Large spin-orbit torque in bismuthate-based heterostructures

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Abstract:

The wider application of spintronic devices requires the development of new material platforms that can efficiently manipulate spin. Bismuthate-based superconductors are centrosymmetric systems that are generally thought to offer weak spin–orbit coupling. Here, we report a large spin–orbit torque driven by spin polarization generated in heterostructures based on the bismuthate $BaPb_{1-x}Bi_xO_3$ (which is in a non-superconducting state). Using spin-torque ferromagnetic resonance and *d.c.* non-linear Hall measurements, we measure a spin–orbit torque efficiency of around 2.7 and demonstrate current driven magnetization switching at current densities of $4 \times 10^5\ Acm^{-2}$. We suggest that the unexpectedly large current-induced torques could be the result of an orbital Rashba effect associated with local inversion symmetry breaking in $BaPb_{1-x}Bi_xO_3$.

INTRODUCTION

Heavy metals with large spin-orbit coupling (SOC) can generate efficient spin-orbit torque (SOT) via the spin-Hall effect (SHE)[1] or the interfacial Rashba effect[2]. However, in order to enhance spintronic device performance, new material systems and spin-current generation mechanisms are required. In complex oxides, a strong interplay between spin, charge, lattice, and orbital degrees of freedom leads to a tunability of the electronic structure via the crystal chemistry. Furthermore, epitaxial complex oxide spintronic materials can combine spin-charge conversion with other functionalities including ferroelectricity[3], multiferroic behavior,[4] and high temperature superconductivity.

Bismuthates — such as $BaPb_{1-x}Bi_xO_3$ (BPBO)[5] and $Ba_{1-x}K_xBiO_3$ (BKBO)[6] — are a class of complex oxide superconductors first studied nearly 50 years ago. The materials offer a range of electronic and structural properties that are linked to their flexible chemistry. The parent insulating compound, $BaBiO_3$ (BBO), hosts a commensurate charge density wave order accompanied by an oxygen breathing mode[7]. Upon cation substitution[8] on either the A or B site the charge density wave order is relaxed and gives way to superconductivity via correlation-enhanced electron-phonon coupling[9]. The structure deviates from ideal cubic perovskites via octahedral rotations which evolve in composition space and, in the case of Pb-doping, lead to a tetragonal-orthorhombic polymorph at superconducting compositions[10]. The electronic properties are dictated by Bi-6s and O-2p orbital hybridization near the Fermi energy mediated via spσ nearest neighbor hopping[11–13]. This promotes dynamic lattice-correlated properties. However, spin-orbit effects are often considered negligible.

Recently, local inversion symmetry breaking has been observed in bulk BKBO using diffuse x-ray scattering[14], a result that has implications for both the superconducting and normal state properties of bismuthates. Systems with global centrosymmetry may derive hidden forms of spin polarization, generated by local electric fields within the unit cell[15,16]. Moreover, experiments exploring the breakdown of superconductivity in BPBO have hinted at a hidden two-dimensionality[17–19] despite the three-dimensional structure. In-particular, superconducting pairing in bismuthates may be linked to Rashba-type electron-phonon coupling. The local, asymmetric arrangement of substituted cations with different on-site energies[14] could, in principle, drive a large crystal field splitting promoting Rashba-like splitting[2,20–22]. In the normal state, the presence of Rashba spin-splitting could drive spin-charge interconversion that could be used for efficient manipulation of the magnetization in ferromagnetic heterostructures[22–26]. At the same time, Rashba spin-splitting in superconducting heterostructures with Rashba SOC has implications for pairing in locally noncentrosymmetric superconductors[27].

In this Article, we report a large SOT in BPBO thin film heterostructures that are in a non-superconducting state but optimally doped for superconductivity (x = 0.25). We show that due to the moderate SOC in BPBO, the efficient SOT requires interpretations beyond bulk SHE. We suggest an alternative mechanism in which Rashba-like spin-splitting, sensitive to local inversion symmetry breaking, is responsible (Fig. 1). The SOT efficiency (θ_{SOT}) is measured to be around 2.7 and the spin Hall conductivity (σ_{SH}) to be around $2.3 \times 10^5 \frac{\hbar}{2e} \Omega^{-1} m^{-1}$. This spin Hall conductivity is comparable to other efficient spin source materials, and 70 times larger than that predicted for the conventional spin Hall effect using first-principles calculations.

MAIN TEXT

Structural and magnetic properties

Interface quality has dramatic effects on the efficient transfer of spin angular momentum while unwanted disorder suppresses superconductivity. In this respect, fabrication of BPBO heterostructures is made difficult by the relatively large lattice parameter (~4.26Å) compared to many common perovskite oxides (~4Å). Strategies to grow fully or partially coherent epitaxial BPBO have included the use of large lattice parameter substrates[19] and multilayer template engineering[28]. However, despite the large lattice mismatch (>8%), we show that fully-relaxed, highly (001) oriented BPBO thin films are possible on common perovskite substrates such as $SrTiO_3$ (STO) and $(La_{0.3}Sr_{0.7})(Al_{0.65}Ta_{0.35})O_3$ (LSAT).

To measure SOT in representative all-oxide epitaxial devices we grow $La_{0.7}Sr_{0.3}MnO_3$ (LSMO)/BPBO bilayers on (001) STO by pulsed laser deposition. Out-of-plane x-ray diffraction and scanning transmission electron microscopy (STEM) are used to confirm high quality heterostructures with good crystallinity and a sharp interface between LSMO and BPBO (Fig. 2a). A saturation magnetization is measured to be 400 emu/cm^3, which is consistent with the bulk value for this system, with the magnetization lying in-plane. (Supplemental Note 2)

A perpendicular magnetic anisotropy (PMA) is preferred for high-density memory and allows for simple readout in device switching experiments using the anomalous Hall effect. For this, we utilize Pt(Co) multilayers which show strong, reliable PMA. In samples with the structure BPBO/$[Pt(0.92nm)/Co(0.4nm)]_4Pt(0.92nm)$, BPBO is grown by 90° off-axis rf-magnetron sputtering on (001) (LSAT) substrates. X-ray diffraction again confirms good crystallinity and clear Kiessig fringing suggests a sharp BPBO interface. Meanwhile, magnetometry measurements show the desired out-of-plane magnetic easy axis with anisotropy field, H_K, estimated to be 280 mT and saturation magnetization of 400 emu/cm^3.

Spin-orbit torque efficiency

Spin-torque ferromagnetic resonance (ST-FMR)[29,30] is used to probe current driven torque in LSMO/BPBO heterostructures; shown schematically in Fig. 2b. Polarized spin accumulation at the interface of BPBO interacts with the adjacent LSMO and exerts a torque on the magnetization. Oscillating fields generated by the injection of rf current (I_{rf}) drive the magnetization in LSMO through resonance while sweeping an external in-plane magnetic field (H_{ext}). The resonance signal is read as a mixing voltage (V_{mix}) of I_{rf} and anisotropic magnetoresistance (AMR). The resulting resonance peak is fitted using symmetric (V_S) and antisymmetric (V_A) Lorentzian functions (Supplemental Note 4) proportional to the damping-like (τ_{DL}) and field-like (τ_{FL}) torque components respectively as shown in Fig. 2c. Using established methods[29], the SOT efficiency ($\theta_{SOT} = (2e/\hbar)\, j_S/j_C$) is then determined from the ratio of the symmetric to antisymmetric amplitudes where j_S and j_C are the spin and charge current densities respectively.

To disentangle possible artifacts due to spin pumping and resonant heating, we perform resonant line fitting for both longitudinal (V^{XX}) and transverse (V^{XY}) voltages at many in-plane field angles, ϕ, as described in ref. [30]. The dependence of the symmetric and antisymmetric components on ϕ for both longitudinal and transverse signals are shown in Fig. 2d,e. We find good agreement for the longitudinal amplitudes fit with a $\sin(2\phi)\cos(\phi)$ contribution consistent with the product of AMR in LSMO and conventional Slonczewski-like[31] spin torques of the form $\tau_{y,DL} \propto \hat{m} \times (\hat{m} \times \hat{y})$ and $\tau_{y,FL} \propto \hat{m} \times \hat{y}$ with charge current in the $\hat{x}$ direction and orthogonal in-plane spin polarization. Additionally, the symmetric and antisymmetric transverse signals are fitted as:

$$V_S^{XY}(\phi) = S_{XY}^{PHE/art}\cos 2\phi\cos\phi + S_{XY}^{AHE/art}\cos\phi, \quad (1)$$

$$V_A^{XY}(\phi) = A_{XY}^{PHE}\cos 2\phi\cos\phi + A_{XY}^{AHE}\cos\phi, \quad (2)$$

where $S_{XY}^{PHE/art}$ and $S_{XY}^{AHE/art}$ are the symmetric amplitudes with respective planar Hall effect (PHE) and anomalous Hall effect (AHE) voltages convoluted with artifact voltages. A_{XY}^{PHE} and A_{XY}^{AHE} are the antisymmetric amplitudes due to PHE and AHE voltages respectively. From this, the artifact voltages due to spin pumping or resonant heating are found to be negligibly small ensuring accurate evaluations of θ_{SOT} (Supplemental Note 4). The measured SOT efficiency for many devices with varying thicknesses of BPBO are presented in Fig. 2f. Large efficiencies are observed for all devices with thinner BPBO samples showing slightly larger efficiencies. We note BPBO also shows an increase in resistivity for thinner samples. However, BPBO becomes insulating for thicknesses less than 5 nm, and sample-to-sample variation above this thickness prevents us from drawing conclusions about any physics associated with the thickness dependence (Supplemental Note 4).

The damping-like effective field, H_{DL}, and SOT efficiency in heterostructures with Pt(Co) are estimated by extracting the non-linear Hall I-V behavior[32–34]. The current driven effective field modulates the magnetization in Pt(Co) shown schematically in Fig. 3a. The change in the out-of-plane magnetization read as the anomalous Hall effect (AHE) voltage results in a quadratic relationship with respect to current in addition to the typical linear behavior. The even symmetry contributions to the Hall voltage are extracted from *d.c.* current-voltage (I-V) characteristics, defined as $V_{even} \equiv [V(+I) + V(-I)]/2$. I-V sweeps are performed at a constant in-plane magnetic field and the quadratic behavior is fit using $V_{even} = CI^2$ as shown in Fig. 3b. When the in-plane field is larger than the anisotropy field, the magnetization, M, will become uniformly polarized in-plane. This behavior is confirmed by the in-plane and out-of-plane field dependent Hall resistance measurements in Fig. 3c. Further increasing the field causes a decay of the current driven torque contribution of the form

$$C = -\frac{1}{2}\frac{R_A(\partial H_{DL}/\partial I_{BPBO})}{\mu_0(|H_x| - H_K)} \quad (3)$$

where C is the V_{even} quadratic coefficient, R_A is the saturation AHE resistance and I_{BPBO} is the estimated current in the BPBO layer using a parallel resistor model (Supplemental Note 7). By fitting the field dependence in Fig. 3d with thermoelectric contributions removed (Supplemental Note 5) we determine the current driven damping-like field to be $34 \pm 5\ Oe\ (1\times 10^6 A/cm^2)^{-1}$. Self-torque in Pt(Co) as seen in ref [[35]] is also considered by performing identical experiments on an isolated Pt(Co) control sample (Supplemental Note 5). This comparatively small self-torque-based effective field is subtracted in the results reported here. Using $\theta_{SOT} = (2e/\hbar)\left(\mu_o M_s d_{Pt(Co)}\,\partial H_{DL}/\partial j_{BPBO}\right)$ where $d_{Pt(Co)}$ is the total thickness of the Pt(Co) multilayer, we find the SOT efficiency, 2.7 ± 0.4, to again be very large; consistent with the LSMO/BPBO ST-FMR results.

Current-induced magnetization switching

With the SOT efficiency estimated for heterostructures displaying PMA, we utilize it to switch an out-of-plane moment in an adjacent ferromagnet. The magnetic state is monitored by measuring the AHE resistance while supplying 1 ms-duration current pulses at fixed in-plane field H_x. The in-plane field is used to break the symmetry of the in-plane SOT due to the out-of-plane magnetization and in-plane spin polarization. Fig. 4a,b show deterministic switching at -10mT and +10mT respectively. The switching direction is reversed upon reversal of the field direction consistent with SOT induced switching[31]. The critical current density is defined as the point of sign change of the Hall resistance and is estimated as

$j_{BPBO} \approx 4 \times 10^5 Acm^{-2}$. Further evidence of magnetization switching is seen using a magneto-optic Kerr effect (MOKE) microscope. Fig. 4c-f shows the color contrast of +z and -z magnetization nucleating and expanding at higher current densities until the device is fully switched when the Hall resistance changes sign.

A maximum of ~90% current-induced magnetization switching based on resistance measurements is achieved near $H_x = \pm 10$ mT and decreases with application of larger fields (Supplemental Note 6). Partial SOT switching has been observed in previous studies[36,37] indicating irreversible randomly distributed domain formation. Domain dynamics are also known to reduce critical current densities as the energy barrier for domain nucleation and propagation is lower than for nearly coherent rotation of the magnetization[38]. The macrospin approximation breaks down considerably in micrometer sized devices making a direct relationship between critical current densities and torque efficiency unreliable. Nevertheless, the observed critical current density is an order of magnitude smaller than in many other promising SOT materials reported. Meanwhile, no deterministic switching was observed in the isolated Pt(Co) control sample.

Origin of spin-orbit torque in BPBO-based heterostructures

The observation of giant SOT efficiency in measurements consisting of ST-FMR, non-linear *d.c.* Hall and magnetization switching emphasize the robustness of our result. Additionally, this torque is seen in BPBO heterostructures with various growth techniques, magnetic materials (both epitaxial and non-epitaxial), and magnetic anisotropy, making it applicable to future studies employing diverse materials combinations. When compared to other spin source materials (Supplemental Note 8), the SOT efficiency is as large as or greater than the most efficient material systems reported including heavy metals, 2D materials, and topological insulators. This is surprising and remarkable because BPBO is not expected to have strong SOC near the Fermi energy.

The largest contributions to calculated spin Hall conductivities in heavy metals arise due to SOC induced spin splitting of nearly degenerate bands in momentum space. However, the conduction in BPBO is dominated by weakly spin-orbit-coupled O-2p orbital character. From our first-principles calculations of the conventional spin Hall effect (Supplemental Note 3), the estimated spin Hall conductivity in BPBO is only $\sigma_{SH} = 3400 \frac{\hbar}{2e} \Omega^{-1} m^{-1}$ which is nearly 70 times smaller than our experimental value. We also consider the effect of rigid octahedral rotations in BPBO[10]. However, applying these rotations had little effect on the calculated spin Hall conductivity, suggesting these particular distortions and any associated phase separation[39] or octahedral rotation-based strain relaxation are unlikely to explain our results. The large discrepancy in experimental and calculated values leads us to conclude that conventional SHEs alone cannot account for our experimental observation.

Instead, we speculate that the giant SOT in bismuthate heterostructures may be attributed to hidden Rashba-like effects promoted by local inversion symmetry breaking. Efficient spin polarization utilizing Rashba effects associated with inversion symmetry breaking has been widely reported in systems including metallic interfaces[24], oxide 2DEGs[25], heavy metal/ferromagnet/oxide systems[23,26], and polar semiconductors[40]. Furthermore, inversion symmetry breaking need not apply globally, i.e., at the interface or in the crystal structure. This is highlighted by hidden spin polarization predicted theoretically[15,16] and observed experimentally[41–46] in globally centrosymmetric systems due to electric fields associated with the local symmetry. The recent observation of local inversion symmetry breaking seen in BKBO[14] raises the possibility of hidden Rashba physics in bismuthates not captured in our first principles calculations. In principle, local inversion symmetry breaking in BPBO due to the distinct electrostatic environments of random cation substitutions could result in asymmetric orbital hybridization of nearest neighbors. These local dipoles create crystal field splitting of bands with opposite orbital chirality (Fig. 1c); a phenomenon termed the orbital Rashba effect[21,22,47]. In the limit of much larger crystal field splitting, the SOC acts as a perturbation and thus the contributing effects of atomic spin-orbit interactions are maximized[20]. Because SOC within O-2p orbitals is weak, the primary role of local inversion symmetry breaking is to establish a large crystal field splitting. The crystal field splitting is independent of SOC and the subsequent role of SOC is to spin-split the degenerate orbital bands (Fig. 1b).

We emphasize that our proposed orbital torque mechanism remains largely qualitative and requires further experiments and advancements in theory to confirm. Alternative to the bulk orbital Rashba effect, a purely interfacial Rashba effect may exist due to an electric field generated by inversion symmetry breaking at the interface. As noted, the thickness dependence is inconclusive in determining if SOT is purely interfacial. However, an apparent lack of field-like torque in our devices as discussed in Supplemental Note 4 is inconsistent with previous reports on interfacial spin Rashba SOT[48,49]. Future studies exploring the interfacial effects and relevant length scales may benefit from further development of methods to reduce the epitaxial lattice mismatch. Another possible origin of SOT which relies on current shunting and SOC in the ferromagnet is known as anomalous spin-orbit torque (ASOT)[50]. The current shunting in Pt(Co) is significant and increases with decreasing temperature. In contrast, the current driven field decreases with decreasing temperature (Supplemental Note 7). The inverse relationship between current shunting and damping-like field excludes current in Pt(Co) and ASOT as a dominant source in our devices.

The most surprising finding in this work is the giant SOT in heterostructures including BPBO which is not expected to show large SOC. Bismuthate heterostructures are therefore introduced as a versatile system which challenges traditional concepts in materials engineering for efficient spintronics. New approaches, for which complex oxides are well suited, may include structural and orbital engineering rather than conventional strategies focused on increasing atomic SOC. The physical properties of bismuthates are highly sensitive to the bonding environment which is tunable by cation substitution. Although local inversion symmetry breaking has been observed in BKBO, there are distinct differences in the global structure and bonding environment when compared to other bismuthates such as BPBO. The relationships between the bonding environments, global crystal symmetry, and local structural distortions are poorly understood at this time and should be addressed moving forward. Future studies may provide further insights into the structural and orbital contributions by chemical substitution in BPBO, BKBO, or analogous superconducting compound $Ba_{1-x}K_xSbO_3$[51]. Meanwhile, the implementation of other complex oxides such as magnetoelectric perovskites[4] or magnetic insulating oxides[52,53] could eliminate current shunting problems, improve performance, and introduce additional functionality. While our results are strictly in the normal state, they have intriguing implications for the superconducting properties as well. The observation of current driven fields in the normal state of a locally non-centrosymmetric superconductor suggests these heterostructures may support parity mixing or topological phases[27]. Our results serve to stimulate further exploration of the interplay between hidden spin polarization and superconductivity in bismuthate heterostructures.

Conclusions

We have reported a SOT in BPBO-based heterostructures with an efficiency of around 2.7 and a spin Hall conductivity of $2.3 \times 10^5 \frac{\hbar}{2e} \Omega^{-1} m^{-1}$. This spin Hall conductivity is 70 times larger than that predicted for the conventional spin Hall effect using first-principles calculations. Questions remain regarding the exact origin of this effect, but we suggest that the unexpectedly large current-induced torques may be the result of an orbital Rashba effect associated with local inversion symmetry breaking in BPBO, which has previously been observed with diffuse x-ray scattering in BKBO[14]. Our results highlight the need to widen the exploration of spin manipulation in order to include materials and mechanisms that may not rely solely on large intra-atomic SOC. Furthermore, our observation of a large charge-to-spin conversion in the non-superconducting state of bismuthate heterostructures suggests that they could be a model system for investigating the interplay of hidden spin–orbit phenomena and superconductivity. Ultimately, our work could provide new routes in materials engineering that can be used to develop efficient spin-orbitronics.

Methods

Thin Film Growth and Fabrication. For BPBO/LSMO devices, BPBO and LSMO were grown by pulsed laser deposition (PLD) using a 248 nm KrF excimer laser. The LSMO was deposited first at a substrate temperature of 700 °C, fluence of 2 J/cm^2, O_2 pressure of 150 mTorr, and pulse rate of 5 Hz. The LSMO was cooled to 525 °C for BPBO deposition, where a fluence of 1 J/cm^2, O_2 pressure of 100 mTorr, and pulse rate of 5 Hz were used. The samples were then annealed in 400 Torr O_2 at 470 °C for 1 hour to improve transport properties and stability. ST-FMR devices were patterned using optical lithography and argon-ion milling. Electrical contacts were added using optical lithography and liftoff of sputtered Pt. In order to passivate the surface of STO which is known to be made conductive by ion milling, we anneal the devices in Oxygen at 400°C for 3 hours. We also exclude possible STO substrate conductivity artifacts as a cause for our high SOT efficiency by measuring the SOT efficiency on an LSAT substrate and finding the same order of magnitude for the SOT efficiency.

For BPBO/Pt(Co) devices, BPBO was grown by 90° off-axis RF-magnetron sputtering in a 57:3 Ar:O_2 200 mTorr operating pressure. Temperature was held at 575°C during growth and films were subsequently cooled in 400 mTorr O_2. Samples were then transferred for *ex situ* deposition of Pt(Co) multilayers. The Pt(Co) multilayers were subsequently grown on the BPBO/LSAT samples by DC magnetron sputtering in a vacuum chamber with a base pressure below 1×10^{-8} Torr at an Ar pressure of 3 mTorr. The growth rates of Pt and Co films were calibrated using X-ray reflectivity. Hall bar devices of varying sizes were patterned using optical lithography and argon-ion milling. Electrical contacts were added using optical lithography and liftoff of Ti/Pt.

ST-FMR Measurements. ST-FMR measurements were done on the devices fabricated from BPBO/LSMO bilayers. A BNC 845 RF signal generator supplied a fixed GHz frequency current at 15 dBm, which was applied to the sample through a bias tee and a three-tipped probe. For each frequency, we swept over a range of fields and measured the mixing voltage using a Keithley 2182A nanovoltmeter on the DC end of the bias tee. For the Hall-STFMR and angle dependent measurements, an Amplitude modulated GHz frequency signal was sourced from an E8257D Analog Signal Generator and SR830 lock-in amplifiers measured the DC responses from the bias tee and across a sample with patterned Hall contacts. Both lock-in amplifiers reference the same AM signal, with $f_{\mathrm{AM}} \approx 1700$ Hz and the microwave frequencies in the range of 3 – 5 GHz. The in-plane field was applied at various angles using a projected-field magnet.

Hall Non-linear IV Measurements. Spin-torque of BPBO/Pt(Co) was determined via Hall measurements carried out on 100 μm long and 10 μm wide Hall bars in a Quantum Design PPMS. Current up to $I_{max} = 9$ mA was sourced by linked Keithley 6221 and 2182a devices which provided linearly-spaced current sweeps from - I_{max} to I_{max} to - I_{max}, with voltage read at each step. Such measurements were performed at fixed in-plane magnetic fields aligned parallel to the current direction, with positive and negative polarity. IV sweeps were combined to isolate the magnetic field-dependent quadratic component. The spin-torque values were computed from the field dependence of the quadratic component from field values below 1.5 T, but still in the high-field limit. A detailed description of the analysis and measurement procedure is presented in Supplemental Note 4.

Device Switching. For the pulse switching measurements, the films were patterned into conventional Hall bar structures with a channel width of 100 μm and length of 500 μm by using optical lithography and Ar-ion beam etching. A Keysight B2901A current source and a Keithley 2182A Nanovoltmeter were used in the Hall measurement. The external in-plane and out-of-plane magnetic fields were generated by coils driven by a Kepco power supply. The anomalous Hall resistance R_H as a function of the external magnetic field was measured under a small continuous current of 100 μA. Current-induced SOT switching was measured by applying a 1 ms current pulse with different amplitude (Keysight B2901A) to the current path of the Hall bar under a static in-plane magnetic field H_x. After the current injection, the Hall resistance was subsequently measured with a voltmeter (Keithley 2182A) under a low probe current of 100 μA. During the measurements, a high-resolution Kerr microscope was used to observe the switching of magnetic domain walls in the device. All measurements were conducted at room temperature.

Data availability

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

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Author contributions

A.L.E., T.N., C.B.E., I.A.H., and R.R. conceived the research. A.L.E. and Y.C. carried out film growth and device fabrication of BPBO/Pt(Co) samples. I.A.H. carried out film growth and device fabrication of LSMO/BPBO samples. I.A.H., M.M.M., X.H., and D.C.R. performed ST-FMR measurements and analysis. N.G.C. and M.S.R. conducted Hall non-linear I-V measurements. Y.C. and T.N. carried out device switching experiments. G.G. and E.Y.T. performed theoretical calculations. S.S. performed the STEM measurements. A.L.E., N.G.C., and C.B.E. wrote the manuscript with contribution from all other co-authors.

Competing interests

The authors declare no competing interests.

Figure 1 | Schematic of proposed spin torque mechanism. a, Electronic conduction in BPBO is dictated by spσ nearest neighbor hopping. These nearest neighbor bonds (i.e. $sp\sigma_1$ and $sp\sigma_2$) are necessarily equivalent when inversion symmetry is preserved. **b,** Energy diagram of band splitting when inversion symmetry is broken. Asymmetric nearest neighbor hopping now induces crystal field (E_{CF}) splitting of two spin degenerate bands with opposite orbital angular momentum, L (Orange and green arrows). Spin-orbit coupling (SOC) further splits the orbital bands into spin-split bands with the same orbital angular momentum but opposite spin angular momentum, S

(Blue and red arrows). **c,** Schematic of Rashba-like orbital textured Fermi surface in momentum space axis k_y and k_x. Colored arrows indicate opposite orbital angular momentum. The current density, j, along x, shifts the Fermi surfaces along the same axis by an amount Δk and a tangential net orbital angular momentum accumulation, ΔL. **d,** The addition of atomic SOC to (c) further splits the bands with spin-momentum locking. An electric field will then accumulate spin which when current is supplied through BPBO (Blue layer) a torque will be applied on the magnetization (Orange arrow) of the adjacent ferromagnet (Orange layer).

Figure 2 | ST-FMR of LSMO/BPBO bilayers. a, Scanning transmission electron microscope image of LSMO/BPBO on (001) STO. Larger image is aligned to BPBO [001] and the inset is a section of LSMO while aligned to LSMO [001]. See Supplemental Note 1 for details. **b,** Schematic of the ST-FMR geometry for evaluating damping-like torque (τ_{DL}) and field-like torque (τ_{FL}) where Φ is the angle between the rf current I_{rf} and in-plane external magnetic field H_{ext}. **c,** Mixing voltage V_{mix} ST-FMR signal spectra with corresponding fit for LSMO(35 nm)/BPBO(17 nm) with rf frequency of 3.5 GHz and Φ at 225°. V_S and V_A are respectively the symmetric and antisymmetric components of the fit. **d,** Field dependence of symmetric (V_S^{XX}) and antisymmetric (V_A^{XX}) amplitudes of longitudinal ST-FMR signal with fits to sin(2Φ)cos(Φ) for LSMO(14 nm)/BPBO(14 nm) at 3.5 GHz. **e,** Transverse signals of (**d**) with symmetric (V_S^{XY}) and antisymmetric (V_A^{XY}) amplitudes fit to Equations 1 and 2. **f,** SOT efficiency θ_{SOT} for devices with varying BPBO thickness t_{BPBO}. The error bars are standard deviation estimates of uncertainty including error propagation of parameters in the fit analysis and sample-to-sample variations. For samples with higher θ_{SOT} the asymmetric Lorentzian components are smaller and more difficult to extract, thus typically leading to higher error primarily due to larger uncertainty in the fit. Measurements with uncertainty larger than 30% were not included. The number of total measurements n used to determine uncertainty is n = [24, 40, 27, 15, 80, 40, 4, 25, 36, 27] for respective samples with nominal thickness of BPBO in nm t_{BPBO} = [7, 8, 11, 12, 13, 13.9, 14.1, 17, 22, 23] where the efficiency of 14.1 nm sample was determined using Hall ST-FMR.

Figure 3 | Determination of damping-like SOT in BPBO/(Pt/Co) by non-linear I-V Hall measurements. a, Schematic of measurement geometry. The magnetization direction, M, is changed from out-of-plane (transparent blue arrow) to in-plane (solid blue arrow) along the x-axis with application of an in-plane magnetic field. The sourced *d.c.* current, I_{dc}, in BPBO produces a damping-like field H_{DL} and damping-like torque τ_{DL}. **b,** Even symmetry voltage V_{even} component in I-V sweeps at different H_x. **c,** Hall resistance R_{Hall} measured as a function of out-of-plane, H_z, and in-plane, H_x, magnetic field. **d,** Quadratic coefficient C from quadratic V_{even} fits measured at different in-plane field fit to Equation 3.

Figure 4 | Current induced magnetization switching in BPBO/Pt(Co). a,b, Anomalous Hall resistance R_{Hall} measured after each 1 ms-current pulse I_{pulse} while supplying an in-plane field H_x of -10 mT (**a**) and +10 mT (**b**). The current density in BPBO j_{BPBO} is calculated. **c-f,** MOKE images of magnetization switching with pulsed current density j_{BPBO} in the BPBO denoted above the corresponding image. Color contrast shows magnetization along ±z direction. Position of each image in the resistance measurements are shown in (b).

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