Experimentally tunable chiral spin transfer torque in domain wall motion

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Keywords: chiral spin torque, spin hall effect, domain wall motion

Abstract

Domain walls (DWs) can be moved very efficiently with nanosecond long current pulses in perpendicularly magnetized Co/Ni/Co nanowires formed with platinum under- and over-layers due to a chiral spin torque mechanism. In these structures the DWs exhibit a chiral Néel structure that has been proposed is set by a Dyzaloshinskii–Moriya exchange interaction (DMI) arising from the Pt/Co and Co/Pt interfaces. The strength of this interaction can be measured from the longitudinal field dependence of the current induced DW velocity. We show, thereby, that the magnitude and sign of the DMI is strongly dependent and monotonically changes as small changes in the thicknesses of the Co layers are made. However, due to the chiral nature of the DW we show that the magnitude and sign of the DMI is determined by the difference between the respective DMI at the upper and lower interfaces, which compensate each other. Thus, we find that the DMI increases as the lower Co thickness is increased but decreases as the upper Co thickness is increased, changing sign in both cases.

1. Introduction

The phenomenon of current induced domain wall motion (CIDW) in ferromagnetic (FM) nanowires has been a subject of considerable interest due to its possible applications in novel memory and logic devices [1, 2]. Early studies focused on in-plane magnetized nano-wires formed from permalloy and related soft magnetic alloys for which a spin-transfer torque (STT) derived from volume spin dependent scattering causes the DWs to move along the electron flow direction [3–7]. Recently, much higher DW velocities have been observed in FM wires formed from Co based magnetic multilayers with large perpendicular magnetic anisotropy (PMA) [8–10]. Moreover, the DWs move along the current or electron flow direction depending on tiny modifications to details of the magnetic multilayered structures [10, 11].

To account for this unusual behavior, two mechanisms have been proposed based on spin–orbit coupling which gives rise, in the presence of current, to Rashba fields at the FM nanowire surfaces [12–14] or to spin accumulations derived from the spin Hall effect (SHE) [15, 16] in heavy metal underlayers or overlayers. The latter has been identified as the root cause of CIDW in Co/Ni/Co sandwiched formed with Pt underlayers and overlayers but an essential ingredient is the stabilization of a chiral counterclockwise Néel DW structure in these sandwiches due to a Dyzaloshinskii–Moriya exchange interaction (DMI) [10, 17–21]. Charge currents in the Pt layers are converted to spin currents via a SHE in Pt that diffuse into the Co/Ni/Co layers and provide a STT that tilts the magnetic moments in the Néel DW structure towards a Bloch-like DW structure. In tandem with the damping torque the chiral DWs then move in the direction of current [10]. It has been shown that the DMI interaction is manifested as a longitudinal local magnetic field at the DW. The most challenging issue in the CIDW is to confirm whether its DW direction and velocity are controllable by changing the physical parameters.

Recently, some studies have shown that the CIDW mechanism is strongly dependent on the detailed structures of the wires. For example, it has been reported that the metal layer interfaced with the Co/Ni/Co stack is responsible for the difference in the CIDW mechanism, that is, the chiral spin torque (CST) for Pt, Pd, and Ir layers, and the STT for Au layer [22]. Moreover, the CIDW in an asymmetric Co/Ni wire has exhibited the...
transition of the mechanism from the CST to the STT with increasing the number of Co/Ni stacks [23, 24]. Also, the synthetic antiferromagnetic structure inserted by Ru layer gave rise to the exchanged-coupled DMI under the CST, resulting in the largest DW velocity [25]. Nevertheless, the underlying physics on the effect of the DMI under the CST on the CIDW is still unclear. In this letter we show how the sign and strength of the DMI, as determined from the longitudinal crossing field at which the DWs cannot be moved with current, can be systematically varied in Pt/Co/Pt nanowires by changing the thicknesses of the upper and lower Co layers. As these thicknesses are increased we find that the proximity-induced magnetizations in the adjacent Pt layers increases but at a much higher rate for the upper as compared to the lower Co/Pt interface. At the same time, the effective PMA $K_{eff}$ hardly changes at all as the thickness of the top Co layer is changed whereas there is a significant change as the lower Co layer thickness is adjusted. We conclude that the Pt/Co and Co/Pt interfaces are very different.

2. Experimental details

In these studies the current-induced motion of individual DWs was investigated using Kerr magneto-optical microscopy in nanowires 2 $\mu$m wide and 50 $\mu$m long (figure 1(a)) that were fabricated by optical lithography and
argon ion mill etching. An optical micrograph of a typical nanowire device is shown in figure 1(a). Nanosecond long current pulses are applied to contacts formed at the left and right ends of the device. First, by using an external magnetic field perpendicular to the plane of the nanowire whose magnitude is approximately that of the coercive field of the contact region (which is typically below that of the nanowire itself), a DW is nucleated in the contact region and then moved into the nanowire by a smaller magnetic field. Once a single DW is created the motion of the DW along the nanowire is measured using a sequence of Kerr images that are taken after a burst of current pulses of fixed magnitude and duration are applied. Typical results are shown in figures 1(b) and (c). By analyzing these images the position of the DW along the wire versus the integrated time that the current has been applied is found. Excluding any regions where the DW may be pinned the DW velocity is found.

The films were deposited by magnetron sputter deposition at ambient temperature on Si(100) substrates covered with amorphous SiO2. The structure of the films (see figure 1(d)) is of the form 50 Å Ta/10 Å Au/5 Å Pt/y Å Co/7 Å Ni/x Å Co/20 Å Pt/50 Å TaN, where the thicknesses of the two Co layers are varied (x = 2.0, 3.0 and 4.0 and y = 2.5, 3.0 and 3.5): we will label the samples by [x|y] for simplicity. Note that all the samples display PMA with square magnetic hysteresis loops, which enables us to easily make and manipulate the individual DWs.

3. Results and discussion

The direction of the DW motion driven by current could be tuned from the electron flow to the current flow direction by adjusting the upper Co thickness. For example, for the [2.5|x] samples, the DW moves in the direction of electron flow for [2.5|2.0], does not move at all for [2.5|3.0], and moves in the opposite direction along the current flow for [2.5|4.0]. This is clearly illustrated in the Kerr images shown in figures 1(b) and (c) for [2.5|2.0], [2.5|3.0], and [2.5|4.0].

Figure 2. Dependence of v on Hx measured using a current density of J ∼ 1.7 × 10⁸ A cm⁻² for nine different [x|y] samples with x,y values shown indicated in the panels. Data are shown for ↑↓ and ↓↑ DWs (red and blue symbols, respectively) and for positive and negative currents (open and closed symbols, respectively).
the [2.5|2.0] and [2.5|4.0] samples, respectively. The detailed dependences of the DW velocity \( v \) on the current density \( J \) are shown in figures 1(e)–(g) for the [2.5|2.0], [2.5|3.0], and [2.5|4.0] nanowires, respectively. The DW velocities are quite modest in these samples compared to structures with only one Pt/Co interface, as can be seen from figures 1(e)–(g). The reason is that the lower Pt/Co and the upper Co/Pt interface are competing with each other with regard to the spin–orbit torque that is driving the DWs. In particular, the spin currents generated by the SHE in the upper and lower Pt layers will be in opposite direction and directly annul each other. Since we have chosen the upper Pt layer to be much thicker (\( \sim 20 \) Å) than the lower Pt layer (\( \sim 5 \) Å) most of the SHE induced spin current will arise from the upper Pt layer. On the other hand the DMI is also chiral which means that the lower Pt/Co interface gives rise to a counter-clockwise DW, whereas the upper Co/Pt interface gives rise to a clockwise DW, as illustrated in the schematic diagram in figure 1(d). In this paper we show that the competition between the DMIs at the two Co/Pt interfaces can be sensitively affected by even slight changes in the Co layer thicknesses.

Previously it has been shown that the DW velocity is strongly influenced by a magnetic field directed along the nanowire perpendicular to the magnetization of the nanowire. In the absence of current this longitudinal field, \( H_x \), has little effect and the DWs do not move even for large \( H_x \). However, in the presence of current \( H_x \) either increases or decreases the DW velocity depending on the DW configuration, whether formed from domains pointing from an up to a down magnetization direction \( \uparrow \downarrow \), or from the opposite configuration \( \downarrow \uparrow \). The DW velocity increases or decreases approximately linearly with increasing \( H_x \) and, most importantly, becomes zero for a critical value of \( H_x = H_{CR} \). The magnitude of this crossing field reflects the strength of a DMI that was mentioned earlier. We find that \( H_{CR} \) varies sensitively with the thicknesses of the Co layers in the nanowire as discussed next.

The dependence of \( v \) on \( H_x \) measured using a current density of \( J \sim 1.7 \times 10^8 \) A cm\(^{-2} \), is shown in figure 2 for nine different [y|x] samples. Data are shown for both \( \uparrow \) and \( \downarrow \) DWs (red and blue symbols, respectively) and for positive and negative currents (open and closed symbols, respectively). As can be seen in figure 2 the DWs have zero (or nearly zero) velocity in the absence of \( H_x \) at the current density chosen for these experiments. However, even small values of \( H_x \) result in DW motion (although only in the presence of the current). In each case \( v \) varies nearly linearly with \( H_x \) with a slope \( \eta \) except for a field region near zero field for which the DW velocity is zero. The center of this field region is the crossing field \( H_{CR0} \), which is obtained by extrapolation of the \( v \)

\[ \text{Figure 3. Dependence of } H_{CR}, \eta, \text{ and } H_{MAX} \text{ as a function of (a), (c) and (e) the upper Co thickness } x, \text{ and (b), (d) and (f) the lower Co thickness, } y, \text{ respectively.} \]
versus $H_c$ curves, obtained at larger positive and negative fields, to $\nu = 0$ and taking the mean of these values. We find that $H_{CR}$ has the same magnitude but the opposite sign for $\uparrow\downarrow$ and $\downarrow\uparrow$ DWs as is clearly shown in figure 2. We note that the sign of $\eta$ is reversed compared to that reported previously for Co/Ni/Co stacks with only a single lower Pt/Co interface and, consequently, a dominant SHE induced spin current of the opposite sign to that in the samples discussed here.

To quantitatively understand the CIDW motion within a CST model, the magnitudes of $H_{CR}$, $\eta$, and $H_{MAX}$ are plotted as a function of the upper and lower Co thicknesses in figure 3, where $H_{MAX}$ is defined as the maximum field that can be applied without nucleating reverse magnetic domains. Note that $H_{MAX}$ varies little as the upper Co thickness $x$ is varied except for a weak dependence on $y$ for the $[3.5|x]$ samples, as can be seen in figure 3(c). $H_{MAX}$ is closely related to the magnitude of $K_{eff}$. $K_{eff}$ was measured from the difference in the magnetic fields required to saturate the magnetization of the same sample in-plane and out-of-plane from SQUID magnetometry studies. Values of $K_{eff}$ are plotted in figure 4(c) and the dependences of $K_{eff}$ on $x$ and $y$ have the same form as those of $H_{MAX}$.

The most important result in figure 3 is that the crossing field systematically decreases as the upper Co layer thickness is increased and systematically increases as the lower Co layer thickness is increased. Moreover, the variation of $H_{CR}$ with change in Co layer thickness, namely, $dH_{CR}/dx$ and $dH_{CR}/dy$, are almost linear in the range of Co layer thicknesses studied and have approximately the same value of $\sim 100$ Oe/Å. What this result clearly indicates is that the DMI at the upper and lower Co/Pt interfaces are compensating each other and that the dominant DMI derives from the bottom interface if we assume that the strength of the DMI increases as the Co magnetization at that interface increases.

![Figure 4](image-url). Dependence of $M_s$, $K_{eff}$, $H_{eff}$ and $H_{L}$ on $x$, (a), (c), (e) and (g) the upper Co thickness $x$, and (b), (d), (f) and (h) the lower Co thickness $y$, respectively.
The variation of the magnetic moment per unit area of the magnetic film, $M_{sat}$, (where $M_s$ is the saturation magnetization, and $t$ is the total thickness of the magnetic layers) versus the thickness of the upper and lower Co thicknesses is shown in figures 4(a) and (b), respectively. In both cases $M_{sat}$ increases as the Co thickness is increased but the added moment per unit area per unit thickness of Co is much higher for the upper layer than for the lower Co layer. We estimate that the rate of increase of $M_{sat}$ versus $x$ and $y$ are $\sim 1.57 M_{Co}$ and $\sim 1.16 M_{Co}$ respectively, where $M_{Co}$ is the saturation magnetization measured for a $\sim 500$ Å film of Co at the same temperature (all measurements are at ambient temperature). The increased moment beyond that of the added Co layers, i.e. $\sim 0.57 M_{Co}$ and $\sim 0.16 M_{Co}$, for the upper and lower Co layers, respectively, is likely due to increases in the proximity induced magnetization (PIM) in the adjacent Pt layers, as well as changes in the integrity of the multilayered structure, and finally a possible finite size effect that will increase the Curie temperature of the magnetic multilayer stack as its thickness is increased. Such a difference in the PIM of the two interfaces is considered to be due to the difference of the microscopic textures between the Co clusters in Pt layer and the Pt clusters in Co layer, where the former structure includes more (111) textures giving rise to the effectively larger spin–orbit coupling [26]. This effect may also has an influence on the opposite trend of $K_{eff}$ on the upper and lower Co thicknesses as seen in figures 4(c) and (d) since magnetic anisotropy is roughly proportional to spin–orbit coupling [27].

Values of $\eta$ are shown in figures 3(e) and (f). According to the 1D model of the CIDW that is developed in [10], $\eta$ is given by

$$\eta = \frac{\gamma \Delta + \frac{\gamma h_{ restitution}}{H_{SHE}}}{{\gamma h_{ restitution} + \alpha_k}},$$

where $\gamma$ is the gyromagnetic ratio, $\Delta$ is the DW width, $H_{SHE}$ is the effective field derived from the SHE, $\alpha$ is the Gilbert damping parameter, and $H_s$ is the DW in-plane shape anisotropy field. This model thus shows that $\eta$ depends only weakly on $H_{SHE}$ and, in any case $J$ is the same for all samples discussed here. The most important dependence of $\eta$ is on $\Delta$ on which it depends linearly. $\Delta$ is proportional to $(A_{ex}(K_{eff}))^{1/2}$ where the $A_{ex}$ is the exchange stiffness. Since $K_{eff}$ varies little with the upper Co thickness, as shown in figure 4(c), the increase in $\eta$ with this Co thickness may be attributed to an increase in $A_{ex}$. We note that $A_{ex}$ is decreased in Co–Pt alloys compared to pure Co [28]. On the other hand $\eta$ decreases as the lower Co thickness is increased concomitant with an increase in $K_{eff}$ (see figure 4(d)). We note that most of the change in $K_{eff}$ with varying Co thickness results from changes in the magnetization of the Pt/Co/Ni/Co/Pt stacks. The perpendicular anisotropy field, shown in figures 4(g) and (h) increases only slightly as the Co layer thicknesses are varied.

4. Conclusion

In summary, we report that the strength of the DMI that gives rise to chiral spin torque driven DW motion perpendicularly magnetized Pt/Co/Ni/Co/Pt racetracks is extraordinarily sensitive to small variations in the respective Co layer thicknesses. It is found that the change in DMI strength increases at approximately the same rate with increases in either of the Co layer thicknesses. However, the net contribution to the DMI from the upper Co/Pt and lower Pt/Co interfaces is opposite so that the DMI strength can be readily changed in sign with small variations in either of the Co layer thicknesses. This is the experimental finding that the transition of the DW motion between the current and electron flows can be controlled only by the change of the DMI under the negative SHE, not by the volume STT, which gives considerable insight into the CST mechanism.

Acknowledgments

This research was partially supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education(NRF-2015R1D1A1A01059698).

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