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Current detection of vortex motion in patterned S-shape wires with constrictions

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The current-driven effect on the vortex domain wall in a series-connected permalloy S-shape patterns was investigated. When a domain wall is initially formed in the wire section, in contrast to the ac result, applying a low dc current ($J \sim 10^5$ A/cm^2) will break the degeneracy of the switching energy in different connected sections. Moreover, three kinds of effects on vortex states are observed by applying a high dc current ($J \sim 10^7$ A/cm^2). The current applied slightly below the original switching field will drive vortices to constrictions while the current applied far below the original switching field will only perturb the vortex to another stable state. At the fields slightly over the original switching field, the domain walls are initially trapped at constrictions, injecting current will cause both the depinning and deformation of vortices. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2166591]

I. INTRODUCTION

Current-induced magnetization switching has attracted a great interest recently.[1–6] When a large dc current flows across a domain wall, several effects, including Oersted field from the current itself, the spin torque transfer, the domain drag, and the linear domain transfer, are expected to occur.[7–9] Most theoretical results predict spin current modifies wall structure;[9–11] however, more experimental evidences are still needed. It has been *in situ* demonstrated experimentally that the velocity of a wall driven by pulsed current will vary with the spin configuration of the domain wall.[12] In this study, we investigate the current-driven vortex domain-wall motion in S-shape patterned wires by applying continuous high and low dc currents. Current-driven effect with different initial magnetic structures is also discussed.

II. EXPERIMENT

S-patterned $Ni_{80}Fe_{20}$ narrow wires with a geometry as shown in Fig. 1(a) were examined. The wires consist of seven identical, series-connected half-ring units, which are of 1 μm linewidth and 5 μm diameter. To effectively trap the domain wall, a tip-to-tip notch of 200 nm width was fabricated to connect two adjacent half-rings. Ti/Au leads for magnetoresistance (MR) measurement are patterned at both ends of the S-patterned wire. The wires and the leads were prepared by electron-beam lithography (Hitachi 4200) and lift-off techniques. During the MR measurement, the resistance was measured by a four-channel detection system at 77 K with applied magnetic field up to 4 kOe. The magnetization reversal processes and domain structures in the films were investigated by magnetic force microscopy (MFM) (DI 3100) and numerical simulation using object oriented micromagnetic framework (OOMMF) (code from the National Institute of Standards and Technology). High-density dc currents for measuring the current-driven effect are provided by Keithley 6430.

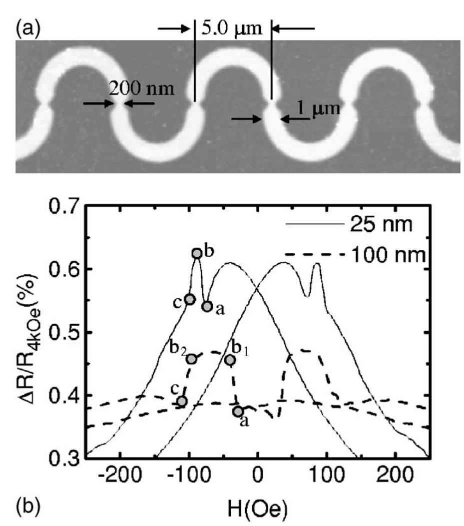

FIG. 1. AFM image of the series-connected S-shaped $Ni_{20}Fe_{80}$ wire. (b) The field-dependent magnetoresistance curves measured at 77 K for film thicknesses of 25 and 100 nm, respectively. The magnetic field is applied perpendicular to the long axis of the structure.

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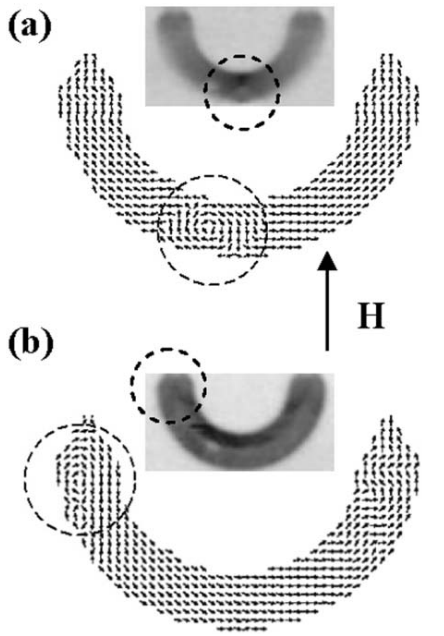

FIG. 2. Simulation results for the propagation of vortex state (a) before and (b) after magnetization switching. The inset shows the corresponding MFM images. The arrow indicates the instant magnetic-field direction.

III. RESULTS AND DISCUSSION

Figure 1(b) shows the typical variation of MR ratio $[\Delta R/R_{4\ \mathrm{kOe}}=R(H)-R(4\ \mathrm{kOe})/R(4\ \mathrm{kOe})]$ as a function of applied magnetic field for films with 25 and 100 nm thickness. The field was applied in the in-plane transverse direction, i.e., perpendicular to the long axis of the S-shape pattern. The MR curves can be basically interpreted through the anisotropic magnetoresistance (AMR) effect. When the magnetic field decreases from the positive saturation, the magnetic moments gradually rotate from field-parallel toward wire-parallel directions due to the shape anisotropy. After the magnitude of field keeps increasing in the negative direction, the magnetization tends to deviate away from the wire, resulting in the formation of vortex domain walls in the wire sections, as shown in Fig. 2(a). Due to the transverse magnetization component in the vortex wall and multidomain in the wire, the MR curve shows a local minimum [Fig. 1(b), point *a*]. The MR value then jumps [Fig. 1(b), point *b*] when the vortex wall moves to the constriction and is trapped there, i.e., Fig. 2(b), where most magnetizations are along the wire. For 25 nm films, the vortex domain wall can be easily depinned and pushed to another wire section by slightly increasing the negative field to about 2 Oe, which causes an abrupt decrease in MR [Fig. 1(b), point *c*]. The pinning state is more stable and easily observed for 100 nm films, where domain walls may include parts of Bloch-wall structures. In this study, we focused on the current-driven effect on the vortex wall of 25 nm films, which can be treated as pure Néel wall structure.

In order to discuss the influence of the intrinsic magnetic configuration, the current-driven experiment is performed by applying a high dc current at the fields with two different initial states as in Figs. 2(a) and 2(b). Figure 2 shows that the MFM images obtained under real time scanning field correspond well with the numerical simulation results. The vortex wall width estimate from the images are of the same order as the wire width, i.e., about 1 μm, which is the general result for metallic films. In this thick-wall-width case, theoretical results predict that the spin-transfer effect will be much stronger than the momentum-transfer effect and thus dominate the behaviors of current-driven domain-wall motion.[9] In Fig. 3(a), the original MR curves were first measured under small ac ($I_{\mathrm{rms}}\sim 10\ \mu$A) and dc ($I\sim 20\ \mu$A) currents for comparison. The positive dc currents are defined so that the direction of electron flow is the same as the domain-wall motion during switching. Unlike ac measurement, the degeneracy of magnetization switching in different wire sections is broken when a small dc current, only with a current density $J\sim 10^5\ \mathrm{A/cm^2}$, is applied. Several independent jumps are observed in the dc detection. This result implies that the small dc current can assist the domain-wall motion. It causes perturbation on the vortex structure, forming differ-

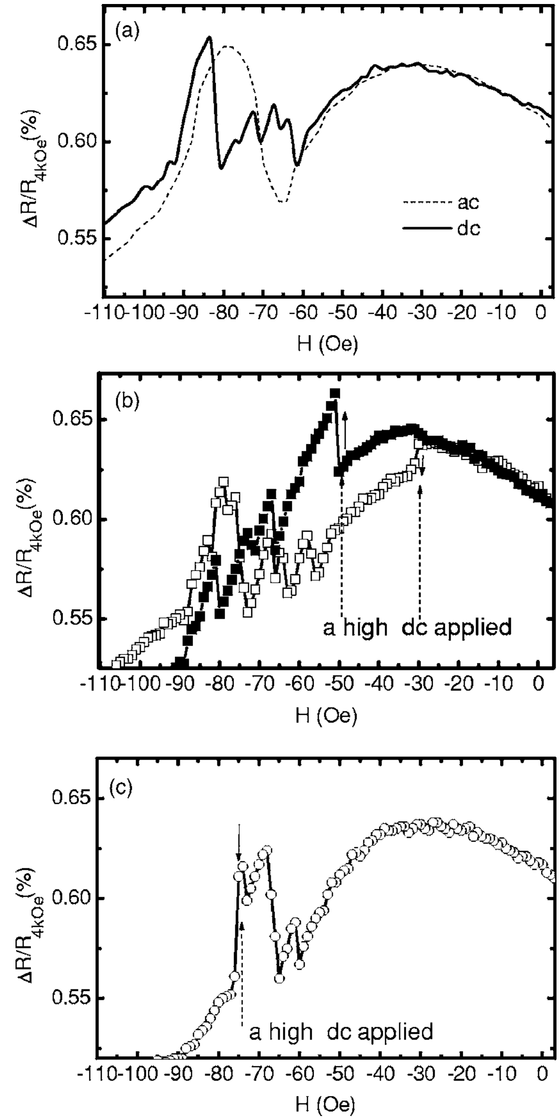

FIG. 3. (a) Magnetoresistance curves measured by applying a small ac current ($I_{\mathrm{rms}}\sim 10\ \mu$A) and a small dc current ($I\sim 20\ \mu$A). The variation of magnetoresistance curves by injecting a dc current in an initial state (b) before (−30 and −50 Oe) and (c) after (−75 Oe) the trapping of vortex domain wall in the constriction.

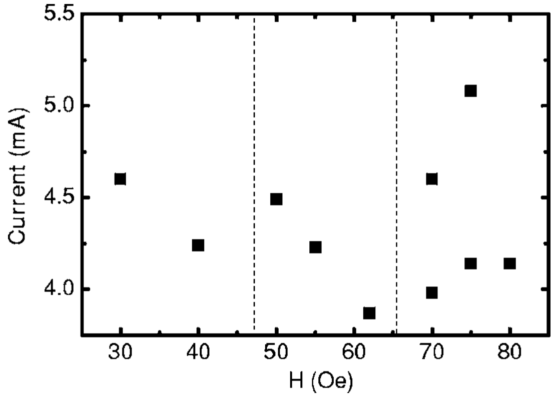

FIG. 4. Plot of critical currents as a function of the applied field. The critical currents were determined from the peaks of the differential resistance ($\Delta R = V_n/I_n - V_{n-1}/I_{n-1}$) by voltage-current measurement.

ent local stable states, and may need further theoretical explanations based on the coupling of spin waves.

During the current-driven experiment, the applied magnetic field was fixed at the desired field, with injecting a high dc current which gradually increased from 0 to 8 mA ($J \sim 3\times10^7$ A/cm^2). Figures 3(b) and 3(c) show the continuing scanned MR curves after injecting dc currents in the initial states as in Figs. 2(a) and 2(b), respectively. The original switching field, where vortices move from wire sections to the constrictions, under a low dc current ($J \sim 10^5$ A/cm^2) is about −65 Oe. In Fig. 3(b), the variation of MR curves after applying a high dc current ($J \sim 10^7$ A/cm^2) can be classified into two kinds of behaviors. The current applied at fields $H=-45$ to −60 Oe will cause instant resistance jumps, which correspond to the driving of vortices in the wire to constrictions. When the current applied in the field region $H=-20$ to −40 Oe, the MR decreased slightly after injecting a dc current, but the switching fields remained unchanged, which implies that the current only perturbs the vortex state to another stable state. In some published intrinsic observations by applying pulsed current, these stable states are deformed vortices or transverse domain walls.[12,13] Figure 3(c) shows the MR behavior after injecting a high dc current at fields slightly over the original switching field, i.e., $H=-70$ to −80 Oe. In the initial states with vortices trapped at the constrictions, the abrupt decrease of the MR value shows that the current depins the vortices and pushes the vortices to the wire section.

Figure 4 shows the variation of critical currents (current density $J \sim 10^7$ A/cm^2) versus applied fields. The critical current I_c is the lowest current needed to change the magnetic states in the wire. In this study, it was experimentally determined from the current with the abrupt variation of resistance (~0.5%) during dc current scanning (0–8 mA) at a fixed magnetic field. Similarly, three kinds of tendencies are shown in Fig. 4. In the field range below switching field $H=-65$ Oe, the needed critical currents decrease with the applied field. The discontinuity at $H=-45$ Oe may correspond to the transformation of initial vortex state. In the field range above $H=-65$ Oe, two resistance jumps are observed during the current scanning, which are similar to the results obtained in a longitudinal field.[14] The critical currents ~4.2 mA of first resistance jumps are supposed to depin the walls. The driven-current densities are about 8.4×10^7 A/cm^2 in the 200-nm-wide constriction. Moreover, these first critical currents do not vary with fields significantly. The most probable explanation is that the depinning of the domain wall from the narrow constriction should be considered as a strong-pinning problem, where the magnitude of the critical current is mainly determined from the pinning potential.[9] In contrast, the second critical currents (4.5–5.5 mA) might cause deformation on the vortex wall and drive it to a local stable position. The driven-current densities are about 2×10^7 A/cm^2 in the 1-μm-wide ring wire and increase monotonically with fields. The obvious variation of critical currents is affected by the anisotropy and stability of the vortices. Again, this result shows that the initial magnetic states play important roles in spin-transfer torque effect and implies the existence of local stable states after injecting continuous dc current.

IV. CONCLUSION

The current-driven vortex domain-wall motion in series-connected S-shape wires was investigated. The results of applying a small dc current for detection or injecting a high dc current at specific states both imply that temporary stable states may form even the domain wall is driven by continuous currents. The variation of magnetoresistance behaviors when applying a high dc current at different fields reveals the significance of initial magnetic states in spin-transfer torque effect.

ACKNOWLEDGMENT

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