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Vortex domain wall depinning by polarized current in submicron half-ring wires

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Domain wall pinning force in the junctions (corners), with different shapes of square, semicircle, or triangle, of half-ring in-series wires is considered to study the current injection induced wall movements. This geometry has less thermal activation at the region of domain wall nucleation in contrast to notch structures. The wires with square corners have the largest domain pinning force to resist polarized current-induced magnetization reversal, judging from the largest slope in the current-field dependence ($\Delta I/\Delta H = 0.274$). *© 2006 American Institute of Physics.*

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I. INTRODUCTION

The influence of a high current density injected into a single magnetic film was predicted[1] and proved[2] in many studies on current-induced magnetization reversal. It is expected to be applied to the local magnetization switching method, which is different from switching by external field in the present magnetic random access memories (MRAMs) and other magnetoelectronic devices. These current-induced phenomena have attracted much attention not only in interesting scientific research but also in applications. From the original predictions of Berger,[3] the current flow exerting a torque on the magnetic moment of the ferromagnet excites spin waves or directly flips the magnetic moment because of the transfer of spin angular momentum. This means that the polarized current can also be used for current-induced domain wall motion. The critical current density to drive the domain wall is dependent on two factors[4] the domain wall pinning force and the material-dependent Gilbert damping coefficient. Permalloy ($Ni_{80}Fe_{20}$) is studied in our experiment for its shape anisotropy. The effect of current injection to different domain wall pinning forces is the main purpose of our study. Recently, structures such as notches[5] were employed to trap domain walls. However, current density on the cross section of notches increases and raises temperature locally when polarized current is injected. Although most researches confirmed that the current-induced magnetization reversal was by the mechanism of spin momentum transfer, the local influence of thermal activation in these kinds of structures may reduce its practical use. Therefore, we make use of discontinuous corners of half-ring in-series wires[6] to nucleate and trap domain walls in this experiment. Boundary conditions of different shapes [the left side of Figs. 1(a)–1(c)] in the ends of corners were designed to cre-

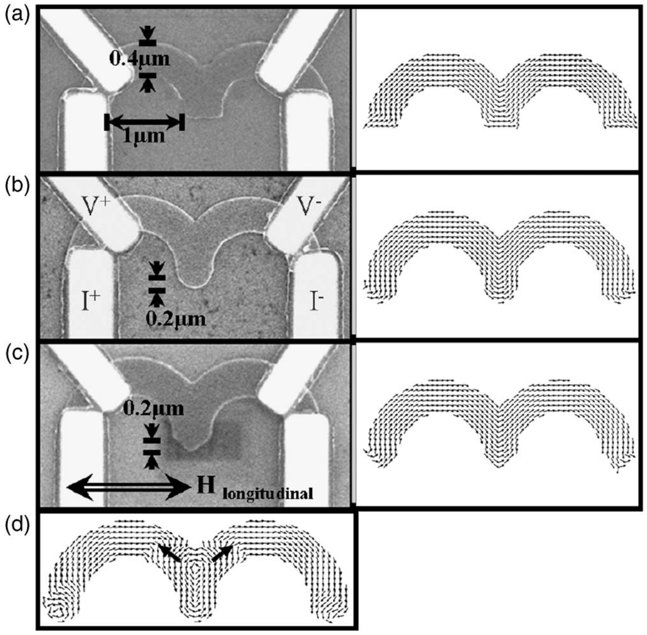

FIG. 1. SEM images and micromagnetic simulation configurations at zero field of (a) SQ, (b) SC, and (c) TA shape corners at the half-ring in-series wires. There is one corner producing domain wall between electrodes. The SQ sample has different domain structure from the other two shapes. (d) Spin configuration simulation image of the SC sample on the field near the switching field showing the domain wall nucleation at the corner region and the beginning of domain wall motion (the larger arrows indicate the directions of motion).

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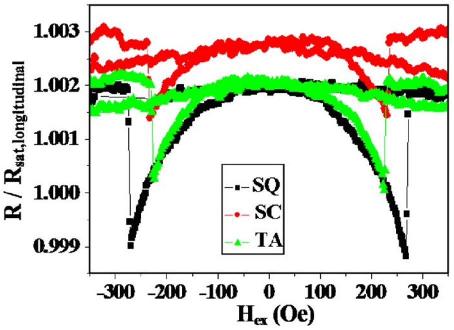

FIG. 2. Typical longitudinal MR loops of the wires measured at 295 K.

TABLE I. The critical current density data at different H_{ex} of sample SQ.

External field (Oe)	−219	−221	−223	−225	−227
Critical current density (A/cm^2)	2.88×10^7	2.32×10^7	2.08×10^7	1.38×10^7	5.5×10^6

ate different domain wall pinning force, which resists against current-induced domain wall motion.

II. EXPERIMENT

We fabricated several sets of 0.4 μm wide $Ni_{80}Fe_{20}$ wires of two inner radius 0.5 μm half-rings in series with the corners shapes[7] of square (SQ), semicircle (SC), or triangle (TA) by using electron beam lithography and lift-off technique, as shown in the scanning electron microscope (SEM) images on the left hand side of Figs. 1(a)–1(c). By using magnetron sputtering with the working pressure of 1×10^{-3} Torr, the ferromagnetic layer with about 25 nm thickness was deposited onto 50 nm SiO_2 coated silicon (100) substrates. Ti/Au leads for the four-point measurement were made by similar techniques on two sides of each wire. Before dc current from 10 μA to 3 mA with steps of 10 μA was applied to induce magnetization reversal by domain wall motion, the switching field (coercive field) of each sample was found first from the magnetoresistance (MR) loops. Then the current-driven wall motion at different external fields lower than its switching field was carried out. The experiments were performed at room temperature (295 K). Different sets of samples showed the same trend of behaviorsdiscussed in the following.

III. RESULTS AND DISCUSSIONS

Typical longitudinal MR loops of $Ni_{80}Fe_{20}$ samples normalized by saturation resistance are shown in Fig. 2. These MR loops can be understood by the anisotropic MR (AMR) effect during magnetization reversal process. When the external magnetic field was swept through zero from positive (or negative) saturation field, 6000 Oe, the gradual drop in the MR curve represents that the transverse components of the magnetization increased slowly. The right hand side of Figs. 1(a)–1(c) shows the simulation results at the remanent state. It is clearly seen that the SQ sample has the end domain structure typically seen in a rectangular shape. However, the SC and TA samples have different domain structures due to the local shape anisotropy. Figure 1(d) shows the simulation results in the SC sample at a field of −224 Oe, lower than the simulated switching field. The magnetization reversal caused by domain walls being pushed away from the wire at the switching field results in the MR curve jumps back to the high resistance state. This switching process (reversible followed by irreversible) has been observed in each sample. The SQ sample has the largest longitudinal switching field $H_{sw}=268\pm2$ Oe, while $H_{sw}=230\pm2$ Oe for the SC sample and $H_{sw}=228\pm2$ Oe for the TA sample.

Figure 3 shows that there was a resistance jump at the critical current $I_c=2.32$ mA for the resistance versus current curve of sample SQ at external field $H_{ex}=-221$ Oe. The I_c data at different H_{ex} of sample SQ is listed in Table I. The variation of resistance (ΔR) caused by current injection was about 200–230 mΩ, which was close to the value of ΔR of the MR loop at the switching field. The agreement of ΔR's suggests that the changes of magnetization states caused by external field and by dc current are similar. The background resistance by Joule heating can also be clearly seen to increase with the applied dc current in Fig. 3. So, the differential resistance ($\Delta R=R_n-R_{n-1}$) as a function of injected current at different fields is a good approach to eliminate this effect, as shown in Fig. 4. The resistance R_n represents the nth point of resistance measurement. The larger field is applied on the samples; the smaller critical current is needed to induce the magnetization reversal (domain wall depinning). Through the linear fit of critical current versus external field, the samples SQ, SC, and TA have theslopes (mA/Oe) of

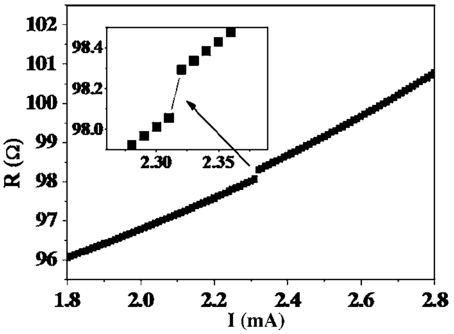

FIG. 3. The SQ sample resistance as a function of the injecting current at external fields $H_{ex}=-221$ Oe.

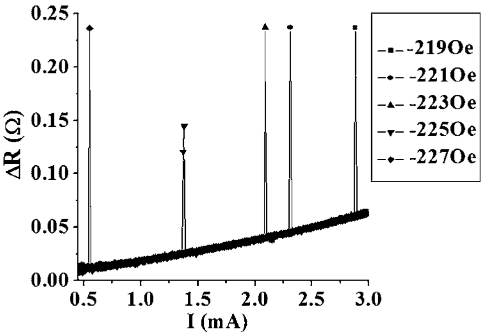

FIG. 4. The differential resistance of the SQ sample as a function of the injected current at external fields $H_{ex}=-219,-221,-223,-225$, and −227 Oe.

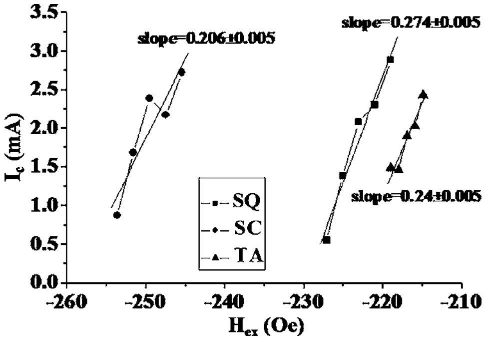

FIG. 5. The critical current of three samples as a function of the external magnetic field. The least square fits to the data and their slopes are also shown.

$\sim 0.274 \pm 0.005$, $\sim 0.206 \pm 0.005$, and $\sim 0.24 \pm 0.005$, respectively, as shown in Fig. 5. The magnitude of $\Delta I / \Delta H$ indicates the ease of domain wall depinning. The larger the $\Delta I / \Delta H$, the more polarized current is needed to drive the domain wall away from the corners, thus suggesting the larger domain wall pinning force. Obviously, the square shape corners have the largest domain wall pinning force, which resists current-induced domain wall motion. This result is in agreement with the switching field of MR loops. However, for samples SC and TA, there is a deviation of trend which is different from the result of switching field in the MR loops. The shunt effect of current distribution around the corner could be responsible for this result.

IV. CONCLUSION

The structure of the designed wire including two half-ring parts with strong shape anisotropy can confine domain wall nucleation at corner (connected part) easily. Through the MR loops and current-induced domain wall motion, we have proved that the domain wall pinning force can change with the designed corner shapes of the samples. Using half-ring in-series wires with different designed corners to create different domain wall pinning force offers a way to study the pinning force. Our results offer good alternatives to notch structures for trapping domain wall with different pinning force.

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