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Yi-Chun Chen, Yu-An Lin, Dong-Chen Chen, Yeong-Der Yao, Shang-Fan Lee, and Yung Liou

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# Current-assisted magnetization switching in submicron permalloy S-shape wires with narrow junctions

Yi-Chun Chen[a)]
*Institute of Physics, Academia Sinica, Taipei 115, Taiwan, Republic of China and*
*Department of Physics, National Cheng Kung University, Tainan 701, Taiwan, Republic of China.*

Yu-An Lin
*Department of Physics, National Chung Cheng University, Chiayi 621, Taiwan, Republic of China*

Dong-Chen Chen
*Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu 300, Taiwan, Republic of China*

Yeong-Der Yao, Shang-Fan Lee, and Yung Liou
*Institute of Physics, Academia Sinica, Taipei 115, Taiwan, Republic of China*

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We report the results of the current-assisted magnetization switching in submicron permalloy S-shape wires with narrow junctions (or notches). Domain walls were initially formed and pinned in the vicinity of the notches. Two distinct behaviors are observed in the current-assisted magnetization reversal process. When the applied field is near switching field ($\Delta H < 7$ Oe), the injected current directly switched the wire magnetization, and the needed critical current varied linearly and significantly with the field intensity. In contrast, when the field is relatively far from the switching field ($\Delta H > 7$ Oe), the current only moves the domain wall to a local stable state, and the critical current varied slightly with the field. Moreover, two resistance jumps during current scanning are observed in the cases with magnetization reversals. These results reveal that the current driven effect is closely related to the initial domain states, and are explained by a theoretical model based on spin transfer effect. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1850254]

## I. INTRODUCTION

The control of magnetization switching by injecting electric current instead of applying magnetic field has recently become one of the key topics in spintronics. The influence of a high current density on the magnetic state of a ferromagnet was proposed theoretically[1,2] and subsequently demonstrated in experiments, especially in the multiplayer nanopillar structure.[3–6] The current-driven domain wall motion is first theoretically predicted by Berger, who argues that the electric current exerts a force on the domain wall by exchange coupling[7] and a spin-polarized current applies a torque on the magnetization of the wall.[8] Published experimental results in single layer film are mainly based on the observations of current-driven pinning or depinning of a single domain wall at a neck formed by two adjacent pads with different geometrical ratios.[9–12] In this study, we study the current-induced magnetization reversals in an S-shape patterned permalloy wire with notches, where the domain wall can be initially induced by adjusting the direction of magnetic field. The interesting behaviors of the current-driven effect in this multidomain wire are also investigated.

## II. EXPERIMENT

S-patterned $Ni_{80}Fe_{20}$ narrow wires with Ti/Au leads for magnetoresistance (MR) measurement were prepared by electron-beam lithography (Hitachi 4200) and lift-off techniques. Both the ferromagnetic films and leads were deposited by dc magnetron sputtering with a base pressure of $5 \times 10^{-7}$ Torr. As shown in Fig. 1, the wire consists of seven identical half-ring units, which have 1 μm linewidth and 5 μm diameter. The film thickness for all the examined samples was about 25 nm. To effectively trap the domain wall, a tip-to-tip notch was fabricated to connect two adjacent half-rings. During the measurement, the field was applied in the in-plane longitudinal direction (Fig. 1). The resistance was measured by four-channel measurement 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 *in situ* magnetic force microscopy (MFM, DI 3100) and numerical simulation using object oriented micro-

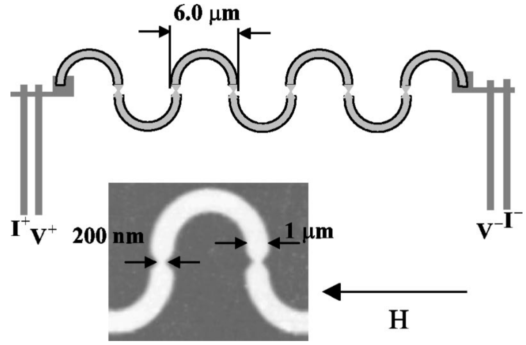


FIG. 1. Schematic representation of the series-connected S-shaped $Ni_{20}Fe_{80}$ wire. The inset shows the AFM image of a single S-shaped wire section. The arrows show the initial field direction to saturate the sample.

[a)]Electronic mail: ycchen93@mail.ncku.edu.tw

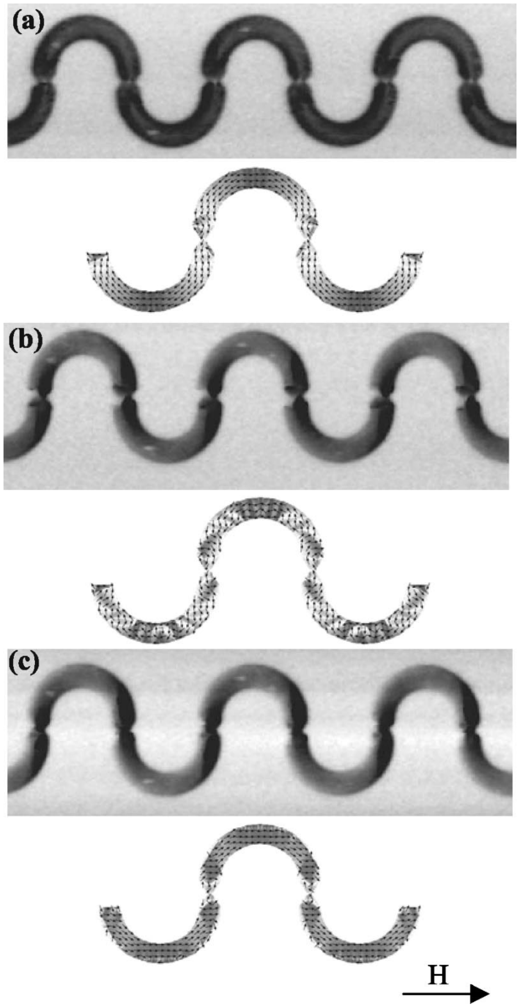


FIG. 2. MFM images and micromagnetic simulations of the domain structures (a) before, (b) near, and (c) after magnetic switching. The arrow shows the instant field direction.

magnetic framework (OOMMF, code from the National Institute of Standards and Technology). When performing the current-driven effect experiment, we use Kiethly 6430 to provide high density dc.

## III. RESULTS AND DISCUSSION

The magnetization reversal processes in the wires are clearly revealed in the MFM images and computer simulation results. Figure 2 illustrates the domain structures during switching. The phase shift ($\Delta\phi$) of the MFM probe is proportional to the force gradient of the vertical stray field, and the magnetic configuration in MFM images is found to correspond to the simulation results well. Figure 2(a) shows that the magnetization direction is mainly along the wire; Fig. 2(b) corresponds to the multidomain structures before the switching field. The intense contrast in MFM images from the stray field near the notch shows the existence of the domain walls; Fig. 2(c) illustrates that most magnetic moments are along the wire and already switched. It should be noted that domain walls were initially formed at the corners connecting the wire and the notch, where the transverse component of the demagnetizing field occurs to initiate the nucleation. The micromagnetic simulation in Fig. 2(c) shows the

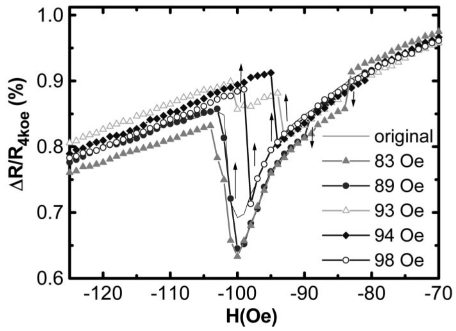


FIG. 3. The variation of magnetoresistance jumps after injecting a polarized dc current at different magnetic fields.

domain wall even exists at the corners after the magnetization in the wire completely switched, namely, the domain wall is locally stable and pinned at the corners. Similar behavior is also obtained in the MFM image, which is distinguished from the contrast at the wire edges of the notch. Therefore, in our S-shaped pattern wire, there are two stable domain walls symmetrically existing in one half ring near the switching field. Both domain walls play key roles during the current-driven experiment.

The current-assisted domain wall motion is investigated by applying a high dc at the fields around domain wall trapping states. As shown in Fig. 3, we inject the current at the fields with magnitude slightly smaller than the switching field, i.e., the initial domain structures in the wires are the states between those in Figs. 2(a) and 2(b). The original MR curve which has a switching field $H_s \sim -110$ Oe was measured under small dc (20 μA) for comparison. During the current-driven experiment, the applied magnetic field was first scanned from the positive saturation and then fixed at the desired field, with injecting current which negatively increased from 0 to −8 mA. Figure 3 also shows the continuing scanned MR curves after applying dc. It is observed that the MR behaviors can be classified into two kinds. When the field is fixed in the range of −83 Oe to −92 Oe, i.e., $\Delta H > 7$ Oe from the switching field, the MR decreased slightly after injecting dc and the switching field remained unchanged; When the field is fixed in the range of −94 Oe to −99 Oe, i.e., $\Delta H <$ Oe from the switching field, the injecting current directly switches the wire magnetization, which is revealed by the abrupt jump in the MR curve after the high dc is removed, and no switching behavior is further observed when the applied magnetic field keeps increasing in negative direction. These results imply that for $\Delta H > 7$ Oe, the current only moves the domain wall to a local stable state while for $\Delta H < 7$ Oe, the current effectively de-pins the domain wall and assists the magnetization reversals. It is interesting to notice that when the field is fixed at −93 Oe ($\Delta H = 7$ Oe), the MR value jumps partially after applying the dc, and then abruptly increases again at the switching field $H_s \sim -110$ Oe. The most probable explanation is that at the critical field $H = -93$ Oe, the magnetization in some half rings switched by the current successfully while that in the remaining half rings finished switching at the field $H_s = -100$ Oe.

The critical current to drive the domain wall motion is obtained from the abrupt change of resistance during dc

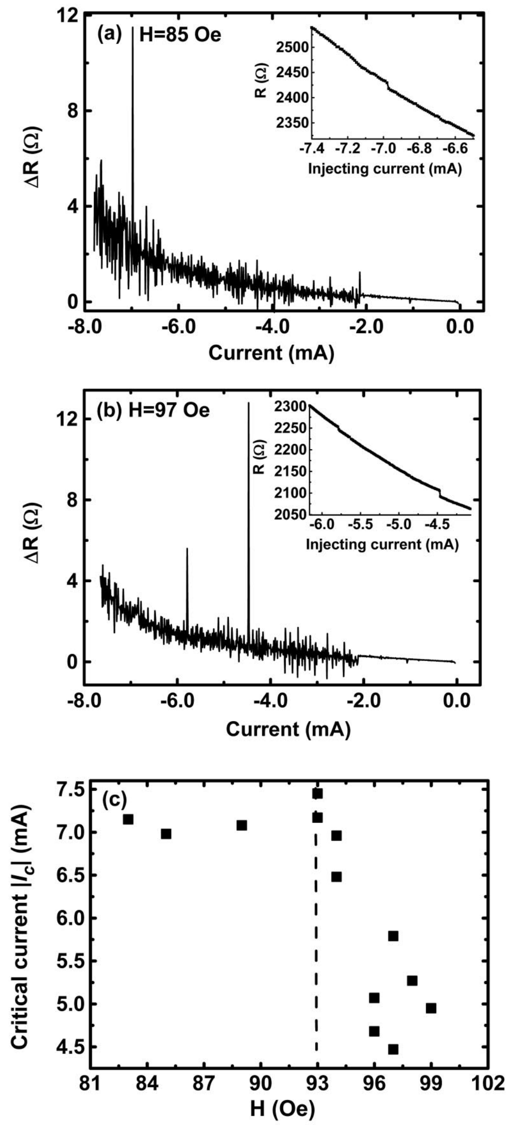


FIG. 4. The differential resistance ($\Delta R = V_n/I_n - V_{n-1}/I_{n-1}$) vs injection current at the magnetic fields of (a) 85 Oe and (b) 97 Oe. The spikes in the traces occur at critical current $I_c$ with the insets, which show the magnetoresistance traces of the same measurement. (c) The critical current as a function of the applied field.

scanning (0 to $-8$ mA). To clearly display the small resistance variation ($\sim$0.5%) due to current-driven effect, we plot the differential resistance ($\Delta R = V_n/I_n - V_{n-1}/I_{n-1}$) as a function of injection current at different magnetic fields. Figures 4(a) and 4(b) show two typical resistance curves, which represent the dc effect for $\Delta H > 7$ Oe and $\Delta H < 7$ Oe, respectively. The spikes in the traces occur at critical currents $I_c$ and correspond to the resistance steps shown in the insets, which represent the MR traces of the same current scanning measurement. The main difference between the MR versus current plots for two different cases is that only one critical is shown at the fields with $\Delta H > 7$ Oe while two spikes are observed at those with $\Delta H < 7$ Oe. Moreover, field dependence of absolute value of the switching current shown in Fig. 4(c) also possesses two kinds of tendencies separated by the line at $H = 93$ Oe. In the field range of $H < 93$ Oe, the critical current varied insignificantly with the field. On the other hand, the critical current varied linearly and substantially with the field intensity in the range $H > 93$ Oe. Both behaviors are similar to that of weak pinning domain wall predicted by the published theory of domain wall dynamics based on spin moment transfer.[13] We try to further explain our results with the theory. For $\Delta H > 7$ Oe, the transferred spin is absorbed by the magnetization rotating in the domain wall and the energy is dissipated during the propagation due to the transverse anisotropy of the film. Therefore, the domain wall is only driven to a finite displacement, and only one domain wall (one spike), which moves to wider wire section following the electric current direction, is driven. For $\Delta H < 7$ Oe, the dispassion by the anisotropy is no longer able to support the transferred spin, and the domain wall keeps moving until the magnetization reversal is finished. In these cases, both domain walls (two spikes) are driven to finish the magnetization switching in the wire.

## IV. CONCLUSION

The current-assisted magnetization reversals in the S-patterned wire with narrow junctions are carefully investigated. Near the switching field, two trapped domain walls are found at the corners of the connecting notches. Two distinct steps are observed in the current-assisted magnetization reversal processes, which are theoretically explained. The results reveal that the current-assisted effect is mainly from the spin moment transfer from conduction electron to magnetic domain wall.

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