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Current induced domain wall motion in antiferromagnetically coupled (Co₇₀Fe₃₀/Pd) multilayer nanowires

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We investigate the current induced domain wall (DW) motion in the ultrathin CoFe/Pd multilayer based synthetically antiferromagnetic (SAF) structure nanowires by anomalous Hall effect measurement. The threshold current density (J_{th}) for the DW displacement decreases and the DW velocity (v) increases accordingly with the exchange coupling J_{ex} between the top and bottom ferromagnetic CoFe/Pd multilayers. The lowest $J_{th} = 9.3 \times 10^{10}$ A/m² and a maximum $v = 150$ m/s with $J = 1.5 \times 10^{12}$ A/m² are achieved due to the exchange coupling torque (ECT) generated in the SAF structure. The strength of ECT is dependent on both of J_{ex} and the strong spin-orbit torque mainly generated by Ta layer. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4964261>]

The manipulation of magnetic domain wall (DW) motion using electrical current has been intensively investigated due to their potential applications, such as racetrack memory (RM).¹ In comparison with the in-plane magnetized materials, materials with perpendicular magnetic anisotropy (PMA) exhibit higher storage density and lower driving current density for DW motion, which are favorable for device application.^{2,3} Furthermore, lowering energy consumption and increasing the data transmission speed are also important for practical application of RM. Previous reports^{4,5} have shown that J_{th} is proportional to magnetic moment in PMA films. Thus, the reduction of the magnetic moment would lead to a decrease in J_{th} . One possible method to dramatically reduce the magnetic moment⁶ is to use a synthetic antiferromagnetic (SAF) structure, which consists of two ferromagnetic (FM) layers separated by a nonmagnetic spacer layer.⁷ The magnetization of the top (M_{s1}) and bottom (M_{s2}) FM layers favors antiparallel alignment as a result of exchange coupling via the spacer layer. Additionally, a very large DW velocity (v) of 750 m/s in antiferromagnetically (AFM) coupled magnetic nanowires has been observed,⁸ which is attributed to a large exchange coupling torque (ECT) generated in the SAF structure. Furthermore, the dipolar fringing field from the adjacent magnetic domains is dramatically reduced in the SAF structure nanowires, which is beneficial to increase the storage density of RM.⁹ All these features indicate that the SAF structure is a promising candidate for the spin-torque DW devices.

We have shown in our previous study that the ultrathin (CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)₉ SAF structure possesses high interlayer exchange coupling (H_{ex}) and high

PMA.¹⁰ In this work, we systematically investigate the J_{th} and v for current induced DW motion in the (CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)_N SAF structure.

The SAF structure samples with a stack of Si/SiO₂/Ta(3)/Pd(3)/[CoFe(0.16)/Pd(0.22)]₈/CoFe(0.16)/Ru(0.8)/Pd(0.2)/[CoFe(0.16)/Pd(0.22)]_N/Ta(3) (all the number in brackets indicates the thickness of the layer with unit in nanometer) were grown on the thermal oxidized Si (100) substrates. The N ranges from 4 to 9. The samples were deposited using DC magnetron sputtering in an ultrahigh vacuum chamber. The 30 μ m-long and 300 nm-wide nanowire devices were fabricated. The details of the experimental setup and DW velocity measurement were described in Refs. 11 and 12. All measurements were performed at room temperature. The single DW in the nanowire was imaged using magnetic force microscopy (MFM) at the remanent state. The duty cycle and pulse width (t_p) of each pulse current in the DW velocity (v) measurements were fixed at 1/1000 and 5 ns, respectively.

Figure 1(a) shows the normalized Hall resistance hysteresis loops (R_H -H) for the nanowires with a structure of [CoFe/Pd]₈/CoFe/Ru/Pd/[CoFe/Pd]_N for N = 5, 6, and 7. The sharp reversal behaviors of all R_H -H loops indicate that the CoFe/Pd multilayers exhibit PMA. As the Hall resistance (R_H) is proportional to the perpendicular component of magnetization in the anomalous Hall effect,¹³ the R_H -H loops also demonstrate the variation of magnetization for the SAF structure. The loops start at a field larger than the saturation field and thus the magnetic moments of top and bottom multilayers are aligned in parallel and the effective magnetization is $|M_{s1} + M_{s2}|$. As H decreases, the first magnetization reversal is observed before H reaches zero. This signifies that the two FM [CoFe/Pd] multilayers are antiferromagnetically coupled through the spacer layer. At remanent state ($H = 0$), the magnetic moments of the top and bottom multilayers are aligned antiparallel and the magnetization of the SAF structure is $|M_{s2} - M_{s1}|$. When H is increased in the

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FIG. 1. (a) Normalized Hall resistance hysteresis loops (R_H - H) under H perpendicular to the film plane for 300 nm-width nanowires with a structure of Ta(3)/Pd(3)/[CoFe(0.16)/Pd(0.22)]₈/CoFe(0.16)/Ru(0.8)/Pd(0.2)/[CoFe(0.16)/Pd(0.22)]_N/Ta(3) with $N=5, 6, 7$. The schematic diagrams present the magnetization configuration in the SAF structure. The variation of (b) net magnetization M_n ($=|M_{s2} - M_{s1}|$) and (c) J_{ex} of [CoFe/Pd]₈/CoFe/Ru/Pd/[CoFe/Pd]_N SAF structure as functions of N .

other direction, the magnetization directions of the top and bottom layers switch simultaneously as they couple together and operate as a single magnet. Further increasing H to the saturation field leads to the alignment of magnetization of both layers in the other direction. In the low field region $|H| < 0.1$ T, the strong antiferromagnetic coupling between the top and bottom layers dominates the net magnetic moment reversal.¹⁴ We define $m_r = \frac{|M_{s2} - M_{s1}|}{|M_{s1} + M_{s2}|}$ and $M_n = |M_{s2} - M_{s1}| = \frac{2m_r}{1+m_r} M_{s2}$ can thus be obtained. Here, $M_{s2} = 452$ kA/m is the magnetization of the bottom layer with a fixed thickness. The m_r is obtained from the normalized hysteresis loop.

Figure 1(b) shows the dependence of M_n on N . The M_n decreases as N varies from 4 to 9, which is attributed to the difference in magnetization between the top and bottom [CoFe/Pd]_N multilayers that reduces with N . The smallest $M_n = 79$ kA/m is achieved when $N=9$, which is due to the identical nominal total thickness (1.44 nm) of the CoFe magnetic layer in the top and bottom CoFe/Pd multilayers. The exchange coupling strength J_{ex} between the two FM layers is expressed as $J_{ex} = H_{ex}M_s t$,⁷ where M_s and t are saturation magnetization and overall thickness of the top FM layer, respectively. The J_{ex} as a function of N is shown in Fig. 1(c). It is found that J_{ex} increases with N , which is mainly due to the $M_s t$ of top CoFe/Pd multilayers increases with N . In the following discussion, we shall focus on the current induced DW displacement in the region that magnetization of the top and bottom FM layers are aligned antiparallel as to study the effect of ECT on the DW motion.

Prior to each measurement, DW was first nucleated at the joint between the triangular contact pad and nanowire (see MFM image in Fig. 2(a)). The DW is pinned in the wire due to the intrinsic pinning strength after its nucleation.¹⁵ Subsequently, a pulsed current is injected into the nanowire to induce the DW motion. The bottom of Fig. 2(a) confirms

the DW displacement after applying the pulsed current with current density $J > J_{th}$. The R_H is measured after each pulse to detect the DW motion.¹¹ Figure 2(b) shows R_H as a function of the integrated pulse duration t with $J = +0.93 \times 10^{11}$ A/m², $+0.85 \times 10^{11}$ A/m², and -0.93×10^{11} A/m² under $H=0$. The positive and negative signs of J denote the electrons are flowing along and opposite to the direction of the DW motion, respectively. For $J = +0.93 \times 10^{11}$ A/m², a sudden jump of R_{Hall} in Fig. 2(b) indicates that the DW driven by the current has passed through the Hall cross. The value of R_H changes around 0.2Ω , which is almost the same as the variation of R_H for different orientations of $|M_{s1} - M_{s2}|$ in [CoFe/Pd]₈/CoFe/Ru/Pd/[CoFe/Pd]₉ SAF structure (see [supplementary materials](#) for details on the R_H measurement). This confirms that the current induced DW motion occurs when magnetization of the top and bottom FM layers are aligned antiparallel. On the other hand, no switching is observed when $J = -0.93 \times 10^{11}$ A/m², indicating that the DW moves in the direction of electron flow. Additionally, no switching of R_H is observed when the J is decreased to 0.85×10^{11} A/m². This suggests that the driving force generated by applied pulse current is not strong enough to drive the DW motion. Notably, the low threshold current density J_{th} for driving the DW motion is of importance to device applications.²¹

In order to determine J_{th} , current-switching measurements were performed 10 times at each J . The probability (η) of the DW motion is defined as the ratio of the number of the events that DW passing through the Hall cross to the total number of measurements. The J_{th} is determined as the lowest current density when $\eta = 1$. Figure 2(c) shows J_{th} of the [CoFe/Pd]₈/CoFe/Ru/Pd/[CoFe/Pd]_N SAF structure nanowire as a function of N . All measurements were performed at zero field. The J_{th} decreases with N and a smallest $J_{th} = 9.3 \times 10^{10}$ A/m² is obtained for $N=9$. This value is significantly lower in comparison with other perpendicularly Co-based-ferromagnetic

FIG. 2. (a) The top MFM image shows that DW was formed by the local Oersted field of injected pulse current at the joint between contact pad and the nanowire in the $[\text{CoFe(0.16)/Pd(0.22)}]_8/\text{CoFe(0.16)/Ru(0.8)/Pd(0.2)}/[\text{CoFe(0.16)/Pd(0.22)}]_4$ SAF structure sample. The bottom MFM image shows that the DW position is changed after flowing the pulsed current with the $J > J_{th}$ along the nanowire. A schematic diagram presents the domain and DW configuration in the SAF structure. The red and blue regions represent areas that are oppositely magnetized. (b) The Hall resistance R_{Hall} as a function of integrated pulse duration t measured with driving pulse current densities $J = +0.93 \times 10^{11} \text{ A/m}^2$ (opened circle), $+0.85 \times 10^{11} \text{ A/m}^2$ (opened rectangle), and $-0.93 \times 10^{11} \text{ A/m}^2$ (opened triangle) under zero magnetic field, respectively. The SAF structure of the nanowire device is $[\text{CoFe(0.16)/Pd(0.22)}]_8/\text{CoFe(0.16)/Ru(0.8)/Pd(0.2)}/[\text{CoFe(0.16)/Pd(0.22)}]_9$. (c) The threshold current density (J_{th}), hard axis anisotropy ($K_{h,a}$) and (d) depinning field (H_{dep}) as functions of repeated number N for the $[\text{CoFe/Pd}]_8/\text{CoFe/Ru/Pd}/[\text{CoFe/Pd}]_N$ SAF structure nanowire.

multilayer nanowires, such as Co/Ni ($J_{th} \sim 4-5 \times 10^{11} \text{ A/m}^2$),^{16,17} Co/Pt ($J_{th} \sim 1 \times 10^{12} \text{ A/m}^2$),¹⁸ CoFe/Pt ($J_{th} \sim 1.43 \times 10^{12} \text{ A/m}^2$),¹⁹ and CoFe/Pd ($J_{th} \sim 1.44 \times 10^{11} \text{ A/m}^2$).²⁰ To further understand the small value of J_{th} in our samples, we investigate the pinning effect on the J_{th} and measure the depinning field (H_{dep}) for the SAF structure nanowires with different N . The details of the H_{dep} measurements can be found in Ref. 11. Figure 2(d) shows the dependence of H_{dep} on N . The variation of H_{dep} is in the range of 40 to 70 mT and H_{dep} has a local maximum of 70 mT at $N = 7$. This excludes the possibility of the reduction of J_{th} due to the lowering of H_{dep} .

Returning back to Fig. 2(c), it shows that J_{th} dramatically decreases from 2.8×10^{11} to $9.3 \times 10^{10} \text{ A/m}^2$ by a factor of 3 as N increases from 5 to 9. There are two important factors determining the J_{th} , which are the energy barrier and the driving force.² The DW has to overcome the energy barrier arising from the hard-axis anisotropy energy ($K_{h,a}$)^{21,22} for motion.²³ Fig. 2(c) shows that the $K_{h,a}$ decreases with N in our SAF samples, which indicates the height of the energy barrier decreases with N . On the other hand, previous simulation²⁴ and experimental^{8,9} results show that an exchange coupling torque (ECT) proportional to J_{ex} can be generated in a SAF structure. The ECT works as a driving force to help in depinning DWs in the two different layers^{8,25} and J_{th} can be decreased with reducing J_{ex} . As J_{ex} increases with N (changing from 5 to 9), the driving force increases with N . Therefore, the dramatic reduction of J_{th} can possibly be attributed to the reduction of the energy barrier and the increase in the driving force.

Figure 3 shows the averaged DW velocity (v) as a function of J for N ranging from 4 to 9. For a given sample, as J is increased from J_{th} , v increases linearly with J till J_w . Above J_w , the v slightly changes with J and subsequently increases linearly as J is further increased. The dependence of v on J can be explained by considering the Walker breakdown model.^{26,27} In this model, three regimes of the DW motion are predicted for Walker breakdown limit in the SAF structure. First, a steady-state DW motion occurs at low J , in which a linear dependence between v and J is expected.

FIG. 3. The variation of the v as functions of J under zero applied field for the $[\text{CoFe/Pd}]_8/\text{CoFe/Ru/Pd}/[\text{CoFe/Pd}]_N$ SAF structure nanowires with N ranging from 4 to 9. The inset is the enlarged portion with J is in the range of $0.93 \times 10^{11} \text{ A/m}^2$ to $3 \times 10^{11} \text{ A/m}^2$. Each data point is the averaged value of 10 measurements at fixed current density. The error bars indicate the standard deviation.

Then the v slightly decreases in the Walker breakdown regime of $J_w \leq J \leq J_p$, where J_w is defined as the Walker breakdown current density. The Walker breakdown limit originates from the demagnetization field that generates a torque on the magnetization. This torque has an opposite direction with the magnetization, resulting in the DW structure undergoes periodic configurations.² In the third region for high current density, v increases linearly as J is further increased above J_p and the DW motion changes to a precessional regime.^{2,28,29} The J_p is defined as the lowest J , above which the DW starts a precessional motion. These predictions are in good agreement with our results of v dependent on J in the SAF structure nanowires. Additionally, we only show the data for $J \leq 1.5 \times 10^{12}$ A/m² since a higher J would easily burn out the device due to Joule heating (the details on the Joule heating are discussed in the [supplementary materials](#)).

In comparing the DW velocity among the different samples under the same driven current density, v increases with N and correspondingly the J_{ex} value. The maximum velocity $v_{max} = 150$ m/s in the SAF structure nanowire is significantly larger in comparison with our previous work using the same material but without the SAF structure and other common Co-based multilayer nanowires, such as CoFe/Pd ($v_{max} \sim 8$ m/s),¹¹ Co/Ni ($v_{max} \sim 60$ m/s),¹⁷ and CoFe/Pt ($v_{max} \sim 1.5$ m/s).¹⁹ These observations again agree with the prediction of ECT promote domain wall motion.

We note that ECT is dependent on the spin-orbit torque (SOT) originating from the adjacent heavy metal layer.⁸ The SOTs will cause the magnetization of the top and bottom FM in SAF to rotate to the spin accumulation direction (transverse to the length of nanowire). This will further result in an exchange field on the top and bottom FM, driving them back to their equilibrium state.⁸ ECT is then generated through exchange field, which drive the DWs in the two different layers to move in the same direction. The SOTs could arise from spin Hall effect (SHE) and Rashba field as a consequence of breaking of structure inversion symmetry and the interfaces. It is expected that the heavy metals Ta,^{30–32} Pd and Ru³³ have nonzero spin Hall angle, which will generate the SOT due to SHE and influence the amplitude of ECT in the Ta/Pd/(CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)_N/Ta structure samples. Thus, the SOT and ECT need to be further considered. Ru has a smaller spin Hall conductivity compared with Ta, which may result in a smaller spin Hall effect for Ru than for Ta.^{33,34} Ru is inserted into the (CoFe/Pd)_n multilayers to induce the antiferromagnetic coupling. In order to understand the major contribution to the ECT, we compare the v as a function of J for three nanowire samples with different SAF structures, which are Ta(3)/Pd(3)/(CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)₉/Ta(3) (sample A), Ta(3)/Cu(3)/(CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)₉/Ta(3) (sample B), and Ta(3)/Pd(3)/(CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)₉/Cu(3) (sample C) as shown in Fig. 4(a). The Ta/Cu seed layer (Cu cap layer) is used to replace the Ta/Pd seed layer (top Ta layer) to exclude the effect of SOT generated by the Pd seed layer (top Ta layer). The Ta/Cu seed layer can also induce the (CoFe/Pd)_n fcc (111) texture for high PMA.³⁵ The dependence of v on J for samples A and B are almost the same, indicating the SHE of the Pd seed layer has little effect on the DW

FIG. 4. (a) The v as functions of J for three nanowire samples A, B, and C with different SAF structures; (b) and (c) show the dependence of ΔH_L and ΔH_T after planar Hall effect correction on J for samples A and C, respectively. The $\pm M_z$ indicates the positive/negative initial magnetization states. The layered structures for samples A, B, and C are Ta(3)/Pd(3)/(CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)₉/Ta(3), Ta(3)/Cu(3)/(CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)₉/Ta(3), and Ta(3)/Pd(3)/(CoFe/Pd)₈/CoFe/Ru/Pd/(CoFe/Pd)₉/Cu(3), respectively.

motion due to the small spin Hall angle.³⁶ However, the v of sample C dramatically decreases as compared with samples A and B. This result indicates the high v is mainly dependent on the top Ta layer. The Ta has a large spin Hall angle and can generate strong SOT,³⁰ which will directly influence the amplitude of ECT and the v value.

In order to quantify the SOT generated by Ta, the harmonic Hall voltage measurement with the planar Hall effect correction^{31,37–41} was performed for obtaining the effective fields along the longitudinal (ΔH_L) or the transverse (ΔH_T) direction for samples A and C, respectively (the details on the harmonic Hall voltage measurement and planar Hall effect correction method are described in the [supplementary materials](#)). The dependence of effective fields ΔH_L and ΔH_T on J are plotted in Figs. 4(b) and 4(c) for samples A and C, respectively. The magnitude of ΔH_L and ΔH_T increases linearly with J . We define the longitudinal (β_L) and transverse (β_T) SOT efficiencies^{39,41} as $\beta_{L(T)} = \Delta H_{L(T)}/J$ and the $\beta_{L(T)}$ values can be obtained from the slope. The $\beta_L(\beta_T)$ is enhanced from $0.9 \text{ mT cm}^2/10^7 \text{ A}$ ($0.2 \text{ mT cm}^2/10^7 \text{ A}$) for sample C to $4 \text{ mT cm}^2/10^7 \text{ A}$ ($0.7 \text{ mT cm}^2/10^7 \text{ A}$) for sample A. These results indicate that although the thickness of the top and bottom Ta layers is identical (3 nm), the top and bottom Ta layers generate non-identical SOTs on the SAF structure due to the Pd insertion in the bottom. The small SOT in sample C originates from the bottom Ta/Pd and the SAF structure.⁴² It also shows that the top Ta layer produces much larger SOT than the bottom one. This structure asymmetric leads to the enhancement of the spin injection efficiency from the Ta to (CoFe/Pd)_n multilayers based SAF structure.³¹

We note that $v = 150$ m/s at $J = 1.5 \times 10^{12}$ A/m² achieved in this study is smaller than $v \sim 380$ m/s with identical J in

Ref. 8. One possible reason for the smaller v in our sample is that the SOT generated by the top Ta is smaller than Pt in Ref. 8. Additionally, the SOT will be attenuated through the thickness of $(\text{CoFe/Pd})_n$ multilayer based SAF structure. Our SAF structure thickness (~ 8 nm) is larger than that in the Co/Ni/Co based SAF structure (~ 4 nm),⁸ which will lead to smaller ECT and v .

In conclusion, we have systematically studied the threshold current density (J_{th}) and DW velocity (v) in ultrathin CoFe/Pd multilayer based SAF structure nanowires. A low $J_{th} = 9.3 \times 10^{10}$ A/m² and a maximum $v = 150$ m/s are achieved for the sample with J_{ex} of 0.0158 J/m³. The small J_{th} and high v is due to an exchange coupling torque (ECT) generated in the SAF structure. The amplitude of ECT is dependent on the spin-orbit torque from Ta and J_{ex} . The results suggest that SAF structure nanowires based on ultrathin [CoFe/Pd] multilayers with a large spin orbit torque is beneficial for the spin-torque DW devices.

See [supplementary material](#) for the detailed discussion of Hall resistance (R_H) measurement, the spin orbit torque (SOT) measurement, planar Hall effect (PHE) correction to harmonic measurements, and thermal effect.

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