Programmable Dynamics of Exchange-Biased Domain Wall via Spin-Current-Induced Antiferromagnet Switching

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Magnetic domain wall (DW) motion in perpendicularly magnetized materials is drawing increased attention due to the prospect of new type of information storage devices, such as racetrack memory. To augment the functionalities of DW motion-based devices, it is essential to improve controllability over the DW motion. Other than electric current, which is known to induce unidirectional shifting of a train of DWs, an application of in-plane magnetic field also enables the control of DW dynamics by rotating the DW magnetization and consequently modulating the inherited chiral DW structure. Applying an external bias field, however, is not a viable approach for the miniaturization of the devices as the external field acts globally. Here, the programmable exchange-coupled DW motion in the antiferromagnet (AFM)/ferromagnet (FM) system is demonstrated, where the role of an external in-plane field is replaced by the exchange bias field from AFM layer, enabling the external field-free modulations of DW motions. Interestingly, the direction of the exchange bias field can also be reconfigured by simply injecting spin currents through the device, enabling electrical and programmable operations of the device. Furthermore, the result inspires a prototype DW motion-based device based on the AFM/FM heterostructure, that could be easily integrated in logic devices.

1. Introduction

Combining antiferromagnet (AFM) and ferromagnet (FM) adds versatile functionalities to spintronic devices and related technologies. In the AFM/FM heterostructure systems, FM spins, being coupled with adjacent AFM spins, tend to form an alignment different from a conventional ferromagnetic state in consistence with the AFM spin states close to the interface. Phenomenologically, this effect appears as the presence of an effective internal magnetic field, commonly referred as exchange bias effect. Exchange bias has conventionally been utilized to pin FM reference layers in recording heads or magnetic random-access memory. Very recently, exchange bias are being exploited in many spintronics device applications to implement the novel concepts of magnetic skyrmion and field-free spin-orbit torque switchings. In these examples, external magnetic fields (H_{ext}), which normally acts globally with respect to the system dimensions, are replaced by localized exchange bias.

In the meantime, it is noted that the exchange bias can also be considered for an effective route to manipulate magnetic domain wall (DW) dynamics. In an ultrathin perpendicular magnetic system with broken structural inversion symmetry, the asymmetric exchange interaction, so called Dzyaloshinskii–Moriya interaction (DMI), is known to give rise to an in-plane effective field H_{DMI} on the DW. Therefore, it has received extensive attention due to the key role it can play in the formation of stable chiral DW and magnetic skyrmions. The presence of DMI also introduces additional possibilities into the dynamics of DW, i.e., asymmetric and/or tilted DW motions. Both experimental and theoretical works show that the asymmetric or tilted DW propagations arise from the modulation of DW structure which is stabilized by the Zeeman interactions between the DMI-preferred chiral DW and an in-plane H_{ext}. Such method, however, may not be scalable for practical applications. In this regard, substituting the in-plane H_{ext} with exchange bias field would be advantageous for the integration of DW motion based-devices into electrical circuits. Despite such prospects, however, combining the exchange bias and DW dynamics has not been sufficiently explored yet.
We hereby investigate the manipulation of field-driven DW motion in ultrathin perpendicular magnetic anisotropy (PMA) layer which is exchange coupled with adjacent AFM IrMn layer. In general, simultaneous application of both in-plane and out-of-plane fields on the PMA FM layer is required in order to induce asymmetric DW motion.\[15,16\] In the present work, however, propagation of asymmetric DW was realized without applying an in-plane $H_{ext}$, which is effectively replaced by the exchange bias. In particular, the direction of the exchange bias is controlled by the polarity of a current pulse injected through AFM layer, realizing the control of DW tilt directions. Finally, we show that the programmable imprinting of DW propagation pattern at a cross-bar device, which could be adopted to magnetic DW logic devices.

2. Results and Discussion

2.1. Existence of DMI in the Exchange Coupled HM/FM/AFM Trilayers

Multilayers of Ti (4 nm)/Pt (4 nm)/Co (0.6 nm)/Pt (0.4 nm)/IrMn$_3$ (8 nm)/Pt (4 nm) on SiO$_2$ substrate were deposited at room temperature by magnetron sputtering as illustrated in Figure 1a. Depositions were carried out without $H_{ext}$ to establish randomly distributed orientations of AFM domains in the initial as-deposited state of the film. To confirm the existence of DMI in the deposited multilayers, the circular domain expansion with application of $H_x$ and $H_z$ was examined using a magneto-optical Kerr effect (MOKE) microscope.\[15\] First, successive expansions of circular DW by repeated application of pulsed $\pm H_x$ (+30 mT and −30 mT of $H_x$ for the top and bottom images, respectively) were measured and overlaid together as shown in Figure 1b. The circular DW expansion under the application of $H_x$ without $H_z$ is clearly symmetric. On the other hand, Figure 1c shows asymmetric DW expansion under the pulsed $\pm H_x$ with $H_z$ bias of +45 mT. This asymmetric DW motion originates from different configurations between the in-plane magnetic field $H_x$ and $H_{DMI}$.

Depending on whether the $H_z$ is parallel (red dotted box) or antiparallel (blue dotted box) to the Néel-wall component induced by $H_{DMI}$, the DW motion can be regarded to be assisted or disturbed, respectively. Figure 1d displays the speed of DW ($v_{DW}$) in the red box with respect to applied $H_x$. According to Je et al.,\[15\] the DW energy ($\sigma_{DW}$) in the presence of applied $H_x$ and $H_{DMI}$ is expressed by

$$\sigma_{DW} (H_x) = \sigma_0 + 2K_{DMI} \lambda - \pi \lambda M_s \cdot |H_x + H_{DMI}|$$

where $\sigma_0$ is the Bloch-type DW energy density, $K_{0}$ is the anisotropy energy density of DW, and $\lambda$ is the DW width. In the DW creep regime,\[22\] greater $\sigma_{DW}$ results in lower $v_{DW}$. The maximum of $\sigma_{DW}$ occurs when $|H_x + H_{DMI}| = 0$, meaning that $H_{DMI}$ is compensated by $H_x$. In Figure 1d, the minimum of $v_{DW}$ is observed at $H_x$ of approximately −25 mT, indicating that $H_{DMI}$ is around 25 mT in the red dotted box, also confirming the existence of DMI in the deposited multilayers.

2.2. Tunable Asymmetric DW Motion via Reconfiguration of AFM Spins

DW propagation was then investigated in the 10 µm-width wire patterns as shown in Figure 2. It is generally known that the DW
Figure 2. a) Up domain (top) and down domain (bottom) propagations in a wire-patterned sample, initially in the as-deposited state, without Hx bias. For all images in this figure, top panel (bottom panel) displays up (down) domain motion driven by +Hx (−Hx). b,c) Schematic diagram of magnetic fields acting on DW and experimental DW propagation in the presence of ±Hx. d) The schematic of the injection of spin current, generated from top Pt layer, into AFM IrMn layer for an alignment of AFM spins. e,f) Schematic diagram of magnetic fields acting on the DW and the experimental DW propagations after the onset of ±HAfM by the electric pulse injections. DWs with upward and downward motions were marked by yellow and blue dotted lines, respectively.

in a wire-patterned sample typically propagates as circular arc-shaped due to the pinning effect along both edges of the wire.\cite{22,23} Figure 2a shows propagation of DW (top: up domain propagation, bottom: down domain propagation) by the pulsed ±Hx (±30 mT) without an application of Hx. The DWs move with an arc-shape having nearly identical displacements at both edges. As demonstrated by the asymmetric DW motion in Figure 1, the \( v_{DW} \) can be modulated with the change of domain wall energy due to the Hx application in combination with DMI effect. Thus, we investigate the DW motion with simultaneous application of both Hx and Hx. Figure 2b,c shows the images of DW propagations by Hx (±30 mT) for Hx of +90 and −90 mT, respectively. Different from the case of Hx = 0 mT (Figure 2a), the application of Hx results in tilted DW propagation and the tilt angles are opposite for opposite directions of Hx. The schematic diagrams in Figure 2b,c illustrates why the DW moves with tilt angle. Hx is decomposed into two orthogonal components, perpendicular (H⊥) and parallel (H∥), with respect to DW segment.

Domain wall speed, \( v_{DW} \), varies depending on the relative configurations of Hx and HDMI at a specific DW segment, as formulated in Equation (1) with the Hx substituted by Hx in the present case. The \( v_{DW} \) is greatest when Hx is parallel to HDMI, and lowest when Hx and HDMI are antiparallel. Consequently, with the application of positive Hx (+90 mT) bias, the up-down (from up domain to down domain) DW speed at the right edge of the wire should be higher than the speed along the left edge in the upper images of Figure 2b, while the down-up DW speed at the left edge is higher in the bottom images. On the other hand, DW propagation under the application of identical ±Hx with negative Hx (−90 mT) bias in Figure 2c shows opposite behavior with the fast up-down DW speed at the left edge and the fast down-up DW speed at the right edge. These asymmetric behaviors of tilted DW are in good agreement with the previous investigation by Kim et al.\cite{16} where a crucial role of DMI for the asymmetric response of DW was pointed out.

It is notable that the FM layer in the multilayers has been exchange coupled to the adjacent AFM layer, but the coupling did not influence the dynamics of FM domains as the AFM layer is composed of many AFM domains with their Neel axes oriented randomly. Then the FM spin alignment at the interface between FM Co layer and AFM IrMn layer was introduced to influence the motion of tilted DW. It is particularly conceivable that the AFM spin alignment might alleviate the need for application of external Hx. Furthermore, there are increasing number of recent reports on the improved manipulations of local magnetic ordering state of AFM material employing the applications of electric current,\cite{24–29} mechanical strain,\cite{30,31} optical light with helicity,\cite{32} and electric field.\cite{33,34} Recent demonstration of AFM
Néel vector switching by current-induced spin-orbit torque (SOT) in various AFM systems has received increased attention, and been found to be particularly interesting as well as useful. It was reported that the electrical manipulating Néel order of AFM by SOT could be realized through two possible mechanisms attributed to field-like torque in AFM CuMnAs[24] and Mn$_3$Au,[36] and damping-like torque exerted by the polarized spin sources from heavy metal (HM) Pt layer due to a spin Hall effect (SHE) in Pt/AFM bilayers system such as Pt/CoO,[37] Pt/NiO,[38,39] Pt/α-Fe$_2$O$_3$,[40] Pt/Mn$_3$Au,[41] and Pt/Mn$_2$Sn.[42] In the present works, spin current from HM Pt layer was injected to the AFM IrMn$_3$ layer for the realignment of AFM spins as validated previously.[27] Considering a much higher resistivity of IrMn (269.3 $\mu\Omega$·cm)[43] than that of Pt (17.3 $\mu\Omega$·cm),[44] applied current should mainly flow through the Pt layer and SHE in Pt is expected to play a dominant role over the presence of SHE in IrMn.[45] Following an analogous procedure of flowing the charge current through the neighboring Pt layer directing the polarized spin Hall current to the adjacent IrMn AFM layer as illustrated in Figure 2d, proper AFM ordering of IrMn spins was achieved to exert an effective in-plane exchange bias field on the FM layer. The polarized spin, S$_p$, is directed normal to the charge current as represented by S$_p \propto I \times q$,[46] where I and q represent charge and spin current flows, respectively. The damping-like torque can be expressed as $\tau \propto m \times (m \times S_p)$, where m is magnetic moment vector of the AFM spin. Thus, individual magnetic moments in the AFM can be turned by the exerted spin torques, $\tau$, to align all spins into a uniformly ordered AFM state. Figure 2e,f shows perpendicular field-driven DW propagation without application of $H_x$ after positive and negative currents ($\pm I$) were flown along the length of the patterned wire. Surprisingly, after injecting a current pulse with $\pm 45$ mA-amplitude and 1 ms-length into the multilayers, the tilted DW propagation, which is usually activated by $H_x$, is achieved without $H_x$. We attribute this observation to the onset of $H_{IAFM}$, the effective field due to the uniformly ordered AFM state of IrMn layer, that serves in place of $H_x$ on the DW. The right-polarized spins generated from Pt top layer were injected and exerted torque to turn the spins in the adjacent AFM IrMn layer. Thus, randomly distributed IrMn spins of the as-grown state can be aligned uniformly along one transverse direction with respect to the wire due to the injection of right-polarized spins. Consequently, the effective field, $H_{IAFM}$ (represented as blue arrow in Figure 2e) due to a uniform ordering of AFM spins at the interface brings a change of typical arc shaped DW motion, implying that it plays the role of the applied external $H_x$. The perpendicular and parallel components of $H_{IAFM}$ ($H_z$ and $H_x$) to DW segment are illustrated in Figure 2e. The perpendicular component of $H_{IAFM}$ ($H_z$) is along the same direction as $H_{DMI}$ at the right edge and in opposite direction at the left edge, thereby the relationship between $H_z$ and $H_{DMI}$ leads to a local difference in DW energy. Figure 2e shows the propagation of tilted DW with high up-down DW speed at right edge under $+30$ mT of $H_z$ (top three images) and high down-up DW speed at the left edge under $-30$ mT of $H_z$ (bottom three images). Thus, we conclude that the tilted DW propagation is controlled by the uniform alignment of AFM spins only and note that the application of $H_x$ is not necessary.

It is worth pointing out that the magnetic state of AFM does not change in the body of the AFM itself upon the 180° rotations of AFM Néel vector via the injection of either positive or negative polarized spin currents. However, exchange bias effect of the FM layer coupled to the adjacent AFM reflects the spin alignment state at the interface between AFM and FM, hence the switching of $H_{IAFM}$ can be realized by 180° rotation of AFM Néel vector as well as the coupled uncompensated spins at the interface. Realignments of AFM spins at the interface in the opposite direction can also be readily achieved with the negative current pulse of $-45$ mA due to uncompensated interfacial AFM moments. The $H_{IAFM}$ (red arrow in the illustration of Figure 2e), by realignment of AFM spins in the left direction after the injection of oppositely polarized spins, have an opposite effect on the DW motion in comparison to the $H_{IAFM}$ (blue arrow in illustration of Figure 2e).

As a result, Figure 2f shows opposite behavior of tilted DW propagation with fast up-down DW speed at the left edge and fast down-up DW speed at right edge with respect to the results in Figure 2e due to the left edge aligned in the same direction as $H_{DMI}$. It was apparently demonstrated that the uniform realignment of AFM spins through the injection of negative or positive spin Hall current can decide a tilt direction of the DW as it propagates along the line-patterned magnetic track without an application of external transverse field, $H_x$. In general, alignment of AFM spins for the exchange bias effect has conventionally been carried out by the field-cooling method.[1] While reliable, the conventional field-cooling method may not be applicable to a multifunctional device with complex submicron scale structures because the direction of exchange bias is non-switchable once it is set. In this regard, our electrical and switchable approach is particularly advantageous for the realization and repeated operations of the miniaturized DW motion-based devices.

In order to quantify $H_{IAFM}$, we investigated the DW propagation under an application of $H_x$ bias field so that $H_{IAFM}$ and $H_x$ compete with each other. Initially, positive current pulse ($+45$ mA-amplitude, 1 ms-length) was injected into the wire, then the tilted DW with a tilt angle, $\theta_{tilt}$, was observed with an applied $H_x$ of $+30$ mT and zero-$H_x$ in the image (i) of Figure 3a. The magnitude of $\theta_{tilt}$ is about 35° at zero-$H_x$. With the addition of $H_x$, the tilt angle changes depending on the magnitude of $H_x$. As shown in the DW propagation image (ii) of Figure 3a, it is remarkable that the $\theta_{tilt}$ can be set to nearly 0° under simultaneous application of $H_x = -70$ mT. The variation of $\theta_{tilt}$ during DW propagation driven by a constant $H_x$ was measured as a function of applied $H_x$ ranging from 0 to $-70$ mT with a step of $-10$ mT. Figure 3b shows that the $\theta_{tilt}$ decreases gradually to zero as the magnitude of applied $H_x$ increases. Therefore, we concluded that the $H_{IAFM}$, induced by the aligned AFM spins, is effectively offset by the negative $H_x$. From the $H_x$ resulting in the zero tilt angle, the magnitude of $H_{IAFM}$ can be deduced to be approximately 70 mT. Therefore, from the results of Figures 2 and 3, it is noteworthy that the uniformly aligned AFM spins within a plane, coupled to FM with DMI, successfully replaces the $H_x$ leading to the tilted DW motion. Additionally, to check whether the previous observations also hold for a system with the opposite DMI, we prepared multilayers of SiO$_2$/Ti (4 nm)/Pt (4 nm)/IrMn$_3$ (8 nm)/Pt (0.4 nm)/Co (0.6 nm)/Pt (2 nm), deposited in a reversed order (Figure S1a, Supporting Information) as compared to the previous multilayer stack. We find that the opposite DW tilt directions are observed for the same AFM setting currents (Figure S1b,c, Supporting Information), suggesting that our explanation for the
2.3. Feasibility of Magnetic DW Logic Device

Recently, Luo et al.\(^{[47]}\) demonstrated that the chiral coupling between adjoining magnetic domains with competing DMI and the magnetic anisotropy could be exploited for the current-driven DW logic circuits. Accordingly, in our present work, tunable asymmetric DW motion with competing DMI and unidirectional exchange anisotropies (H_{DMI} and H_{AFM}, respectively) should have a great potential to be utilized in the DW logic devices. In order to explore the feasibility with DW logic device, we present that the tilted DW propagation can be used to select its propagation path at the wire junctions or intersections by controlling the H_{AFM}.

Figure 4 shows the propagation of tilted DW in the cross-patterned film with identical layer structure to the one in Figure S1 (Supporting Information). Arc-shaped down-up DW motion at a point of intersection was observed with the application of only negative H_{x} in the as-grown state of the sample without aligned AFM spins as shown in Figure 4a. Successive images (i) and (ii) in Figure 4a shows arc-shaped DW without tilt before it arrives the intersection of the cross pattern. As it propagates through the junction, the DW trifurcate symmetrically into three channels and progress continuously at the same speed as shown in the images (iii) and (iv). On the other hand, when the AFM spins are aligned as in Figure 4b,c, the tilted DW propagations show asymmetric motion as it turn around corners of the intersection. In the case of AFM spin alignment with a positive current pulse (Figure 4b), successively taken images (i) and (ii) indicate clockwise-tilt of down-up DW. The DW speed is higher at the left edge of the wire, hence the DW turns early toward the left branch. Thus, the DW in the left channel propagated much faster than in the right channel, and the arrival time of the DW’s at the branch ends are different. After the AFM spins have been realigned in opposite direction by injecting a negative current pulse, reversed DW tilt angle could be confirmed as mentioned previously, and the counterclockwise-tilt of the down-up DW is observed as shown in images (i) and (ii) of Figure 4c. Due to the opposite tilt of the DW front, as displayed in the images (iii) and (iv) of Figure 4c, the DW turns around the right corner easily and arrives at the right end earlier. Therefore, depending on the programmed direction of H_{AFM} by the current pulse polarity, the cross-patterned device can allow DW to arrive at only one of the channels first, emulating logic operation.

Finally, we demonstrate that the DW propagation pattern in the cross-patterned device can be imprinted by the combinations of H_{AFM} setting the currents in x and y axes directions. Figure 4d,e displays typical examples of DW propagation patterns when the setting current combination are in (+x, −y) and (−x, −y), respectively. While the vertical propagation channels show the same DW tilt direction, the horizontal channels show the opposite DW tilt direction. This will result in additional selection of DW propagation when the horizontal channel encounters another intersection. In this cross-patterned device, basically 4 different patterns can be programed. These results indicate the opportunity of controlling DW motions independently at a localized area within a complex patterned structure through a local and independent setting of H_{AFM} in contrast to an inconvenient operation mechanism based on global application of external magnetic field. Furthermore, with the extension of the present study, controlled dynamics of asymmetric DW would be able to provide a novel mechanism to DW logic gates in spintronics devices comprised of complex patterns.

3. Conclusions

In summary, we introduced exchange coupling to the ultrathin PMA FM layer with DMI by placing an adjacent AFM layer. In the HM/FM/AFM trilayers, the behavior of perpendicular field-driven DW motion was examined to find the modulation depending on the AFM spin configurations at the interface between AFM and FM layers. It was successfully demonstrated that the asymmetric DW propagates with a tilt angle controlled by an effective field of the uniformly aligned AFM spins (H_{AFM}) in combination with DMI field (H_{DMI}) and that the control can be achieved by perpendicular field only without a need for in-plane external magnetic field. Furthermore, the tilt angle of the DW front can be reliably reversed by the injection of spin current. Ultimately, it was shown that the propagation of tilted DW can be modulated or switched by the combined action of inherent H_{DMI} and spin current-controlled H_{AFM}. Further development of the concept to combine the DMX and exchange bias for the controlled DW state as well as its dynamics is expected to bring an understanding of novel mechanism for the controlled SOT switching or manipulation of ultra-small magnetic textures, that need to be resolved in relation with the recently raised issues on the field-free SOT switching of perpendicular magnetization\(^{[7]}\) and
Figure 4. In the crossbar-patterned sample, various behaviors of perpendicular field driven down-up DW motions without \( H_X \) can be generated depending on the configuration of AFM spins. DW propagations were measured in a) as-grown state with randomly distributed AFM domains, and after current injections of b) positive and c) negative currents along the vertical direction (\( y \)-axis), respectively. DW motions in the horizontal branch after injection of d) positive current and e) negative current along \( x \)-axis were also measured.

Stable skyrmion manipulations in exchange coupled AFM/FM structures,\(^{[5,6]} \) respectively.

4. Experimental Section

Two types of multilayers consisting of Ti (4 nm)/Pt (4 nm)/Co (0.6 nm)/Pt (0.4 nm)/IrMn\(_3\) (8 nm)/Pt (4 nm) with positive sign of DMI and Ti (4 nm)/Pt (4 nm)/IrMn\(_3\) (8 nm)/Pt (0.4 nm)/Co (0.6 nm)/Pt (2 nm) with negative sign of DMI were deposited on SiO\(_2\) substrates at room temperature by magnetron sputtering with a base pressure of \( \approx 1 \times 10^{-6} \) torr. Deposition process was carried out without applying an external magnetic field on the substrate resulting in the randomly oriented AFM and FM magnetic domains. The wire and cross-patterns with 10 \( \mu \)m width were manufactured by photolithography. Magnetic domains and the DW motions were observed by MOKE microscope. The duration of pulsed \( H_Z \) was 100 ms in the DW motion experiments. \( H_X \) and \( H_Z \) were biased by using in-plane and out-of-plane electromagnets, connected to the power supplies (BOP 20-20DL and PBZ20-20 manufactured by Kepco Inc. and Kikusui Electronics, Inc., respectively). In order to accurately align the \( H_X \) parallel to the film plane, the tilt sample stage was employed in the MOKE microscopy.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.
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