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Field-free spin Hall effect driven magnetization switching in Pd/Co/IrMn exchange coupling system

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All electrical manipulation of magnetization is crucial and of great important for spintronics devices for the sake of high speed, reliable operation, and low power consumption. Recently, widespread interests have been aroused to manipulate perpendicular magnetization of a ferromagnetic layer using spin-orbit torque (SOT) without field. We report that a commonly used antiferromagnetic material IrMn can be a promising candidate as a functional layer to realize field-free magnetization switching driven by SOT in which IrMn is employed to act as both the source of effective exchange bias field and SOT source. The critical switching current density within our study is $J_c = 2.2 \times 10^7$ A/cm^2, which is the same magnitude as similar materials such as PtMn. A series of measurements based on anomalous Hall effect was systematically implemented to determine the magnetization switching mechanism. This study offers a possible route for IrMn application in similar structures. *Published by AIP Publishing.*
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Spin-orbit-torque magnetic random access memory (SOT-MRAM) with 3 terminals has become a promising candidate for the next generation of data storage and logic due to higher safety of tunnel barriers brought by separating read and write paths and higher operation speed, compared with conventional spin-transfer-torque magnetic random access memory (STT-MARM).[1–4] A spin current accompanied by a charge current perpendicular to the plane in metallic ferromagnetic multilayers will generate a STT strong enough to rotate the magnetization in one of the layers.[5,6] The magnitude of the critical current density is about 10^6–10^7 A/cm^2, which undoubtedly will induce strong electrical stress on the barrier layer, causing irreversible damage. Therefore, a large amount of researches have been devoted to manipulate perpendicular magnetization using spin-orbit torques (SOT) generated by spin-Hall effect (SHE) and/or Rashba effect.[7–22] These experimental studies as well as theoretical[4,7,23–28] studies show an in-plane field is indispensable to break symmetry and further to realize deterministic switching no matter switching is coherent or incoherent. Aiming to realize field-free SOT-MRAM, several schemes by introducing an effective in-plane field have been experimentally testified recently. The effective field could be induced via a wedge structure,[24] or exchange coupling with another ferromagnetic layer which possesses in-plane anisotropy[29] or exchange bias with an in-plane antiferromagnetic layer.[13] Among the above alternatives, the structure containing antiferromagnet/ferromagnet as adopted in Ref. 13 is most attractive for its compatibility with recent magnetic tunnel junction (MTJ) technology. In Ref. 13, an antiferromagnetic PtMn adjacent to a magnetic layer functions both as a spin current source and also origin of in-plane effective field, with the other side of the magnetic layer able to connect with MgO tunnel barriers. Besides of the PtMn, can other antiferromagnetic materials function as the dual roles? Here, we will show that IrMn, a widely used antiferromagnetic material, can also be used as the source of H_{ex} and SOT in a structure of IrMn/Co/Pd, which could make this kind of antiferromagnet/ferromagnet structure closer to practical applications in SOT-MRAM.

The stacks studied in this work were deposited on thermally oxidized silicon substrates via DC/RF magnetron sputtering. The stacks structure is, from bottom to top, SiO_2// Pd(5)/Co(1)/IrMn(10)/Pd(2) (the thickness in nanometers). A subsequent annealing was performed at 350 °C for 1 h with a base pressure 3×10^{-4} Pa and a magnetic field of 0.75 T normal to the sample plane to obtain perpendicular anisotropy. Then, the stacks were patterned into Hall bars with the magnetic film size of 20 μm $\times$ 20 μm [Fig. 1(a)]. The Hall devices are then connected by Cu-Au electrodes. The magnetic properties were obtained via vibrating sample magnetometer (VSM, micro sense EZ-9). The transport properties were measured in physical property measurement system (PPMS-9T, Quantum Design). All measurements were performed at 300 K.

Fig. 1(a) schematically shows the structure of the device. The Z direction is orthogonal to the film plane, and an in-plane current pulse with 50 ms duration is applied along the X direction to generate SOT. Then, the anomalous Hall resistances R_H proportional to the vertical moment of the Co layer were detected via the electrodes along the Y

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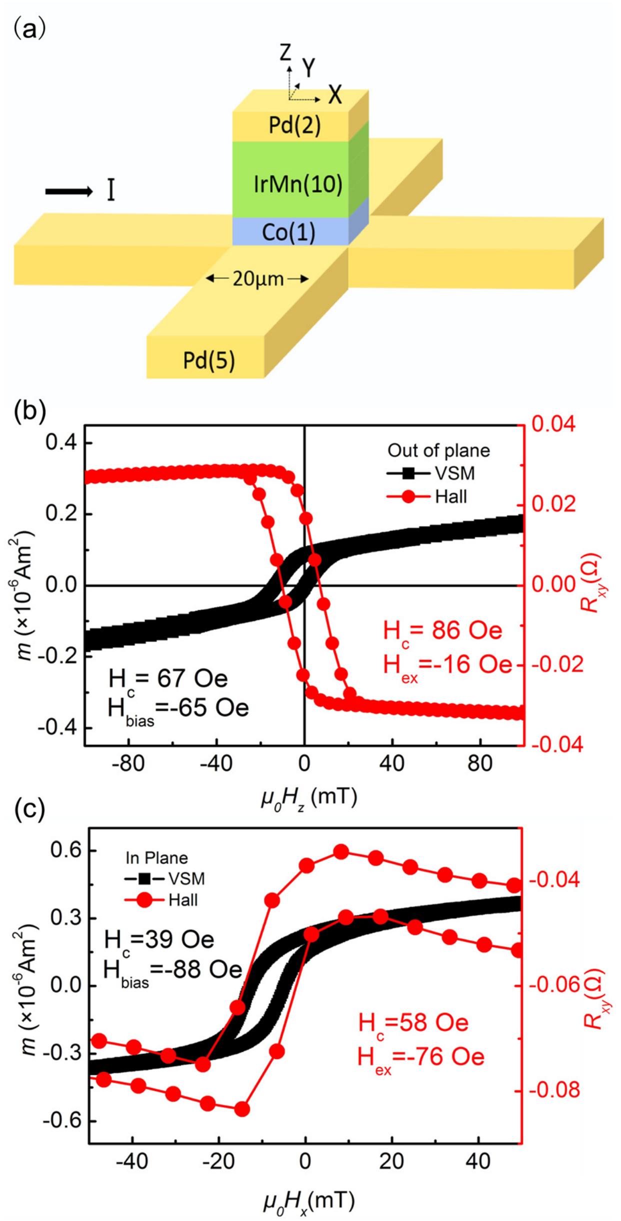

FIG. 1. (a) The structure of Hall bar with the size of 20 $\mu m \times 20\ \mu m$. Outer electrodes were not shown here for simplicity. (b)The out of plane field $\mu_0 H_z$ and (c) the in plane field $\mu_0 H_x$ dependence of Hall resistance (in red line) and magnetic moment (in black line). All measurements are performed at room temperature using a charge current of 2 mA, leading to the heating effect of current to be negligible.

direction. In addition, a planar Hall resistance arising from anisotropic magnetoresistance was also observed. The obtained Hall resistance R_{xy} as a function of applied vertical magnetic field in Fig. 1(b) establishes the existence of the perpendicular anisotropy.[30] The extracted coercivity and exchange bias field $\mu_0 H_{ex}$ are 8.6 mT and 1.6 mT, respectively. μ_0 is the permeability of free space. It should be emphasized that the magnitude of the varieties of $R_{xy}(\Delta R)$ is about 0.05 Ω, which corresponds to complete reversal of the perpendicular magnetization. Moreover, the hysteresis loop of magnetization versus vertical field H_z was also shown in Fig. 1(b). The $\mu_0 H_{ex}$ for the deposited films observed in hysteresis loop is 6.5 mT. Similarly, Fig. 1(c) illustrates the in-plane field (H_x) dependence of R_{xy} and the moment. No significant amount of differences in the extracted H_{ex} was obtained. The H_{ex} obtained in R_{xy} measurement is smaller than that in the magnetization measurement. The coercivity derived via both magnetization and R_{xy} are consistent with each other. The origin of the effective exchange field is the exchange interaction at the interface between IrMn and Co.

To support our result, an in-plane magnetic field H_x was applied to extract the H_{ex} along the X direction, and thus, the charge current dependence of R_{xy} was measured. For magnetization switching, a SOT is applied to the magnetization when the spin current is absorbed by the adjacent magnetic layer. The SOT is unable to reverse the magnetization without the aid of the in-plane (effective) field as the H_{ex} was completely cancelled out by an applied field. In a macrospin model, switching process can be described using the following equation:[4]

$$H_{an} \sin\theta \cos\theta - (H_{ex} + H_0)\cos\theta + \frac{\tau}{\mu_0 M_s} = 0. \quad (1)$$

Here, H_{an} is the anisotropic field, μ_0 is the permeability in vacuum, H_0 and M_s is offset field and perpendicularly saturation magnetization, respectively, τ is the spin-orbit torque which is proportional to the charge current, θ is the angle between the Z direction and the magnetization in the XZ plane. When $H_{ex} + H_0$ equals to 0, there are always bistable solutions for Equation (1) without deterministic switching. The effective magnetic field is also indispensable in the model based on chiral domain wall motions. The in-plane magnetic field could rotate the center spins of domain walls. In this condition, an effective perpendicular field generated by charge current will ensure domain walls to propagate, completing the switching. However, this mechanism needs involvement of strong Dzyaloshinski-Moriya interaction (DMI)[31,32] since it is crucial to form Néel-type domain walls with some chirality. Perez also reported that incoherence switching could still be qualitatively reproduced by the macrospin model in the case of weak DMI.[31] Due to much smaller spin-orbit coupling strength in IrMn than Pt as indicated by much smaller spin Hall angles,[33,34] it is more probable that DMI in IrMn/Co interface would also be much weaker than in the Pt/CoFe system. Therefore, the macrospin model is still applied in our case. On the contrary, the switching is forbidden without the in-plane magnetic field. The switching loop (R_{xy} vs. I) with $\mu_0 H_x$ scanned from −2.6 mT to −1.0 mT in Fig. 2 shows the $\mu_0 H_{ex}$ is 1.8 mT. Specifically, an in-plane charge current spanning from −70 mA to 70 mA with 50 ms duration is applied in the channel and the offset Hall resistance is detected. In each measurement process, the applied offset field H_x keeps constant. For the applied field above and below −1.8 mT, the switching direction of the IrMn/Co/Pd is clockwise and anticlockwise, respectively, also indirectly demonstrating that the effective in-plane bias field between the Co and IrMn is 1.8 mT.

The SOT generated by the pure spin current is directly proportional to the charge current density. To confirm the existence of SOT, R_{xy}–H_z hysteresis with different measurement currents were implemented [Fig. 3(a)]. When the charge current is above 30 mA which corresponds to a charge current density $J = 8.3 \times 10^6\ A/cm^2$, the R_{xy} vs. I

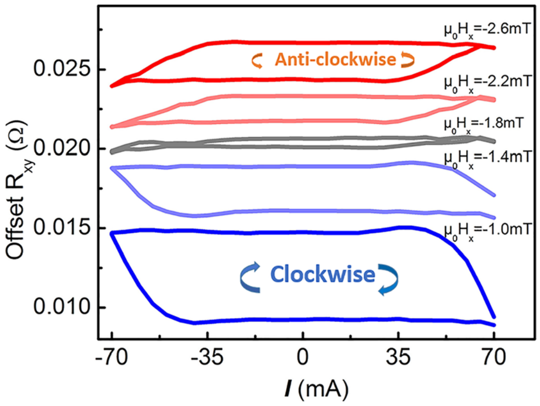

FIG. 2. The offset Hall resistance R_{xy} as a function of current, an offset field is applied to counteract the effective exchange bias field. The loops are shown in narrow field range. Moreover, the switching polarization is examined.

hysteresis is almost fully suppressed. Here, to calculate the charge current density, we simply assumed the current is homogeneously distributed within the cross-section of $18\,\text{nm} \times 20\,\mu\text{m}$. The extracted coecivity field from the R_{xy} vs. I hysteresis decreases monotonically and remarkably with the increase in the measuring current [Fig. 3(b)], which confirms the existence of SOT as elaborated in a macrospin model discussed below. The calculated results are illustrated in Figs. 3(c) and 3(d), which are in qualitative agreement with our study. Considering the spin Hall angle of IrMn is much larger than that of Pd,[34–36] the SOT is dominantly generated within IrMn or arises from the interface of IrMn/Co. Therefore, in this system, IrMn is the robust source of SHE and exchange bias effect.

Fig. 4(a) shows the current dependence of R_{xy} at zero applied field. The zero field is approached in the PPMS by the oscillation mode from a large field of 2 T. Due to the in-plane exchange bias field, up-and-down magnetization switching induced by SOT without the applied field are realized when the charge current was scanned from 80 mA to −80 mA. The variation of R_{xy} induced by the current is $\Delta R = 0.046\ \Omega$ while the full ΔR measured in R_{xy}–H_z curve is about 0.05 Ω, indicating that the perpendicular magnetization was almost completely switched. The critical switching current is around 80 mA that corresponds to a current density $J_c = 2.2 \times 10^7\ \text{A/cm}^2$. In a coherent switching system, the spin Hall angle can be estimated via the following equation:[7,37]

$$\Theta_{SHE} = \frac{2e}{\hbar}\frac{M_s t_F}{J_c}\left(\frac{H_k^{eff}}{2} - \frac{H_x}{\sqrt{2}}\right). \tag{2}$$

Here, e is the elementary charge, $\hbar$ is the reduced Planck constant, θ_{SHE} is the effective spin Hall angle, and H_k^{eff} and t_F are the effective anisotropy field and thickness of the ferromagnetic layer, respectively. In our experiment, H_{ex} takes the place of H_x while $\mu_0 H_k^{eff}$ is about 0.2 T, which is much larger than the magnitude of H_{ex}, so that H_x in the parentheses can be ignored. The nominal thickness of Co layer is 1 nm and M_s is about 10^6 A/m. Considering all the parameters above, we derived the effective spin Hall angle θ_{SHE} equals to 1.36. The overestimated spin-Hall angle strongly indicated that the magnetization switching here is essentially incoherent. In this case, average H_{an} of whole film used to estimate spin Hall angle in the macrospin model should be replaced by an effective H_{an} experienced by nanomagnets in nucleation process. Thus, the spin Hall angle is exaggerated. Besides, it should be noted that a current more than 80 mA will finally cause irreversible damage to this kind of Hall devices, according to our preliminary experience. This is the reason why the maximum current adopted in our switching measurement is 80 mA. By cautiously limiting the current within 75 mA, we verified the reproducibility of magnetization switching. Three switching circles are shown in Fig. 4(b), and the derived ΔR is about 0.004. This much smaller ΔR also means nucleation

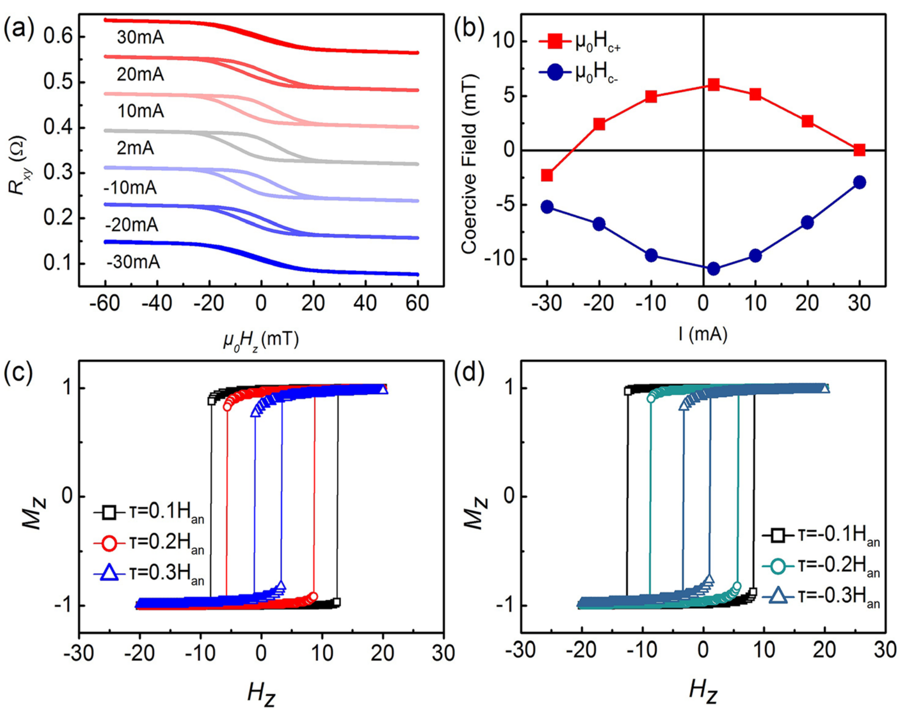

FIG. 3. (a) R_{xy}-$\mu_0 H_z$ loops obtained by various charge current, respectively, the magnitude of the current is ranging from −30 mA to 30 mA, Hc_+(red solid line) and Hc_- (blue solid line) extracted from R_{xy}-H_z loops are shown in (b), (c) and (d) the calculated results of M_z-H_z while maintaining fixed H_x and SOT.

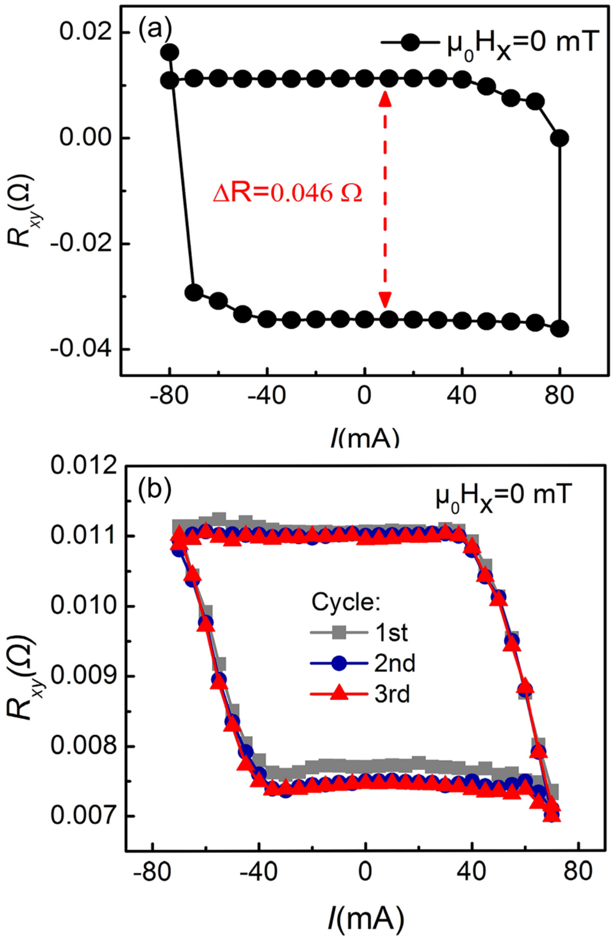

FIG. 4. (a) The reversal loop of magnetization at the zero magnetic field, confirming the moments are fully switched. To determine the reproducibility of the device, (b) the reversal are repeated with the current, ramping from −75 mA to 75 mA.

and domain wall propagation dominate in the switching process and the SOT generated by 75 mA current only causes a fraction of perpendicular magnetization to reverse as well as the domain wall propagation.[25] The effective bias field along the charge current direction generated by the antiferromagnetic layer IrMn is of importance during this process. As a result of the bias field, the fairly robust switching of magnetization could be obtained in our measurement, indicating IrMn is a remarkable, robust, and promising material to be used as a bi-functional layer to induce an effective exchange bias field and to provide a pure spin current.

In summary, our work shed a light upon the potential use of IrMn in 3-terminal MRAM devices based on the SOT-driven magnetization switching mechanism. The effective exchange bias field arising from the interface of IrMn/Co allows magnetization to reverse at zero applied field. Furthermore, the H_{ex} along the charge current is attentively confirmed via a static offset field. It should be emphasized that the detected effective H_{ex} via magnetization measurement is 3 times larger than that obtained via Hall resistance measurement, which also results from the difference of the deposited films and the patterned device in addition to joule heating effect. The joule heating effect will not lead to deterministic magnetization switching with or without applied field. The magnetization switching is robustly achieved without magnetic field. To conclude, though understanding of switching mechanism is still in early stage, IrMn has been experimentally demonstrated as a promising antiferromagnetic material for switching magnetization by providing both strong enough SOT and exchange-bias interaction.

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