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Achieving optimized spin-orbit torque efficiency and energy savings with $\text{Pt}_{1-x}(\text{VO}_2)_x/\text{Co}$ multilayer films

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ABSTRACT

Spin-orbit torque (SOT)-driven magnetization switching has demonstrated exceptional scalability, high-speed operation, and low-power characteristics in spintronic devices, making it a promising candidate for next-generation energy-efficient memory technologies, such as spin-orbit torque magnetic random-access memory (SOT-MRAM). Traditional Pt-based materials often enhance the SOT efficiency through alloying or doping, but these approaches typically involve trade-offs between power consumption and SOT performance. To address these limitations, this study proposes an innovative strategy by uniformly incorporating VO_2 into Pt, achieving dual optimization of SOT efficiency and electrical performance. The magnetization switching current density was reduced to $3 \times 10^6 \text{ A/cm}^2$, corresponding to a damping-like torque efficiency (ξ_{DL}) of 0.27, and the volume power density decreased to $5.1 \times 10^{11} \text{ mW cm}^{-3}$. The values are reduced by approximately nine-fold and 40-fold, respectively, compared to pure Pt. Thus, VO_2 -doped Pt provides a pathway for the design of low-power, high-efficiency SOT-MRAM devices.

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Spin-orbit torque (SOT)-driven magnetization switching has become a significant research focus in the fields of nonvolatile memory and spintronics, particularly in spin-orbit torque magnetic random-access memory (SOT-MRAM) and emerging spin logic devices.^{1,2} Compared to traditional spin-transfer torque (STT)-MRAM, SOT-MRAM offers superior scalability, high operation speed, and low power consumption, making it an attractive candidate for next-generation energy-efficient memory technologies.^{3,4} In SOT-MRAM, pure spin currents J_s are generated via mechanisms such as the spin Hall effect (SHE)^{5,6} and interfacial Rashba effect.^{7,8} Among them, heavy metals (HMs) like Pt, Ta, and W, due to their strong spin-orbit coupling (SOC), can efficiently convert in-plane charge currents into out-of-plane spin currents.^{9–11} These vertical spin currents exert spin-orbit torques on adjacent ferromagnetic layers, enabling magnetization switching. By carefully selecting the materials and engineering the interfaces, the strength of the generated spin currents can be boosted, leading to enhanced SOT-MRAM performance.

For Pt-based materials, various strategies have been developed to enhance the spin-orbit torque (SOT) efficiency. One common approach is alloying Pt with metals such as Au,¹² V,¹³ or Pd,¹⁴ which slightly increases the spin Hall angle while maintaining relatively low resistivity. Another method involves doping Pt with oxides like MgO ,¹⁵ GdO_x ,¹⁶ or TiO_2 ,¹⁷ which significantly enhances the spin Hall angle but at the expense of substantially increased resistivity. This severely limits their applicability in low-power, high-performance integrated systems, making the conductivity-SOT efficiency trade-off a critical challenge. Considering that VO_2 may exhibit a metallic phase when doped into Pt at room temperature, introducing VO_2 into Pt provides a strategy to enhance SOT performance. We have demonstrated that it could not only significantly enhance the spin-orbit torque efficiency but also maintain metallic-level conductivity, outperforming conventional doped Pt systems.

Here, by doping VO_2 in Pt, a switching current density (J_c) as low as $3 \times 10^6 \text{ A/cm}^2$, with a volume power density (P) of only

$5.1 \times 10^{11} \text{ mW cm}^{-3}$ has been achieved in $\text{Pt}_{0.91}(\text{VO}_2)_{0.09}/\text{Co}$ heterostructure. Compared to Pt/Co structures, the J_c was reduced by approximately nine-fold. At the same time, VO_2 doping significantly improved the spin Hall effect of Pt, achieving a damping-like torque efficiency (ξ_{DL}) of 0.27, which is attributed to the extrinsic side-jump effect associated with spin-orbit coupling, leading to a significant enhancement of ξ_{DL} . Furthermore, volume power density has decreased by approximately 40-fold. These findings provide a material design strategy for developing next-generation low-power, high-efficiency SOT-MRAM devices and demonstrate the broad application prospects of VO_2 -doped Pt in the field of spintronics.

The schematic of the multilayer film structure grown by an ultra-high vacuum (UHV)-sputter machine, is shown in Fig. 1(a), consisting of a 3 nm Ta buffer layer, a 4 nm $\text{Pt}_{1-x}(\text{VO}_2)_x$ SOT layer, a 1 nm Co magnetic layer, and a 2 nm Ta capping layer. Figure 1(b) shows the anomalous Hall effect (AHE) curves of the multilayer. The results exhibit good perpendicular magnetic anisotropy (PMA) for the VO_2 doping concentration (x) from 0 to 0.09, with coercivity (H_c) decreasing as x increases. The extracted H_c is shown in Fig. 1(c) (left axis), demonstrating a linear dependence on x within the PMA region. The saturation magnetization of the Co layer M_s^{Co} was determined to be $1007 \pm 17 \text{ emu/cm}^3$ (Fig. S1) by Vibrating Sample Magnetometer (VSM), consistent with previous reports.¹⁷ Figure 1(c) (right axis) illustrates the variation of the M_R/M_s ratio with x . When x is less than 0.09 (green region), the M_R/M_s ratio is close to 1, indicating that the samples exhibit PMA. When x exceeds 0.09 (blue region), the M_R/M_s ratio is close to 0, indicating a transition to in-plane magnetic anisotropy (IMA). Figure 1(d) presents the resistivities (ρ_{HM}) of the $\text{Pt}_{1-x}(\text{VO}_2)_x$ layer. In the range of 0–0.07, the resistivity gradually increases with increasing x . However, ρ_{HM} remains nearly constant at around $\sim 56.8 \mu\Omega\text{cm}$ within $x=0.07$ –0.11, which further reduces the power consumption of the device. We annealed $\text{Pt}_{1-x}(\text{VO}_2)_x$ films (various x) at 100–300 °C for 30 min. As shown in Fig. S2(a), the resistivity

trend after annealing remains consistent with that before annealing, and even conductivity improves due to annealing improved material quality. Furthermore, the SOT switching behavior of the device shows improvement after annealing at 300 °C [Fig. S2(b)], further confirming the $\text{Pt}_{1-x}(\text{VO}_2)_x$ films' thermal stability.

Figure 2(a) displays the interfaces and thicknesses of each layer by high-resolution transmission electron microscopy (HRTEM). Combined with the energy-dispersive x-ray spectroscopy (EDS) mapping results [Figs. 2(b)–2(f)], distinct layers corresponding to the 2 nm Ta capping layer, 1 nm Co magnetic layer, 4 nm $\text{Pt}_{0.91}(\text{VO}_2)_{0.09}$ SOT layer, and 3 nm Ta buffer layer can be identified, and they agree well with the designed specifications. The EDS images further demonstrate the distribution of Ta, Co, Pt, and V elements, indicating the precision and uniformity of the thin film fabrication process.

X-ray photoelectron spectroscopy (XPS) survey analysis (Fig. S3) reveals that the $\text{Pt}_{0.91}(\text{VO}_2)_{0.09}$ film primarily consists of Pt, V, and O elements in the 0–1100 eV range. Figure 2(g) provides a detailed view of the Pt 4f characteristic peaks in the film. The $4f_{7/2}$ and $4f_{5/2}$ peaks of Pt appear at 71.6 and 74.95 eV, respectively, which are very close to the theoretical value.¹⁸ Additional peaks at 72.23 and 75.6 eV correspond to the Pt^{2+} oxidation state. This suggests that during the co-sputtering process of Pt and VO_2 , the high-energy plasma may have facilitated the combination of oxygen from VO_2 with Pt, forming oxides such as PtO_x .¹⁹ Figure 2(h) further demonstrates the XPS spectra of V 2p and O 1s. The O 1s peaks, located at 532 and 530.25 eV, correspond to adsorbed water vapor on the sample surface and the oxygen in VO_x , respectively. The V 2p spectrum shows multiple oxidation states of vanadium, including the $2p_{1/2}$ orbital of V^{4+} , the $2p_{1/2}$ orbital of V^0 , the $2p_{3/2}$ orbital of V^{5+} , and the $2p_{3/2}$ orbital of V^{4+} at 523.7, 520.2, 517.5, and 515.9 eV, respectively.

Second harmonic analysis is a widely used method for studying spin-orbit torque. Based on the derivation of the Landau-Lifshitz-Gilbert (LLG) equation, the first harmonic amplitude (V_{10}) and second

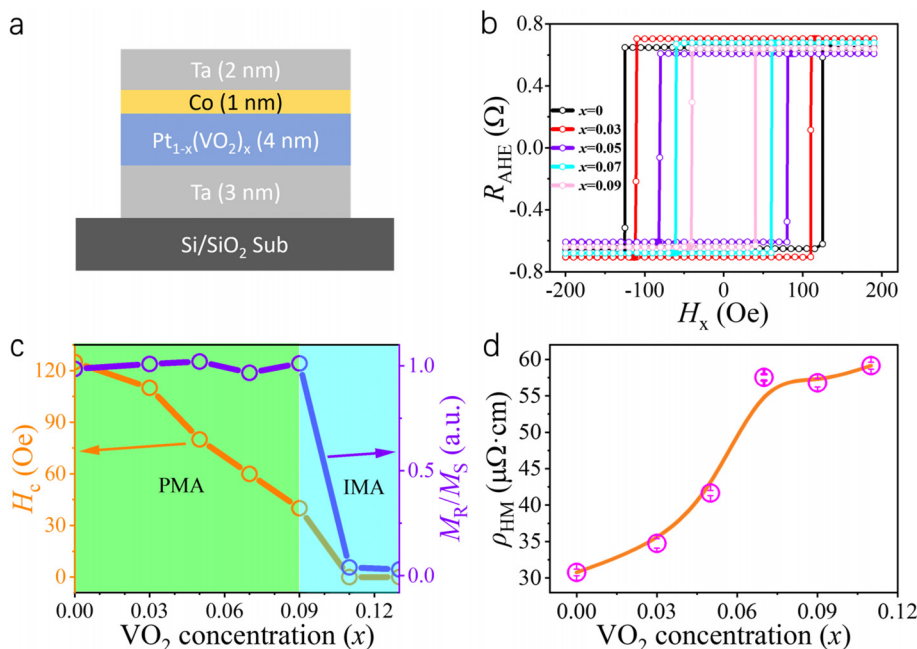


FIG. 1. (a) Schematic of the Ta (3 nm)/ $\text{Pt}_{1-x}(\text{VO}_2)_x$ (4 nm)/Co (1 nm)/Ta (2 nm) multilayer structure. (b) AHE curves of the multilayers, showing a decrease in H_c with increasing x . (c) H_c (left) and PMA window (right) as a function of x . The green-shaded region indicates PMA and blue-shaded region represents IMA. (d) ρ_{HM} increases as a function of x , reaching saturation beyond $x = 0.07$.

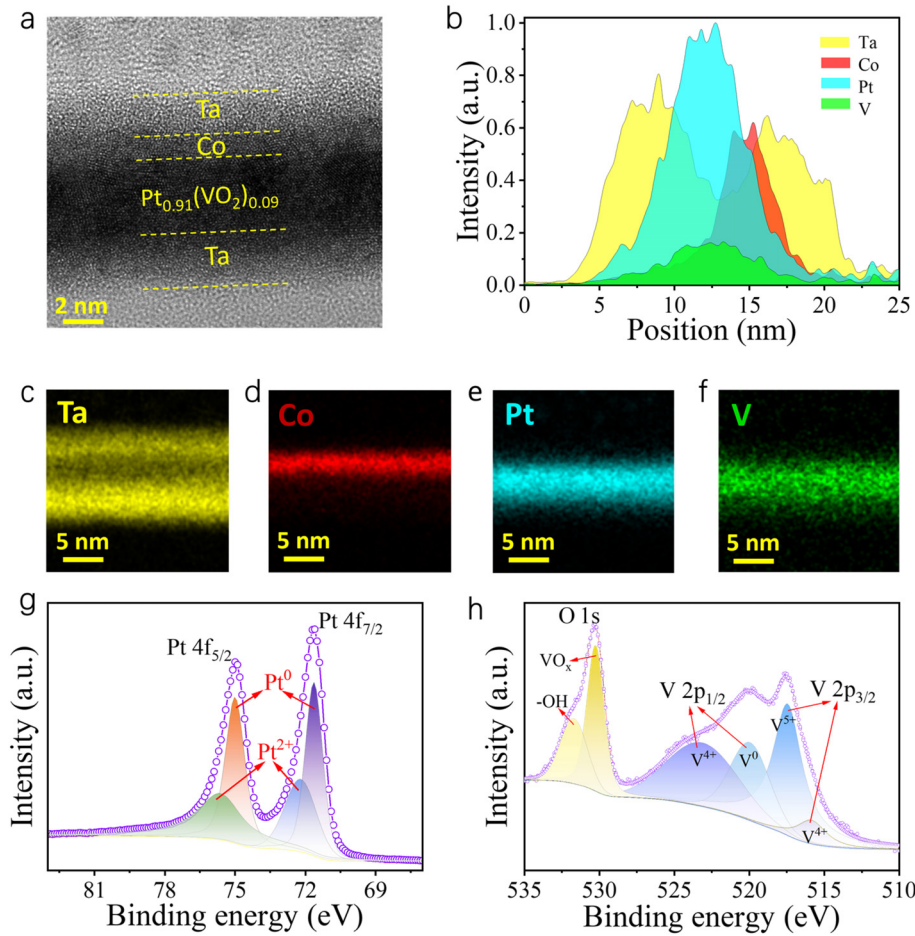


FIG. 2. (a) Cross-sectional HAADF-STEM image of the Ta/Pt_{0.91}(VO₂)_{0.09}/Co/Ta multilayer structure. (b) Atomic fraction and spatial distribution of Ta, Co, Pt, and V elements in the multilayer, determined via EDS line scan. EDS elemental maps of (c) Ta, (d) Co, (e) Pt, and (f) V in the multilayer. High-resolution XPS spectra of (g) Pt, (h) O, and V in the Pt_{0.91}(VO₂)_{0.09} film.

harmonic amplitude ($V_{2\omega}$) can be expressed as functions of the magnetic field strength,^{20,21}

$$B_x = \left(\frac{\partial V_{2\omega}}{\partial H_x} \right) / \left(\frac{\partial^2 V_{2\omega}}{\partial H_x^2} \right), \quad (1.1)$$

$$B_y = \left(\frac{\partial V_{2\omega}}{\partial H_y} \right) / \left(\frac{\partial^2 V_{2\omega}}{\partial H_y^2} \right), \quad (1.2)$$

where x and y represent the fixed magnetic field components along the x -axis and y -axis, respectively. Furthermore, the expressions for the damping-like term field (H_{DL}) and the field-like term field (H_{FL}) can be derived as follows:

$$H_{DL} = -2 \frac{(B_x \pm 2\zeta B_y)}{1 - 4\zeta^2}, \quad (1.3)$$

$$H_{FL} = -2 \frac{(B_y \pm 2\zeta B_x)}{1 - 4\zeta^2}, \quad (1.4)$$

where $\zeta = \frac{R_{PHE}}{R_{AHE}}$, R_{AHE} and R_{PHE} represent the anomalous Hall resistance and planar Hall resistance, respectively. Typically, the planar Hall resistance R_{PHE} is much smaller than the anomalous Hall

resistance R_{AHE} , and thus it is often neglected.²² Furthermore, the $V_{2\omega,x}$ and $V_{2\omega,y}$ correspond to the damping-like and field-like components of the spin-orbit interaction, respectively. The slope of $V_{2\omega,x}$ is significantly greater than that of $V_{2\omega,y}$, indicating that H_{FL} is negligible compared to H_{DL} (as shown in Fig. S4). Therefore, this study focuses solely on the damping-like SOT effectively.

Figures 3(a) and 3(b) present the harmonic Hall measurements for samples with $x=0$ and 0.07, while the corresponding data for $x=0.03$, 0.05, and 0.09 are provided in Fig. S5. As shown, $V_{1\omega}$ exhibits a quadratic dependence on the magnetic field, whereas $V_{2\omega}$ shows a linear relationship. By fitting the data using Eq. (1.3), H_{DL} was extracted as a function of current density, as depicted in Fig. 3(c). H_{DL} scales linearly with the applied current density and approaches zero when the current is turned off, confirming the reliability of the measurement. Furthermore, the effective field (β_{DL}) was extracted for various values of x , as summarized in the inset of Fig. 3(c). The results demonstrate a monotonic increase in the equivalent field with increasing VO₂ content, peaking at $x=0.07$. Notably, the Ta/Pt_{0.93}(VO₂)_{0.07}/Co/Ta device achieves a β_{DL} of 87.7 Oe (10^7 A/cm²), corresponding to a 60% enhancement compared to the reference Ta/Pt/Co/Ta structure.

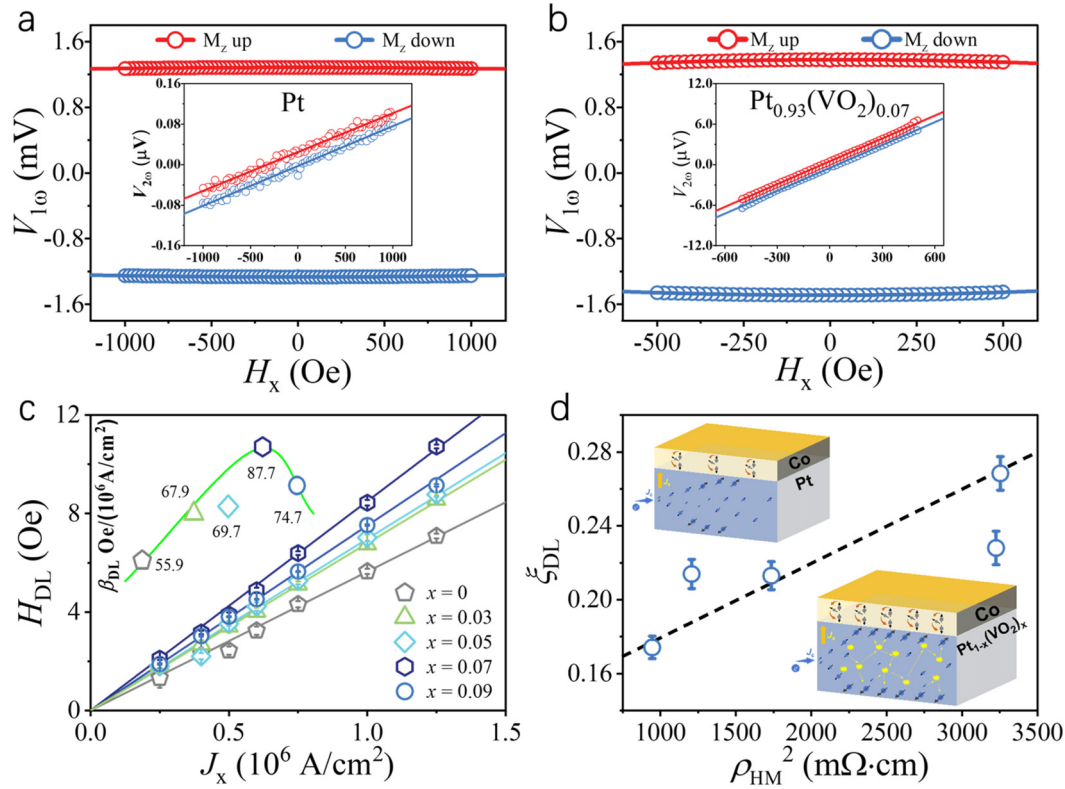


FIG. 3. ($V_{1\omega}$) and ($V_{2\omega}$, inset) curves as a function of the magnetic field for (a) Ta/Pt/Co/Ta and (b) Ta/Pt_{0.93}(VO₂)_{0.07}/Co/Ta. (c) H_{DL} as a function of applied current density at different values of x . Its slope reflects β_{DL} , and is shown in the inset. (d) Linear relationship between ξ_{DL} and ρ_{HM}^2 , suggesting the presence of the extrinsic side-jump scattering mechanism.

The heavy metal Pt, due to its strong spin-orbit coupling properties, has been widely studied as a typical material for the intrinsic spin Hall effect. In the conductivity range of 10^4 – $10^6 \Omega^{-1} \text{ cm}^{-1}$, numerous theoretical and experimental studies have shown that the intrinsic mechanism in Pt is the main contribution to the spin Hall effect.^{23–25} Furthermore, Long *et al.*²⁶ and Zimmermann *et al.*,²⁷ based on electronic structure and the Boltzmann equation, further studied skew scattering in Pt, Au, and Pd host systems containing Cr, Mn, Fe, Co, and Ni impurities. They found that the contribution of skew scattering to the spin Hall angle is only 1%. In our experiments, we extracted the relationship between the damping-like torque efficiency (ξ_{DL}) and ρ_{HM}^2 [as shown in Fig. 3(d)], revealing a clear linear correlation. This linear trend is primarily attributed to the extrinsic side-jump scattering mechanism.^{28,29} Specifically, during electron scattering with VO₂ impurities, spin-orbit coupling induces a transverse displacement of the electrons, known as a “side-jump,” which is spin-dependent. This transverse motion facilitates enhanced spin current injection into the magnetic free layer, thereby significantly improving the SOT efficiency [as illustrated in the inset of Fig. 3(d)]. Consequently, the co-contribution of both intrinsic and extrinsic mechanisms after VO₂ doping results in a high level of SOT efficiency in the material.

Figure 4(a) presents a schematic diagram of the SOT switching measurement setup. The switching curves of the Ta/Pt_{0.91}(VO₂)_{0.09}/Co/Ta multilayer under varying in-plane assist magnetic fields (H_x)

are shown in Fig. S6, while the corresponding dependence of switching current density (J_c) on the assist field is summarized in Fig. 4(b). The results reveal that J_c decreases with increasing H_x and exhibits a pronounced symmetric behavior with respect to $H_x = 0$, indicating reliable and stable magnetization switching under varying field conditions. Figures 4(c) and 4(d) present the switching curves for devices based on pure Pt and Pt_{0.91}(VO₂)_{0.09}, while the corresponding data for Pt_{0.97}(VO₂)_{0.03}, Pt_{0.95}(VO₂)_{0.05}, and Pt_{0.93}(VO₂)_{0.07} multilayers are provided in Fig. S7. All samples exhibit typical SOT switching characteristics, but the Pt_{0.91}(VO₂)_{0.09} device shows a notably lower switching current compared to the undoped Pt sample. To further elucidate the impact of VO₂ incorporation, the relationship between J_c and x was extracted and plotted in Fig. 4(e). J_c is found to decrease monotonically with increasing x , reaching a minimum of $3 \times 10^6 \text{ A/cm}^2$ at ($x = 0.09$). This trend further confirms that VO₂ doping enhances SOT efficiency and effectively reduces the power consumption of the device.

To further elucidate the underlying mechanism behind the significant reduction in switching current (I_c), we analyzed the effects of H_c and the parameter β_{DL} on I_c . Based on the domain wall depinning model, we obtain the following formula:^{30–32}

$$I_c = \frac{2e}{\hbar} \mu_0 M_s (t_{FM} - t_{dead}) \left(\frac{2}{\pi} \right) \left(\frac{H_c}{\xi_{DL}^j} \right). \quad (1.5)$$

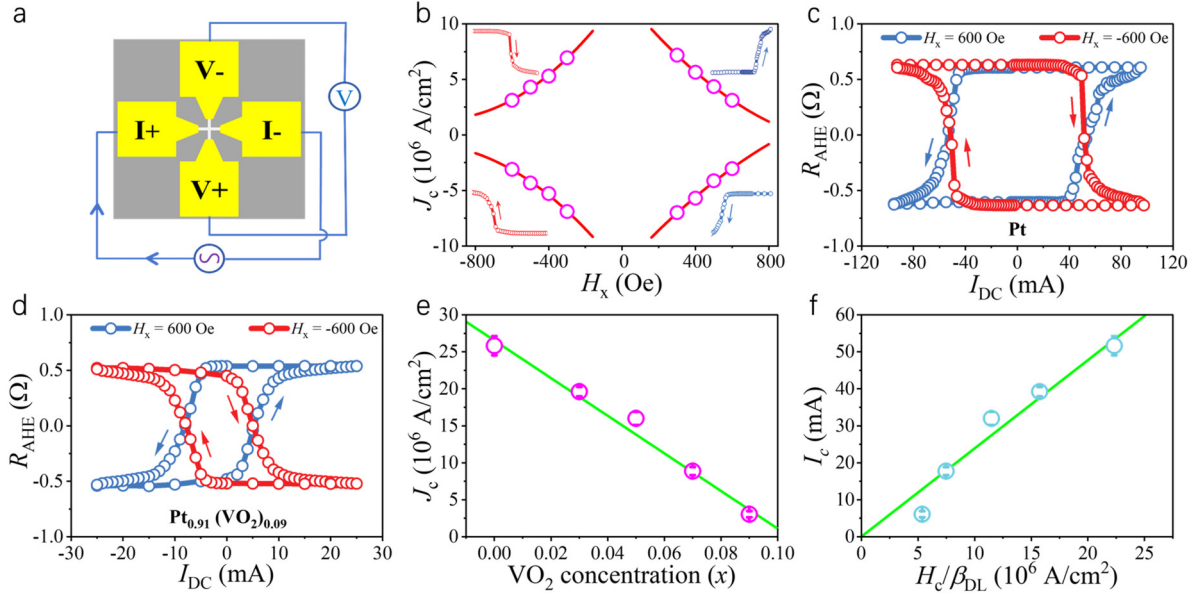


FIG. 4. (a) Schematic inset of the electrical transport measurement circuit. (b) Relationship between J_c and H_x for the Ta/Pt_{0.91}(VO₂)_{0.09}/Co/Ta sample, showing robust and stable switching behavior. Current-induced magnetization switching curves under an in-plane ± 600 Oe assist magnetic field for (c) Ta/PtCo/Ta, (d) Ta/Pt_{0.91}(VO₂)_{0.09}/Co/Ta. (e) J_c under a 600 Oe assist field shows a minimum at $x = 0.09$. (f) Linear relationship between I_c and H_c/β_{DL} . This means the reduction in I_c is due to both enhanced SOT efficiency and reduced H_c .

Here, $\zeta_{DL}^j = \frac{2eM_s t_{Co} \beta_{DL}}{\hbar}$, since the electron charge e , the vacuum permeability μ_0 , the saturation magnetization M_s , the free layer thickness t_{FM} , and π are all constants, it can be derived that

$$I_c \propto \frac{H_c}{\beta_{DL}}. \quad (1.6)$$

Figure 4(f) demonstrates the linear correlation between I_c and H_c/β_{DL} , validating the domain wall depinning model in our multilayer structure.^{22,33} This suggests that the reduction in I_c is not only due to the improvement in SOT efficiency but also due to the reduction in

H_c . These findings provide a theoretical foundations and regulatory means for optimizing the performance of spin-orbit torque devices.

ζ_{DL} is also a key metric for evaluating the performance of SOT devices. By analyzing the linear relationship between H_{DL} and J_c , ζ_{DL} can be calculated. The expression for ζ_{DL} can be written as^{32,34}

$$\zeta_{DL} = \frac{2eM_s t_{Co}}{\hbar} \frac{H_{DL}}{J_c}. \quad (1.7)$$

Here, e is the elementary charge, $\hbar$ is the reduced Planck constant, μ_0 is the vacuum permeability, M_s and t_{Co} represent the saturation

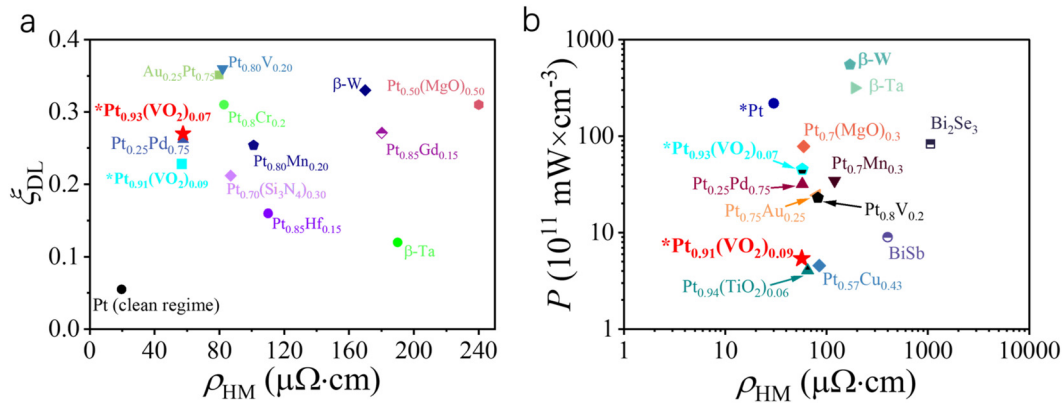


FIG. 5. (a) The relationship between ρ_{HM} and ζ_{DL} for commonly studied Pt-based heavy metal layers, such as Pt-clean regime,³⁵ Pt_{0.8}Cr_{0.2},³⁶ Pt_{0.85}Hf_{0.15},³⁷ Pt_{0.70}(Si₃N₄)_{0.30},³⁸ Pt_{0.25}Pd_{0.75},¹⁴ Pt_{0.80}Mn_{0.20},³⁹ Pt_{0.85}Gd_{0.15},⁴⁰ Pt_{0.50}(MgO)_{0.50},¹⁵ *Pt_{0.93}(VO₂)_{0.07}, *Pt_{0.91}(VO₂)_{0.09}, Pt_{0.80}V_{0.20},¹³ Au_{0.25}Pt_{0.75},¹² β -Ta,¹⁰ and β -W.¹¹ (b) The relationship between P at room temperature and ρ_{HM} for commonly used SOT materials, such as β -Ta,¹⁰ β -W,¹¹ *Pt, Pt_{0.57}Cu_{0.43},⁴¹ Pt_{0.75}Au_{0.25},¹² Pt_{0.7}Mn_{0.3},³⁹ Pt_{0.25}Pd_{0.75},¹⁴ *Pt_{0.93}(VO₂)_{0.07}, *Pt_{0.91}(VO₂)_{0.09}, Pt_{0.7}(MgO)_{0.3},¹⁵ BiSb,⁴² and Bi₂Se₃.⁴³ The asterisk symbols correspond to the results of this work.

magnetization and thickness of the Co layer, respectively, J_c is the switching current density, and H_{DL} is the effective field of the damping-like term.

In Pt-based doping studies, $\text{Pt}_{0.93}(\text{VO}_2)_{0.07}$ demonstrates a high ξ_{DL} of 0.27 and shows a low resistivity of $56.8 \mu\Omega \text{ cm}$, exhibiting better overall performance compared to most Pt-based doping systems, such as those doped with Mn, V, Gd, and Hf [Fig. 5(a)]. The high SOT efficiency arises from the co-contribution of intrinsic and extrinsic effects induced by VO_2 doping. Furthermore, we further estimated the volume power density (P) of the device using the formula $P = \rho_{HM} J_c^2$ and compared it with other common Pt-based doping materials [Fig. 5(b)]. The results show that the P of $\text{Pt}_{0.91}(\text{VO}_2)_{0.09}$ is as low as $5.1 \times 10^{11} \text{ mW cm}^{-3}$, placing it at an excellent level among common Pt-based doping materials. The results show that VO_2 doping effectively lowers the switching current density while maintaining a relatively low resistivity. The values of ρ_{HM} , ξ_{DL} , J_c , and P for a wider range of previously reported materials are summarized in Table S1.

In summary, this study utilizes ultra-high vacuum (UHV) sputtering system to fabricate the Ta (3 nm)/ $\text{Pt}_{1-x}(\text{VO}_2)_x$ (4 nm)/Co (1 nm)/Ta (2 nm) multilayer structure and achieves dual optimization of the spin-orbit torque (SOT) efficiency and electrical performance. Through harmonic Hall voltage analysis and current-induced magnetization switching measurements, VO_2 -doped Pt demonstrates significant enhancement of the spin Hall effect, with a high damping-like torque efficiency ($\xi_{DL} = 0.27$), which is a noticeable improvement compared to pure Pt. At the same time, the switching current density of $\text{Pt}_{0.91}(\text{VO}_2)_{0.09}/\text{Co}$ has been lowered to $3 \times 10^6 \text{ A/cm}^2$, approximately ninefold lower than the Pt/Co structure, with a low resistivity ($\sim 56.8 \mu\Omega \text{ cm}$). Furthermore, the volume power density decreases significantly to $5.1 \times 10^{11} \text{ mW cm}^{-3}$, which is approximately 40-fold lower than that of pure Pt, with the overall performance surpassing most spin Hall materials. These results demonstrate that VO_2 doping in Pt not only optimizes the SOT efficiency but also effectively reduces power consumption, underscoring its potential for low-power, high-efficiency SOT-MRAM applications.

See the [supplementary material](#) for experimental details regarding VSM characterization and thermal stability of Ta/ $\text{Pt}_{1-x}(\text{VO}_2)_x/\text{Co}$ /Ta multilayers, XPS analysis of the $\text{Pt}_{0.91}(\text{VO}_2)_{0.09}$ film, harmonic Hall voltage measurements, SOT switching loops under various in-plane assist fields, and a comparative summary of spin-orbit torque parameters in previously reported materials.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Caitao Li: Writing – original draft (equal); Writing – review & editing (equal). **Shuanghai Wang:** Supervision (equal); Validation (equal);

Writing – review & editing (equal). **Kun He:** Supervision (equal); Validation (equal). **Yongkang Xu:** Supervision (equal); Validation (equal). **Taikun Wang:** Supervision (equal); Validation (equal). **Yu Liu:** Supervision (equal); Validation (equal). **Xingze Dai:** Supervision (equal); Validation (equal). **Yao Li:** Supervision (equal); Validation (equal). **Jun Du:** Supervision (equal); Validation (equal). **Yonglei Wang:** Supervision (equal); Validation (equal). **Yongbing Xu:** Funding acquisition (equal); Resources (equal); Supervision (equal); Validation (equal). **Liang He:** Funding acquisition (equal); Resources (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article and its [supplementary material](#).

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