Angular Dependence of Magnetoresistance During Magnetization Reversal on Magnetic Tunnel Junction Ring

C. C. Chen[1], C. C. Chang[1], Y. C. Chang[1], C. T. Chao[1], C. Y. Kuo[1], Lance Horng[1], J. C. Wu[1], Teho Wu[2], G. Chern[3], C. Y. Huang[4], M. Tsunoda[5], and M. Takahashi[5]

[1]Taiwan SPIN Research Center, National Changhua University of Education, Changhua 500, Taiwan, R.O.C.
[2]Taiwan SPIN Research Center, National Yunlin University of Science & Technology, Yunlin 640, Taiwan, R.O.C.
[3]Taiwan SPIN Research Center, National Chung-Cheng University, Chia-Yi 621, Taiwan, R.O.C.
[4]National Taiwan Normal University, Taipei 106, Taiwan, R.O.C.
[5]Department of Electronic Engineering, Graduate School of Engineering, Tohoku University, Miyagi 980-8579, Japan

Microstructured magnetic tunnel junction ring with outer/inner diameter of 2/1 μm has been fabricated to investigate the angular dependence of magnetoresistance during magnetization reversal process. The minor loop of magnetoresistive curve reveals four distinct resistance levels associated with four magnetization configurations within the free layer throughout the magnetization reversal. The magnetoresistance decreases with increasing angle between applied external field and biasing direction, which is resulted from the relative alignment of total magnetization of pinned and free layer. An extra feature appeared in the minor loop when the external field is transverse to the biasing direction; this can be attributed to a vortex-pair formation/annihilation in the free layer. Furthermore, a series of schemes of magnetic configurations of pinned and free layers are illustrated to explain the routes of minor loops.

***Index Terms*—Magnetization reversal, magnetoresistance, magnetoresistive devices.**

I. Introduction

THE magnetic and electric properties of ring-shaped magnetic thin films have intensively attracted much interest due to the practical applications [1]–[3], such as magnetic random access memory (MRAM), which was first proposed by Zhu [4]. As a result, a variety of the characteristics showing simple, stable, reproducible, and fast switching processes of the magnetic annularly shaped devices have been reported by many groups. For many of them, the main themes were focused on single-film devices [5]–[7]. To date, for real functional devices, the attention have been inevitably then transferred to a magnetic multilayer system, for instance, a giant magnetoresistance (GMR) and magnetic tunnel junction (MTJ) system [8], [9]. The current-in-plane (CIP) pseudo-spin-valve elliptical ring devices [8] and current perpendicular-to-plane (CPP) GMR ring [9] were reported to discuss the magnetotransport behavior of GMR effect, revealing high magnetoresistance (MR) ratio in comparison with single-film devices. Recently, we have shown that the fabrication and characterization of a microstructured MTJ ring device revealed a higher MR ratio and multistep magnetization reversal process [10]. For the application aspect, the angular dependence of MR of MTJ devices, which was dominated by the angle between the moments of two ferromagnets and predicted by Slonczewski's theory [11], was also an important issue. The experiments on angular-dependent MR of ring-shaped mutilayer system devices were just appearing in a CIP-GMR [12] system but never in a CPP-MTJ system. Therefore, we present a study of MR measurement in the presence of differently external filed direction relative to biasing direction during magnetization reversal on microstructured MTJ ring. The main goal was focused on the relative alignment of magnetic moment between pinned and free layer.

Digital Object Identifier 10.1109/TMAG.2006.888511

II. Experiments

The MTJ thin films consisting of Si/SiO_2 50-substrate/Ta 5/Cu 20/Ta 5/NiFe 2/Cu 5/MnIr 10/CoFe 4/Al-N 1.5/CoFe 4/NiFe 20/Ta 5-cap (thickness in nanometers) were first prepared by the dc magnetron sputtering method. The microstructured MTJ ring with an outer/inner diameter of 2/1 μm, as shown in Fig. 1, was fabricated by a top-down technique combining photolithography, electron-beam lithography, and ion-milling process. Special care was taken during the ion-milling process using low-angle vertical etching, followed by high-angle lateral etching to prevent the edge shorting problem. A series of schemes showing fabrication processes can be seen in our previous work [8].

The MR measurements were carried out using a typical four-terminal dc technique in the presence of external field that was tuned with various angles between external field and biasing direction, as shown in inset of Fig. 1.

III. Results and Discussion

Fig. 2(a)–(d) shows the angular-dependent MR major loops. The biasing field of about 730 Oe measured at external field parallel to biasing direction was just slightly smaller than that of nonpatterned films, 760 Oe, which was extracted from M–H

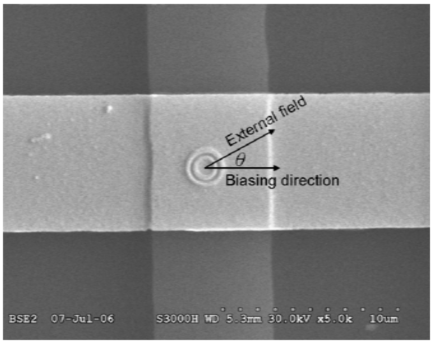

Fig. 1. SEM micrograph of microstructured MTJ ring with outer/inner diameter of 2/1 μm. The inset was the definition of the angle (θ).

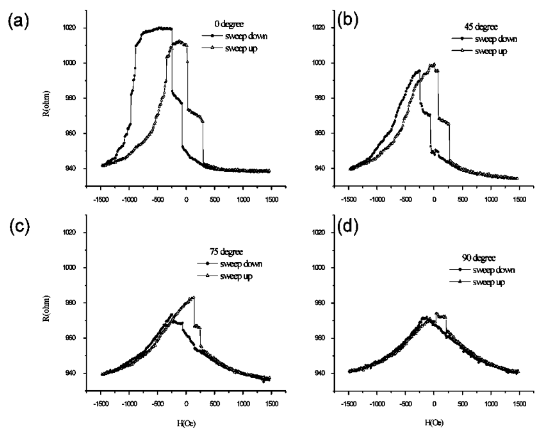

Fig. 2. Angular-dependent MR major loops of (a) 0°, (b) 45°, (c) 75°, and (d) 90°. The full circle and open triangle represent field sweep down and sweep up process, respectively.

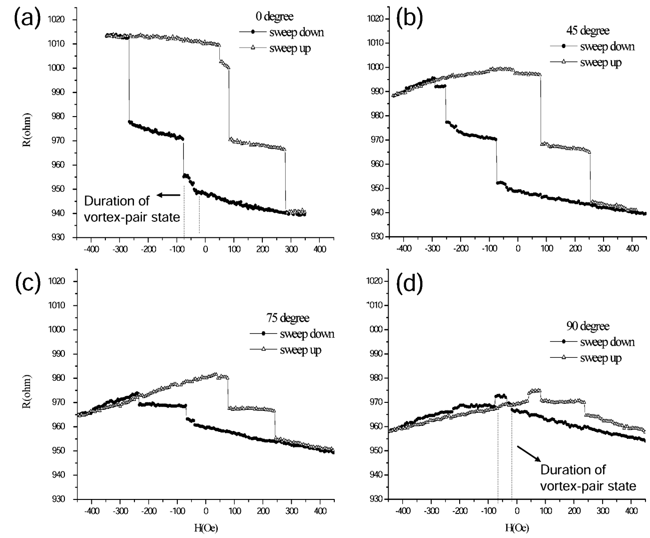

Fig. 3. Angular-dependent MR minor loops of (a) 0°, (b) 45°, (c) 75°, and (d) 90°. The full circle and open triangle represent field sweep down and sweep up process, respectively.

loop measured by alternating gradient magnetometry (AGM), indicating that the magnetic state of pinned layer was almost in uniform state. As the angle increased, the pinned layer magnetization was more easily to rotate to parallel the external field, as shown in Fig. 2(b) and (c), resulting in decreasing biasing effect in major loops.

Fig. 3(a)–(d) shows the angular-dependent MR minor loops. The 0° minor loop reveals 8% MR ratio and four distinct resistance levels associated with four magnetic states, i.e., onion, vortex-pair, vortex, and reverse onion states within the free layer throughout the magnetization reversal and fixed uniform pinned layer [13]. The MR ratio decreased with increasing angle since the total magnetization of pinned and free layer could not attain the completely parallel configuration in the range of $+500$ to -500 Oe. Interestingly, an extra feature appeared with the angle of 90° revealing no more hysteresis-like minor loop. The highest resistance level occurs during the vortex-pair formation and annihilation processes in free layer, as shown in inset of Fig. 3(d).

A series of schemes of magnetic configurations of pinned and free layer, as shown in Fig. 3(a)–(c), during free-layer reversal process were illustrated to describe these situations more explicitly. For simplifying the condition, we assume that the magnetic state of pinned layer was invariably in onion state. Fig. 4(a) expresses the schemes of 0° situations during of free-layer reversal processes. The lowest resistance level was because of the magnetization of pinned and free layer completely parallel to each other. Then, as the free layer in the vortex-pair state, the resistance reached the first higher level due to the reduced total magnetization of free layer. When the free layer was in the vortex state, the difference of magnetization of the free and the pinned layer was $180^\circ/360^\circ$ parallel and $180^\circ/360^\circ$ antiparallel resulting in a second higher resistance level. Finally, the reverse onion state in the free layer was totally antiparallel to a pinned layer, leading to the highest resistance level. Fig. 4(b) demonstrates the schemes of 75° situations: The lowest resistance level was with $210^\circ/360^\circ$ parallel between pinned and free layer. The first higher resistance level was also because of the vortex-pair state in free layer, consequently total magnetization less than $210^\circ/360^\circ$ parallel. As the free layer in vortex state, $180^\circ/360^\circ$ parallel magnetization produced second resistance level. Eventually, the reverse onion state was $150^\circ/360^\circ$ parallel leading to highest resistance level. Furthermore, as the increasing external field, the pinned layer started rotating its biasing direction to create more parallel magnetization parts then diminishing the resistance gradually. The above elaboration can also explain the MR ratio decreased with increasing angle. The most interesting case appeared in 90° situations, as shown in Fig. 4(c). The magnetization was $180^\circ/360^\circ$ parallel between pinned and free layer when the free layer with onion, vortex and reverse onion. The highest resistance level occurred in free layer with vortex-pair state and formed a plateau. Hence the minor loop manifests no more hysteresis-like behavior.

IV. Conclusion

In summary, we have fabricated microstructured MTJ ring to investigate the angular dependent MR measurements. The 0° minor loop reveals three transitions due to four magnetic states within the free layer during the free-layer switching process with a fixed quasi-uniform pinned layer. The MR ratio decreased with increasing angle resulted from the relative angle of total magnetization of pinned layer and free layer.

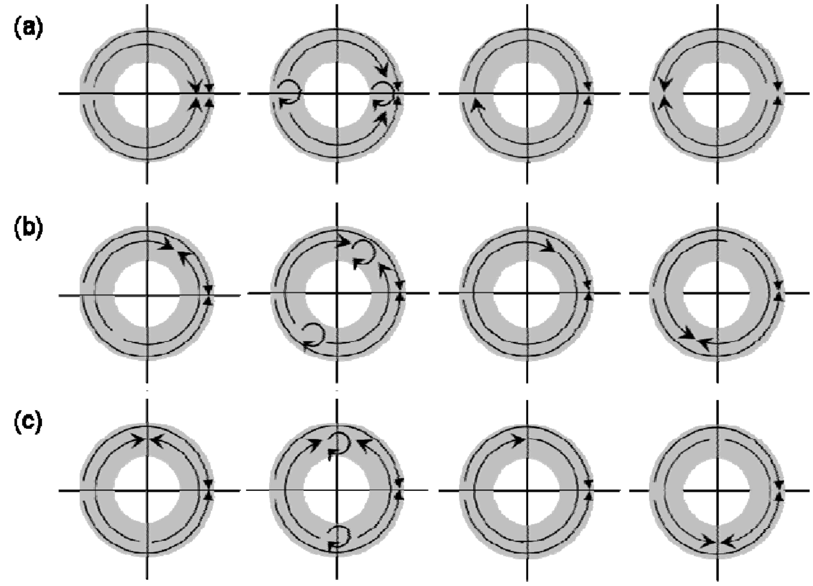

Fig. 4. Series of schemes illustrate the corresponding magnetic states in pinned and free layers during free-layer switching process under different external field angle: (a) 0°, (b) 75°, and (c) 90°. The outer/inner arrows represent the magnetization direction of pinned/free layer.

An extra feature appeared in a 90° MR loop showing no more hysteresis-like behavior. The highest resistance level occurs in the vortex-pair formation and annihilation processes of the free layer. A series of schemes of magnetic configurations of the pinned and free layer during the free-layer switching process were also illustrated to identify the MR behaviors.

ACKNOWLEDGMENT

This work was supported by the Ministry of Economic Affairs of Taiwan under Grant No. 95-EC-17-A-01-S1-026 and by the National Science Council of Taiwan under Grant No. 95-2112-M-018-004-MY3.

REFERENCES

[1] M. Kläui, C. A. F. Vaz, J. A. C. Bland, W. Wernsdorfor, G. Faini, and E. Cambril, "Domain wall pinning and controlled magnetic switching in narrow ferromagnetic ring structures with notches," *J. Appl. Phys.*, vol. 93, pp. 7885–7890, May 2003.

[2] J. Rothman, M. Kläui, L. Lopez-Diaz, C. A. F. Vaz, A. Bleloch, J. A. C. Bland, Z. Cui, and R. speaks, "Observation of a bi-domain state and nucleation free switching in mesoscopic ring magnets," *Phys. Rev. Lett.*, vol. 86, pp. 1098–1101, Feb. 2001.

[3] M. F. Lai, Z. H. Wei, C. R. Chang, J. C. Wu, J. H. Kuo, and J. Y. Lai, "Influence of vortex domain walls on magnetoresistance signals in permalloy rings," *Phys. Rev. B*, vol. 67, pp. 104–419, Mar. 2003.

[4] J. G. Zhu, Y. Zheng, and G. A. Prinz, "Ultrahigh density vertical magnetoresistive random access memory," *J. Appl. Phys.*, vol. 87, pp. 6668–6673, May 2000.

[5] L. Lopez-Diaz, M. Kläui, J. Rothman, and J. A. C. Bland, "Precessional switching in narrow ring nanomagnets," *J. Magn. Magn. Mater.*, vol. 306, pp. 211–215, 2001.

[6] S. P. Li, D. Peyrade, M. Natali, A. Lebib, Y. Chen, U. Ebels, L. D. Buda, and K. Ounadjela, "Flux closure structure in cobalt rings," *Phys. Rev. Lett.*, vol. 86, pp. 1102–1105, Feb. 2001.

[7] M. Kläui, C. A. F. Vaz, J. A. C. Bland, L. J. Heyderman, C. David, E. H. C. P. Sinnecker, and A. P. Guimarães, "Multistep switching phase diagram of ferromagnetic ring structures," *J. Appl. Phys.*, vol. 95, pp. 6639–6641, Jun. 2004.

[8] F. J. Castaño, D. Morecroft, W. Jung, and C. A. Ross, "Spin-dependent scattering in multilayered magnetic rings," *Phys. Rev. Lett.*, vol. 95, pp. 137–201, Sept. 2005.

[9] M. T. Moneck and J. G. Zhu, "Fabrication and testing of deep submicron annular vertical magnetoresistive random access memory elements," *J. Appl. Phys.*, vol. 99, pp. 08H709 1–3, Apr. 2006.

[10] C. C. Chen, C. C. Chang, C. Y. Kuo, L. Horng, J. C. Wu, T. Wu, G. Chern, C. Y. Huang, M. Tsunoda, and M. Takahashi, "Fabrication and characterization of microstructured magnetic tunnel junction rings," *IEEE Trans. Magn.*, vol. 42, pp. 2766–2768, Oct. 2007.

[11] J. C. Slonczewski, "Conductance and exchange coupling of two ferromagnets separated by a tunneling barrier," *Phys. Rev. B.*, vol. 39, pp. 6995–7002, Apr. 1989.

[12] D. Morecroft, F. J. Castaño, W. Jung, and C. A. Ross, "Angular dependence of the giant magnetoresistance in multilayer rings with different contact configurations," *J. Appl. Phys.*, vol. 99, pp. 08T104–, Apr. 2007.

[13] C. C. Chen, C. Y. Kuo, Y. C. Chang, C. C. Chang, L. Horng, T. Wu, G. Chern, C. Y. Huang, M. Tsunoda, M. Takahashi, and J. C. Wu, "Size dependence of magnetization reversal of ring shaped magnetic tunnel junction," *J. Magn. Magn. Mater.*, submitted for publication.

Manuscript received August 10, 2006 (e-mail: phjcwu@cc.ncue.edu.tw).