

## Lower switching-current density in Ta/(Pt/X)<sub>n</sub>/Pt/Co/Ta (X = Ta, Mn, Cu, V, Zr, Bi; n = 3, 4) multilayers based on a domain-wall-depinning model

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In recent years, spin-orbit torque (SOT) generated by heavy metal (HM) has garnered increasing attention. However, SOT-magnetic random-access memory based on HM suffers from a low spin Hall angle and high current density. Here, we demonstrate that the critical switching-current density ( $I_c$ ) in a multilayer structure of Ta/(Pt/Ta)<sub>4</sub>/Pt/Co/Ta has been reduced by 79% compared with that of Ta/Pt/Co/Ta, achieving a value of  $5.88 \times 10^6$  A/cm<sup>2</sup>. This value is considerably low among all reported values in the Pt/Co system literature. The reduction of  $I_c$  is accompanied by enhanced dampinglike torque efficiency ( $\beta_D$ ) and reduced coercive force ( $H_c$ ). A perfect linear correlation has been observed between  $I_c$  and  $H_c/\beta_D$ , which supports the domain-wall depinning model of the SOT-induced magnetization reversal in this system. Crucially, this linearity extends to several metal dopants possessing the identical superlattice structure. This research offers insights into the future of low-power, high-density magnetic memory technology based on HM materials.

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Spintronic devices that utilize spin-orbit torque (SOT) not only enhance our comprehension of fundamental physics but also provide an effective solution for data writing in magnetic memories and logic computing technologies [1–6]. In the multilayer structure composed of HM and ferromagnetic (FM) layers, the spin-orbit coupling (SOC) of HM generates a transverse spin current as the electron current passes through it. When the spin current is large enough, it interacts with the magnetic moment of the FM layer, resulting in aligning the magnetic moment with the spin direction of the electrons [7–11].

Currently, the application of SOT-based storage devices faces two primary challenges. Firstly, deterministic switching requires the breaking of symmetry, which has been achieved through the application of an external magnetic field [12–14], exchange bias [15,16], crystal structure asymmetry [17,18], tilted anisotropy [19,20], wedge-shaped growth of heavy metals [21,22], and tilted

annealing [23], etc. Secondly,  $I_c$  is excessively high. To reduce  $I_c$ , attention has been focused on enhancing  $\beta_D$ , which involves the utilization of topological materials with very strong SOC, such as Bi<sub>2</sub>Se<sub>3</sub> [24] and Bi<sub>0.9</sub>Sb<sub>0.1</sub> [25], as well as doping impurities into the heavy metal layer, including MgO [26], TiO<sub>2</sub> [27], Nb [28], and Hf [29], etc. On the other hand,  $H_c$  also exhibits a positive correlation with  $I_c$  based on the domain-wall depinning model [30–32], while this remains largely unexplored.

In this study, multilayer structures of Ta/(Pt<sup>1</sup>/Ta)<sub>n</sub>/Pt<sup>2</sup>/Co/Ta were grown by sputtering. It was found that the  $I_c$  of the sample with the superlattice buffer layer was significantly reduced through the anomalous Hall effect (AHE) and SOT switching measurements. The reduction in  $I_c$  mainly stems from two factors. Firstly, the increase in  $\beta_D$  is a result of the interfacial scattering introduced by the ultrathin metal interlayer [28,29]. Secondly,  $H_c$  has been reduced due to the decrease of the interfacial roughness by the superlattice buffer layer. Furthermore, it was discovered that  $I_c$  scales with  $H_c/\beta_D$  linearly. Most importantly, this linear relationship can be applied to many other metal dopants with the same superlattice structure.

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TABLE I. Thicknesses of each layer corresponding to different periods.

Sample name	A0	A1	A2	A3	A4	A5
Period ( $n$ )	N/A	1	2	3	4	5
Thickness of Pt <sup>2</sup> (nm)	4	1.9	1.2	0.85	0.64	0.5
Thickness of Ta (nm)	0	0.2 × 1	0.2 × 2	0.2 × 3	0.2 × 4	0.2 × 5
Thickness of Pt <sup>1</sup> (nm)	0	1.9 × 1	1.2 × 2	0.85 × 3	0.64 × 4	0.5 × 5

The multilayers of Ta/(Pt<sup>1</sup>/Ta)<sub>*n*</sub>/Pt<sup>2</sup>/Co/Ta were deposited on Si/SiO<sub>2</sub> substrates by magnetron sputtering with a base pressure of  $3 \times 10^{-7}$  Torr. The Ta layers at the bottom served as adhesion layers, while the superlattice buffer layers were responsible for generating spin current and imparting perpendicular magnetic anisotropy. The top Ta layer functioned as a protective cover, preventing the oxidation of the films. The diameters of all the targets are 50.8 mm. The purity of Ta target is 99.95%, while Pt and Co are 99.99%. The sputtering gas used is 99.999% Ar for all the materials. For material deposition, the pressure is kept at 6 mTorr and the dc power remains at 10 W. The deposition rates are 0.16 Å/s, 0.2 Å/s, and 0.14 Å/s for Ta, Pt, and Co layers, respectively. During deposition, the substrates were kept at room temperature.

The as-grown samples are shown in Table I with the specific names and thicknesses of each layer. The structure of the Sample A-series is illustrated in Fig. 1(a). The control samples of B-series, i.e., Ta<sub>3</sub>/(Pt<sub>*x*</sub>:Ta<sub>0.2</sub>)<sub>*n*</sub>/Pt<sub>*x*</sub>/Co<sub>1</sub>/Ta<sub>2</sub>,

and C, i.e., Ta<sub>3</sub>/Pt<sub>3.16</sub>/Ta<sub>0.2</sub>/Pt<sub>0.64</sub>/Co<sub>1</sub>/Ta<sub>2</sub>, are also discussed in this article. Sample A0 is the basic structure with a single Pt buffer layer, and samples A1–A4 have the superlattice buffer layer of (Pt<sup>1</sup>/Ta)<sub>*n*</sub>/Pt<sup>2</sup>. Notably, the total thickness of (Pt<sup>1</sup>/Ta)<sub>*n*</sub>/Pt<sup>2</sup> was maintained constant at 4 nm throughout our experiments. The magnetization-hysteresis (M–H) and AHE loops indicate that all the samples (A0–A4) exhibit good perpendicular magnetic anisotropy, as shown in Figs. 1(b) and 1(c). On the other hand, sample A5 ( $n=5$ ) in Fig. S1 in the Supplementary Material [33] demonstrates in-plane magnetic anisotropy.

The quantity  $H_c$  for all the samples was extracted from M–H and AHE loops. Within the margin of error, they are nearly identical, decreasing from 150 Oe to 57 Oe as the period increased from 0 to 4, as shown in Fig. 1(d). The quantity  $H_c$  is reduced by 62%; this can be attributed to the improved interfacial roughness of the buffer layer, as shown in Fig. S2 in the Supplementary Material [33]. It is found that the roughness decreases from 1.69 nm to 0.57 nm as  $n$  increases. The roughness is directly proportional to the number of pinning sites meaning that, as the roughness increases, so does the abundance of pinning sites, which subsequently hinders domain-wall motion, ultimately resulting in enhanced coercivity [34].

After deposition, the samples were fabricated into a cross-bar device [Fig. 2(a) inset] using standard photolithography and ion beam etching processes. The width of the current channel is 20 μm. Figure 2(a) presents the SOT switching loops of samples A0 and A4 under the applied magnetic fields of ±1000 Oe. Compared with  $\Delta R$  of AHE [Fig. 1(c)], the two samples show

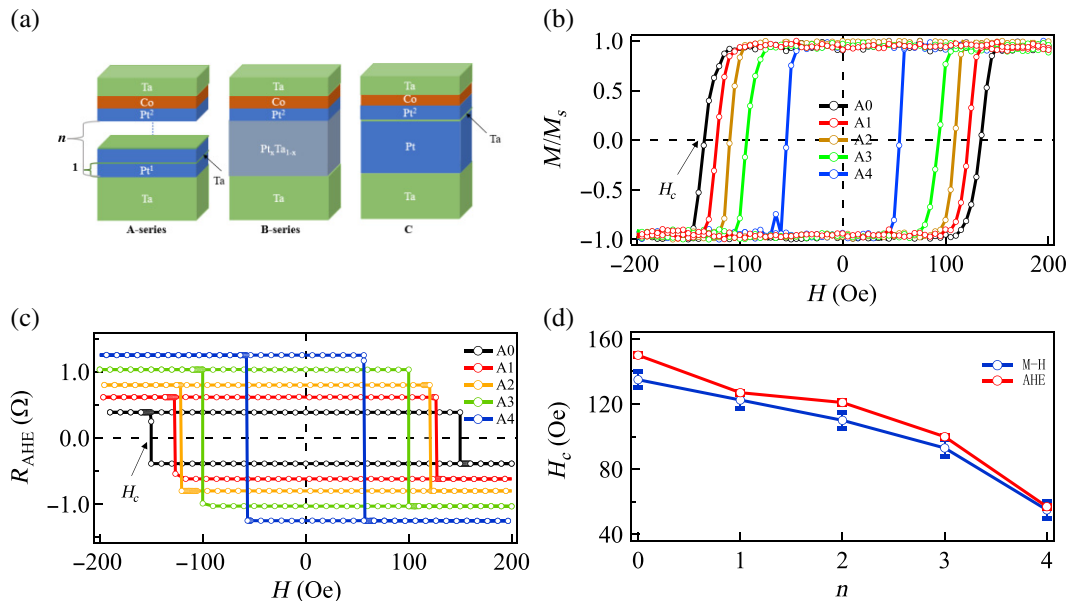


FIG. 1. (a) Structure of sample A-series, B-series, and C. (b) Normalized M–H loops and (c) AHE loops of Samples A0–A4 demonstrate out-of-plane easy axes. (d) The quantity  $H_c$  is extracted from M–H and AHE loops as a function of the period.

a complete switching ratio close to 100%. The quantity  $I_c$  of A4 is significantly reduced by 79% compared with that of A0, achieving a value of  $5.88 \times 10^6$  A/cm<sup>2</sup>. The quantity  $I_c$  value is relatively lower compared with  $1.15 \times 10^7$  A/cm<sup>2</sup> for Pt<sub>0.7</sub>(MgO)<sub>0.3</sub> at 1500 Oe [26],  $1.4 \times 10^7$  A/cm<sup>2</sup> for (Pt/Nb)<sub>7</sub> at 1000 Oe [28], and  $1.7 \times 10^7$  A/cm<sup>2</sup> for [Pt/Hf]<sub>5</sub> at 3000 Oe [29]. Fig. 2(b) demonstrates the switching loops of sample A4 under different in-plane fields  $H_x$ , parallel to the current. The SOT switching loops act in a counterclockwise direction under a positive magnetic field and a clockwise direction under a negative magnetic field. Figure 2(c) exhibits the switching phase diagram of A4. The quantity  $I_c$  of A4 decreases with an increase in the external magnetic field, which is consistent with previously reported results [35,36].

To investigate the dampinglike torque (DLT) of the spin current induced by SOT, a second harmonic method was adopted, as shown in Fig. S3 in the Supplementary Material [33]. The magnetic field is applied along the  $x$ -direction, with a small inclination angle ( $\varphi_H$ ) with respect to the film surface used to prevent the formation of multiple domains. An ac with a frequency of 133 Hz is applied along the  $x$ -direction. Simultaneously, the first ( $V_\omega$ ) and secondary ( $V_{2\omega}$ ) harmonic signals are acquired through a dual-channel lock-in amplifier of OE1022D. Figures 3(a) and 3(b) show  $V_\omega$  and  $V_{2\omega}$  as a function of magnetic field  $H_x$  (with an ac of 1 mA) for samples A0 and A4, respectively. The longitudinal effective field ( $H_L$ ) induced by SOT can be quantitatively extracted using the following

formula [37,38]:

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

The dampinglike effective field ( $H_D$ ) generated by the current can be acquired by the following formula [39]:

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

where  $\xi$  is the ratio of planar Hall resistance to anomalous Hall resistance. In the Pt/Co system, planar Hall values are very small and are often neglected [23]. Thus,  $H_D$  can be simplified as  $-2H_L$ . The extracted  $H_D$  vs  $I_{ac}$  plots are shown in Fig. 3(c) for all the samples. All of them exhibit a linear dependence on the applied current. Moreover, the slopes ( $\beta_D$ ) increase from  $6.9 \times 10^{-6}$  Oe/(A/cm<sup>2</sup>) to  $8.9 \times 10^{-6}$  Oe/(A/cm<sup>2</sup>), as the period increases from 0 to 4, as shown in Fig. 3(d).

To justify the dramatic decrease of  $I_c$  due to the superlattice buffer layer, control samples of B-series and C have been prepared. First, the B-series of samples, specifically Ta<sub>3</sub>/(Pt <sub>$x$</sub> :Ta<sub>0.2</sub>) <sub>$n$</sub> /Pt <sub>$x$</sub> /Co<sub>1</sub>/Ta<sub>2</sub>, has been grown through cosputtering of Pt and Ta, utilizing atomic ratios of 0.84:0.16 and 0.79:0.21 for the superlattice buffer layers, respectively, corresponding to samples A3 and A4. This structure is represented in Fig. 1(a). As shown in Figs. S5(a)–S5(d) in the Supplementary Material [33], the switching current of the samples at 1000 Oe were

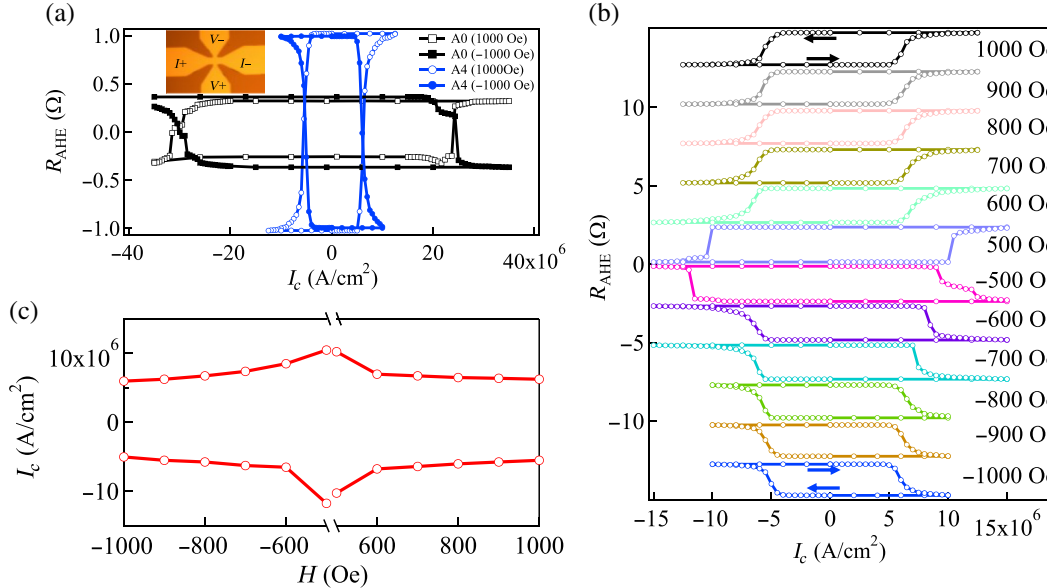


FIG. 2. Magnetic and SOT properties for the A0 and A4. (a) Current-induced magnetization switching in the A0 and A4 under an in-plane magnetic field of  $H_x = \pm 1000$  Oe. (b) Current-induced magnetization switching in A4 is observed under various in-plane magnetic fields  $H_x$  ranging from  $-1000$  Oe to  $1000$  Oe. (c) Switching phase diagram of A4. The quantity  $I_c$  decreases as the applied magnetic field increases.

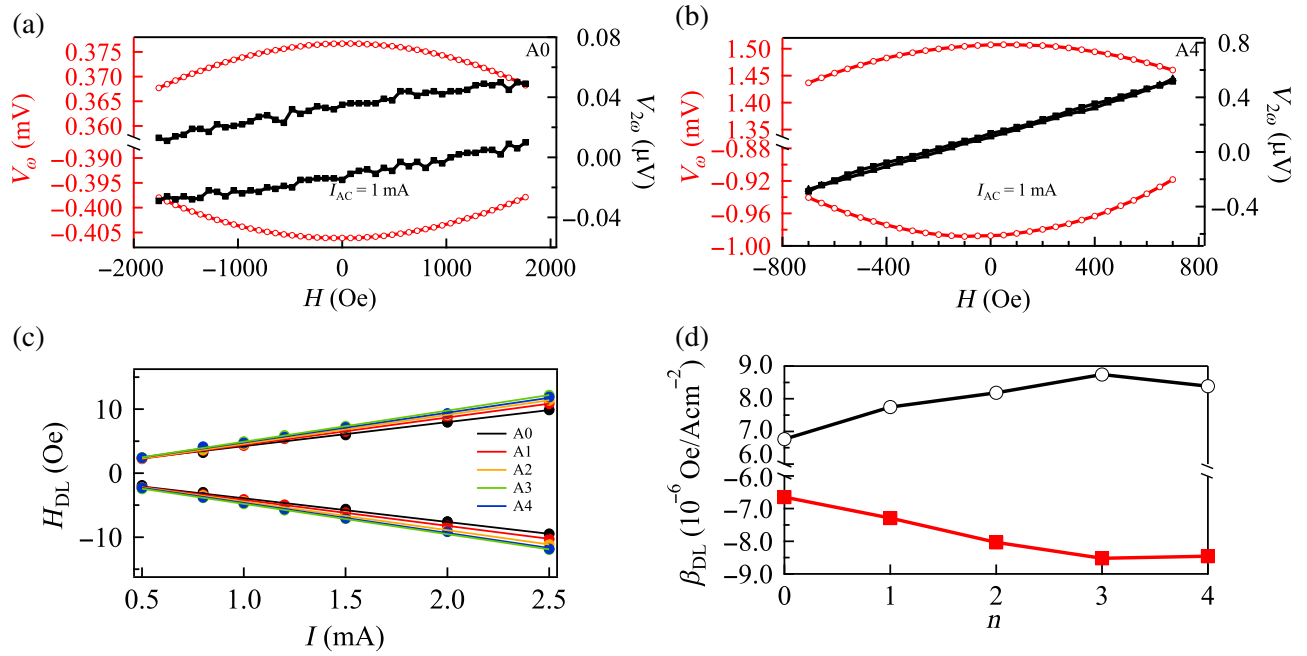


FIG. 3. Harmonic Hall measurements of the Hall-bar devices. The  $V_\omega$  and  $V_{2\omega}$  harmonic Hall voltages as a function of magnetic field  $H_x$  for (a) A0 and (b) A4. (c) Current dependence of  $H_D$  of A0–A4. (d) Variation of the dampinglike efficiency with different  $n$ .

$2.05 \times 10^7$  and  $1.33 \times 10^7$  A/cm<sup>2</sup>, much higher than that of A3 and A4, respectively. Second, Fig. 1(a) shows a sample C of Ta<sub>3</sub>/Pt<sub>3.16</sub>/Ta<sub>0.2</sub>/Pt<sub>0.64</sub>/Co<sub>1</sub>/Ta<sub>2</sub> that has been deposited to demonstrate the effect of a Ta interlayer. The insertion of 0.2-nm Ta near Co resulted in a decrease in  $I_c$  of 20.4% for sample A0, which was still significantly lower than the previous value of 79%, as shown in Figs. S5(e) and S5(f) in the Supplementary Material [33]. Thus, the superlattice buffer layer is the main reason for reducing  $I_c$ .

In order to further clarify the underlying mechanism of the significant reduction of  $I_c$ , we here analyze the effects of  $H_c$  and  $\beta_D$  on  $I_c$ . Based on the domain-wall depinning

model, we find [31,40–42]

$$I_c = \frac{2e}{\hbar} \mu_0 M_s (t_{\text{FM}} - t_{\text{dead}}) \left( \frac{2}{\pi} \right) \left( \frac{H_c}{\beta_D} \right).$$

In our samples,  $e$ ,  $\hbar$ ,  $\mu_0$ ,  $M_s$ ,  $t_{\text{FM}}$ , and  $\pi$  are all constants; thus, we have  $I_c \propto H_c/\beta_D$ . Here, the coercivity ( $H_c$ ) constitutes a pivotal component of the switching barrier, which is directly proportional to the difficulty of domain nucleation; hence, an increase in  $H_c$  corresponds to a heightened challenge to initiate domain nucleation. Furthermore, the parameter  $\beta_D$  exhibits a positive correlation with domain-wall propagation, suggesting that a higher  $\beta_D$

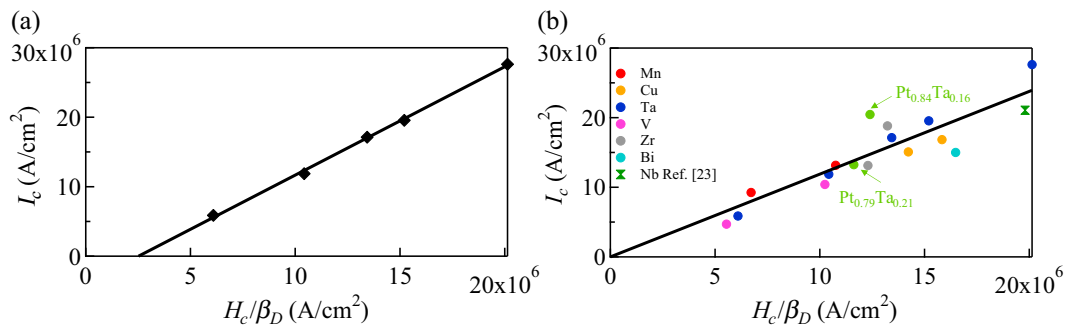


FIG. 4. (a) Relationship between  $I_c$  and  $H_c/\beta_D$  for sample A-series. (b) The  $I_c$  versus  $H_c/\beta_D$  relationship for various metal inserts, including Ta, Zr, Mn, V, Cu, Bi, and cosputtered Pt<sub>x</sub>Ta<sub>1-x</sub>, exhibiting linear trends.

value translates to a more rapid propagation rate. Consequently, the ratio  $H_c/\beta_D$  effectively represents the balance between domain nucleation and domain-wall propagation.

A plot of  $I_c$  vs  $H_c/\beta_D$  is shown in Fig. 4(a). A perfect linear correlation is seen in Fig. 4(a), with all the points located on a straight line. To further corroborate this relationship, more samples with a  $(\text{Pt}/\text{X})_n$  superlattice buffer layer ( $X = \text{Mn}, \text{Cu}, \text{V}, \text{Zr}, \text{and Bi}, n = 3 \text{ or } 4$ ) have been prepared. The quantities  $I_c$ ,  $\beta_D$ , and  $H_c$  were extracted from the AHE and SOT measurements, as shown in Fig. S4 in the Supplementary Material [33]. Figure 4(b) exhibits the same linear relationship between  $I_c$  and  $H_c/\beta_D$  for all the samples, including data from ref. [23]. This provides strong evidence of the validation of the domain-wall depinning model with the linear relationship between  $I_c$  and  $H_c/\beta_D$ .

In summary, by utilizing the superlattice buffer layer,  $I_c$  has been reduced by 79% compared with a pure Pt buffer layer. The reduction in  $I_c$  can be attributed to the increase in  $\beta_D$  due to the interface scattering and the reduction in  $H_c$  because of the decrease in the roughness of the Pt/Co interface. Moreover,  $I_c$  has been found to scale with  $H_c/\beta_D$  linearly, conforming to the domain-wall depinning mechanism. Most importantly, samples with the same superlattice buffer layer structure using different metal layers follow the same trend. Our findings point out an effective way to reduce the critical switching current by increasing  $\beta_D$  and/or decreasing  $H_c$ . This approach exhibits considerable potential in practical applications for SOT-based spintronic devices.

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

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