. Parkin, Role of transparency of platinum-ferromagnet interfaces in determining the intrinsic magnitude of the spin Hall effect. *Nat. Phys.* **11**, 496–502 (2015).
38. T. Nan et al., Comparison of spin-orbit torques and spin pumping across NiFe/Pt and NiFe/Cu/Pt interfaces. *Phys. Rev. B* **91**, 214416 (2015).
39. K.-U. Demasius et al., Enhanced spin-orbit torques by oxygen incorporation in tungsten films. *Nat. Commun.* **7**, 10644 (2016).
40. X. Fan et al., All-optical vector measurement of spin-orbit-induced torques using both polar and quadratic magneto-optic Kerr effects. *Appl. Phys. Lett.* **109**, 122406 (2016).
41. P. Schütz et al., Dimensionality-driven metal-insulator transition in spin-orbit-coupled SrIrO_3 . *Phys. Rev. Lett.* **119**, 256404 (2017).
42. D. J. Groenendijk et al., Spin-orbit semimetal SrIrO_3 in the two-dimensional limit. *Phys. Rev. Lett.* **119**, 256403 (2017).
43. S. H. Chang et al., Thickness-dependent structural phase transition of strained SrRuO_3 ultrathin films: The role of octahedral tilt. *Phys. Rev. B* **84**, 104101 (2011).
44. Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, B. I. Halperin, Nonlocal magnetization dynamics in ferromagnetic hybrid nanostructures. *Rev. Mod. Phys.* **77**, 1375–1421 (2005).
45. A. Vailionis et al., Misfit strain accommodation in epitaxial ABO_3 perovskites: Lattice rotations and lattice modulations. *Phys. Rev. B* **83**, 064101 (2011).
46. C. T. Boone, H. T. Nembach, J. M. Shaw, T. J. Silva, Spin transport parameters in metallic multilayers determined by ferromagnetic resonance measurements of spin-pumping. *J. Appl. Phys.* **113**, 153906 (2013).
47. S. Emori et al., Spin transport and dynamics in all-oxide perovskite $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3/\text{SrRuO}_3$ bilayers probed by ferromagnetic resonance. *Phys. Rev. B* **94**, 224423 (2016).
48. P. Haney et al., Current induced torques and interfacial spin-orbit coupling: Semi-classical modeling. *Phys. Rev. B* **87**, 174411 (2013).
49. C. Pai et al., Dependence of the efficiency of spin Hall torque on the transparency of Pt/ferromagnetic layer interfaces. *Phys. Rev. B* **92**, 064426 (2016).
50. G. Y. Guo, S. Murakami, T. W. Chen, N. Nagaosa, Intrinsic spin Hall effect in platinum: First-principles calculations. *Phys. Rev. Lett.* **100**, 096401 (2008).
51. A. S. Patri, K. Hwang, H.-W. Lee, Y. B. Kim, Theory of large intrinsic spin Hall effect in iridate semimetals. *Sci. Rep.* **8**, 8052 (2018).