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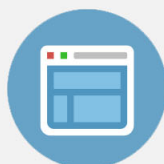
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# Magnetic switching and reversal process in a tip ring structure

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Patterned Permalloy submicron-size structures have been fabricated by *e*-beam lithography in the shape of a ring with a tip. A tip was intentionally added into the ring as a geometrical defect to interrupt the continuity of the magnetization, which aligns along the ring, in order to pin the domain wall. Magnetic switching and reversal process have been measured by the magnetoresistance measurement. The switching field about 260 Oe was obtained. At the remanent state, there was a 0.21% difference in the magnetoresistance between the angles of 90° and 0° that was equivalent to the domain wall magnetoresistance. By applying an external field, the domain wall moved along the ring under a lower field (100 Oe), which is smaller than the switching field. A drop (0.24%) in the resistance between the angle of 70°–120° has been observed that means the domain wall was moving into the voltage measuring region during the rotation. © 2004 American Institute of Physics. [DOI: 10.1063/1.1688672]

## INTRODUCTION

Small ferromagnetic ring structures have received much attention recently because of their potential applications in memory devices.<sup>1–8</sup> It's been reported the domain wall trapping and the spin switching can be observed in this geometry.<sup>9–12</sup> Two distinct stable magnetic states in narrow rings have been reported, the “onion” state with a head-to-head domain structure, and the “vortex” state with a flux-closure domain structure. The magnetoresistance (MR) measurement is sensitive to the magnetic switching, so it is able to monitor the switching between different states in the ring. In the previous reports,<sup>13–17</sup> notches have been introduced into the ring in order to pin the walls more strongly than the other. Since the MR is dominated by the anisotropic MR (AMR), a maximum resistance should be found if the spins

are parallel (or antiparallel) to the current. The MR is lowered if the directions of local spins rotate away from the direction of the current, and that correspond to a domain wall present in the ring, some of the magnetizations in the domain wall are not parallel to the current.

In this study, we have constructed a ring structure sample with a tip similar to the ring with a notch. Since the tip has an asymmetric shape, it will pin the wall even stronger than a notch. In this structure, the wall can not propagate through the tip but go through the wall annihilation and nucleation processes. At low fields, the wall can be forced to propagate at one direction in the ring and annihilate at the tip without passing through the tip. A new wall can be nucleated from the tip after the field has been reversed and increased. The reversal process through two onion states and a vortex state can be controlled. By rotating the sample, the position of a wall can be determined from the MR measurement whenever a wall is fallen into the measurement region.

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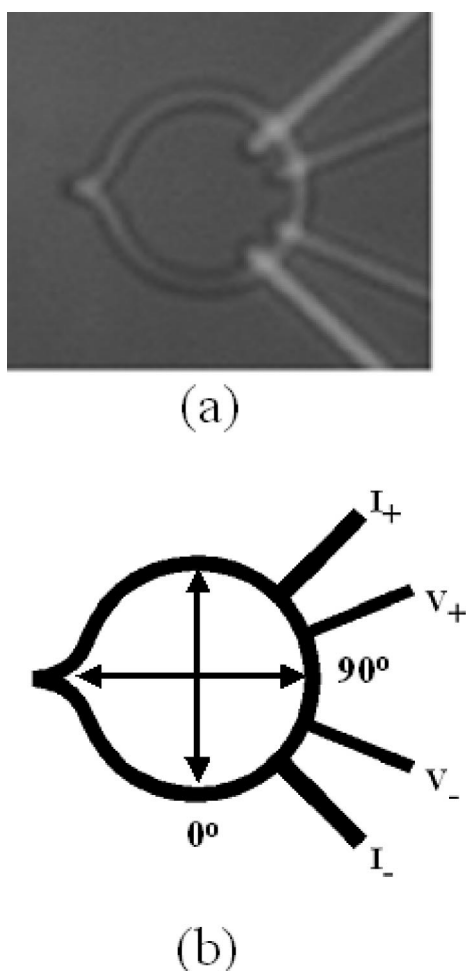


FIG. 1. (a) The optical micrograph and (b) the schematic diagrams of the external magnetic field and the contact electrodes.

## EXPERIMENT

The NiFe rings of  $4.2 \mu\text{m}$  outer diameter and  $3.8 \mu\text{m}$  inner diameter (200 nm in width) were fabricated by an electron-beam lithography and liftoff technique. Electric contact patterns of Ti (5 nm)/Au (25 nm) films were first made by photolithography and sputtering deposition on the Si(100) substrates which have been previously capped with a 50 nm thick  $\text{SiO}_2$  layer. After the electron-beam writing process on the spin-coated copolymer polymethyl methacrylate-co-methacrylic acid film, NiFe films with a thickness of 25 nm were deposited onto it at room temperature by dc magnetron sputtering. To improve the uniform coverage of NiFe into the desired pattern, we have used a collimator between the target and substrate holder. The desired NiFe ring was obtained after the liftoff process. MR measurements were performed by a four-point probe method in fields applied in the plane of the ring with different in-plane orientations at 77 K. An optical microscope image of the ring structure with a tip is presented in the Fig. 1(a). Four-point measurements were executing by the four electrical contacts. Figure 1(b) indicates the angle between the magnetic external field and the ring. At the angle of  $90^\circ$ , the external applied magnetic field ( $H$ ) was along the axis through the tip. At the angle of  $0^\circ$ , the  $H$  field was perpendicular to the axis through the tip.

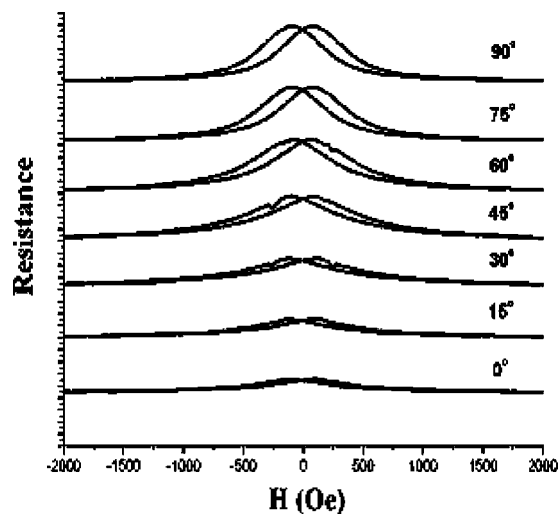


FIG. 2. The MR loops measured at different angles.

## RESULTS AND DISCUSSION

MR loops at different angles have been measured, as shown in Fig. 2. The magnetization configurations under different oriented external fields were shown schematically in Fig. 3 with the help of the computer simulation using the micromagnetic software (OOMMF).<sup>18</sup> The functions of the tip on the ring were to divide the magnetization in the ring into two parts with its anisotropic shape, and to nucleate a new magnetization domain when the external field was reversed. At saturation, the local magnetizations were forced into the same direction of the external applied field, leading to an angle between the current and the local magnetizations and hence to a decrease in the resistance. As the field was lowered, the local magnetizations were rotating toward the direction of the ring, the angle between the current and the local magnetizations decreased due to the anisotropic effect, and the resistance increased. As the field was closed to zero, an onion state with a head-to-head (or tail-to-tail) domain structure was formed. At the angle of  $90^\circ$ , an onion state with a wall existed in the voltage-measuring region after saturation in the field and it stayed until reached the remanent state. As the field was reversed to the opposite direction, the onion state switched into an opposite onion state without seeing large changes in MR loops. At angles above  $60^\circ$  ( $75^\circ$ ,  $90^\circ$ ), all three MR loops showed a similar shape due to the strong anisotropic effect. At angles between  $30^\circ$  and  $45^\circ$ , there were jumps in the MR loops that correspond to the switching of the magnetization in the ring. The magnetization in the ring has switched from a vortex state to an onion state, and the switching field was estimated to be 260 Oe. At angles below  $15^\circ$ , there were little changes in the MR loops that also due to the strong anisotropic effect, and the local magnetizations were almost always paralleled to the current in the measuring region during the switching. At the angle of  $0^\circ$ , an onion state also was formed at remanent state but no wall existed inside the voltage-measuring region at either saturation or remanent state. Hence the difference of the MR (0.21%) between the  $90^\circ$  and  $0^\circ$  is equal to the MR of a domain wall (DW). The effect of DW on the MR was small

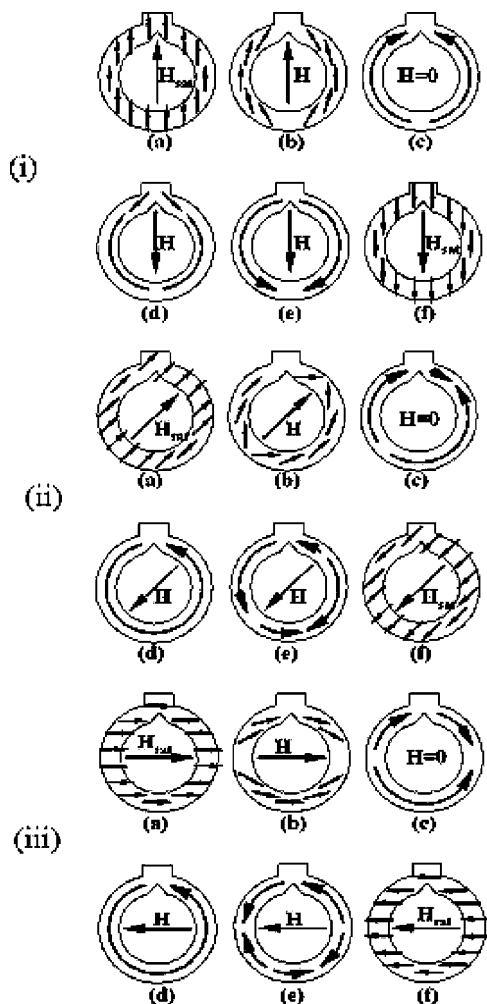


FIG. 3. Schematic figures of magnetization configurations at external fields at: (i) 90°, (ii) 45°, and (iii) 0°.

compared with AMR effect. Unless using a lower field, we could not observe the DW motion in the MR measurement.

By using a low field, we were able to move the DW without switching the local magnetization. At remanent state after saturated at 0°, an onion state existed with two walls at opposite sides of the ring. As the sample was rotating counterclockwise in the external field, the two DWs were dragged along and the onion state was rotating. As one of the two DWs was rotated into the voltage-measuring region (about 70°), the resistance dropped because the local magnetization was not parallel (or antiparallel) to the current. After the DW was rotating out of the voltage-measuring region (about 120°), the resistance (voltage) jumped back to the original magnitude because the local magnetizations in the voltage-measuring region were parallel (or antiparallel) to the current again. It repeated after another 180°, as shown in Fig. 4. The drop of the MR at 90° is about 0.24% which is closed to the DWMR estimated previously.

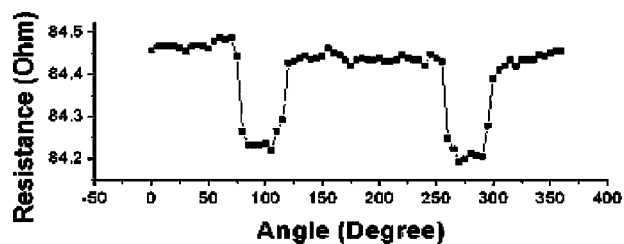


FIG. 4. The resistance measured with external applied magnetic field of 100 Oe at different angles.

### CONCLUSION

We have shown the MR of a ring with a tip at different angles. The magnetization switching process has been observed at angles of 30° and 45° because of their less strong AMR effect. We estimated the switching field is about 260 Oe. The difference in the MR between 90° and 0° was a domain wall MR which is estimated about 0.21%. When we rotated the sample in a field of 100 Oe, a resistance drop of 0.24% between 70° and 120° was observed. At such low field, the local magnetizations were not influenced, but only the domain wall was dragged by the field. A square-wave shape in the MR curve was obtained that was determined by the position of the domain wall.

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