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Spin-orbit torques and magnetization switching in Ta/Pt/Co₂FeAl/Pt/Ta multilayer structures based on Heusler magnetic alloy

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Spin-orbit torque (SOT) in heavy metal and ferromagnetic metal heterostructures (HM/FM) has attracted growing attention. The FMs in most studies are conventional Co, Fe, Ni or their alloys of CoFeB, NiFe, CoFe. However, SOT studies based on HM and half-metallic ferromagnets, such as Co₂FeAl, have been relatively less explored. In this study, a Ta/Pt/Co₂FeAl(CFA)/Pt/Ta multilayered structure was fabricated via sputtering. The perpendicular magnetic anisotropy (PMA) was successfully realized within the multilayer film structure without annealing. Concurrently, SOT-induced magnetization switching was also achieved, with a critical switching current density (J_c) of 7×10^6 A/cm² under 100 Oe. Repeatability and stability tests under multiple magnetic fields showed the sample's stability over 10000 consecutive switching operations. The sample's performance in such aspects makes the Ta/Pt/CFA/Pt/Ta system a promising candidate for future SOT spintronic devices.

Keywords: SOTs; multilayered structure; spintronics; repeatability

PACS:31.15.aj;75.47.-m;81.15.Cd;07.68.+m;

1. Introduction

In the domain of spintronics, conventional magnetization switching via spin transfer torque (STT) has been widely studied for memory and logic devices due to its non-volatility.^{1,2} However, STT typically requires extremely high current densities ($>10^7$ A/cm²), leading to significant energy consumption and thermal challenges, which limits its practical applications.^{3,4} As an alternative, the manipulation of magnetization switching by spin-orbit torque (SOT) in nanoscale thin films holds greater promise for

future low-power devices, owing to its ability to achieve efficient switching at reduced current densities (10^6 – 10^7 A/cm²).^{5–8} SOTs, stemming from the spin Hall effect (SHE) and/or the Rashba-Edelstein effect, have been widely applied in magnetization manipulation, oscillation, domain wall and skyrmion motion, presenting significant potential in spintronic device applications.^{9–12} SOTs have been explored in various heavy metal (HM)/ferromagnetic metal (FM) bilayers.^{13–15} These systems have demonstrated efficient magnetization switching and low critical current density, making them attractive for practical applications.^{16,17} On the other hand, compared to Co₂₀Fe₆₀B₂₀, Co-based and Fe-based Heusler alloys possess advantageous characteristics such as half-metallicity, ultra-low damping, appropriate saturation magnetic moment, high Curie temperature, good substrate compatibility, and low coercive force.^{18–20} Despite these advantages, research on SOT based on CFA-composed multilayer films remains relatively scarce, leaving a gap in understanding their full potential.^{21–24}

Recent advances in spin-orbit torque research have focused on both efficiency optimization and field-free operation. One effective strategy involves tailored heavy-metal combinations with opposite spin Hall angles (e.g., Pt/Ta bilayers), which enhance spin current generation and provide an effective symmetry-breaking field.²⁵ In addition, orbital-current-related mechanisms, together with interface engineering, have been proposed to enhance torque efficiency, particularly the field-like component.²⁶ Furthermore, intrinsic field-free switching has been demonstrated in non-collinear antiferromagnets such as Mn₃Sn owing to their unique magnetic symmetry.²⁷ Emerging materials, including topological insulators (e.g., BiSb), have also shown exceptionally high spin-charge conversion efficiency.²⁸

In this study, we have fabricated a Ta/Pt/CFA/Pt/Ta multilayered structure via sputtering, aiming to explore its potential for efficient magnetization switching. This system is chosen for material synergies: Ta and Pt (strong spin-orbit coupling) boost SOT generation,¹⁵ while CFA (a Co-based Heusler alloy) offers superior half-metallicity, ultra-low damping, and thermal stability compared to conventional ferromagnets/half-metals.^{18–20} First, the perpendicular magnetic anisotropy (PMA) was realized in the multilayered structure, which is crucial for high-density memory applications. Second, SOT switching was successfully achieved in the CFA-based multilayer films. The J_c reached a value of 7×10^6 A/cm² with the assistance of a 100 Oe in-plane magnetic field. Furthermore, repetitive and stability tests under multiple magnetic fields demonstrated that the sample remained stable after 10000 consecutive switching operations, highlighting its robustness and reliability for practical applications.

2. Experimental

The Ta/Pt/CFA/Pt/Ta multilayers were deposited on the Si/SiO₂ substrates by magnetron sputtering machine with a base pressure of 1×10^{-7} Torr. All of the sputtering targets are 2-inch in size. The purity of Ta, and Pt targets is 99.99%, and Co₂FeAl target is 99.9%. During the deposition process, the pressure of sputtering chamber was maintained at 6×10^{-3} Torr with Ar (99.999%) gas. To deposit a uniform film, the substrate is rotated at 10 rpm. The sputtering power of Pt, CFA and Ta was kept 10 W,

10 W and 15W, with the corresponding deposition rate of 0.16 Å/s, 0.2 Å/s and 0.18 Å/s, respectively. All of the deposition processes are kept at room temperature. Subsequent anomalous Hall effect, harmonic Hall effect, and SOT switching measurements were also performed at room temperature (25 °C, 298 K) to ensure consistency and minimize temperature-induced variations in magnetic properties and SOT efficiency. More experimental details could be seen in supporting information.

3. Results and discussion

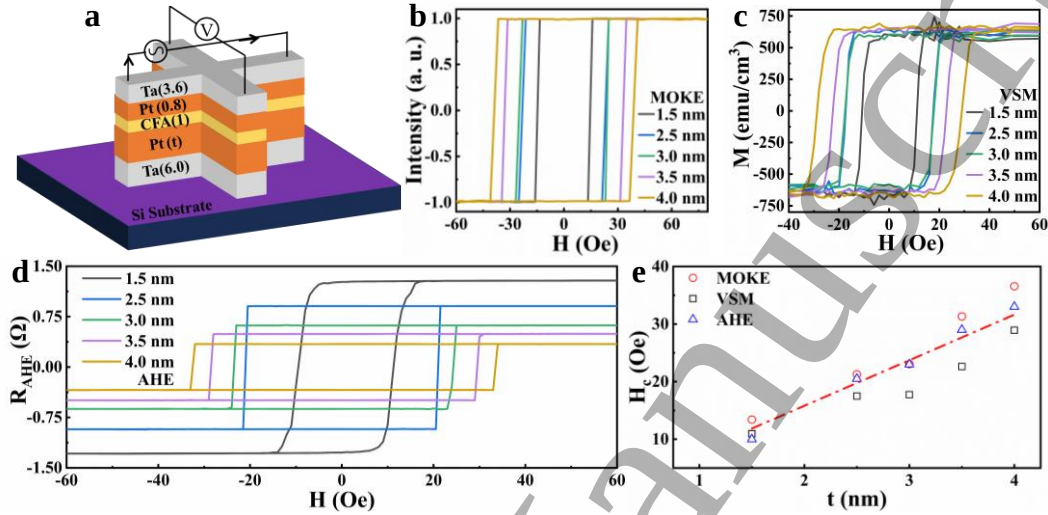


Figure 1. (a) The side view of sample structure. (b) The normalized out-plane MOKE measurement, (c) The out-plane vibrating sample magnetometer (VSM) measurement, and (d) The out-plane AHE measurement of Ta(6)/Pt(t)/CFA(1)/Pt(0.8)/Ta(3.6) ($t=1.5, 2.5, 3, 3.5, 4$) samples. (e) The H_C extracted from MOKE, VSM and AHE vs the bottom Pt thicknesses.

The samples were designed as presented in Figure 1a. The difference between them is that the thickness of the lower Pt layer. All of the other layers have the same thickness and are deposited in the same condition. As shown in Figure 1b, all the samples exhibit PMA, by polar magneto-optical Kerr effect (P-MOKE) measurement with an applied perpendicular field. The images of the switching process can be found in the supporting information Figure S1.

As depicted in Figure 1c, the out-of-plane hysteresis loops measured by VSM, also shows an out-of-plane easy axis. Since the thicknesses of the CFA layer remained unchanged, the magnetization was found to be stable for all the samples, with a saturated magnetization of 623 emu/cm³, which is consistent with previous reports.²⁰ The in-plane VSM measurement of hysteresis loops could be seen in Figure S2. Furthermore, Figure 1d shows the anomalous hall effect (AHE) data after the device fabrication. The square hysteresis loops also demonstrate the perpendicular magnetization. In the Pt/CFA/Pt structure, orbital hybridization occurs between the 3d electrons of Co and Fe atoms in CFA and the 5d electrons of Pt, which enhances spin-orbit coupling. This effect induces a perpendicular orientation of the magnetic moments, thereby realizing PMA. The thinner top Pt layer contributes moderately via limited interfacial coupling. The structure can achieve PMA when the thickness of top Pt

exceeds 0.8 nm. The orbital hybridization occurring at the top and bottom Pt interfaces collectively achieve PMA. Adjacent Ta/Pt interfaces induce weak anisotropy through spin-orbit coupling, secondary to the dominant Pt/CFA interaction. The combination effects of these interfaces (bottom Pt/CFA, top Pt/CFA, Ta/Pt) stabilizes PMA in CFA without post-annealing. The resistance associated with the AHE exhibits an upward trend with the reduction in the thickness of the Pt layer, as shown in the supporting Figure S3. And the schematic diagram could be seen in Figure S4. We also noticed that a decreased trend of the H_C as the thickness of Pt decreases from the three different measurements, as shown in Figure 1e. When the thickness of the bottom Pt layer is reduced from 4 nm to 1.5 nm, the coercivity decreases by 66%. The red dashed line represents a linear fitting. This can be understood as that the interaction of CFA/Pt interface increases with the increase of the bottom Pt layer's thickness, resulting the enhanced PMA of the CFA layer and larger H_C . This is very similar with the reported CFB/Pt interfaces.^{3,29}

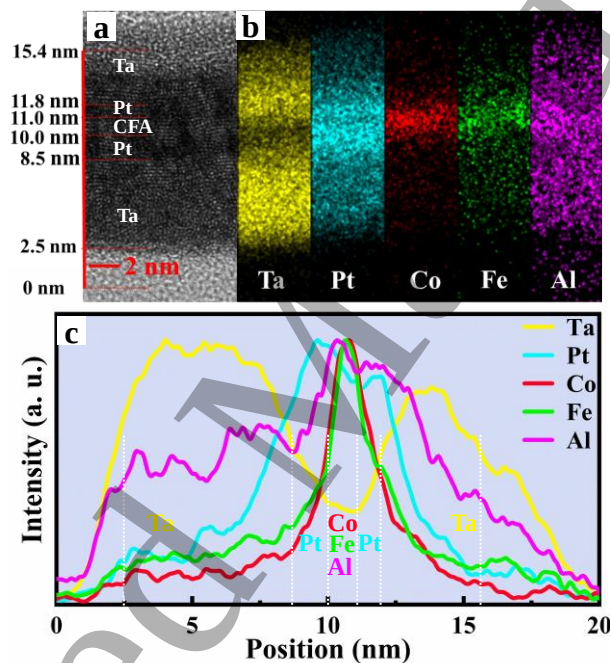


Figure 2. (a) The cross-sectional transmission electron microscopy (HRTEM) image of the Ta(6)/Pt(1.5)/CFA(1)/Pt(0.8)/Ta(3.6) sample. (b) The Energy Dispersive Spectroscopy (EDS) mapping images are respectively for Ta, Pt, Co, Fe and Al. (c) Normalized intensity line distributions of b.

To ensure the structure of the samples, microstructural characterization of the sample was carried out using HRTEM and EDS. Figure 2a shows the cross-sectional view of the HRTEM image of the Ta(6)/Pt(1.5)/CFA(1)/Pt(0.8)/Ta(3.6) sample. Each layer of the entire structure can be clearly distinguished. Figure 2b displays the EDS mapping images of different elements, and each element exhibits a fairly good distribution within its corresponding layer. Figure 2c presents the intensity line distribution profile of the EDS spectrum, by which the Ta layer, Pt layer and CFA layer can be readily distinguished. Both Ta and Pt feature peaks at both the upper and lower ends, in line with the designed structure. The peaks representing Co, Fe and Al are

located between the two peaks of Pt, which is also in line with the design. It has been noticed that Al has a very broad distribution over the whole multilayer structure, this can be attributed to its high diffusivity in such structures.^{2,18}

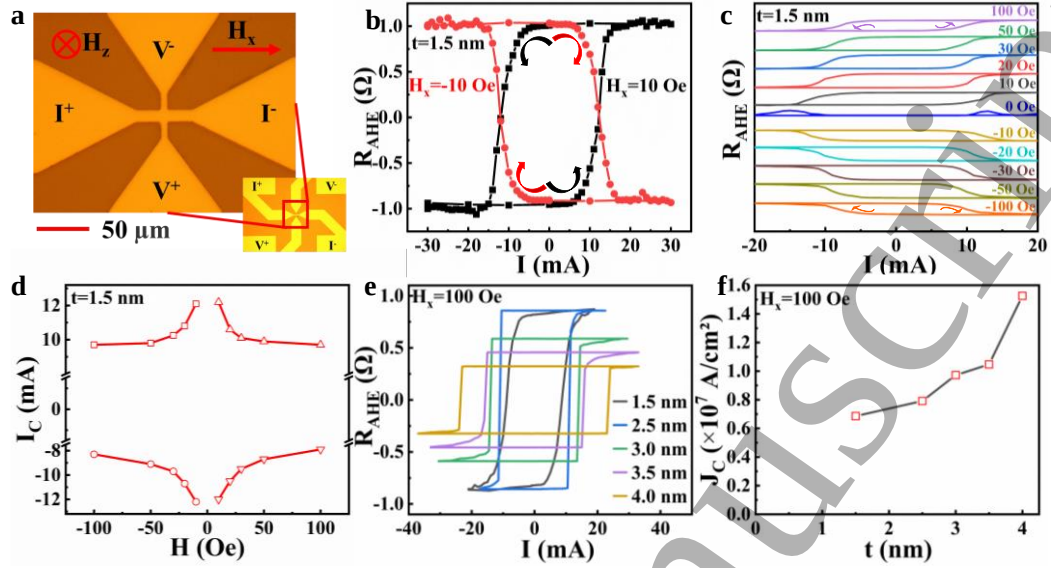


Figure 3. (a) The optical image of the test device after micro-fabrications. (b) Current-induced magnetization switching tests of the sample Ta (6)/Pt (1.5)/CFA (1)/Pt (0.8)/Ta (3.6) under in-plane magnetic field of ± 10 Oe. (c) The in-plane field dependent current-induced magnetization switching tests. (d) The critical switching current phase diagram of the sample determined based on (c). (e) Current-induced magnetization switching tests of all the samples. (f) The critical switching current density of the samples vs the thickness of the bottom Pt layer.

Figure 3a shows the actual device image of the one undergoing AHE test and the SOT switching test under an optical microscope. The device was fabricated through photolithography and ion - beam etching processes. The width of the current channel is 10 micrometers.

Figure 3b displays the current-induced SOT switching loops of the Ta (6)/Pt (1.5)/CFA (1)/Pt (0.8)/Ta (3.6) sample with an external magnetic field $H_x = \pm 10$ Oe, where the in-plane magnetic field are parallel to the current direction. When the current reaches 12 mA, the transformation of the resistance state can be achieved, with the corresponding current density being 9.3×10^6 A/cm². Compared with the change in resistance (ΔR) in the AHE (as shown in Figure 1d), the switching ratio of the sample reaches more than 90%.

Figure 3c illustrates the switching loops of the sample under different H_x . Under the condition of a positive magnetic field, the current-induced switching loop shows a counterclockwise orientation, while under the condition of a negative magnetic field, the switching loop shows a clockwise orientation. The switch direction is the same as in the Pt/CFB system.²⁹ The switching phase diagram, extracted from Figure 3c, is shown in Figure 3d. As observed, the switching current of the sample shows a decreasing trend when the applied magnetic field is increased. Under the current specific conditions, the minimum current required for switching can be achieved at 9 mA with a field of 100

1 Oe.

2 Figure 3e demonstrates the current-induced switching loops of this batch of
 3 samples with the assistance of a 100 Oe in-plane magnetic field. It is noteworthy that,
 4 the corresponding switching current shows a decreasing trend. As shown in Figure 3f,
 5 the corresponding minimum J_c being $7 \times 10^6 \text{ A/cm}^2$. This current density is relatively
 6 lower compared to that of some SOT devices in the Pt/CFB systems.^{29,30} As shown in
 7 Figure S5, we conducted control experiments with fixed bottom Ta and top Pt
 8 thicknesses, confirming that a 6 nm-thick Ta layer is rational. This selection is justified
 9 by its moderate SOT efficiency positioned in the intermediate range, while it also avoids
 10 excessive energy consumption caused by current shunting effects. Concurrently, SOT
 11 switching curves measured with increasing top Pt thickness revealed that the critical
 12 switching current increases with the top Pt thickness. This observation confirms that
 13 the spin current generated by the top Pt layer indeed exhibits a competitive relationship
 14 with that from the bottom Pt layer. The effect of CFA thickness on both the PMA and
 15 the critical switching current density could be seen in Figure S6.

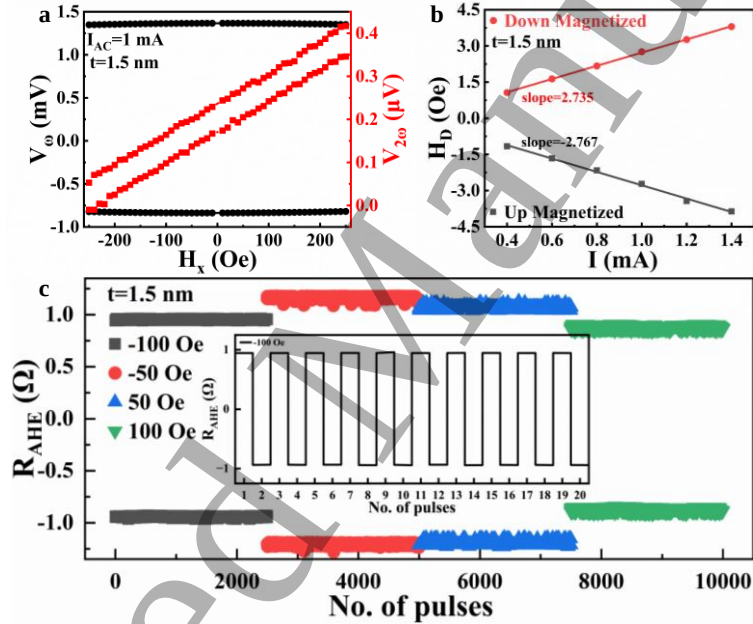


Figure 4. (a) Harmonic Hall measurements diagram conducted on the Hall-bar devices. The harmonic Hall voltages of V_{ω} and $V_{2\omega}$ were examined as a function of the magnetic field H_x . (b) Current dependence of H_D of $Ta(6)/Pt(1.5)/CFA(1)/Pt(0.8)/Ta(3.6)$. (c) 10000 times switching tests of the sample under the magnetic field conditions of ± 50 and ± 100 Oe.

Furthermore, the second harmonic analysis method was also employed to explore the damping-like torque arising from the SHE. Specifically, the magnetic field was applied along the x-direction, and a relatively small inclination angle was formed between the magnetic field and the film surface. This manipulation plays a crucial role in preventing the formation of multi-domain structures.¹³ Meanwhile, an alternating current with a frequency of 133 Hz was applied along the x-direction. An OE1022D two-channel lock-in amplifier was used to collect the first-order (V_{ω}) and second-order ($V_{2\omega}$) harmonic signals at various currents and fields. As depicted in Figure 4a, it

presents the dependence of the V_ω and $V_{2\omega}$ signals on the applied H_x with a 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, and the corresponding calculation formula is presented as follows^{13,26}:

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

The damping-like effective field (H_D) induced by current can be obtained according to the following formula^{13,26}:

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

Herein, the parameter ξ represents the ratio of the planar Hall resistance to the anomalous Hall resistance. In the platinum system, the value of the planar Hall resistance is extremely small and is often neglected in routine analyses.^{26,28} In light of this situation, the H_D can be simplified and expressed as $-2H_L$. The AC current dependent H_D is shown in Figure 4b. It exhibits a linear relationship with the applied AC current, and the slope (denoted as β_D) is 3.53×10^{-6} Oe/(A/cm²). It has been noted that this value is smaller compared to devices with single-layer Pt structures.³²⁻³⁴

The ξ_{DL} is also a key metric for evaluating the performance of SOT devices, and it could be extracted by using the following equation^{13,26,35-37}:

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

In the above equation, e stands for the elementary charge of an electron, M_s represents the saturation magnetization of CFA, t_{CFA} refers to the thickness of Co₂FeAl compound, and $\hbar$ is the reduced Planck constant. Consequently, the ξ_{DL} is calculated to be 0.0675. This value is smaller than commonly reported ξ_{DL} of Pt. And it can be attributed to the counter-effect from the top Pt layer, which produces opposite spin current into the magnetic layer, and lowers the net spin torque.³⁸ Figure S7a illustrates a possible interpretation framework in which the Ta layer provides angular momentum currents that may include orbital components, while the adjacent Pt layer facilitates efficient conversion into spin currents via strong interfacial spin-orbit coupling. Meanwhile, As supported by the comparative experiments in Figure S7b, the ξ_{DL} of the Ta(6)/Pt(4)/CFA(1)/Pt(0.8)/Ta(3.6) and Ta(6)/Pt(4)/CFA(1)/Pt(1.6)/Ta(3.6) structures are 0.191 and 0.0403, respectively. When the thickness of the top Pt layer is fixed, reducing the thickness of the bottom Pt layer from 4 nm to 1.5 nm results in a 65% decrease in the ξ_{DL} . When the thickness of the bottom Pt layer is fixed, increasing the thickness of the top Pt layer from 0.8 nm to 1.6 nm leads to a 77% reduction in the ξ_{DL} . These results confirm that increasing the thickness of the top Pt layer leads to a reduction in the ξ_{DL} . Furthermore, the ξ_{DL} data across the three sets of structures provide direct evidence for the existence of a counter-effect between the top and bottom Pt layers.

During the practical implementation of the Ta/Pt/CFA/Pt/Ta device, its repeatability and stability are of crucial importance. As depicted in Figure 4c, repeatability tests on this device have been carried out. Under the condition of a fixed

magnetic field, as shown in the inset, the resistance state of the device can be repeatedly switched by means of current induction. It is worth noting that even in multiple different magnetic field environments, the device could still maintain stable performance after undergoing as many as 10000 consecutive resistance state transformations. The 10^4 consecutive switching cycles demonstrates the excellent robustness of the fabricated device. It is our objective to enhance the thermal stability of the Ta/Pt/Co₂FeAl/Pt/Ta structure, ensuring that it can still undergo efficient SOT-induced switching even under high-temperature annealing conditions. This constitutes one of our key focuses for future research. Otherwise, the proposed structure exhibits several advantages over other HM/FM heterostructure devices, with a detailed comparison provided in Table S1.

4. Conclusion

In summary, perpendicular magnetic anisotropy of CFA has been realized in the Ta/Pt/Co₂FeAl/Pt/Ta structure using a room temperature sputtering deposition. We demonstrated that magnetization switching can be achieved under the induction of SOT with a critical current density of $7 \times 10^6 \text{ A/cm}^2$, which is smaller than similar Pt/CFB systems. The repeatability and stability tests were carried out on this sample, and the results showed that it could maintain stable performance under various magnetic field conditions. These characteristics make the Ta/Pt/Co₂FeAl/Pt/Ta system an interesting candidate for future spin-orbit torque spintronics devices.

Data availability statement

The data that support the findings of this study are openly available in Science Data Bank at <https://www.doi.org/XXXXXXX>. This statement should be given if some related data have been deposited in [Science Data Bank](#).

Supplementary Material

See the supplementary material for the process of switching based on image MOKE, the out-plane and in-plan VSM measurement of hysteresis loops, the resistance of AHE loops, schematic illustration of HM/FM stacks anomalous Hall resistance measurement, the SOT loops of variation of bottom Ta and top Pt, the slope of current dependence of H_D , experimental details and Comparison table.

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