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In-plane field-driven crossover in the spin-torque mechanism acting on magnetic domain walls in Co/Ni

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We investigate the in-plane field dependence of current-induced magnetic domain wall motion in asymmetric Co/Ni nanowires. The application of an in-plane field changed the direction of domain wall motion. In a systematic study, by varying the magnetic layer thickness, we show that the in-plane field induces a crossover from spin Hall torque to adiabatic spin-transfer torque for the magnetic domain wall motion. Furthermore, the dependence of the threshold current density on the in-plane longitudinal field provides a way for determining the strength of the Dzyaloshinskii-Moriya interaction.

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Since the pioneering works of Slonczewski and Berger [1,2], current-induced domain wall motion (CIDWM) in ferromagnetic nanowires has been intensively investigated due to its fundamental interest [3–23] as well as its potential for device applications [9,24]. The CIDWM has long been described by spin-transfer torques (STTs) such as adiabatic and nonadiabatic STTs [25,26]. In this scenario, a domain wall (DW) is expected to move in the direction of electron flow.

Recently, the DW motion has been observed to oppose the electron flow direction in an ultrathin ferromagnet/nonmagnetic bilayer structure [27–33]. Spin-orbit torques, such as the Rashba effect [27] and the spin Hall torque [28–33], have been proposed as a possible origin of the reversed DW motion. Due to their interface-sensitive properties, the Rashba effect and the spin Hall torque are known to be enhanced in the ultrathin layer.

A recent study on the thickness dependence of DW motion in an asymmetric Co/Ni nanowire, where the Co/Ni layer is sandwiched between MgO and bottom Pt layers, has revealed that the driving mechanism of DW motion changes from spin Hall torque in thinner layers (up to 2.1 nm) to adiabatic STT in thicker layers (from 6.6 to 8.4 nm) [31]. The mechanism transition yields a direction change of DW motion from a current flowing direction in thinner layers to an electron flow direction in thicker layers. Furthermore, the DW dynamics also exhibits an apparent transition depending on the driving mechanism. When the DW is driven by the spin Hall torque, the DW shows a steady motion without precession [34]. On the other hand, the adiabatic STT induces precessional DW motion in a symmetric Co/Ni nanowire, where the Co/Ni layer is sandwiched between the top and bottom Pt layers [12]. This difference in the DW dynamics highlights an important fact: Two driving mechanisms cannot simultaneously drive the DW because the spin Hall torque would be averaged out for precessional motion and the adiabatic STT would not influence the DW motion as long as the DW shows a steady motion. Thus, only one current-induced torque dominates the DW motion at any given time, depending on the magnetic layer thickness.

In this Rapid Communication, we report that the driving mechanism for CIDWM can be selectively switched by applying an in-plane longitudinal field (H_L). The direction of the DW motion as well as the threshold current density (J_{th}) for the DW motion can be controlled by applying H_L. In other words, H_L selectively chooses the current-induced torques on DW motion, namely, the spin Hall torque or adiabatic STT. Further investigation performed by varying the magnetic layer thickness and DW polarity reveals that H_L changes the direction of the magnetic moment in the DW stabilized by the effective field (H_{DMI}) due to the Dzyaloshinskii-Moriya interaction (DMI) [35,36], resulting in the selection of the dominant torque.

Asymmetric Co/Ni films were deposited on an undoped Si substrate using dc magnetron sputtering. The structures of the films were Ta(4)/Pt(2)/MgO(1)/[Co(0.3)/Ni(0.6)]$_{N=3-5}$/Co(0.3)/Pt(2)/Ta(4)/Si substrate, where the number in parentheses indicates the layer thickness in nanometers. The thickness of the magnetic layer $t_{Co/Ni}$ was controlled by changing the stack repetition N. Asymmetric Co/Ni films were made by inserting an MgO layer between the top Pt and Co/Ni layers in the structure. Note that in symmetric Co/Ni films, precessional DW motion driven by adiabatic STT is dominant, independent of the Co/Ni thickness [22]. Figure 1 shows a schematic illustration of the device structure with the measurement setup. The 220-nm-wide and 6-μm-long nanowires were fabricated using electron beam lithography and Ar ion milling. Two Ta(5)/Au(100) electrodes, labeled A and B, were attached to the nanowires to inject current for nucleating or driving the DW. The DW motion was electrically detected by measuring the anomalous Hall resistance (R_{Hall}) at the Hall cross. A small dc current (+20 μA) was injected to measure the Hall resistance, where $+J$ ($-J$) is defined as the current (electron) flowing from electrode A to electrode B.

The CIDWM experiment was performed as follows. After making a single domain state by applying a strong out-of-plane magnetic field ($H_Z = +0.4$ T), we nucleated a down-up DW next to electrode A by injecting a current pulse (−120 mA, 15 ns) through electrode A. After introducing a DW, a series of 10-ns current pulses was injected between electrodes A and B to drive the DW until the total integration time was 1 μs. Then, R_{Hall} was monitored at the Hall cross region to verify DW

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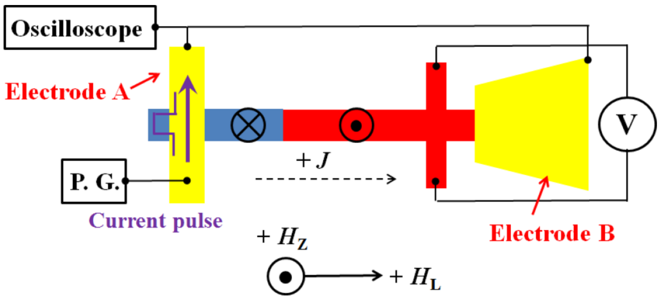

FIG. 1. (Color online) Schematic drawing of the device structure and measurement setup. Directions of perpendicular and in-plane longitudinal fields are defined as $+H_Z$ and $+H_L$. $+J$ shows a direction of current flowing through a magnetic layer.

propagation across the Hall cross. The DW motion probability P_{DW} was determined from ten repeated measurements for each current strength J.

In this study, we chose intermediate thicknesses for the Co/Ni layer ($t_{\mathrm{Co/Ni}} = 3.0$–4.8 nm) in which the CIDWM was not observed without an external magnetic field [31]. We first investigated the CIDWM for $t_{\mathrm{Co/Ni}} = 3.0$ nm. Figure 2(a) shows the DW motion probability P_{DW} as a function of current density J for a down-up DW with various H_L from -60 to $+60$ mT. Here, J is defined as the current density flowing along the magnetic Co/Ni layer, which is determined by considering the sheet resistance of each layer. The direction and sign of H_L are denoted in Fig. 1(a). To drive the DW, we injected a current up to 3×10^{12} A/m^2, above which the current-induced deterioration due to, e.g., electromigration or Joule heating, prevents the observation of DW motion. Without H_L, DW motion was not observed in the current range investigated. However, we found that DW motion is triggered by H_L. With a positive H_L, the DW is moved along the current flow direction. On the other hand, DW is moved along the electron flow direction when we apply a negative H_L. To verify the effect of the DW chirality, we performed the same experiment using an up-down DW. Figure 2 (b) shows the result for an up-down DW. The result is almost the same as that for the down-up DW if we reverse the sign of H_L, indicating that the chirality of DW is fixed in our sample (left-handed chirality, that is, up-left-down DW or down-right-up DW, is preferred [31]). The chirality of DW could be determined by the DMI possibly originating from the interface between the bottom Pt and Co/Ni layers.

In Fig. 3, we schematically illustrate a DW structure in the nanowire used in this study. When we flow a current into the nanowire, the current can exert two torques on the DW. The current injected into the magnetic Co/Ni layer exerts an adiabatic STT on the DW, resulting in DW motion in the electron flow direction [12]. On the other hand, the current flowing in the nonmagnetic Pt layer generates a transverse spin current due to the spin Hall effect. The generated spin current in the Pt layer is injected into the magnetic layer and induces a spin Hall torque on the DW. The direction of DW motion driven by spin Hall torque depends on the relative direction between the injected spin and the magnetic moment of the Néel DW,

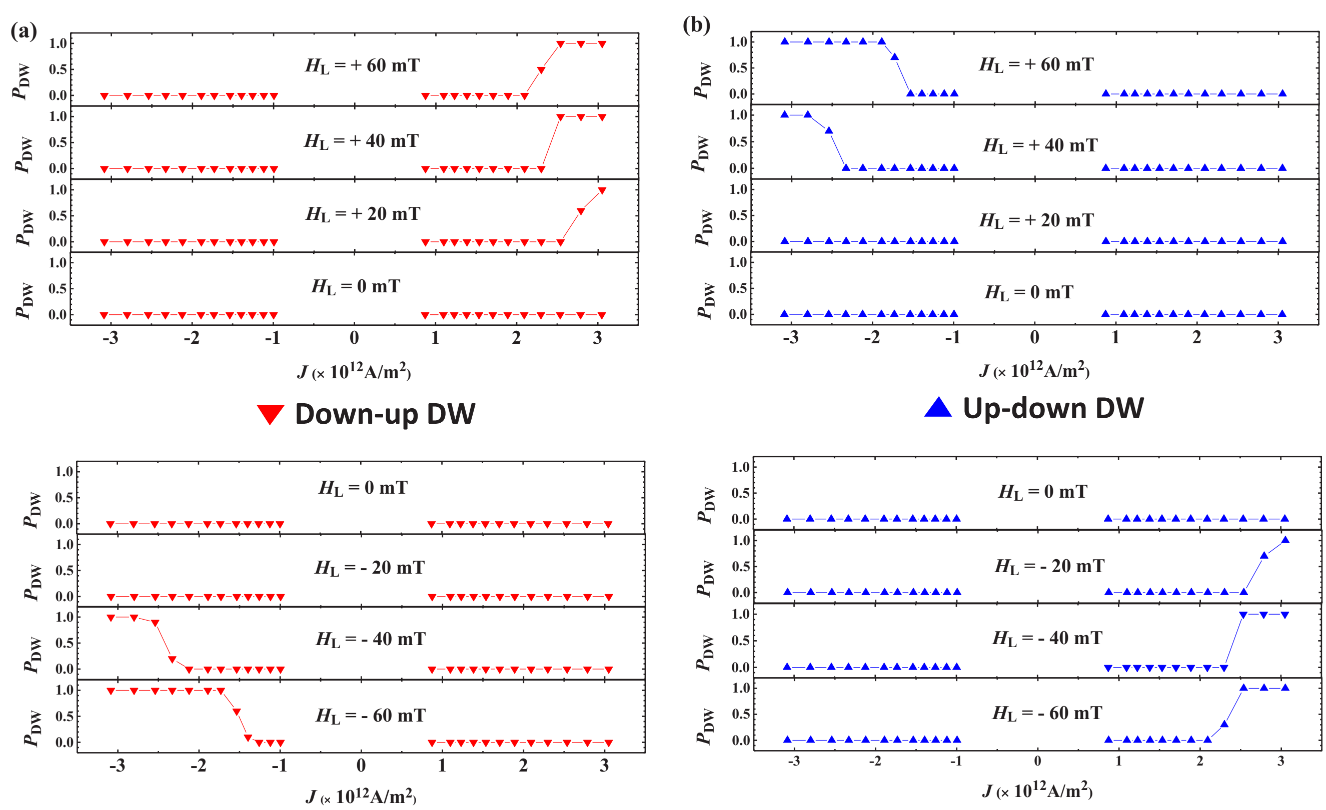

FIG. 2. (Color online) DW motion probability (P_{DW}) as a function of current densities (J) for $t_{\mathrm{Co/Ni}} = 3.0$ nm under an in-plane longitudinal field (H_L) for (a) a down-up DW and (b) an up-down DW. P_{DW} are estimated by ten times measurements for each J.

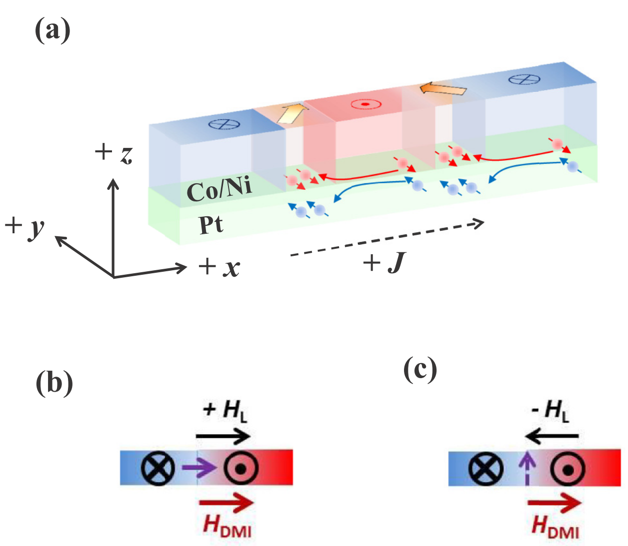

FIG. 3. (Color online) (a) Schematic illustration of the DW structure in a Co/Ni nanowire that is contacted with a Pt layer. DW structures for a down-up and an up-down DW are expected to be in the intermediate state between the Bloch DW and Néel DW due to the reduced effect of the DMI in the intermediate thickness. (b) A Néel DW structure is expected when H_{L} is applied parallel to H_{DMI}. (c) A Bloch-like DW structure is expected when H_{L} is applied in the antiparallel direction to H_{DMI}. The purple arrow shows the magnetic moment inside DW.

which is determined by the DMI. In our device, the spin Hall torque pushes the DW in the direction opposite to the electron flow [31]. Thus, the spin Hall torque and the adiabatic STT drive the DW in the opposite direction in the device. Moreover, DMI is known to rigidify the internal structure of the DW as a Néel DW that, simultaneously, prevents the precessional motion. Recalling that the spin Hall torque induces steady DW motion whereas the adiabatic STT causes precessional DW motion, we infer that the strong DMI enhances the contribution from the spin Hall torque and suppresses the adiabatic STT contribution.

The experimental results in Fig. 2 indicate that neither the spin Hall torque nor the adiabatic STT can drive the DW in the intermediate thickness regime without the presence of H_{L}. This occurs because the DMI in the intermediate thickness regime is too weak to induce a spin Hall torque-driven DW motion and is too strong to induce an adiabatic STT-driven DW motion. Based on this argument, we conjecture that the DW would be an intermediate state between the Bloch DW and Néel DW, as shown in Fig. 3(a). When we apply H_{L}, however, the DW starts to move (Fig. 2), which can be understood as follows. In Figs. 3(b) and 3(c), we schematically illustrate the structure of the DW when H_{DMI} is parallel or antiparallel to H_{L}, respectively. If we apply H_{L} parallel to H_{DMI}, H_{L} strongly rigidifies the Néel DW structure [Fig. 3(b)]. In this case, the spin Hall torque contribution increases because the maximum spin Hall torque can be expected in a perfect Néel DW structure. This argument further explains the results for $+J$ in Fig. 2, where DW moves in the current flow direction under H_{L}. On the other hand, when H_{L} is antiparallel to H_{DMI} [Fig. 3(c)], we expect that H_{L} cancels H_{DMI}, and the DW becomes a Bloch-like structure. Thus, in this situation, DW can easily precess, which enhances the adiabatic STT contribution, resulting in DW motion in the electron flow direction shown in Fig. 2. Based on the above argument, we conclude that the dominant torque for DW motion can be selectively chosen with an appropriate application of H_{L}.

The selectivity of the current-induced torque by H_{L} can be further confirmed by varying the magnetic layer thickness. We investigated the effect of H_{L} on the current-driven DW motion for several Co/Ni thicknesses, $t_{\mathrm{Co/Ni}} = 3.0$–4.8 nm, and plotted J_{th} as a function of H_{L} in Fig. 4. Here, we use an absolute value of H_{L} as an abscissa to exhibit both the results obtained from the up-down and down-up DW. The dependence of J_{th} on H_{L} differs depending on the sign of J, that is, depending on the dominant current-induced torque. For the case of $+J$, where the DW is moved by the spin Hall torque, DW motion is observed when H_{L} is parallel to H_{DMI}. For $t_{\mathrm{Co/Ni}} = 3.0$ nm, J_{th} slightly decreases as H_{L} increases and saturates above $H_L = 60$ mT. This behavior is consistent with the idea that the effect of the spin Hall torque would saturate after the DW becomes a perfect Néel DW. For $t_{\mathrm{Co/Ni}} = 3.9$ nm, the DW motion is observed only above $H_L = 60$ mT, and finally, the DW motion is not observed for $t_{\mathrm{Co/Ni}} = 4.8$ nm, which implies that the effect of the spin Hall torque becomes less effective in thicker layers. On the other hand, for the case of $-J$, where the DW is moved by adiabatic STT, the DW motion is observed when H_{L} is antiparallel to H_{DMI}. In this case, we observed the reduction of J_{th} with H_{L} for all layer thicknesses, indicating that the adiabatic STT does not depend on the layer thickness. Therefore, the thickness dependence on DW motion confirms that H_{L} can be selectively applied to control the current-induced torque.

Finally, we note that the strength of DMI can be quantified when the DW is driven by the adiabatic STT. For the adiabatic STT-driven DW motion where precessional DW motion is predicted, J_{th} should be at a minimum value when H_{DMI} is exactly cancelled by H_{L} because an additional increase of H_{L} prefers a Néel DW with opposite chirality. Thus, we can estimate the strength of the DMI from the observation of the J_{th} minimum value while sweeping H_{L}. The minimum value of J_{th} is indeed observed for $t_{\mathrm{Co/Ni}} = 4.8$ nm, as shown in Fig. 4(c). From this result, we can estimate the strength of H_{DMI} to be 60 mT for $t_{\mathrm{Co/Ni}} = 4.8$ nm. Although the minimum J_{th} is not clearly observed in Figs. 4(a) and 4(b) due to the limited measurement range of H_{L}, H_{DMI} seems to increase as the layer thickness decreases, which is consistent with the interfacial origin of the DMI. Therefore, the H_{L} dependence of J_{th} for adiabatic STT-driven DW motion provides a method for quantifying the strength of the DMI.

We have investigated the in-plane field dependence of current-induced magnetic DW motion in asymmetric Co/Ni nanowires in the intermediate thickness regime where DW motion was not observed in the absence of an external magnetic field. We found that H_{L} triggers the current-induced DW motion and controls the direction of DW motion. Further studies performed by varying magnetic layer thickness, current polarities, and DW polarities revealed that tuning the effective field on DW by the application of H_{L} leads to a selective current-induced torque for the DW motion. Furthermore, the

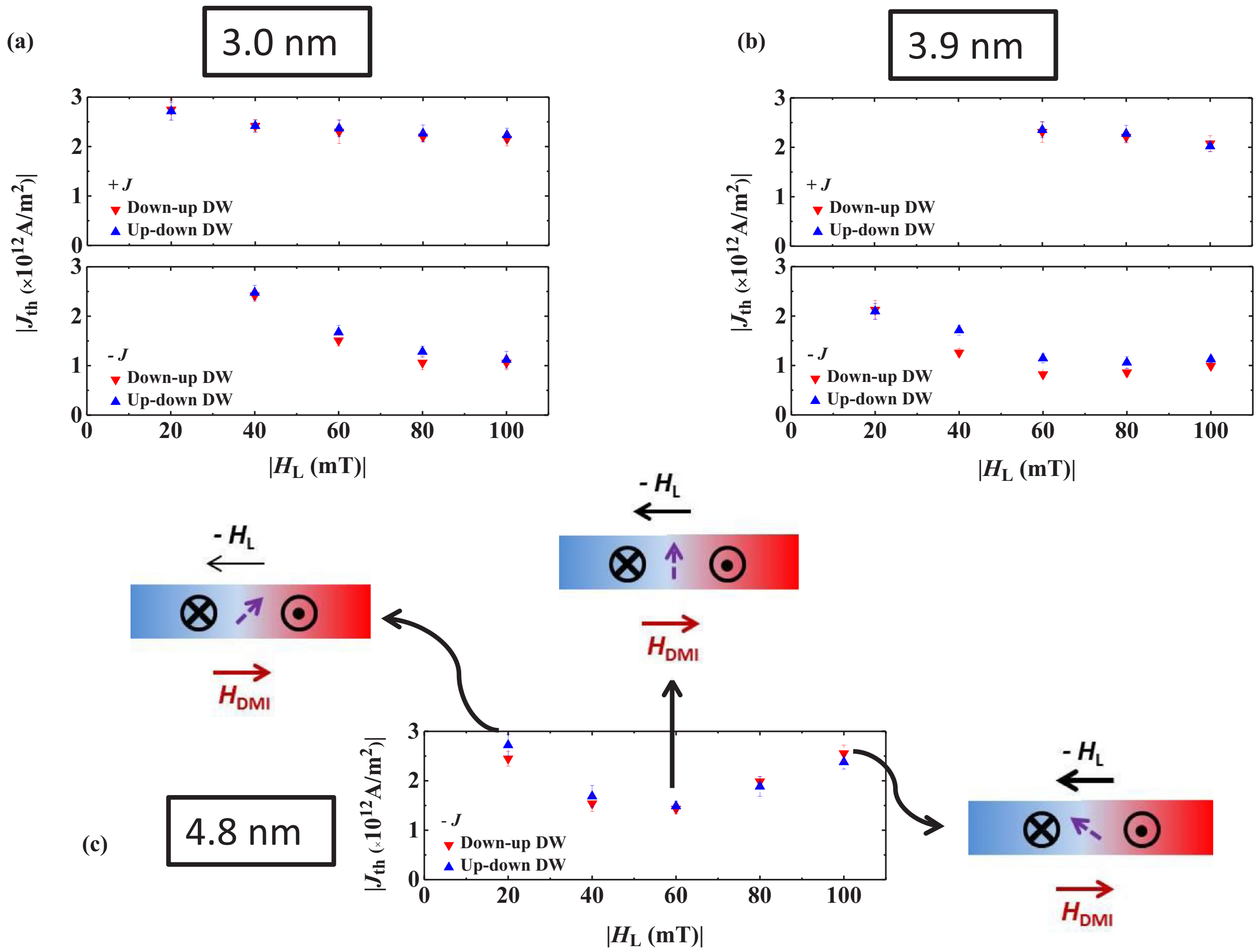

FIG. 4. (Color online) Threshold current density (J_{th}) as a function of in-plane longitudinal field ($|H_L|$) for several magnetic layer thicknesses: (a) $t_{Co/Ni} = 3.0$ nm, (b) $t_{Co/Ni} = 3.9$ nm, and (c) $t_{Co/Ni} = 4.8$ nm. Red and blue triangles show a down-up DW and an up-down DW, respectively. J_{th} is defined as J, where P_{DW} reaches to 0.5. Error bars show 20/80% probabilities. $|H_L|$ indicates an absolute value of H_L. Schematic diagrams in (c) show a transition of the DW structure with H_L.

observation of the minimum J_{th} by sweeping H_L provides a way for determining the strength of the DMI. Our study, therefore, suggests that H_L is a useful tool for manipulating DW motion as well as for quantifying the strength of the DMI.

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