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Field-free spin-orbit torque switching enabled by altermagnetic

RuO₂ doped Pt layer

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Spin-orbit torque (SOT) offers an efficient approach for electrical manipulation of magnetization; however, deterministic switching of perpendicular magnetization typically requires an external magnetic field, which severely limits device integration. In this work, we demonstrate robust field-free SOT-induced magnetization switching in Ta(2)/Pt_{1-x}(RuO₂)_x(4)/Co(1)/Ta(2) multilayer films fabricated by magnetron sputtering. For the x=0.18 sample, field-free switching is obtained with a critical current density (J_c) of 11×10^6 A/cm². This is attributed to the out-of-plane (z-polarized) spin current generated in the altermagnetic RuO₂-doped Pt layer, which exerts a spin-orbit torque on the perpendicular magnetization. Furthermore, the J_c decreases to 5.5×10^6 A/cm² under $H_x = 650$ Oe, for the sample of x= 0.18. Harmonic Hall measurements further reveal an enhanced SOT efficiency, with a maximum ξ_{DL} of 0.286 at x = 0.02. These results suggest oxide-doped Pt as an effective spin source for achieving low-current, field-free SOT switching and provide a practical route toward scalable spintronic devices.

Keywords: SOTs; multilayered structure; spintronics; Field-free

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1. Introduction

Spintronic devices based on magnetization manipulation have attracted extensive attention for next-generation nonvolatile memory and logic applications. Among them, spin-orbit torque magnetic random-access memory (SOT-MRAM) is considered one

of the most promising candidates due to its ultrafast switching speed, high endurance, and compatibility with CMOS technology.¹⁻⁵ Compared with conventional spin-transfer torque (STT) devices, SOT-based switching allows for the separation of read and write current paths, thereby improving device reliability and reducing write latency.³ Consequently, developing efficient SOT systems is of both fundamental and technological importance.^{6,7}

Despite these advantages, in conventional heavy metal/ferromagnet (HM/FM) heterostructures with perpendicular magnetic anisotropy (PMA), an additional in-plane magnetic field is typically required to break the symmetry, which complicates device integration and increases energy consumption.⁸⁻¹¹ Furthermore, minimizing the switching current density (J_c) is also critical for reducing the intrinsic power consumption of SOT devices.¹² Therefore, reducing the J_c while enabling field-free switching has become a central goal in SOT researches.^{13,14}

To address these challenges, extensive efforts have been devoted to material engineering and structural design.^{3,15} On one hand, reducing J_c can be achieved by alloying or doping the heavy metal layer to enhance its spin-orbit torque efficiency, and by interface engineering to increase the spin transparency.³ On the other hand, achieving field-free switching typically relies on breaking symmetries in the system.¹⁶⁻¹⁸ Various approaches have been demonstrated, including structural asymmetry, tilted magnetic anisotropy, exchange bias and the generation of out-of-plane spin polarization components.^{6,8,14,19-23} However, most previous researches focus on optimizing either J_c reduction or field-free switching, while the synergistic regulation of both parameters, which is crucial for the practical application of SOT-MRAM, has not been fully explored.

Recently, altermagnetic material RuO_2 has been reported to possess unconventional spin transport properties and can introduce z-polarized spin components (σ_z) when incorporated into heavy metal systems.²⁴⁻³¹ Based on these findings, it has been proposed to dope RuO_2 into the Pt layer to simultaneously enhance SOT efficiency and to induce an intrinsic effective field that enables field-free switching.

In this work, $\text{Ta/Pt}_{1-x}(\text{RuO}_2)_x/\text{Co}/\text{Ta}$ multilayer structures with systematically controlled RuO_2 doping concentration have been investigated. RuO_2 incorporation preserves the strong PMA while significantly reducing the J_c has been demonstrated. More importantly, an out-of-plane (z-polarized) spin current is generated, enabling robust field-free SOT switching. Harmonic Hall measurements reveal enhanced damping-like torque efficiency, with a maximum SOT efficiency of 0.286 at low doping levels. Our results highlight that RuO_2 doping provides an effective strategy for simultaneously achieving low-power operation and field-free switching, offering a practical pathway toward high-performance SOT-MRAM devices.

2. Experimental

$\text{Ta}(2)/\text{Pt}_{1-x}(\text{RuO}_2)_x(4)/\text{Co}(1)/\text{Ta}(2)$ multilayer films were deposited on Si/SiO_2 substrates by magnetron sputtering, with a base pressure of 1×10^{-7} Torr in the

sputtering system. All the sputtering targets used were 2 inches in size, where the purities of Ta and Pt targets were 99.99%, and that of the Co and RuO₂ target were 99.9%. During the deposition process, the sputtering chamber was maintained at a pressure of 6×10^{-3} Torr with 99.999% argon (Ar) gas. The deposition rates of Co and Ta are 0.2 Å/s and 0.18 Å/s, respectively. The sputtering power of RuO₂ was fixed at 10 W with a deposition rate of 0.15 Å/s. All the films were deposited at room temperature, without post-growth annealing.

3. Results and discussion

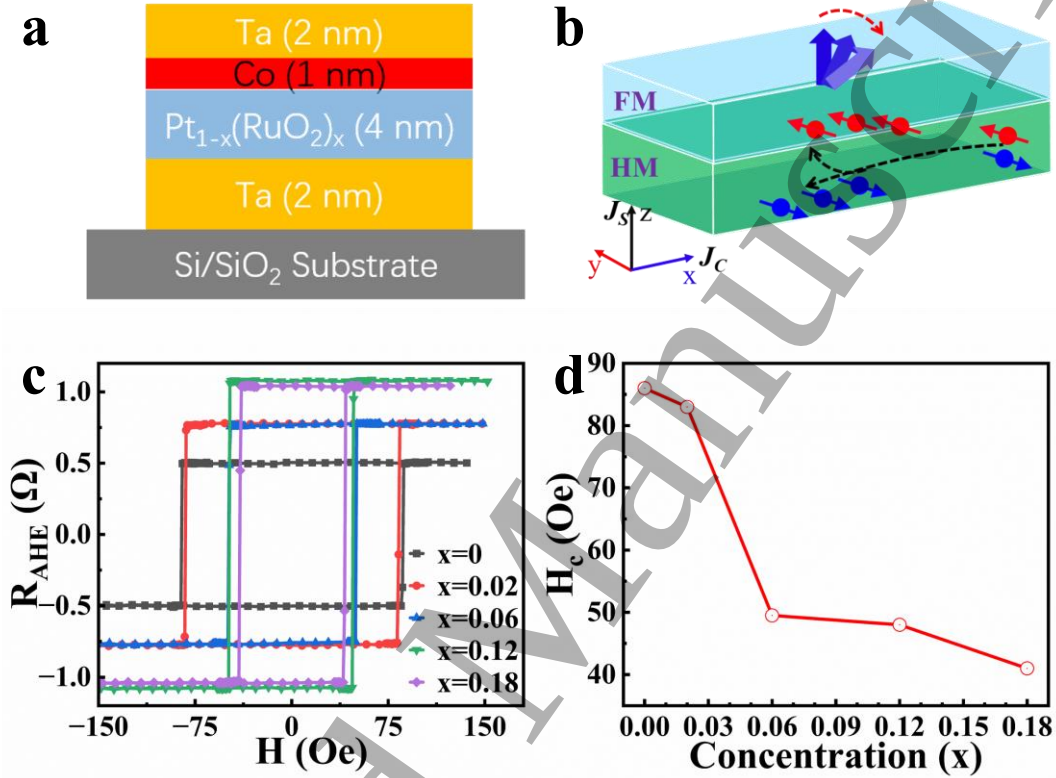


Figure 1. (a) The side view of Pt_{1-x}(RuO₂)_x/Co multilayer structure. (b) The schematic of SOT-driven magnetization switching. (c) Anomalous Hall effect (AHE) measurements measurement of Pt_{1-x}(RuO₂)_x/Co multilayer structures samples. (d) The H_c extracted from AHE vs the doping concentration.

The Fig. 1a illustrates the structural configuration of the samples, which consist of a Ta(2)/Pt_{1-x}(RuO₂)_x(4)/Co(1)/Ta(2) stack (thickness in nm) and were deposited onto a silicon substrate via magnetron sputtering. For the Pt_{1-x}(RuO₂)_x layer, co-sputtering onto the underlying Ta layer is performed by adjusting the Pt sputtering rate to achieve different RuO₂ doping concentrations (i.e., varying x values). Fig. 1b illustrates the SOT system: a spin current generated in the HM layer via the spin Hall effect (SHE) is injected into the adjacent FM layer, where it exerts a longitudinal effective magnetic field (H_L). Fig. 1c presents the anomalous Hall effect (AHE) loops of the as-fabricated multilayer films. The results demonstrate that the multilayers exhibit excellent PMA when the doping concentration of RuO₂ is in the range of 0 to 0.18, with the coercivity (H_c) decreasing monotonically as x increases, as shown in Fig. 1d. The saturation magnetization of the Co layer, measured via a vibrating sample

magnetometer (VSM), is determined to be 784 emu/cm^3 (Fig. S1), which is consistent with the values reported in the existing literatures.³²⁻³⁴ Fig. S2 presents the electrical resistivity (ρ_{HM}) of the $\text{Pt}_{1-x}(\text{RuO}_2)_x$ layer. Within the doping concentration range of $x=0$ to 0.18 , the electrical resistivity increases gradually with the rise of x , eventually reaching a value of approximately $76.4 \mu\Omega\cdot\text{cm}$.

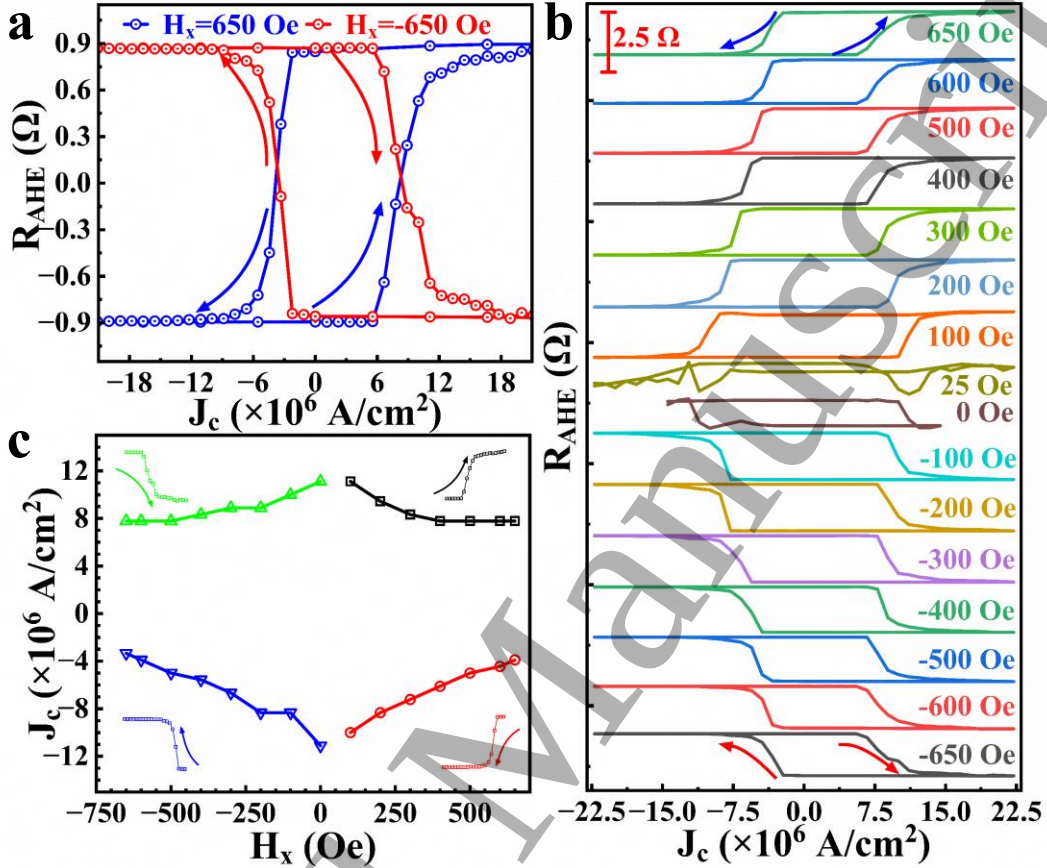


Figure 2. (a) Current-induced magnetization switching of the $\text{Pt}_{0.82}(\text{RuO}_2)_{0.18}/\text{Co}$ sample under in-plane magnetic field of $\pm 650 \text{ Oe}$. (b) (Color online) Current-induced magnetization switching in sample $\text{Ta}/\text{Pt}_{0.82}(\text{RuO}_2)_{0.18}/\text{Co}/\text{Ta}$ is observed under in-plane magnetic fields H_x ranging from -650 Oe to 650 Oe . A 50% switching ratio relative to the full AHE signal is obtained under zero magnetic field. (c) The critical switching current phase diagram of the sample determined based on (b).

Fig. 2a displays the switching curves of the $\text{Ta}/\text{Pt}_{0.82}(\text{RuO}_2)_{0.18}/\text{Co}/\text{Ta}$ multilayer under an in-plane magnetic field of $\pm 650 \text{ Oe}$. The J_c is determined to be $5.5 \times 10^6 \text{ A/cm}^2$, which is the result calculated based on a 10 micrometer current channel and a 9 nm thickness. Fig. 2b presents the switching curves of the $\text{Ta}/\text{Pt}_{0.82}(\text{RuO}_2)_{0.18}/\text{Co}/\text{Ta}$ multilayer under various in-plane magnetic fields (H_x). The SOT switching curves are counter-clockwise under a positive H_x and clockwise under a negative H_x . Under zero magnetic field, a 50% switching ratio relative to the full AHE signal is attained. The J_c is determined to be $11 \times 10^6 \text{ A/cm}^2$ without external field. As shown in Fig. S3, the identical field-free switching behavior observed in the other six devices further demonstrates the reliability of the switching performance for the doped samples.

It has been observed that the sample does not switch at $H_x = +25 \text{ Oe}$, suggesting

a built-in field of approximately -25 Oe. The corresponding relationship between the J_c and the auxiliary magnetic field is summarized in Fig. 2c. The results indicate that J_c decreases with the increase of H_x and exhibits remarkable symmetry at $H_x = \sim 25$ Oe, which demonstrates that the proposed system enables stable and reliable magnetization switching under variable magnetic field conditions.

Fig. S4a shows the device switching curves based on pure Pt and RuO₂-doped samples. All samples exhibit typical SOT switching characteristics. However, compared with the pure Pt counterpart, the device based on Ta/Pt_{0.82}(RuO₂)_{0.18}/Co/Ta multilayer demonstrates a significant reduction in J_c . To further elucidate the mechanism underlying the effect of RuO₂ doping, the correlation data between J_c and the doping concentration x were extracted and plotted in Fig. S4b. The results reveal that J_c shows a monotonically decreasing trend with the increase of x , reaching a minimum value of 6.6×10^6 A/cm² at $x=0.18$ under 500 Oe. This variation trend further confirms that RuO₂ doping can significantly reduce the power consumption of the device.

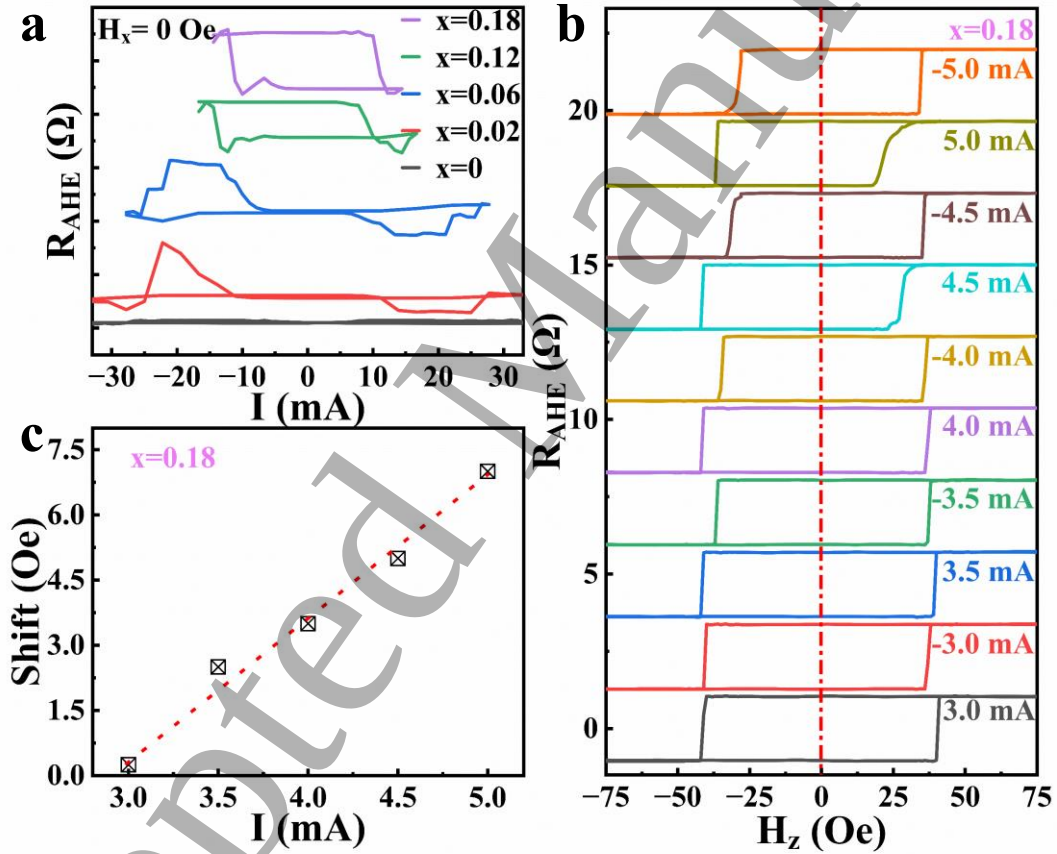


Figure 3. (a) Current-induced magnetization switching of the sample Pt_{1-x}(RuO₂)_x/Co multilayers without H_x . A weak partial field-free switching response emerges at $x=0.12$. (b) AHE curves under different magnitudes and polarities of the test current. (c) The shift (ΔH_z^{eff}) at different bias currents (I) for Pt_{0.82}(RuO₂)_{0.18} without H_x .

Fig. 3a presents the current-induced magnetization switching curves of the Pt_{1-x}(RuO₂)_x/Co samples under zero external magnetic field. No discernible switching

is observed for $x < 0.12$, whereas a weak partial switching response emerges at $x = 0.12$, indicating the onset of field-free magnetization reversal. When the RuO_2 concentration is further increased to $x = 0.18$, the switching response becomes more pronounced and reaches approximately 50.45% of the full AHE signal. In a perpendicularly magnetized SOT system, deterministic switching in the absence of an external in-plane magnetic field requires an additional symmetry-breaking contribution. The concentration-dependent emergence of the zero-field switching therefore suggests that RuO_2 doping introduces a current-induced symmetry-breaking torque, which can be phenomenologically described as an out-of-plane effective field H_z^{eff} . This effective field assists magnetization reversal under zero applied field.

For the $x = 0.12$ sample, the magnitude of H_z^{eff} may be close to the threshold required for domain nucleation and propagation, resulting in only partial reversal. To examine whether such a current-induced out-of-plane effective field is present, AHE hysteresis loops were measured under different bias currents for the $x = 0.18$ sample, as shown in Fig. 3b. The AHE loops exhibit a systematic horizontal displacement when the magnitude of the bias current reaches 3 mA or above. Moreover, the direction of the loop shift reverses with the current polarity, demonstrating a out-of-plane effective field.

Fig. 3c summarizes the dependence of the effective field ΔH_z^{eff} on the applied current I for the sample with $x = 0.18$. Based on the loop shift magnitude, ΔH_z^{eff} is extracted using the formula $\Delta H_z^{\text{eff}} = H_{\text{shift}}(I^+) - H_{\text{shift}}(I^-)$.^{25,35} and $H_{\text{shift}}(I^\pm) = [|H_C^-(I^\pm)| - |H_C^+(I^\pm)|]/2$.^{25,36,37} At an applied current of ± 5 mA, the measured ΔH_z^{eff} is approximately 10 Oe. The notable variation of ΔH_z^{eff} under zero transverse magnetic field H_x , coupled with the occurrence of field-free SOT switching, constitutes compelling experimental evidence for the presence of z-polarized spin currents in the $\text{Pt}_{0.82}(\text{RuO}_2)_{0.18}$ multilayer heterostructure.³² Originating from the introduction of RuO_2 doping, this perpendicular effective field is consistent with conclusions reported in previous literature and enables current-driven switching of perpendicular magnetization without an external magnetic field.²⁵

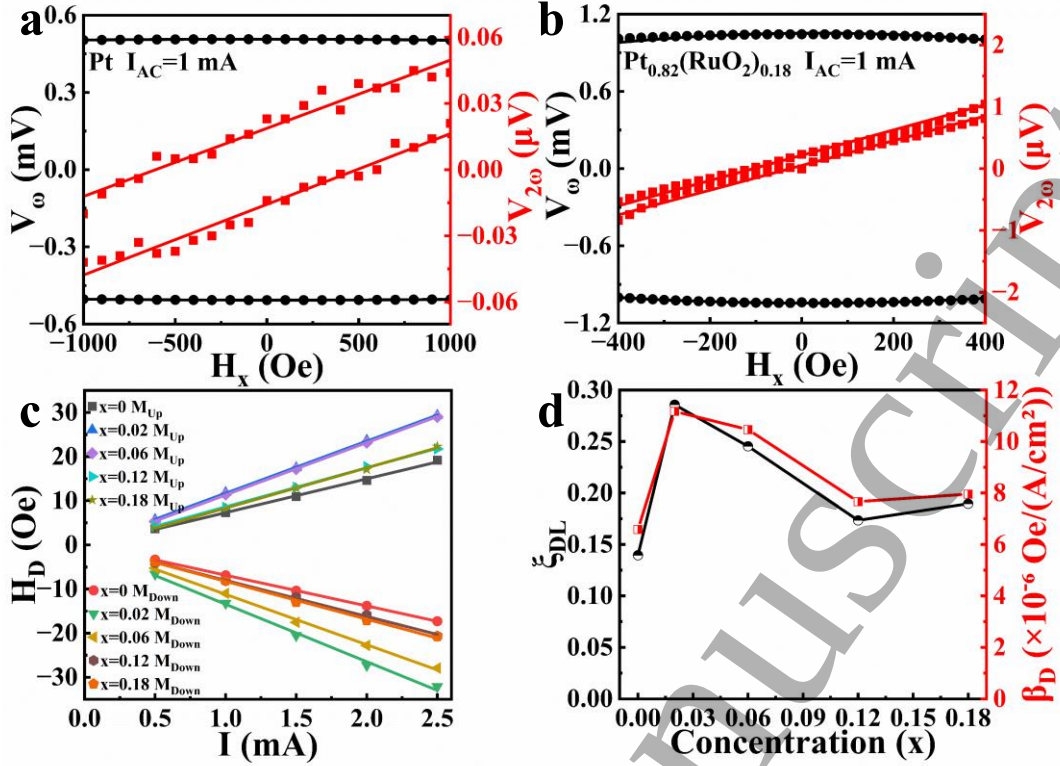


Figure 4. The Harmonic Hall voltages (V_w and V_{2w}) as a function of the applied magnetic field (H_x) for devices with RuO₂ doping concentration of (a) $x=0$ and (b) $x=0.18$. (c) Current dependence of H_D of the sample. (d) The trend of ξ_{DL} and β_D .

The harmonic Hall voltage measurement technique is used to investigate the damping-like torque. The specific experimental procedures are as follows: a magnetic field was applied along the x-direction, forming a small inclination angle with the film surface—this operation plays a crucial role in suppressing the formation of a multi-domain structure. Concurrently, an alternating current (AC) with a frequency of 133 Hz was injected along the x-direction. Using an OE1022D dual-channel lock-in amplifier, the first (V_w) and second harmonic signals (V_{2w}) were collected under different current and magnetic field conditions. Fig. 4a presents the variation of V_w and V_{2w} signals with the applied magnetic field H_x at an AC current of 1 mA. Based on the aforementioned experimental setup, the longitudinal effective field (H_L) induced by SOT can be extracted through quantitative analysis, with its calculation formula given below:^{38,39}

$$H_L = \frac{\partial V_{2w}}{\partial H_x} / \frac{\partial^2 V_w}{\partial H_x^2} \quad (1)$$

The current-induced damping-like effective field (H_D) can be derived from the following equation:

$$H_D = -2 \frac{H_L + 2\eta H_L}{1 - 4\eta^2} \quad (2)$$

where the parameter η denotes the ratio of the planar Hall resistance to the anomalous Hall resistance. In the Pt-based system, the magnitude of the planar Hall resistance is extremely small and are often neglected. On this basis, H_D can be simplified to the expression $-2H_L$.

Figs. 4a and 4b present the harmonic Hall measurement results of the samples with doping concentrations $x=0$ and $x=0.18$, respectively. The corresponding data for the samples with $x=0.02$, 0.06 , and 0.12 are provided in detail in Fig. S5. As illustrated in the Fig.4a and 4b, the V_w exhibits a quadratic dependence on the magnetic field, whereas the V_{2w} shows a linear relationship with the magnetic field. By fitting the experimental data using Equation (1), we extracted the variation of the H_D as a function of current, with the results depicted in Fig. 4c. The H_D displays a linear proportionality to the applied current, which verifies the reliability of the present measurement results, and the slope of the linear fitting line could be extracted.

In addition, the slope (β_D) and SOT efficiency (ξ_{DL}) for different doping concentrations x have been extracted, and are summarized in the Fig. 4d. The results demonstrate that β_D increases initially and then decreases with the increase of RuO_2 doping level, reaching a maximum at $x=0.02$. Notably, the β_D value of the device with $x=0.02$ reach to $11 \times 10^{-6} \text{ Oe}/(\text{A}/\text{cm}^2)$, which represents a 69.8% enhancement compared with that of the reference $\text{Ta}/\text{Pt}/\text{Co}/\text{Ta}$ structure. For the device with $x=0.18$, the β_D value is $7.96 \times 10^{-6} \text{ Oe}/(\text{A}/\text{cm}^2)$.

The SOT efficiency, denoted as ξ_{DL} , is also a critical metric for evaluating the performance of SOT devices, and it can be extracted using the following equation

$$\xi_{DL} = \frac{2e\beta_D M_s t_{Co}}{\hbar} \quad (3)$$

where e is the elementary charge, M_s is the saturation magnetization of Co, t_{Co} is the thickness of the Co layer, and $\hbar$ is the reduced Planck constant. Through quantitative calculation, the ξ_{DL} of the undoped sample is determined to be 0.139. The maximum value of ξ_{DL} (0.286) is achieved at a doping concentration of $x=0.02$, which is twice that of the undoped sample. The SOT efficiency basically follows the same variation trend with β_D . Subsequently, The ξ_{DL} gradually decreases as the doping concentration x increases. When $x = 0.18$, the measured value of the efficiency is 0.19. This value (0.19) is 1.367 times that of the undoped sample.

Table 1. Summary of ρ_{HM} , ξ_{DL} , J_c , VPD and J_c of field-free in previously reported materials.

	ρ_{HM} ($\mu\Omega \cdot \text{cm}$)	ξ_{DL}	H_x (Oe)	J_c ($10^6 \text{ A}/\text{cm}^2$)	VPD ($10^{11} \text{ mW}/\text{cm}^3$)	Field-free [J_c ($10^6 \text{ A}/\text{cm}^2$)]
Pt	27	0.14	5000	12.22	40.3	No
Pt_{0.82}(RuO₂)_{0.18}	76.4	0.19	650	5.5	23.1	Yes (11)
Pt _{0.6} (MgO) _{0.4} ⁴⁰	74	0.28	1500	11.5	97.9	No
Pt _{0.91} (VO ₂) _{0.09} ⁴¹	56.78	0.228	600	3	5.11	No
Pt _{0.75} Au _{0.25} ⁴²	79.89	0.351	50	5.52	24.34	No
Pt _{0.8} Cr _{0.2} ⁴³	82.8	0.31	500	12	119.28	No
Pt _{0.69} Cr _{0.31} ⁴⁴	132.8	0.56	2600	3.2	13.59	No
Pt _{0.57} Cu _{0.43} ⁴⁵	82.5	0.44	600	2.37	4.63	No

Pt _{0.7} Gd _{0.3} ⁴⁶	185	0.27	0	7.04	91.68	Yes (7.04)
Pt _{0.85} Hf _{0.15} ⁴⁷	110.1	0.16	No	No	No	No
Pt _{0.8} Mn _{0.2} ⁴⁸	101.07	0.254	2000	16.2	265.24	No
Pt _{0.25} Pd _{0.75} ⁴⁹	57.5	0.262	100	7.43	31.74	No
Pt _{0.8} V _{0.2} ⁴⁴	82.8	0.36	2600	5.29	23.18	No

The summary of ρ_{HM} , ξ_{DL} , J_c , volume power density (VPD) and J_c of field-free in previously reported literatures were extracted in Table 1. Compared with other Pt-based heterostructures, RuO₂-doped Pt not only enables field-free magnetization switching, but also exhibits excellent comprehensive performance in terms of resistivity, critical switching current density, and power consumption density.

4. Conclusion

In summary, we have demonstrated deterministic field-free spin-orbit torque switching of perpendicular magnetization in Ta/Pt_{1-x}(RuO₂)_x/Co/Ta multilayer films by engineering the Pt layer through RuO₂ doping. The introduction of RuO₂ preserves robust perpendicular magnetic anisotropy while simultaneously reducing coercivity and switching current density. More importantly, RuO₂ doping induces an intrinsic out-of-plane spin polarization, which generate an out-of-plane anti-damping torque, enables reliable field-free switching with J_c of 11×10^6 A/cm² without any external magnetic field. The critical switching current density is reduced to 5.5×10^6 A/cm² under $H_x=650$ Oe, and harmonic Hall measurements reveal a substantial enhancement of the SOT efficiency, with a maximum ξ_{DL} of 0.286. These findings highlight oxide-assisted spin Hall material engineering as an effective route to achieving low-current, field-free SOT switching and provide a promising platform for the development of scalable, energy-efficient spintronic devices.

Supplementary Material

See the supplementary material for the out-plane VSM measurement of hysteresis loops with Pt_{1-x}(RuO₂)_x/Co multilayer structures samples, the electrical resistivity (ρ_{HM}) of the Pt_{1-x}(RuO₂)_x films, current-induced magnetization switching tests of the sample Pt_{1-x}(RuO₂)_x/Co multilayers under in-plane magnetic field of 500 Oe and their switching current density.

Acknowledgment

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