Current- and Field-Driven Domain Wall Motion in L- and C-Shaped Permalloy Nanowires With Different Wire Widths

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We investigated the pulse-current-driven and magnetic-field-driven domain wall (DW) motion in permalloy nanowires with different shapes and wire widths. Two different nanowire types, 600 nm wide L- and 300 nm wide C- shaped, were considered by means of magnetic force microscope and anisotropic magnetoresistance measurement. We confirmed that every time head-to-head vortex DWs were placed at the specific places as we intended for both types of nanowires. We found similar critical current densities ($\sim 5 \times 10^{11}$ A/m^2) and DW velocity (~ 2.0 m/s) for both nanowires in spite of their different shapes and widths. Multiple vortex DWs were also observed when the applied current density exceeded only a few percent of the critical values. We also performed magnetic-field-driven DW propagations. From the pinning and depinning images and anisotropic magnetoresistance measurement, we found the magnetoresistance value of the single vortex type DW for the L-shaped permalloy nanowire.

***Index Terms*—Anisotropic magnetoresistance (AMR), domain wall (DW) motion, spin-transfer-torque.**

I. Introduction

THE spin-transfer-toque is one of the most briskly performing studies in the field of magnetism and magnetic materials [1], [2]. If a magnetic material is long enough to be magnetized in two different directions, a single domain wall (DW) can be generated in the interface separating the two magnetic domains. The DW can be moved by an applying current as a result of the spin-transfer-torque effect or the magnetic field due to minimization of the Zeeman energy. The dynamics of DW motion in magnetic materials opened the door to new practical applications such as novel magnetic shift register memory [3] and logic devices [4]. Many kinds of experimental studies on the current-driven DW motion have been reported so far [5]–[12]. However, the current-driven dynamics of DWs is not well understood. For field-driven case, when a magnetic field is applied to be tilted from the wire direction, it makes an angle between the magnetization direction and the current flow. This causes the decrease of anisotropic magnetoresistance (AMR), which reaches the minimum value when the magnetization direction is perpendicular to the current flow. Thus, from the AMR measurements, the field-driven DW motion can be measured. In this paper, we report the experimental results of the pulse-current-driven and magnetic-field-driven DW motions by using a magnetic force microscope (MFM) and simultaneously measuring the AMR.

II. Experiments

Two Py (permalloy) nanowires with different shapes, L-shaped and C-shaped nanowires, were fabricated on Si/SiO_X substrate. The nanowire patterns were defined by using electron-beam lithography and liftoff method. Fig. 1(a) and (b) show the 600 nm wide L-shaped and the 300 nm wide C-shaped nanowires are the same thickness of 20 nm and the curvatures of the L- and C-shaped nanowires are 1.5 μm and 8 μm, respectively. The width was determined with a scanning electron microscope (SEM) and the thickness was determined with an atomic force microscope (AFM). To visualize the current- and field-driven DW motion, the MFM (SPI4000/SPA-300HV, SII NanoTechnology) was used in vacuum environment. In order to minimize the influence of the stray field from the magnetic probe on the DW, a low-moment probe (SI-MF40L) coated with CoCr was used for MFM images. For the DW generation in the L-shaped nanowire, a large magnetic field of up or down direction at 5 kOe was applied with an angle of 10° to the short wire axis, and then it was reduced to be zero. After the aforementioned DW generation, a pulsed voltage was applied to the sample for studying the current-driven DW motion, which gives rise to the values of critical current density (J_C) and DW velocity (v). In order to detect the real current flow to the sample, we measured the voltage with a sampling oscilloscope after the pulsed voltage input passed the sample. Even though a pulsed input signal was clearly made, the measured voltage pattern after passing the sample showed overshoots within an error bar less than 10% at the edges when rising and falling

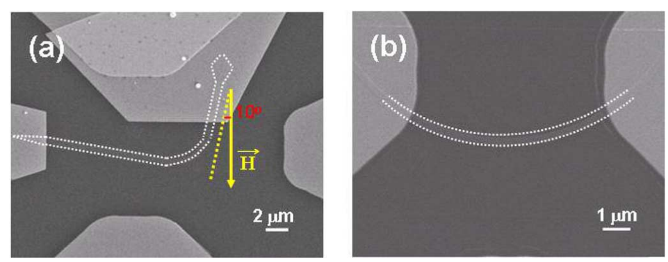

Fig. 1. SEM images of the (a) L- and (b) C- shaped nanowires.

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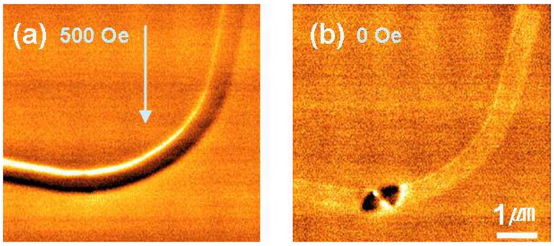

Fig. 2. MFM images of the L-shaped nanowire (a) on the magnetic saturation state in a down direction with a 500 Oe applied field to the down direction. The white arrow represents the applied field direction. (b) The image of the heat-to-head vortex type DW. It was nucleated after reducing the field to the zero.

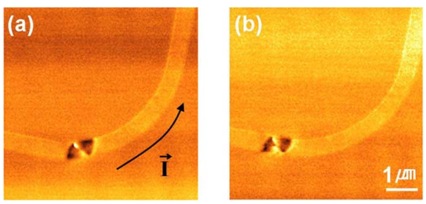

Fig. 3. (a) MFM image after the nucleation of the DW. (b) MFM image after the application of the pulsed current with the current density of 5.0×10^{11} A/m^2 with a pulse duration of 500 ns. The distance of the DW motion is 1.2 μm.

voltages. This may be ascribed to the parasitic capacitance at the contact pad on the sample.

III. Results and Discussion

In order to create a DW at the specific place for L- and C-shaped nanowires, we applied the field carefully and used the shaped anisotropies. For 600 nm wide the L-shaped nanowire, the field was applied along the down direction of the nanowire. Fig. 2(a) shows a MFM image with the direction of the applied field (white arrow). In this image, the dark and bright parts indicated the direction of up and down stray fields, respectively. After that, the applied field is down to the zero. In this case, the head-to-head vortex-type DW can be generated at the bending corner owing to the strong magnetic-shape anisotropy. According to the phase diagram of the DW [13], [14], the vortex-type DW is energetically favorable than the transverse Néel wall. The head-to-head DW is imaged as a dark contrast in Fig. 2(b). As we designed, the DW is placed around the bending corner whose curvature is 1.5 μm.

After we placed the DW at the bending corner, the current pulses were applied. The amplitude of the pulsed voltage was increased until the DW is moved. Fig. 3(a) and (b) show the MFM images before and after a current pulse. The critical current density, $J_C = 5.0 \times 10^{11}$ A/m^2 is found in this experiment for the 500 ns pulse duration. The corresponding DW velocity (v) is 2.4 m/s. It must be mentioned that when the current density increased to 5.1×10^{11} A/m^2, which is corresponding to a few percent larger current density than J_C, a single vortex DW transformed to the double vortex DW. (not shown here) Even though the small change of J_C, the Joule heating of the nanowire can be serious because of the temperature rising is proportional to the square of the J [15], [16]. The temperature increase for

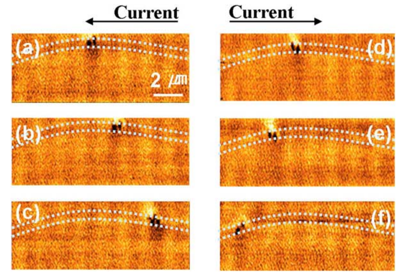

Fig. 4. MFM images of pulsed-current-driven DW motion in the C-shaped Py nanowire after each 1-μs pulse (a)–(c) and (d)–(f) for each polarity of the current with the current density of 5.4×10^{11} A/m^2 with a pulse duration of 1 μs. The distance of the DW motion is 2.0 μm. The black arrows are the current directions.

the nanowire will lower the energy barrier, and make the probability of the transformation from the single to double vortex DW larger [17].

For the 300 nm wide C-shaped nanowire, which is part of a ring structure, the field was initially applied to the up direction to saturate whole structure. After saturation, the field was slowly reduced to zero. With above procedures, a single vortex DW was formed at the top of the C-shaped nanowire, as shown in Fig. 4(a). Fig. 4(a)–(c) shows that the DW was moved from the center to right after the application of the pulsed current from right to left. Furthermore, when the pulsed current direction was reversed, the DW was moved in the opposite direction, as shown in Fig. 4(d)–(f). This indicates that the direction of DW motion is opposite to the current flow, the electron flow direction, as theory expected. At the critical current density of $J_C = 5.4 \times 10^{11}$ A/m^2, DW moved 2 μm with 1 μs current pulse. The correspond $v = 2.0$ m/s is typically observed velocity in several groups [18], [19]. Note that the current-driven DW motion is occasionally accompanied by the reversal of the vortex wall chirality, as pointed out in [20]. These results were highly reproducible during repeating 20 times.

The Joule heating effect was also serious in these experiments. When the applied current density was exceeding 5.5×10^{11} A/m^2, which corresponds to 1.8% increment compared to the critical current density, multidomain structures were quite easily observed. Such kind of transformation from single to multidomain structures manifested itself a serious Joule heating. According to [15] and [16], the temperature increase of the nanowire is $\Delta T \propto \rho w h J^2 / K_S$. Here, ρ, w, and h are resistivity, width, and thickness of the nanowires, and K_S is the thermal conductivity of the substrate. From this formula, we could estimate the temperature increase for the nanowire, which is about 500 K. This suggests that the actual temperature of the nanowire just after applying current pulse is almost the Curie temperature of permalloy. Since all of these experiments were performed for the 300 and 600 nm wide nanowires, and used Si/SiOx substrates whose thermal conductivity is very poor, these nanowires ware easily heated. The Joule heating problem is one of the important issues in current driven domain motion [18].

The magnetic-field-driven DW motions were also studied by using the MFM and simultaneously measuring the AMR. Fig. 5 shows the MFM images observed in various magnetic

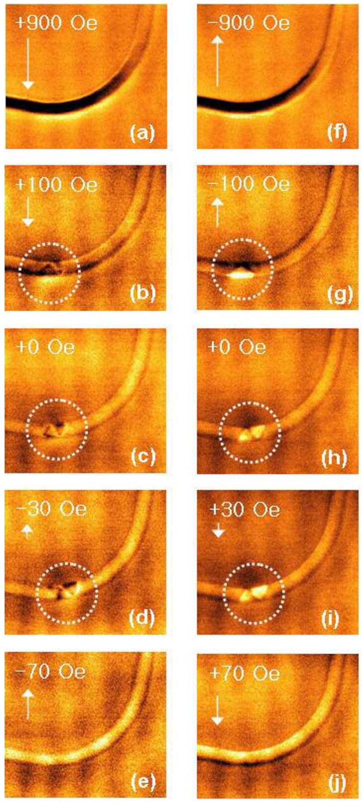

Fig. 5. MFM images of each applied magnetic field for the L-shaped nanowire. The white arrows are the applied magnetic field direction.

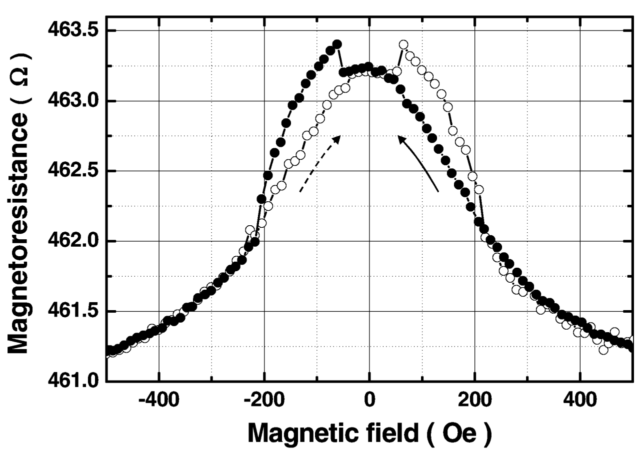

Fig. 6. AMR as a function of the applied magnetic field for the L-shaped nanowire. The dash and solid arrows are the applied field direction from up to down and from down to up, respectively.

fields. A head-to-head-type DW was progressively generated by applying a large field of +900 Oe [Fig. 5(a)] followed by reducing the field to +100 Oe [Fig. 5(b)], and it stayed at a zero field [Fig. 5(c)] and until a magnetic field of −30 Oe was applied in the opposite direction [Fig. 5(d)]. However, the DW suddenly disappeared at −70 Oe [Fig. 5(e)]. These results are quite repeatable when the magnetic field was reversely swept. In order to detect how the DW motion affects the transport properties, we have measured the AMR signal by using four-probe technique under an application of constant current about 10 μA. The applied current cannot affect the DW motion because it is order of three weaker than the critical current density. As shown in Fig. 6, the AMR results are consistent with the MFM observations. A slow deviation between the field-sweep-up and the field-sweep-down curves was observed around 200 Oe, which corresponds to the field when the DW was generated. Furthermore, there was a sharp jump around 50 Oe, which is corresponding to the field when the DW disappeared. The existence of the DW lowers the magnetoresistance of about 0.2 Ω as shown in Fig. 6. Such drop indicates the AMR value of the DW itself, probably corresponding to the single vortex state. This result is compared to that in [20] and [21], where the transverse and vortex states correspond to the resistance changes of 0.2 Ω and 0.3 Ω, respectively. Here, it should be noted that the AMR signal is slowly changed when the DW is nucleated, while the AMR signal shows an abrupt jump when the DW is moved out. These results imply that the DW would be progressively generated by applying the magnetic field, while the DW motion driven by the field would be sudden. Note that a transverse wall is nucleated at 100 Oe, which is transformed into a vortex wall when the field is reduced to zero. The detailed studies on the DW transformation by applying the field will be presented elsewhere, in addition to the micromagnetic simulations.

IV. Conclusion

In conclusion, we designed 600 nm wide L- and 300 nm wide C-shaped nanowires in order to confine a DW at specific places. With procedures of the proper applied field, head-to-head vortex DWs were placed at the desired places. Successive current-driven DW motions were imaged by MFM. We found similar critical current densities and DW velocities for both Py nanowires in spite of their different shapes of the nanowire. We conjectured that the pinning effect of the shapes is smaller than one of the imperfections of nanowire.

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