Electric-field control of spin accumulation direction for spin-orbit torques

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Electric field is an energy-efficient tool that can be leveraged to control spin-orbit torques (SOTs). Although the amount of current-induced spin accumulation in a heavy metal (HM)/ferromagnet (FM) heterostructure can be regulated to a certain degree using an electric field in various materials, the control of its direction has remained elusive so far. Here, we report that both the direction and amount of current-induced spin accumulation at the HM/FM interface can be dynamically controlled using an electric field in an oxide capped SOT device. The applied electric field transports oxygen ions and modulates the HM/FM interfacial chemistry resulting in an interplay between the spin Hall and the interfacial torques which in turn facilitates a non-volatile and reversible control over the direction and magnitude of SOTs. Our electric-field controlled spin-orbitronics device can be programmed to behave either like the SOT systems with a positive spin Hall angle or a negative spin Hall angle.
In a HM/FM heterostructure, current-induced spin accumulation\(^7\) at the HM/FM interface arises from the bulk spin Hall effect (SHE)\(^2\)–\(^6\) and/or from the interfacial spin–orbit coupling\(^1\)–\(^9\). The direction of this spin accumulation is an important parameter in the design of SOT applications such as the magnetic random access memory (MRAM), domain wall memory and skyrmion-based memory as it determines the direction of magnetization switching, domain wall motion and skyrmion motion. However, the relative direction between the current and the generated spin accumulation for a given heterostructure is always fixed which inhibits a flexible design of the above applications. For example, a fixed direction of spin accumulation necessitates the change in the polarity of the applied current in order to switch between two magnetic states\(^2\), which will result in an additional circuitry in SOT-MRAM\(^1\)–\(^3\). In addition, selective switching of multiple bits sharing the same HM write layer cannot be achieved with a fixed and identical direction of spin accumulation. In view of the above drawbacks and requirements, it is imperative to be able to control the direction of current-induced spin accumulation in SOT devices. In the previous works, the direction of SOTs was altered through stack engineering which involved methods such as a substitution of the spin Hall source\(^2\)–\(^3\),\(^11\) variation of the heavy metal\(^6\)–\(^8\)–\(^13\) or capping layer thickness\(^9\) and usage of a dual heavy metal layers\(^1\)–\(^6\). However, all the above methods for the control of SOT direction involve physical alteration of the heterostructure which is not feasible once the SOT devices have been fabricated. Here, we report a modulation of the SOT direction in a Pt/Co/GdO\(_x\) heterostructure by changing the concentration of oxygen in the Co layer using an electric field. The direction of spin accumulation is tuned reversibly in a non-volatile fashion to be in either the \(i \times n\) or \(-i \times n\) direction in a single device. Here, \(i\) and \(n\) represent the direction of the current flow and the film normal, respectively. In essence, our devices can be controlled to behave to be possessing either a positive or a negative effective spin Hall angle without any physical stack modifications. While the previous works\(^7\)–\(^\)\(^{21}\) have offered only a limited electric-field control on the magnitude of SOTs, we demonstrate a sizable control over both the magnitude as well as direction of SOTs. Our findings will offer a substantial improvement to the SOT based memory scheme as well as create opportunities for novel applications such as spin-logic circuits and programmable spin-circuits\(^2\).

Subsequently, a \(V_g\) of \(-10\) V was applied for 120 s on the top gate electrode at 40 °C as illustrated in Fig. 1a. An elevated temperature was used for efficient oxygen migration\(^2\)–\(^4\)–\(^7\)–\(^8\)–\(^13\). Harmonic measurements were then performed after setting \(V_g\) = 0 V and removing the gate voltage connections. The first harmonic hysteresis loop has the same polarity as compared to the initial device state as shown in Fig. 1d. However, the signs of \(SH_{\text{peaks}}\) for both \(H_{\text{ext}}\|\ I_{\text{ac}}\) and \(H_{\text{ext}}\perp I_{\text{ac}}\) configurations are opposite in comparison with the normal device, as shown in Fig. 1e. This reversal of the \(SH_{\text{peaks}}\) indicates that both the \(H_L\) and \(H_T\), and hence the spin accumulation in the device, change their directions after negative \(V_g\) application. Therefore, the SOT direction becomes “negative” rendering the device into the “reversed state” (corresponding to a negative \(\xi_{\text{SOT}}\)). The values of \(H_L\) and \(H_T\) in this reversed state are \(-285\) and \(-219\) Oe per 10\(^1\) A m\(^{-2}\), respectively. A \(V_g\) of \(+4\) V was then applied on the reversed device for 120 s. Subsequent harmonic measurements show that the sign of \(SH_{\text{peaks}}\) and hence the SOT directions, return to their normal state (Fig. 1e). The SOT direction was again reversed by applying a \(V_g\) of \(-10\) V for 120 s. Therefore, we observe that the direction of the current-induced spin accumulation and the sign of \(\xi_{\text{SOT}}\) can be reversibly toggled in the device through gate voltage applications. Moreover, both the normal- and reversed-states of the device are non-volatile and can only be modified by the gate voltage.

Current-dependence for the normal- and reversed device. Figure 2a, b shows that the extracted values of the SOT effective fields have a linear dependence on the current magnitude for both the normal and reversed device states, thereby confirming their current-based origin. In addition, we show that different polarities of \(\xi_{\text{SOT}}\) can be programmed at different locations on a single-device channel (Fig. 2c). A 2-bit Hall bar was fabricated with one of the bits covered with a gate oxide as shown in Fig. 2c. The direction of spin accumulation of the gated-bit is programmed by applying a negative \(V_g\) to be opposite to that of the ungated bit as can be seen from the second harmonic signals measured with \(H_{\text{ext}}\|\ I_{\text{ac}}\) shown in Fig. 2c.

Magnetic hysteresis loop measurement to evaluate the SOT polarity. In order to further verify the observed reversal of SOTs, the anomalous Hall effect (AHE) was measured with positive and negative dc currents (\(\pm 4\) mA) and with \(H_{\text{ext}}\) applied in the direction of currents with a tilt of \(-2°\) towards the film normal\(^2\). For our measurement configuration, the coercivity of the AHE loop should decrease (increase) for a normal state, when a positive (negative) dc current is applied. This is indeed what we observe for a device in the normal state, as shown in Fig. 2d. Conversely, when a negative \(V_g\) was applied to reverse the state of the device, the coercivity of the AHE loop with a positive dc current is larger compared to that with a negative dc current (Fig. 2e). This observation further confirms the opposite direction of the SOTs in the reversed device. It should be noted that the sign reversal of SOT is accompanied by a reduction in \(R_{\text{AHE}}\) and perpendicular magnetic anisotropy (PMA), \(H_p\), of the devices due to Co oxidation (Supplementary Fig. 1). For the device shown in Fig. 2e, the \(R_{\text{AHE}}\) and \(H_p\) reduce from 2.9 Ω and 10.6 kOe to 1.7 Ω and 4.2 kOe from a normal to reversed state, respectively. The non-volatile and reversal modification of the SOT direction was also confirmed on multiple devices (Supplementary Fig. 2). In addition, the sign reversal of SOT can be achieved for a Co layer as thick as \(~2\) nm, thereby signifying the feasibility of realizing a thermally stable SOT memory element (Supplementary Fig. 3). Moreover, by reducing the gate oxide thickness the SOT...
directions can be toggled in the order of seconds at room temperature (Supplementary Fig. 2).

**Mechanism of the electric-field control.** The origin of the voltage control of the SOT direction can be explained by the oxygen ion ($\text{O}_2^-$) migration in the presence of an electric field. In a normal device as shown in Fig. 3a, the SOTs are mainly induced by the SHE of Pt$^7,8$. Although the broken inversion symmetry is also a source of interfacial SOTs like the Rashba torque$^8,9,28$, its magnitude is smaller than that of SHE$^8$. Upon application of a negative $V_g$, the oxygen is driven from the ionic-conductive GdO$_x$ gate into the Co layer as shown in Fig. 3b. Previously, ionic migration in GdO$_x$ has been used to modulate the anisotropy landscape of underlying magnet$^{25,26}$ and later to completely quench its magnetization$^{27}$. It should be noted that apart from the electric-field induced migration of oxygen ion, another competing mechanism for Co oxidation/reduction which involves hydrolysis of water has also been proposed recently$^{29}$. Nevertheless, when the Pt/Co interface is oxidized, it modifies the polarity and strength of the Rashba SOTs$^9,30$–$^32$ by modulating the Rashba coefficient ($\alpha_R$), which is sensitive to the spin–orbit coupling strength and the band structure$^{31,33}$, which in turn depend on the interfacial composition and quality. A similar

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**Fig. 1** Effect of gate voltage application on the SOT effective fields. **a** Schematic of the Hall bar used for the electrical measurements. **b, c** $V_{\omega,2\omega}$ are obtained with $H_{\text{ext}}$ applied parallel (||) and perpendicular (⊥) to the ac current ($I_{\text{ac}}$) flow direction. The measurement schematic with $H_{\text{ext}}$ || $I_{\text{ac}}$ (b) and $H_{\text{ext}}$ ⊥ $I_{\text{ac}}$ (c) are also shown. **d** $V_\omega$ and **e** $V_{2\omega}$ signals for a Pt (2 nm)/Co (0.8 nm) device as a function of in-plane external magnetic field ($H_{\text{ext}}$), with subsequent gate voltage ($V_g$) application events. Measurements were performed at 150 K. At this temperature, the SOT device displayed a good PMA in both the normal- and reversed-states. Both the normal- and reversed-states of devices persist at room temperature as well. The values of $H_L$ and $H_T$ corresponding to a current density of $10^{12}$ A m$^{-2}$ are also shown in **e**. The planar Hall effect was considered in evaluating the SOT effective fields and the anomalous Nernst effect contribution was subtracted from the raw second harmonic data before plotting it.
modification of polarity and magnitude of $\alpha_R$ with oxidation has been predicted and observed earlier on magnetic metallic surfaces\(^\text{31}\). With progressive oxidation of the Co layer and hence the Pt/Co interface, the magnitude of this interfacial Rashba SOT whose polarity is opposite to that of SHE, keeps increasing and when it becomes larger than the SHE-based SOT, a sign reversal of SOTs is realized. It should be noted that oxygen ions cannot migrate beyond the Pt/Co interface into the Pt layer due to the high redox potential of Pt. This is also confirmed by applying negative $V_g$ on a Pt/GdO\(_x\) device which results in no change in the device resistance (Supplementary Fig. 5). When a positive $V_g$ is applied on a reversed device, the O\(^2\)- at the Pt/Co interface are driven back into the GdO\(_x\) layer as shown in Fig. 3c. In this case, the device returns to the normal state with the observed SOTs being dominated by the SHE. Since the oxygen can be driven back and forth from the Pt/Co interface by $V_g$ applications, the state of the device is both reversible and non-volatile.

The underlying competition between the interfacial Rashba and the spin Hall SOTs was further examined by performing a Pt thickness-dependent study (Supplementary Note 5). We find that while devices with a thin Pt layer ($< 2.5$ nm) showed SOT sign reversals on application of gate voltages, no such effect was observed for thicker Pt samples ($> 2.5$ nm) (Supplementary Fig. 6). A relatively small spin Hall angle\(^\text{34,33}\) and a large interface (Pt/Co) to bulk (Pt) ratio in a thin Pt-based heterostructure results in the dominance of the interfacial SOTs over the spin Hall torque after sufficient Pt/Co interfacial oxidation. Hence, a thin Pt device easily enters the reversed state compared to a thick ($\geq 2.5$ nm) Pt device. For devices with a thicker Pt layer, the magnitude of the Rashba torque never dominates over the SHE torque and the SOT device always remains in the normal state. We also perform the Co thickness dependence study in order to obtain additional insight into the role of oxygen in the Co layer (Supplementary Note 3). It is expected that a large Co thickness should result in larger screening effect thereby making O\(^2\)-migration in the Co and subsequent SOT reversal challenging. Indeed, we find that the temperature or thermal energy required to modulate SOTs increases with the increasing the Co thickness (Supplementary Fig. 4). We also ensure that the Co/GdO\(_x\) interface is not the source of reversed SOT. For this a Co (1 nm)/GdO\(_x\) heterostructure was deposited without any Pt layer. There is no visible second harmonic signal for this device (Supplementary Fig. 8).

In order to gain additional insight into the progressive evolution of SOTs in the devices, $H_L$ was measured for a Pt (1.5 nm)/Co (0.8 nm) device after application of successive $V_g$ pulses at room temperature. As shown in Fig. 3d, negative $V_g$ pulse applications, after starting from a normal device state with $H_L$ of 136 Oe per $10^{12}$ A m\(^{-2}\), reduce the $H_L$ slowly before quenching it to zero. The maximum $\xi_{SOT}$ (Supplementary Fig. 9) evaluated for the normal device is 0.05. With each subsequent negative $V_g$ pulses, the $H_L$ gradually evolves in the negative
direction due to progressive oxidation of the Pt/Co interface which results in build-up of Rashba SOTs of negative polarity. We find the minimum ratio of oxygen over cobalt in the Co layer for the sign reversal of SOT to be ~0.35 (Supplementary Fig. 10). The reversed device shows a maximum negative $H_s$ value of $-465 \text{ Oe per } 10^{12} \text{ A m}^{-2}$ which corresponds to $\xi_{\text{SOT}} = -0.10$. Consequently, when positive $V_g$ pulses were applied on this reversed device, the magnitude of $H_s$ begins to reduce as the oxygen starts to migrate away from the Pt/Co interface thereby reducing the interfacial SOTs. The $H_s$ is quenched to zero before finally returning to the normal state as shown in Fig. 3d. The progressive evolution from a normal to a reversed state and back to the normal state articulates the competition of the interfacial and spin Hall SOTs depending on the amount of Pt/Co interfacial oxidation. Furthermore, the above results demonstrate that a desired magnitude and direction of SOTs can be programmed in the device with $\xi_{\text{SOT}}$ ranging from 0.05 to $-0.10$.

**First principle calculations**. In order to further elucidate the effect of Co oxidation on the SOTs in the Co/Pt bilayer we have carried out electronic structure calculations$^{36,37}$ to evaluate the evolution of Rashba torque under different cases of oxidation (Supplementary Note 9). Figure 4a displays the variation of the effective Rashba coefficient (ERC) as a function of oxygen concentration, $x = N_{O}/N_{Co}$ in the Pt (4 ML)/Co (10(1$-x$) ML)/CoO (10x ML) slab (ML represents monolayer). Effectively, $x = 0.1$ means that oxygen is present only in the top layer while $x = 1$ represents completely oxidized Co with oxygen at the Pt/Co interface. The ERC, $\rho_{\text{Rashba}}$, was calculated from the field-like SOT ($\tau_{\text{SOT}}$), using the expression $\rho_{\text{Rashba}} = \hbar^2 M_s \tau_{\text{FL}}/2 m_s \sigma_{\text{xx}}$,$^{38}$ where $P$ is the polarization, $\hbar$ is the reduced Plank’s constant, $M_s$ is the saturation magnetization, $m_s$ is the free electron’s mass and $\sigma_{\text{xx}}$ is the longitudinal conductivity of the structure. The theoretical calculations show an enhancement of the ERC when oxygen is placed on the top Co layer (Fig. 4a). This is in agreement with the experimental data presented in Fig. 3d in which an increase of $\xi_{\text{SOT}}$ (Supplementary Fig. 9) was observed during initial oxidation. It should be noted that similar increase of $\xi_{\text{SOT}}$ was observed in earlier works in which there was limited Co oxidation$^{17,32}$. Furthermore, the calculations show a sign reversal of the ERC around $x \approx 0.8$ which is the cause of the reversed SOT. It should be noted that in the calculations $x > 0.8$ corresponds to the presence of oxygen near the Co/Pt interface. Also note that the theoretical calculations show that the ERC is relatively insensitive to the type of magnetic ordering (ferromagnetic or antiferromagnetic) of the Co layer.

In Fig. 4a we have also plotted the ERC extracted from the experimental data using the expression $\rho_{\text{Rashba}} = \mu_B M_s H_s / J_e$,$^{39}$ where $\mu_B$ is Bohr’s magneton. The experimental value of ERC also becomes negative upon increasing the oxygen concentration in the Co layer which corresponds to the SOT reversal. However, the value of $x$ for which the sign reversal of ERC is observed in the experiment and the calculations is different due to the different way of oxygen filling for the two cases. While in the calculations the Co layers were completely oxidized one by one starting from the top, in the experiments the oxygen penetrates to the Pt/Co interface even before the top Co layers are completely oxidized. Since CoO is an insulator, increasing CoO thickness leads to the decrease of the effective Co thickness. In order to verify that the sign reversal of ERC is not due to the decrease in the effective Co thickness, we have carried out first principles calculations with a single oxygen atom placed on the different Co layers. Figure 4b shows the ERC versus the position of the oxygen atom. The ERC shows an abrupt sign reversal when oxygen is placed at the Co/Pt interface. A separate calculation using a Pt (4 ML)/Co (2 ML) slab with $(2 \times 2)$ planar supercell (compared to the $(1 \times 1)$ planar cell in Fig. 4a) was performed in order to quantify the interfacial oxygen...
ERC sign reversal is obtained for concentration required to reverse the ERC or SOT. The larger planar area allows for the introduction of 4 oxygen atoms at the interface (only one oxygen atom per layer can be added in the $(1 \times 1)$ planar cell in Fig. 4a). We find that for oxygen concentration $\approx 0.3$, the ERC reverse its sign and its magnitude keeps on increasing with additional oxygen as shown in Fig. 4c. The structural geometry in this calculation and the subsequent result are in close agreement with the experiments for which an ERC reverse its sign and its magnitude keeps on increasing with additional oxygen as shown in Fig. 4c. The initial magnetization switching sequence for a normal device of Pt (1.5 nm)/Co (0.8 nm) is anticlockwise (clockwise) for a positive (negative) direction of $H_{\text{assist}}$. A $V_g = -4$ V for 120 s was then applied at room temperature to reverse the SOT directions. The subsequent switching measurement on this reversed device shows an opposite switching sequence that is clockwise (anti-clockwise) for the positive (negative) direction of $H_{\text{assist}}$ (Fig. 5a). After subsequent application of a positive $V_g$ for 60 s, the switching sequence reverts back to normal. Finally, the switching sequence is reversed again after the application of a negative $V_g$. In essence, the device shows a unipolar switching behavior. For a given direction of the current and the $H_{\text{assist}}$, the magnet can be stabilized in either upward or downward direction depending on the state of the device. The unipolar operation of the device, in which the device can switch between two states without changing the current polarity, is demonstrated in Fig. 5b using gating.

**Discussion**

The modulation of SOTs is realized by regulating the amount of oxygen at the Pt/Co interface using an electric field. The reversible and non-volatile modulation (Supplementary Fig. 12) of SOT direction is demonstrated by both harmonic Hall voltage and current-induced switching measurements. The capability to generate an opposite switching sequence in a single device is a significant step toward a flexible realization of SOT-MRAM architecture. For example, simultaneous writing into different directions of multiple bits by placing them on a shared write layer served by a single transistor is possible. The control of SOT direction in a single device will not only accelerate the adoption of SOTs in spintronic memories but will also facilitate novel applications such as multi-bit memory cells, spin-logic devices and reprogrammable spin-circuits.

**Methods**

**Sample preparation.** MgO (2 nm)/Pt (t nm)/Co (0.8 nm)/GdO$_x$ (3 nm) films were deposited on a Si$_x$SiO$_y$ substrate using dc and rf magnetron sputtering at a base pressure of $10^{-9}$ Torr. The Pt thickness, $t$, was varied from 1.5 to 3 nm. Thickness calibration was done prior to deposition. GdO$_x$ for the top layer and the gate oxide was deposited using reactive sputtering of Gd in the presence of oxygen. An optimized oxygen flow rate of 0.5 sccm compared to 20 sccm for Argon was used during GdO$_x$ deposition. Deposition pressure was kept less than 3 mTorr for all the layers. The as-deposited films were annealed at 250 $^\circ$C for 1 h to induce PMA. The
along \((H_{	ext{ext}} \parallel I_{\text{rms}})\) or orthogonal \((H_{	ext{ext}} \perp I_{\text{rms}})\) to the current flow direction (tilted \(-2^\circ\) to the sample normal). The first and second harmonic Hall voltages were recorded simultaneously while sweeping the magnetic field. For SOT effective field evaluation, a uniform current density was assumed through the heterostructure.

**Current-induced switching measurements.** The anomalous Hall resistance was probed while sweeping a pulsed dc current through the Hall channel. 100 μs wide current pulses were used for the measurements. An in-plane assist field \((H_{\text{assist}})\) of 1000 Oe was applied during the measurement to achieve deterministic switching. It should be noted that the device state (both normal and reversed) persists at room temperature, even though some experiments were conducted at low temperatures in order to regain PMA.

**First principles calculations.** The density functional theory calculations for the Co/Pt bilayer slabs were carried out using the Vienna ab initio simulation package (VASP)\(^{36,42}\). The pseudopotential and wave functions are treated within the projector-augmented wave (PAW) method\(^{43,44}\). Structural relaxations were carried using the generalized gradient approximation as parameterized by Perdew et al.\(^{45}\) when the largest atomic force is smaller than 0.01 eV Å\(^{-1}\). A 15 Å thick vacuum region is introduced to separate the periodic slabs along the stacking direction. The plane wave cutoff energy is 500 eV and a 10 × 0 × 1 k-points mesh is used in the 2D Brillouin Zone (BZ) sampling. The GGA + U method with a Hubbard U of 3 eV has been used to treat the localized 3d orbitals of the Co atoms in the CoO monolayers (MLs). The tight-binding (TB) Hamiltonian was obtained from the VASP-Wannier90 calculations\(^{46,47}\), and the SOT was calculated using the approach introduced in ref.\(^{37}\).

**Data availability**

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

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**Fig. 5** Current-induced switching measurements. a The Hall resistance \(R_H\) as a function of pulses current magnitude \(I_{\text{pulse}}\) for a Pt (1.5 nm)/Co (0.8 nm) device after successive \(V_g\) application at room temperature. The switching loops in a are shown for the assist field \((H_{\text{assist}})\) direction along \((H_{\text{assist}})\) and opposite \((-H_{\text{assist}})\) to the current flow direction. b Repeated toggling of the \(R_H\) by a unidirectional current after modulating the state of device with positive and negative \(V_g\). The switching measurements for the reversed device in a, b were performed at 150 K at which the device regained PMA.

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**References**

1. Miron, I. M. et al. Current-driven spin torque induced by the Rashba effect in a ferromagnetic metal layer. *Nat. Mater.*, 9, 230–234 (2010).
2. Liu, L. et al. Spin-torque switching with the giant spin hall effect of tantalum. *Science* 336, 555–558 (2012).
3. Demidov, V. E. et al. Magnetic nano-oscillator driven by pure spin current. *Nat. Mater.*, 11, 1028–1031 (2012).
4. Miron, I. M. et al. Perpendicular switching of a single ferromagnetic layer induced by in-plane current injection. *Nature* 476, 189–193 (2011).
5. Emori, S., Bauer, U., Ahn, S.-M., Martinez, E. & Beach, G. S. D. Current-driven dynamics of chiral ferromagnetic domain walls. *Nat. Mater.*, 12, 611–616 (2013).
6. Kim, J. et al. Layer thickness dependence of the current-induced effective field vector in Ta/CoFeB/MgO. *Nat. Mater.*, 12, 240–245 (2012).
7. Garello, K. et al. Symmetry and magnitude of spin–orbit torques in ferromagnetic heterostructures. *Nat. Nanotechnol.*, 8, 587–593 (2013).
8. Fan, X. et al. Quantifying interface and bulk contributions to spin–orbit torques in magnetic bilayers. *Nat. Commun.*, 5, 3042 (2014).
9. Qiu, X. et al. Spin–orbit–torque engineering via oxygen manipulation. *Nat. Nanotechnol.*, 10, 333–338 (2015).
10. Oboril, F., Bishnoi, R., Ebrahimi, M. & Tahoori, M. B. Evaluation of hybrid memory technologies using SOT-MRAM for on-chip cache hierarchy. *IEEE Trans. Comput. Aided Des. Integr. Circuits Syst.*, 34, 367–380 (2015).
11. Lee, S. W. & Lee, K. J. Effect of wavy spin-transfer torque on ultrafast unipolar switching of a nanomagnet with out-of-plane polarization. *IEEE Trans. Magn.*, 47, 3872–3875 (2011).
12. Baek, S. C., Oh, Y. W., Park, B. G. & Shin, M. Novel operation of a multi-bit SOT memory cell addressed with a single write line. *IEEE Trans. Magn.*, 53, 3401405 (2017).
13. Bai, C.-F. et al. Spin transfer torque devices utilizing the giant spin Hall effect of tungsten. *Appl. Phys. Lett.*, 101, 224402 (2012).
14. Ramaswamy, R., Qiu, X., Dutta, T., Pollard, S. D. & Yang, H. Hf thickness dependence of spin-orbit torques in Hf/CoFeB/MgO heterostructures. *Appl. Phys. Lett.*, 108, 202406 (2016).
15. Torrejon, J. et al. Interface control of the magnetic chirality in CoFeB/MgO heterostructures with heavy-metal underlayers. *Nat. Commun.*, 5, 4635 (2014).
16. He, P. et al. Continuous tuning of the magnitude and direction of spin-orbit torque using bilayer heavy metals. *Adv. Elect. Mater.*, 2, 1600210 (2016).
17. Emori, S., Bauer, U., Woo, S. & Beach, G. S. D. Large voltage-induced modification of spin-orbit torques in Pt/Co/GdOx. *Appl. Phys. Lett.*, 105, 222401 (2014).
18. Liu, R. H., Lim, W. L. & Urazhdin, S. Control of current-induced spin-orbit effects in a ferromagnetic heterostructure by electric field. *Phys. Rev. B* **89**, 220409 (2014).

19. Fan, Y. et al. Electric-field control of spin–orbit torque in a magnetically doped topological insulator. *Nat. Nanotechnol.* **11**, 352–359 (2016).

20. Yan, Y. et al. Strong electrical manipulation of spin–orbit torque in ferromagnetic heterostructures. *Adv. Elect. Mater.* **2**, 1600219 (2016).

21. An, H. et al. Current-induced magnetization switching by an electrically insulating spin-torque generator. *Sci. Adv.* **4**, eaar2250 (2018).

22. Dery, H., Dalal, P., Cywiński, Ł. & Sham, L. J. Spin-based logic in semiconductors for reconfigurable large-scale circuits. *Nature* **447**, 573–576 (2007).

23. Qiu, X. et al. Angular and temperature dependence of current induced spin-orbit effective fields in Ta/CoFeB/MgO nanowires. *Sci. Rep.* **4**, 4491 (2014).

24. Jamali, M. et al. Spin-orbit torques in Co/Pd multilayer nanowires. *Nat. Phys.* **14**, 411–416 (2018).

25. Bauer, U. et al. Magneto-ionic control of interfacial magnetism. *Nat. Mater.* **14**, 174–181 (2014).

26. Bauer, U. et al. Magneto-ionic control of interfacial magnetism. *Nat. Mater.* **14**, 174–181 (2014).

27. Bi, C. et al. Reversible control of Co magnetism by voltage-induced oxidation. *Phys. Rev. Lett.* **113**, 267202 (2014).

28. Skinner, T. D. et al. Spin-orbit torque opposing the Oersted torque in ultrathin Co/Pt bilayers. *Appl. Phys. Lett.* **104**, 062401 (2014).

29. Tan, A. I. et al. Magneto-ionic control of magnetism using a solid-state proton pump. *Nat. Mater.* **18**, 35–41 (2019).

30. Bychkov, Y. A. & Rashba, E. I. Properties of a 2D electron gas with lifted spectral degeneracy. *J. Exp. Theor. Phys. Lett.* **39**, 78–81 (1984).

31. Krupin, O. et al. Rashba effect at magnetic metal surfaces. *Phys. Rev. B* **71**, 014405 (2005).

32. Bekele, Z. A., Meng, K., Miao, J., Xu, X. & Jiang, Y. Modulated spin orbit torque via controlling the oxidation level of Ti in Pt/CoTiOx heterostructures. *Solid State Commun.* **284**, 5–10 (2018).

33. Park, J.-H., Kim, C. H., Lee, H.-W. & Han, J. H. Orbital chirality and Rashba interaction in magnetic bands. *Phys. Rev. B* **87**, 041301 (2013).

34. Wang, Y., Deorani, P., Qiu, X., Kwon, J. H. & Yang, H. Determination of intrinsic spin Hall angle in Pt. *Appl. Phys. Lett.* **105**, 152412 (2014).

35. Nguyen, M.-H., Ralph, D. C. & Ruhrman, R. A. Spin torque study of the spin hall conductivity and spin diffusion length in platinum thin films with varying resistivity. *Phys. Rev. Lett.* **116**, 126601 (2016).

36. Mahfouzi, F., Kim, J. & Kioussis, N. Intrinsic damping phenomena from quantum to classical magnets: an ab initio study of Gilbert damping in a Pt/Co bilayer. *Phys. Rev. B* **96**, 214421 (2017).

37. Mahfouzi, F. & Kioussis, N. First-principles study of the angular dependence of the spin-orbit coupling in Pt/Co and Pd/Co bilayers. *Phys. Rev. B* **97**, 224426 (2018).

38. Manchon, A. & Zhang, S. Theory of spin torque due to spin-orbit coupling. *Phys. Rev. B* **79**, 094422 (2009).

39. Manchon, A. & Zhang, S. Theory of nonequilibrium intrinsic spin torque in a single nanomagnet. *Phys. Rev. B* **78**, 212405 (2008).

40. Yang, J. J., Strukov, D. B. & Stewart, D. R. Memristive devices for computing. *Nat. Nanotechnol.* **8**, 13–24 (2012).

41. Kresse, G. & Furthmüller, J. Efficient iterative schemes for ab initio total-energy calculations using a plane-wave basis set. *Phys. Rev. B* **54**, 11169–11186 (1996).

42. Kresse, G. & Furthmüller, J. Efficiency of ab-initio total energy calculations for metals and semiconductors using a plane-wave basis set. *Comput. Mater. Sci.* **6**, 15–50 (1996).