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Zelalem Abebe Bekele,^{1,2} Yuan-Yuan Jiang,^{3,4} Kun Lei,^{1,2} Xiukai Lan,¹ Xiangyu Liu,^{1,2} Hui Wen,^{1,2} Ding-Fu Shao,^{3,a)} and Kaiyou Wang^{1,2,a)}

AFFILIATIONS

¹State Key Laboratory of Semiconductor Physics and Chip Technologies, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

²Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

³Key Laboratory of Materials Physics, Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences, Hefei 230031, China

⁴University of Science and Technology of China, Hefei 230026, China

^{a)}Authors to whom correspondence should be addressed: dfshao@issp.ac.cn and kywang@semi.ac.cn

ABSTRACT

Spin-orbit torques (SOTs) generated through the conventional spin Hall effect (SHE) and/or Rashba–Edelstein effect offer potential for magnetization manipulation. However, deterministic switching of perpendicular ferromagnets via SOTs requires a strong symmetry-breaking perturbation, typically an external magnetic field. Here, we demonstrate that field-free SOT switching of perpendicular magnetization can be facilitated with the assistance of the orbital Hall effect (OHE). Using a representative Co/PtGd bilayer SOT device, we find that while the planar Hall effect (PHE) generates a finite out-of-plane damping-like torque, representing a lateral symmetry-breaking effect, the SHE-induced torque achievable at practical current densities is insufficient to switch the perpendicular magnetization. Incorporating a Mo underlayer and exploiting its strong OHE can amplify the in-plane damping-like torque via orbital-to-spin conversion, enabling efficient field-free deterministic switching without complex device geometries or low-symmetric spin sources, providing a straightforward, scalable strategy for high-speed, low-power spintronics.

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Spintronics uses spontaneous magnetic states in materials to encode information, which underpin non-volatile memories, logic devices, and neuromorphic computing.^{1,2} High-performance spintronic devices can efficiently manipulate (write) and detect (read out) magnetic states. Ferromagnetic materials exhibiting perpendicular magnetic anisotropy (PMA) are particularly advantageous for high-density applications due to their thermal stability and scalability.^{2–6} However, efficient electrical manipulation remains a challenging problem.

A promising approach is spin-orbit torque (SOT), in which an in-plane charge current J (x direction) generates a nonequilibrium spin polarization $\mathbf{p}$, exerting a damping-like torque $\tau \sim \mathbf{m} \times (\mathbf{m} \times \mathbf{p})$ on the magnetization $\mathbf{m}$ of a ferromagnetic (FM) layer.^{3–5} In conventional SOT devices, the spin polarization $\mathbf{p}$ is generated via the spin Hall effect (SHE)^{3,4} or the Rashba–Edelstein effect (REE).^{5,6} Due to symmetry constraints, the generated $\mathbf{p}$ is aligned with the direction of $J \times \mathbf{z}$, i.e., the p_y , where $\mathbf{z}$ is the film normal, resulting in an in-plane damping-like torque $\tau_y \sim \mathbf{m} \times (\mathbf{m} \times p_y)$. However, switching SOT

devices with τ_y is inefficient and non-deterministic. First, a large current is required to generate a sufficiently strong p_y and the associated τ_y , since τ_y needs to overcome the precession induced by the anisotropy field. Second, the τ_y can only pull $\mathbf{m}$ toward the y direction while applying the current, and the relaxation of $\mathbf{m}$ cannot be controlled when the current is released.⁷ This is because the states of $\mathbf{m}$ pointing along $+z$ or $-z$ directions are degenerate in a perpendicularly magnetized FM film. These degeneracies are the root cause of the need for an external magnetic field to break the symmetry and achieve deterministic switching.

Although an in-plane electric field breaks most symmetry operations connecting the two states, a mirror symmetry M parallel to the electric field and perpendicular to the film plane may be preserved. Therefore, an additional perturbation is required to break M and realize deterministic switching. Two paradigms exist to break this symmetry: using an in-plane assisting magnetic field (an external field^{8,9} or an exchange bias)^{10,11} or introducing lateral asymmetry (such as wedged FM,¹² composition gradient,^{13,14} or an unconventional spin

source layer with low crystal or magnetic symmetry).^{15–29} A lateral asymmetry is typically accompanied by an additional spin current with a z -spin component in $\mathbf{p}$ (p_z), generating out-of-plane damping-like torque $\tau_z \sim \mathbf{m} \times (\mathbf{m} \times p_z)$ that can directly reverse the $\mathbf{m}$.^{30–32} Moreover, when p_z is sufficiently strong, the switching current can be significantly reduced since the associated τ_z does not compete with magnetic anisotropy but directly changes the effective damping in FMs.^{31,32}

Studies suggest that asymmetric boundary conditions in a single-layer ferromagnetic film can generate finite p_z by breaking M symmetry via reorienting $\mathbf{m}$ to the direction oblique to the film plane.^{33,34} This symmetry breaking manifests in spin-dependent transport properties, notably the planar Hall effect (PHE) and anisotropic magnetoresistance (AMR),^{33–35} which serve as the measure of the M symmetry breaking and can induce a spin current flowing and polarized along $\mathbf{m}$ direction, generating a finite p_z . However, this approach has not yet been used to switch the perpendicular $\mathbf{m}$, possibly due to the out-of-plane PHE current (J_{PHE}) only occurring during the thermal fluctuations of SOT-driven dynamics, and thus is insufficient to generate strong p_z to assist SOT switching. Field-free deterministic switching mediated by SOT shows significant potential for advancing next-generation numerical computing architectures.^{36–39}

In this work, we present an effective method for field-free switching of perpendicular magnetization by synergistically combining the orbital Hall effect (OHE) and an enhanced PHE. The OHE produces a transverse orbital current, capable of being converted into a y -polarized spin current with greater strength than that generated by conventional SHE and REE. In a Co/PtGd/Mo heterostructure, the Mo layer contributes a strong OHE, amplifying p_y generation through efficient orbital-to-spin conversion in a PtGd layer. The Co/PtGd interface yields a moderate p_z by an enhanced PHE. The combination of large τ_y and finite τ_z enables efficient field-free deterministic switching. This approach does not rely on complex device geometries or low-symmetry crystals, making it highly promising for practical high-density spintronics.

The Pt(1.5)/Co(0.8)/PtGd(2)/Mo(a)/Ta(0.5) and Pt(1.5)/Co(0.8)/Pt(2)/Ta(0.5) thin films were grown on thermally oxidized Si substrates using magnetron sputtering (layers from top to down, thicknesses in parentheses are in nm), where a can be 0, 1, 2, 3, and 4 nm. A 0.5 nm Ta seed layer was used to promote adhesion, and a 1.5 nm Pt capping layer was used to prevent oxidation. The Pt_{0.65}Gd_{0.35} alloy films' stoichiometry was achieved by co-sputtering Pt and Gd-targets at powers of 30 and 21 W, respectively. The bottom Mo layer served as a source of orbital Hall current. After deposition, the stacks were pre-annealed at 350 °C for 10 min to enhance PMA. The annealing treatment may not only improve the quality of the crystalline phase⁴⁰ but also promote the segregation of Co and Gd atoms at the interface,^{41,42} which will be responsible for the presence of PMA.

Devices were fabricated using a two-step process. First, Hall bars (6 μm width, 3 μm voltage arms) were patterned for standard magneto-transport measurements. Second, to isolate the SOT switching behavior and avoid contributions from spin currents in the top Pt capping layer, the device was further patterned into a 3 μm -diameter pillar using Ar ion milling.

The PHE is a magneto-transport phenomenon [$J_{PHE} = \Delta\sigma_{AMR}\mathbf{m}(\mathbf{m} \cdot \mathbf{E})$] in magnetic materials associated with AMR,

where $\Delta\sigma_{AMR}$ is the conductivity associated with AMR, and $\mathbf{E}$ is the electric field. The J_{PHE} is then polarized collinear to $\mathbf{m}$ and flows along the direction of $\mathbf{m}(\mathbf{m} \cdot \mathbf{E})$.^{33–35} The out-of-plane component J_{PHE} ($J_{PHE,\perp}$) can introduce a net spin accumulation in the FM film under an asymmetric boundary condition.³⁴ We note that for a FM film with $\mathbf{m}$ perfectly pointing along the z direction, the $J_{PHE,\perp}$ is vanishing. However, $\mathbf{m}$ may be pulled away from the z -direction by thermal fluctuation or during the SOT-driven dynamics, allowing a nonvanishing p_z in any ferromagnetic films. However, the deterministic switching of perpendicular magnetization associated with PHE has not yet been demonstrated, possibly because PHE in common ferromagnetic metals is insufficient to assist SHE- or REE-driven switching at achievable current densities. To realize this approach in practice, one needs to find a strategy to enhance efficiency $\Delta\sigma_{AMR}$ and hence the J_{PHE} for a moderate p_z and use a new mechanism beyond SHE or REE to boost p_y , as reflected by our magnetic dynamics simulations in [supplementary material](#) Sec. 1. We propose that the PHE can be enhanced by engineering the interfacial exchange coupling between the perpendicular ferromagnet layer and a suitable adjacent layer, and the sufficiently large p_y can be generated by including an additional layer to the SOT device to generate OHE.

We begin by highlighting the interfacial PHE enhancement in the SOT devices illustrated in [Figs. 1\(a\)–1\(c\)](#). A 0.8 nm ferromagnetic Co layer was deposited atop the commonly employed spin source Pt layer with a thickness of 2 nm [denoted as Co(0.8)/Pt(2)], as shown in [Fig. 1\(a\)](#). The good PMA of the Co layer is confirmed by the measurement of the anomalous Hall effect (AHE) resistance (R_H), as shown in [Fig. 1\(d\)](#).

Since PHE is closely related to AMR and shares the same physical origin,^{43,44} both effects are governed by the same magnetization-dependent resistivity anisotropy. A direct measurement of the out-of-plane PHE would provide the most direct evidence for the PHE-induced z -spin polarized current. However, this measurement is experimentally challenging in a conventional Hall-bar geometry, because the out-of-plane PHE corresponds to a transverse response along the film-normal direction. We measure the transverse PHE and longitudinal AMR anisotropic magnetoresistive response of this device as a magnetic field rotates in the x - y and x - z planes. We find that the PHE/AMR is relatively small in Co(0.8)/Pt(2), as it originates from spin-orbit coupling (SOC), which is small for Co even when interfaced with the heavy metal Pt. Considering that PHE/AMR may be enhanced by stronger interfacial coupling, we replace the Pt layer with a PtGd alloy with the stoichiometry Pt_{0.65}Gd_{0.35}. We find that the perpendicular anisotropy is well maintained with the presence of the PtGd layer, where the R_H is enhanced, as shown in [Fig. 1\(d\)](#). Although the magnetic order in PtGd alloy is absent,²⁴ a thin Pt-Gd-Co alloy intermediate layer may appear across the interface between the Co and PtGd layers, which may be ferromagnetic and strongly coupled with the top Co layer,⁴⁵ and thus may lead to the different R_H and introduce a substantial enhancement of PHE/AMR. This is clearly shown in [Figs. 1\(e\) and 1\(f\)](#), where the PHE/AMR for the Co(0.8)/PtGd(2) sample is much stronger than that of Co(0.8)/Pt(2), and is qualitatively consistent with our first-principles calculations (see [Fig. S2](#) in [supplementary material](#) Sec. 2). The PHE/AMR can be further enhanced in the presence of a Mo layer underneath the PtGd. Recent studies suggest that PHE/AMR may also be contributed by the orbital magnetic moments of Bloch electrons.^{46–48}

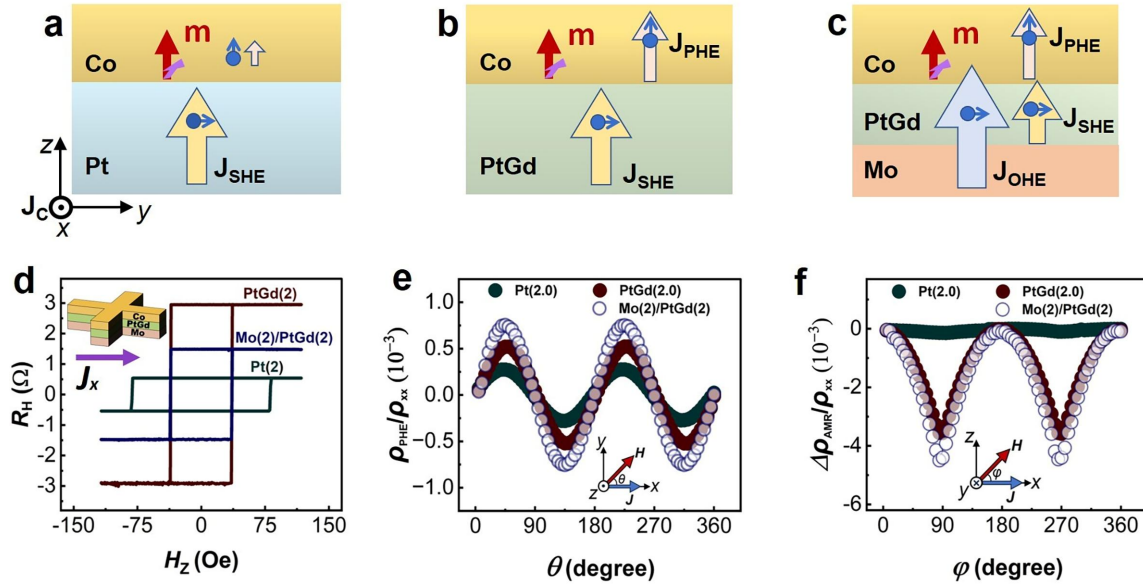


FIG. 1. (a) A Co/Pt bilayer SOT device. The Co layer has perpendicular anisotropy. A current J along the x direction generates a negligible z -polarized J_{PHE} in the Co layer and a moderate y -polarized spin current by SHE (J_{SHE}) in the Pt layer. The J_{SHE} enters the Co layer and exerts a moderate τ_y . (b) A Co/PtGd bilayer SOT device where PtGd supports a moderate J_{SHE} , and the J_{PHE} in the Co layer is enhanced due to the Co/PtGd interface coupling. The J_{PHE} can exert an additional τ_z in the Co layer besides τ_y due to J_{SHE} . (c) A Co/PtGd/Mo trilayer SOT device. In addition to a not-too-small J_{PHE} in the Co layer and a moderate J_{SHE} in the PtGd layer, there is a strong orbital current due to OHE (J_{OHE}) in the Mo layer flowing along the out-of-plane direction, which will be converted into an additional J_{SHE} when passing through the PtGd layer, and will significantly boost τ_y . The purple light arrow represents the side view of the magnetization vector m deflected in the x - and y -directions. (d) R_H as a function of an out-of-plane magnetic field H_z for Co(0.8)/Pt(2), Co(0.8)/PtGd(2), and Co(0.8)/PtGd(2)/Mo(2) Hall bar devices by applying a 50 μ A current. (e) The planar Hall effect resistivity ratio (ρ_{PHE}/ρ_{xx}) for Co(0.8)/Pt(2), Co(0.8)/PtGd(2), and Co(0.8)/PtGd(2)/Mo(2) heterostructure along the x - y plane. (f) Anisotropic magnetoresistivity ratio (ρ_{AMR}/ρ_{xx}) for Co(0.8)/Pt(2), Co(0.8)/PtGd(2), and Co(0.8)/PtGd(2)/Mo(2) samples in the x - z plane. Both PHE and AMR were measured at a large scanning field of 1.2 T, which is significantly larger than the anisotropy field H_k of about 0.72 T (supplementary material Sec. 3). ρ_{xx} is the electrical resistivity (supplementary material Sec. 4).

However, all the PHE/AMR measurements for our devices show a twofold symmetry, indicating that the PHE and AMR can be explained by a conventional phenomenological picture. Notably, finite interlayer diffusion is commonly observed in multilayer systems and can introduce strong disorder scattering, thereby enhancing the PHE and, consequently, the z -polarized spin current.

Theoretical and experimental advancements have demonstrated that asymmetric spin transport across interfaces between magnetic and nonmagnetic layers can generate a substantial z -polarized spin current, a phenomenon supported by measurements of surface-interface PHE.^{33,34,49,50} Wang *et al.* demonstrated that a pronounced PHE, predominantly influenced by contributions from the orbital Hall effect, can occur even in systems characterized by weak SOC.⁵⁰ This enhanced PHE mediates z -spin polarization p_z , which is critical for breaking symmetry and enabling field-free switching. To better understand the role of PHE in inducing z -component spin accumulation and enabling symmetry breaking in the Co/PtGd/Mo trilayer, we describe a simple analysis as shown in Fig. S6 in supplementary material Sec. 5. This analysis demonstrates that the PHE-induced z -spin accumulation is *even* in the current direction, thereby generating a symmetry-breaking contribution.

A strong magnetic anisotropy in Gd, which may significantly enhance the magnetic anisotropies, leads to a strong AMR/PHE. The introduction of a bottom Mo layer further amplifies the orbital moment of Gd (see Fig. S8 in supplementary material Sec. 6), thereby

increasing the magnetic anisotropy. In the Co/PtGd/Mo trilayer, the orbital current from the Mo layer leads to a markedly enhanced interfacial PHE. This effect is consistent with our experimental evidence, which shows strongly enhanced PHE and AMR [Figs. 1(e) and 1(f), and S3(b) in supplementary material Sec. 3]. This may lead to a notable z -polarized J_{PHE} in the Co layer.

To show the phenomenon of symmetry breaking, we measure the hysteresis loop of the R_H - H_z in the presence of a bias DC J_x . If there were a finite p_z in J_{PHE} , the associated τ_z would cause an abrupt shift in the R_H - H_z hysteresis loop when τ_z is sufficiently strong to overcome the intrinsic damping of Co, verifying the existence of p_z in SOT devices.^{16,17,21,51} We find negligible shift of the loop in the Co(0.8)/Pt(2) sample even for a large J_x [Fig. S11(a) in supplementary material Sec. 10]. For the Co(0.8)/PtGd(2) sample, we find negligible shift for small J_x , while sizable positive and negative shifts emerge when J_x is larger [Fig. 2(a)], indicating the existence of p_z . We define the shift of the R_H - H_z hysteresis loop as $\Delta H_z = H_{center}(J_x^+) - H_{center}(J_x^-)$, where $H_{center}(J_x^\pm) = \frac{[H_r^+(J_x^\pm) + H_r^-(J_x^\pm)]}{2}$ is the center of the hysteresis loop shifts determined by the difference between positive (negative) magnetization-reversal fields, H_r^+ (H_r^-) is the rightward (leftward) coercivity field that corresponds to a positive (negative) H_z field, and $J_x^\pm$ are the current densities of positive/negative currents. Figure 2(a) inset curve shows the ΔH_z as a function of J_x , where the ΔH_z is negligible when J_x is small and increases linearly when $J_x > 11 \times 10^6$ A cm⁻²

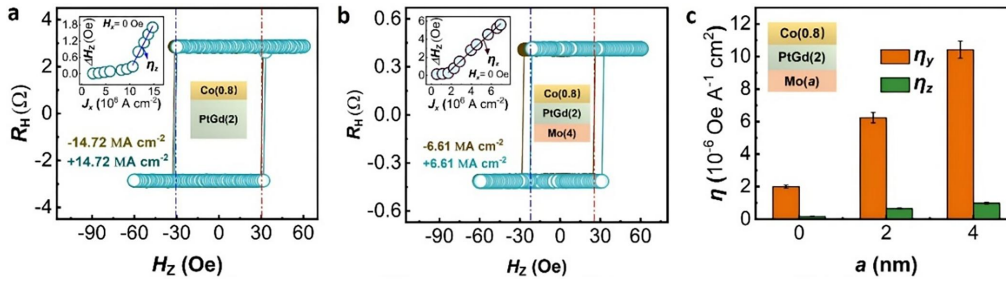


FIG. 2. (a) and (b) R_H vs H_z curves for Co(0.8)/PtGd(2) and Co(0.8)/PtGd(2)/Mo(4) Hall bar SOT devices measured by a bias current J_x . For the Co(0.8)/PtGd(2) sample (a). For the Co(0.8)/PtGd(2)/Mo(4) sample (b). The inset diagram shows the ΔH_z as a function of J_x for the Co(0.8)/PtGd(2) and the Co(0.8)/PtGd(2)/Mo(4) sample in the absence of H_x . (c) The drive τ_y -associated SOT effective field η_y and τ_z -associated SOT effective field η_z for Co(0.8)/PtGd(2)/Mo(a) samples.

for the Co(0.8)/PtGd(2) sample. Similarly, the R_H - H_z hysteresis loop shift is observed for the Co(0.8)/PtGd(2)/Mo(4) sample; we found sizable R_H - H_z hysteresis loop shifts emerge when J_x is large [Fig. 2(b)]. ΔH_z is negligible when J_x is small and increases linearly when $J_x > 2 \times 10^6$ A cm $^{-2}$ [inset of Fig. 2(b)], indicating the enhancement of p_z . The R_H - H_z loops are shifted to the opposite field direction in the absence of H_x field, corresponding to the SOT-induced out-of-plane effective field.¹⁶ This phenomenon cannot occur in conventional SOT devices supporting only p_y , where ΔH_z can only be generated in the presence of an H_x field.^{16,21,29} The effective SOT field $\eta_z = \Delta H_z/J_x$ contributed by p_z is then determined with $H_x = 0$ Oe [Figs. 2(a)–2(c)]. Subsequently, using a standard harmonic Hall voltage measurement technique, we evaluate the SOT effective field η_y , as described in Fig. S13(c) in [supplementary material](#) Sec. 11. For the Co(0.8)/PtGd(2) sample, the contribution of p_z from J_{PHE} results in SOT field efficiency $\eta_z = 0.17 \times 10^{-6}$ Oe A $^{-1}$ cm ^{2} , while the p_y attributed to J_{SHE} yields SOT field efficiency $\eta_y = 2.01 \times 10^{-6}$ Oe A $^{-1}$ cm ^{2} [Fig. 2(c)]. Despite these contributions, both η_y and η_z may not be strong enough in the device, as evident from the absence of field-free switching of $\mathbf{m}$ in Co/PtGd [Fig. 3(a)]. This is in agreement with our previous finding in similar Co/PtGd SOT devices with an ultrathin 2 nm PtGd layer.²⁴

To enhance p_y and its associated η_y , we utilize the recently discovered OHE, which generates a transversal current J_{OHE} that flows perpendicular to the longitudinal current.^{52–55} OHE can exist in materials with weak SOC, such as Mo, Ru, Ti, and Nb.^{53–56} The J_{OHE} can be converted into J_{SHE} when passing through a layer with strong SOC, which can be significantly stronger and promising for spin-orbit

torque generation.⁵⁷ We thus introduce a Mo layer under the PtGd layer in the SOT device, where J_{OHE} is generated by J_x in the Mo layer and transformed to a spin current via SOC when flowing through the PtGd layer [Fig. 1(c)]. We find that the η_y is enhanced by two times and four times in the presence of the Mo underlayers with a thickness of 2 and 4 nm, respectively, as shown in Fig. 2(c). Such a significant enhancement of η_y clearly proves the efficiency of OHE in the generation of p_y . Due to the synergy between the substantial orbital current generated by Mo and its effective conversion to a spin current via the strong SOC PtGd interface, this result is in agreement with the previous report.^{56–58} We also measure the R_H - H_z hysteresis loop shifts for Co(0.8)/PtGd(2)/Mo(a) devices and find that the η_z is slightly increased in the presence of the Mo layer, as shown in Fig. 2(c). This is consistent with the PHE enhancement [Fig. S3(b) in [supplementary material](#) Sec. 3].

We then fabricated pillar-shaped Co(0.8)/PtGd(2)/Mo(a) SOT devices to examine the switching behavior. Figure 3 shows the changes in normalized R_H ($R_H^J/R_H^{H_z(S)}$) as a function of J_x applied to these SOT devices. Here, the $R_H^{H_z(S)}$ signifies the saturation R_H of the pillar-shaped devices, induced by the H_z field as shown in Figs. S9(a) and S9(b) in [supplementary material](#) Sec. 7. In contrast to the flat R_H - J_x curve observed in the absence of Mo ($a = 0$) [Fig. 3(a)], a hysteretic behavior and a sign change in R_H - J_x curve emerges when the Mo layer is introduced ($a > 0$) [Figs. 3(b) and 3(c)]. In the regime of high J_c , the sample undergoes heating and exhibits non-uniform magnetization switching behavior, as shown in Figs. 3(b) and 3(c). This phenomenon has been commonly observed in previous studies of deterministic magnetization switching.^{59–61} The device's temperature

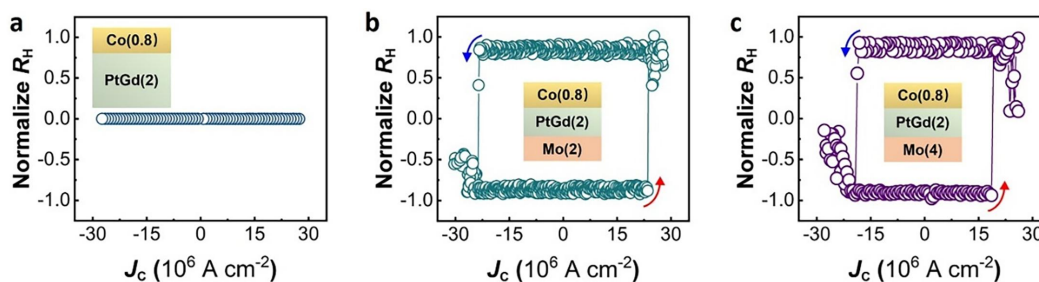


FIG. 3. (a)–(c) The changes of R_H (normalized) as a function of an in-plane current J_x applied to Co(0.8)/PtGd(2)/Mo(a) pillar-shaped SOT devices without an in-plane field for $a = 0$ nm (a), $a = 2$ nm (b), and $a = 4$ nm (c). The red and blue arrows indicate the direction of the SOT switching.

rise due to Joule heating is anticipated to be smaller than 37 K at SOT switching current density of 22.52 MA cm^{-2} , as illustrated in Fig. S14 in [supplementary material](#) Sec. 12, where Joule heating is unlikely to play a dominant role. The high thermal stability and conductivity of the Mo layer ensure efficient heat spreading,^{25,62} effectively mitigating the modest Joule heating generated in the Co/PtGd/Mo SOT devices across the operating current density. Notably, we observed about $\sim 100\%$ field-free magnetization switching in the Co pillar-shaped SOT devices for both $a = 2$ and 4 nm [Figs. 3(b) and 3(c)]. This observation reflects that a substantial y -polarized J_{OHE} and a finite z -polarized J_{PHE} can result in field-free switching.

In conclusion, we have successfully demonstrated efficient current-induced field-free switching of perpendicular magnetization in a Co/PtGd/Mo SOT device assisted by OHE. In the presence of a PHE-induced moderate p_z and hence the finite out-of-plane damping-like torque in the Co/PtGd bilayer, an additional Mo bottom layer contributes a strong p_y via OHE, generating a significant in-plane damping-like torque. With the combined influence of these SOTs, the perpendicular magnetization of Co is efficiently switched without an external magnetic field. Importantly, this approach does not require strong symmetry breaking, typically induced by engineering the device geometry or by using a low-symmetric spin source, making it particularly attractive for practical applications.

See the [supplementary material](#) for additional information, including macro-spin simulation and micromagnetic simulation results, electrical resistivity, x-ray absorption spectroscopy measurement, Joule heating effect, harmonic measurements, and quantitative analysis of the effective SOT torque term.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Zelalem Abebe Bekele and Yuan-Yuan Jiang contributed equally to this work.

Zelalem Abebe Bekele: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yuan-Yuan Jiang:** Validation (equal);

Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Kun Lei:** Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **Xiukai Lan:** Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **Xiangyu Liu:** Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **Hui Wen:** Methodology (equal); Writing – original draft (equal); Writing – review & editing (equal). **Ding-Fu Shao:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Methodology (equal); Project administration (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Kaiyou Wang:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (lead); Project administration (lead); Supervision (lead); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

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

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