Controllable Remanent States on Microstructured Magnetic Tunnel Junction Rings

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Controllable remanent states have been studied on the microstructured magnetic tunnel junction (MTJ) rings through magnetoresistance measurements. These rings were designed accordingly with an outer/inner diameter of 2/1 and 1/0.5 μm to reveal two and one metastable states, respectively, during the magnetization reversal process on the free layer. The distinct magnetoresistance levels based on the tunneling magnetoresistance effect are associated with the relative alignment of magnetization of free layer and pinned layer. As a result, four and three controllable remanent magnetic states on the free layer were manipulated by ramping external magnetic fields, applied in the biasing direction, with various field ranges, giving rise to four and three stable mangetoresistance values at zero field. These results may provide a great potential in magnetic multibit memory applications using ring-shaped cells.

***Index Terms*—Magnetic tunneling junction (MTJ), magnetoresistance, multibit application, ring-shaped cells.**

I. INTRODUCTION

OVER the years, the magnetic tunnel junction (MTJ) devices have been extensively discussed due to their potential for spintronic devices such as magnetic random access memory (MRAM) and magnetic field sensor [1]–[3]. For the key issues of reproducible switching process and ultra-high density, the annular shape was proposed to be the most applicable design for memory cells [4]. In the antecedent studies, which were mainly focused on single magnetic film, the switching process and possible stable magnetic states in magnetic ring structures were identified by experimental as well as simulation results [5]–[8]. Generally, there are two magnetic states, i.e., the onion and the vortex state in narrow and/or thin magnetic rings, and extra states like vortexpair and vortexcore states were observed in wider and/or thicker magnetic rings.

It has been known that the tunneling magnetoresistance effect is associated with the relative alignment of magnetization of the free layer and pinned layer. Therefore, knowing the magnetization reversal on the free layer of MTJ rings can lead to determination of the magnetoresistance since the pinned layer possesses a uniform magnetization. In other words, one may control various stable remanent states; thus, the corresponding magnetoresistance values at zero fields are acquired.

Recently, we have demonstrated, for the first time, the concept of utilizing MTJ rings for the investigation of magnetization reversal and size dependence of magnetoresistance [9], [10]. The practical applications and complicated situations of ring-shaped multilayer systems can thus be deliberated and analyzed. In the present paper, we have investigated the remanent behaviors of stable states in microstructured MTJ rings through magnetoresistance measurements. The main goal focused on a possible way of having multilevels of magnetoresistance at zero field; a multibit storage can then be achieved.

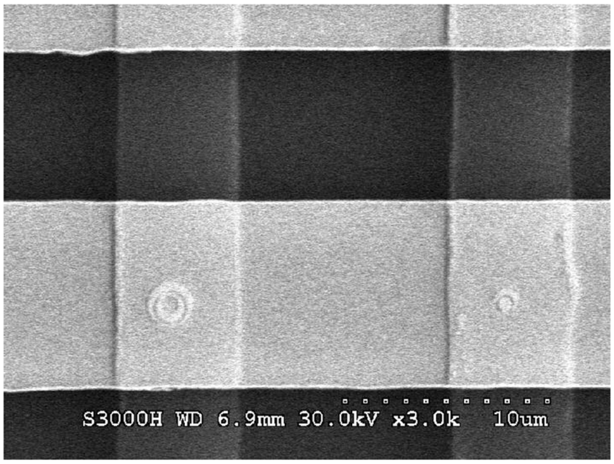

Fig. 1. SEM micrograph shows the complete magnetic tunnel junction ring devices with an outer diameter of 2/1 and inner diameter of 1/0.5 μm.

II. EXPERIMENTS

An MTJ stack 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 [11] (thickness in nanometers) was first prepared by the dc magnetron sputtering method. Two different-sized MTJ rings with an outer diameter of 2/1 μm and an inner diameter of 1/ 0.5 μm, as shown in Fig. 1, were fabricated by a top-down technique; hereafter, they are defined as sample A and B in sequence. The schema of the fabrication flow was shown in our previous work [9]. First, the isolated bottom electrode was defined by photolithography and etched by ion milling with photoresist mask. After removing the photoresist, a hard mask of Ti with a ring shape was then created by standard

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Digital Object Identifier 10.1109/TMAG.2007.894206

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electron beam lithography through a lift-off process. Following a two-step ion-milling process that was adopted to avoid edge shorting, the ring pattern was utilized to transfer to the MTJ structure until the top of bottom Cu layer. A stencil mask, constructed from electron beam lithography and reactive ion etching with gas of CF_4 after SiN_x sputtered onto the cell area, was used to form the top contact trench of the cell. Finally, a top electrode of 1000 Å Au was deposited by thermal evaporation. The MR measurements were carried out using a typical four-terminal dc technique in the presence of the tunable external magnetic field applied along the biasing direction.

III. RESULTS AND DISCUSSION

Fig. 2(a) represents the major loop, which shows the exchange biased field of pinned layer about 730 Oe measured on sample A, and thus, the pinned layer magnetization configuration is supposed to be uniform state in the minor loop regime of this study, i.e., ± 400 Oe. The minor loop, as shown in curve 1 of Fig. 2(b), reveals a three-transition magnetization reversal, which can be inferred to be onion, vortexpair, vortex, and reverse onion states. The insets of Fig. 2(b) represent the magnetization configuration of pinned and free layer in the different resistance levels.

To examine the remanent behaviors of these stable states of sample A, we measure the subloops of minor loop, i.e., starting from the negative/positive saturation field and sweeping to the field in the duration of some stable state, then backing to the negative/positive saturation field. The remanent behaviors of stable states are shown in curves 2 to 5 of Fig. 2(b) and (c). Curve 2 of Fig. 2(b) exhibiting hysteretical behavior was measured in a cycle from −350 to +60 Oe, and the evolution of magnetic state comparing with curve 1 was starting from the onion to the vortexpair, then back to the onion state at the field of −100 Oe. The hysteretical behavior also manifests in other subloops. Curve 3 of Fig. 2(b) was measured between −350 to +100 Oe, and its corresponding magnetic state evolution was from the onion to the vortex through the vortexpair, then back to the onion state at the field of −260 Oe. These irreversible transitions imply that the onion, vortexpair, and vortex state can still exist at remanence in this multilayer system ring. Curves 4 and 5 represent the subloops data measured from the positive saturation field to the first and second metastable state duration field, and the magnetic state evolutions are as curve 2 and 3. Notice that in curve 4, it is not easy to finetune the field into the vortexpair state and reveal no hysteretical behavior, which may be due to the coupling between the free and pinned layer, resulting in the duration difference. In this case, duration 1 and duration 2 are both with the vortexpair state in free layer. Duration 1 is smaller than duration 2, which indicates the antiparallel coupling. Hence, four controllable remanent states were found in sample A.

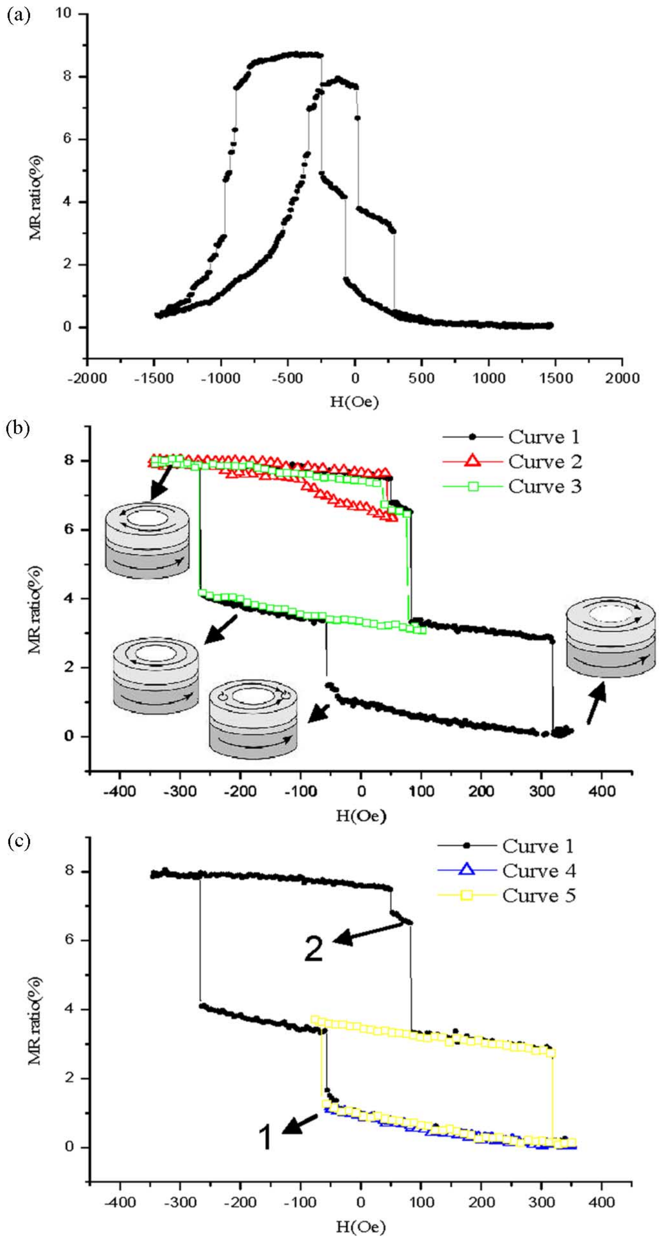

Fig. 2. MR loops for sample A. (a) Major loop. (b) Minor loop (curve 1) and subloops (curves 2 and 3) measured from negative free layer saturation field. The bottom and top layer of insets represent the magnetization configuration of pinned and free layer, respectively. (c) Minor loop (curve 1) and subloops (curves 4 and 5) measured from positive free layer saturation field.

Curve 1 of Fig. 3(a) is the minor loop of sample B. The smaller-sized sample B possesses simpler two-transition magnetization reversal, which develops from the onion to the reverse onion state through the vortex state. Curve 2 of Fig. 3(a) was measured in a cycle between −350 to +150 Oe and also showed hysteretical behavior. The corresponding magnetic state evolution was from the onion to the vortex, then back to the onion state at the field of−265 Oe. Similarly, curve 3 of Fig. 3(b) was the one measured from the positive saturation field. Note that curves 2 and 3 stand the same magnetoresistance level at zero field. Therefore, there are three controllable remanent states of the onion, vortex, and reverse onion states in sample B.

IV. CONCLUSION

In conclusion, we have investigated the remanent behaviors of stable states in microstructured MTJ rings through magnetoresistance measurements by ramping external magnetic fields with various field ranges. It is found that the onion, vortexpair, and vortex state exist at remanence, giving rise to four and

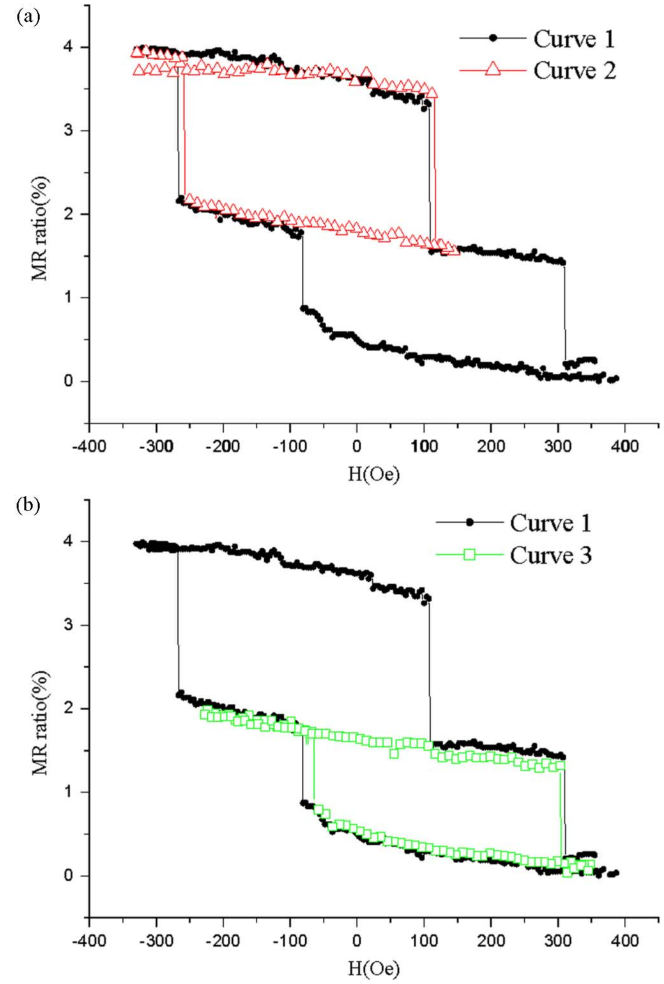

Fig. 3. MR loops for sample B. (a) Minor loop (curve 1) and subloop (curve 2) measured from negative free layer saturation field. (b) Minor loop (curve 1) and subloop (curve 3) measured from positive free layer saturation field.

three stable mangetoresistance values at zero field for ring devices with an outer/inner diameter of 2/1 and 1/0.5 μm, respectively. More efforts are needed in creating and optimizing the remanent behavior of stable states. These results may provide a great potential in magnetic multibit memory applications using ring-shaped cells.

ACKNOWLEDGMENT

This work was supported by the Ministry of Economic Affairs with Grant No. 94-EC-17-A-01-S1-026 and the National Science Council with Grant No. 95-2112-M-018-004-MY3.

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Manuscript received Octobor 31, 2006 (e-mail: phjcwu@cc.ncue.edu.tw).