Nanoring magnetic tunnel junction and its application in magnetic random access memory demo devices with spin-polarized current switching (invited)

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Current-driven magnetization switching was observed in the nanoring-shaped magnetic tunnel junctions (NR-MTJs) with key stack layers of both spin-valve-type antiferromagnetic/ferromagnetic/insulator/ferromagnetic and sandwich-type hard ferromagnetic/insulator/soft ferromagnetic structures. We successfully fabricated a series of ring-shaped MTJs with different ring-outer diameters of between 80 nm and 4 μm and different ring width of between 25 nm and 2 μm. Tunneling magnetoresistance ratio between 20% and 80% with different thickness of thin Al–O barrier was measured at room temperature as we apply a magnetic field or a pulsed current. When the electric current density exceeds a critical value of the order of 6 × 10^6 A/cm², the magnetization of the two free and reference magnetic rings can be switched back and forth between parallel and antiparallel onion states. The experiments show that the spin transfer torque plays a main switching role in the magnetization reversal and the current-induced circular magnetic field plays an assisted-switching role in such NR-MTJs. © 2008 American Institute of Physics. [DOI: 10.1063/1.2839774]

I. INTRODUCTION

Although the magnetic recording density of higher than 300 Gbits/in.² in hard disk driving (HDD) system has been realized within the last few years using the tunneling magnetoresistance (TMR) effect and Al–O barrier-based magnetic-tunnel-junction (MTJ) read head, an applicable magnetic random access memory (MRAM) device with the density or capacity more than 256 Mbits/in.² has not yet been achieved despite a ten year effort. 1–3 Especially, among the predicted advantages of the MRAM which includes the nonvolatility, antiradiation, unlimited endurance, high speed, high density, low power consumption, etc., the last two items have not been realized based on either the conventional magnetic field magnetization switching or the elliptic/rectangular-shaped MTJ structures in the state of the present MRAM devices. The main cause is that the stray field energy and the shape anisotropy energy of a nanoscale size MTJ increase distinctly with increasing density, resulting in the very large coercivity and switching field and further higher power consumption compared with that of a microscale size MTJ. In addition, the strong stray field interactions between the ferromagnetic layers inside of a MTJ or/and between the nearest neighboring MTJ cells can result in large magnetoconjunction effect and magnetic noise, which can whittle the independence and consistency for each MTJ as a memory cell. 4 In this regard, conventional elliptic-or rectangular-shaped MTJ structures may restrict the present MRAM device development. The newfangled MRAM devices with the capacity of 16 and 4 Mbits using the Astroid and Toggle model designs are fabricated, respectively. 5,6 Therefore, increased power consumption and reduced thermal stability are two major obstacles in developing ever smaller magnetic elements and higher density for advanced magnetic memory technology. 7,8

Previous experiments demonstrated that the power consumption for switching the spin-valve pillars 9 or magnetic tunnel junctions 10 can be decreased by using the spin transfer torque (STT) effect from the spin-polarized current, in which the shape of the magnetic element has been patterned into elliptic or rectangular shape. Undesired properties such as a large shape anisotropy and a strong stray field would place a severe limitation on these magnetic elements for ultrahigh density memory devices. To simultaneously improve the power consumption and the thermal stability for developing the MRAM, it is desirable to nanofabricate ring-shaped MTJs whose magnetization directions can be directly controlled by the spin-polarized current and spin transfer torque effect. 11 With a ring-shaped magnetic monolayer and giant magnetoresistance (GMR) multilayers or spin valve, it can offer a significant improvement in terms of eliminating the stray field and enhancing the thermal stability since the magnetization will form a vortex structure free of magnetic poles. 12,13 However, the GMR of spin valves is contrarily smaller than that of the TMR of MTJs to be useful for memory application. Clearly, MTJs would have much larger TMR (Refs. 14–16) than the GMR of spin valves.

In this work we report the observation of both current-driven magnetization switching and magnetic field magnetization switching in the nano- and microring-shaped MTJs (NR-MTJs and MR-MTJs). We successfully fabricated a se-

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ries of ring-shaped MTJs with the different ring-out diameters of between 80 nm and 4 μm and the different ring width of between 25 nm and 2 μm. The TMR ratio between 20% and 80% with the different thickness of thin Al–O barrier was achieved at room temperature (RT) as we apply a pulsed current or a magnetic field. When the electric current density exceeds a critical value of the order of $6 \times 10^6$ A/cm$^2$ in the nanoring-shaped MTJs, the magnetization of the two free and reference magnetic rings can be switched back and forth between parallel and antiparallel onion states. The experiments and theoretical analysis show that both the spin transfer torque and the current-induced circular magnetic field play main switching and assisted-switching roles, respectively.

II. EXPERIMENTAL METHOD

We successfully made a series of two types of ring-shaped MTJ structures with a high TMR ratio of between 20% and 80% at RT, the different ring-out diameters of between 80 nm and 4 μm, and the different ring width of between 25 nm and 2 μm. Here the TMR ratio is defined as $TMR = (R_{AP} - R_P) / R_P$. First, spin-valve ring-shaped MTJs were fabricated with the key stack layers of antiferromagnetic (AFM)/ferromagnetic (FM)/insulator (I)/ferromagnetic (FM). And second, sandwich-type ring-shaped MTJs were fabricated using the key stack layers of hard ferromagnetic (HFM)/insulator (I)/soft ferromagnetic (SFM) structures for discarding the easily diffused Mn-alloy layer as the AFM pinning layer. The sandwich-type ring-shaped MTJs also have potential applications in fabricating memory devices due to its good compatibility to fitting the semiconductor annealing and integrated techniques.

The MTJ films were first deposited on the Si(100)/SiO$_2$ substrate under a built-in in-plane magnetic field of about 100 Oe using an ULVAC TMR R&D Magnetron Sputtering System (MPS-4000-HC7) with a base pressure of $1 \times 10^{-6}$ Pa. The Al oxide barrier was fabricated by inductively coupled plasma (ICP) oxidizing among 0.6, 0.7, and 0.8 nm Al layer with an oxidation time of 10 and 20 s in a mixture of oxygen and argon at a pressure of 1.0 Pa in a separate chamber. Two electrodes situated above and below the NR-MTJ to measure its characteristics were patterned by ultraviolet optical lithography (UVL) combined with Ar-ion beam milling and reactive ion etching (RIE). The active ring-shaped junction area was patterned by electron beam lithography (EBL) with a Raith 150 scanning electron microscope using positive E-beam resist of polymethyl methacrylate (PMMA) and negative E-beam resist of hydrogen silsesquioxane (HSQ) techniques. The nanoring MTJ pillar including the top resist was then buried by SiO$_2$ deposition using a KJLC sputtering system. Finally, the resist and SiO$_2$ on the top of a nanoring were removed using a lift-off process, before the top electrode was patterned in the perpendicular direction. Transport properties were measured using a standard four probe method or a physical property measurement system (PPMS) at RT.

III. RESULTS AND DISCUSSION

A. Sandwich-type nanoring-shaped MTJs

The MTJ films with the key layer structure consists of Ta(5)/Co$_{50}$Fe$_{20}$B$_{20}$(2.5)/Al(d)-oxide/Co$_{60}$Fe$_{20}$B$_{20}$(2.5)/Ta(5)/Ru(5) (thickness unit: nm and $d=0.6, 0.7,$ and 0.8) were deposited on Si/ SiO$_2$ substrate, then patterned to get the sandwich-type single or array NR-MTJs as shown in Fig. 1 and 2. Figure 1(a) and 1(b) is a sketch of the designed sandwich-type nano-ring MTJ structure and scanning electron micrograph (SEM) of a typical patterned nanoring MTJ with outer diameter $D=100$ nm and ring width $W=30$ nm.

![Diagram of a designed sandwich-type nano-ring MTJ structure.](image)

**FIG. 1.** (Color online) (a) A designed sandwich-type nano-ring MTJ structure. Three stable magnetization patterns of vortex, symmetric onion, or asymmetric onion states can be respected to exist in each ring-shaped FM layer at zero magnetic field. (b) Scanning electron micrographs (SEMs) of a typical patterned nanoring MTJ with outer diameter $D=100$ nm and ring width $W=30$ nm.
The magnetization state of a typical NR-MTJ can usually have three possible stable configurations at the remanent state: vortex, symmetric onion and asymmetric onion magnetization states. Since our deposited MTJ FM layers have an in-plane field induced easy magnetization direction (EMD), the magnetization of both ferromagnetic free and reference layers for the ring-shaped MTJs with remanent state can usually form the symmetric onion states after the patterned procedure. Especially, the onion states remain stable after an external alignment magnetic field is turned off, although the onion states are metastable states comparing with the vortex state. During the magnetization process under an external field, the asymmetric onion states also can be formed due to the magnetostatic interaction of two domain walls or the pinning effect of nonsmooth ring-shaped defects, etc. The different asymmetric onion states can result to one or multiple interim magnetoresistance states between the minimum (parallel) and maximum magnetoresistance (antiparallel) states as shown in Fig. 3.

Figure 3 shows the tunnel resistance ($R$) as a function of the magnetic field ($H$) at RT which were measured with an in-plane field for a typical sandwich-type NR-MTJ. A small current of between 10 and 20 $\mu$A is used to measure the tunnel resistance, so that the current does not affect the magnetic state. At a large field, magnetization of both ring-shaped free and reference FM layers is in the parallel onion

![Image](image-url)
state and thus the resistance is the lowest. When the field is reduced, the stray field of the domain walls makes the onion state of the upper and lower ring-shaped FM layers to rotate in the opposite direction to reduce the magnetostatic energy between the two onion states. Since the anisotropy of the two layers is small, each onion state will oppositely rotate 90° to form an antiparallel configuration, in such case the tunnel resistance becomes maximum. Further reversing of the magnetic field forces the onion state of the two layers aligned in parallel state again. The TMR ratio of around 39%, lower and higher resistances of 1320 Ω and 1830 Ω, minimum and maximum resistance-area product RA of 7.77 Ω μm² and 10.78 Ω μm² at RT were, respectively, observed for the NR-MTJ with a size of 5.89 nm². Although vortex states with the lowest energy state (which possibly appears in the more thick free and reference FM layers) are more stable than the onion states, our experiments and the related micromagnetic simulations by Wei et al.\(^{18}\) show that the transition from the onion state to the vortex state does not occur when one sweeps the in-plane magnetic field from a large positive to a negative value for the samples with only a 2.5 nm thick FM layer. Instead, the domain walls of the onion state travel along the ring until the polarization of the onion state is reversed.

Figure 4 shows the tunnel resistance (R) versus spin-polarized current (I) loops driven by a pulse dc for a low resistance NR-MTJ with outer diameter of 100 nm and ring width of 25 nm. The use of the pulse current rather than a steady current can avoid any significant heating effect and thermal noise as well as reduce the thermally assisted magnetization reversal. Before each resistance measurement, a current pulse with amplitude I and width between 200 and 500 ns was applied. Then, the resistance is measured by using a low readout current of 10 μA that will not disturb the magnetic state of the NR-MTJ. By repeating the above process for an increasing/decreasing amplitude of I, we obtained the full R-I loop as shown in Fig. 4. The TMR ratio of around 7.5%, lower and higher resistances of 265 and 285 Ω, and minimum and maximum resistance-area product RA of 1.56 and 1.68 Ω μm² at RT were, respectively, observed for the NR-MTJ with a size of 5.89 nm². In such NR-MTJs, a relatively small critical value \(I_C\) of switching current between 450 and 650 μA at RT can switch the free Co\(_{75}\)Fe\(_{25}\)B\(_{20}\) (2.5 nm) layer magnetization from the parallel to antiparallel onion state relative to that of the reference Co\(_{75}\)Fe\(_{25}\) (2.5 nm) layer.

**B. Spin-valve-type nanoring-shaped MTJs**

The MTJ stack layers with the AFM/FM/I/FM key structure of Ta(5)/Ir\(_{22}\)Mn\(_{78}\)(10)/Co\(_{32}\)Fe\(_{28}\)(2)/Ru(0.75)/Co\(_{60}\)Fe\(_{20}\)B\(_{20}\)(2.5)/Al(0.7)-oxide/Co\(_{90}\)Fe\(_{20}\)B\(_{20}\)(2.5)/Ta(3)/Ru(5) (thickness unit: nm) were deposited on Si/SiO\(_{2}\) substrate, then patterned to get the spin-valve-type single or array NR-MTJs. Figure 5 shows the tunnel resistance (R) versus magnetic field (H) loops of a typical spin-valve NR-MTJ with outer diameter \(D=200\) nm and ring width \(W=35\) nm at RT. The TMR ratio of around 52%, lower and higher resistances of 11.54 and 17.57 kΩ, and minimum and maximum resistance-area product RA of 208 and 318 Ω μm² at RT were, respectively, observed for this spin-valve NR-MTJ with a size of 18.1 nm². Under the external applied field, the NR-MTJs show a spin-valve type of R vs H curves, as shown in Fig. 5. In addition to two stable onion magnetization states where the magnetizations of the free layer and pinned layer are aligned parallel (low resistance) and antiparallel (high resistance) as observed in the sample, some metastable magnetization states in such \(D=200\) nm NR-MTJs are also formed due to the appeared asymmetric onion states.

Figure 6 shows the tunnel resistance (R) versus spin-polarized current (I) loops driven by a pulse dc for one typical spin-valve-type NR-MTJs with the outer diameter of 100 nm and ring width of 25 nm and barrier thickness of Al(0.70 nm) oxide. For the NR-MTJ with a size of 5.89 nm², TMR ratio of 30%, lower and higher resistances of 2684 and 3486 Ω, and minimum and maximum resistance-area product RA of 15.8 and 20.5 Ω μm² at RT.
were observed, respectively. The critical value \( I_C \) of switching current between 400 and 550 mA for the free Co8Fe20B20(2.5 nm) layer was observed at RT.

Our experiments and further simulations both in sandwich-type nano-ring-shaped MTJs by Wei et al. \(^\text{18}\) and in spin-valve-type nanoring-shaped MTJs by Wei et al. \(^\text{19}\) show that two plausible mechanisms are responsible for the switching of the magnetization by the current. First, the spin transfer torque is a dominant factor for the observed switching. Second, the pulse dc induces a circular magnetic field (Oersted field) of smaller than 15 Oe at the outer boundary of the 100 nm diameter ring, which can affect the magnetization states as assisted-switching mechanism. Furthermore, the observed relative smoothly quadrate \( R-I \) curves (Figs. 4 and 6) compared to the \( R-H \) curve (Figs. 3 and 5) indicate that the local pinning plays a less important role for the current-switching magnetization reversal and the spin torque effect is dominant.

The TMR and \( R \) vs \( I \) loops driven by a pulse spin-polarized dc in the NR-MTJs for the above listed sandwich-type and spin-valve-type NR-MTJs show a good quadratic shape for a memory cell application in MRAM device. \(^\text{20,21}\) The critical switching current from antiparallel (parallel) to parallel (antiparallel) states is smaller than 1.0 mA; this corresponds to the critical switching current density about \( J_C = 6 \times 10^6 \text{ A/cm}^2 \). The \( J_C \) values can be expected to further decrease by using other soft alloy FM layers of NiFe, CoFeSiB, etc. The TMR ratio and resistance of NR-MTJs can be conveniently optimized and modified by changing the FM materials, barrier thickness, ring size, and width to fit the requirements as memory cell applications for developing MRAM devices. \(^\text{22}\) Figure 7 shows a designed prototype of \( 2 \times 2 \) nanoring MRAM demo device based on one NR-MTJ and one transistor structure. Here the word line, also as the gate line, plays the role of addressing each bit together with the cross bit line. Clearly, the thin MgO(001) barrier-based NR-MTJs would be expected to have much larger TMR ratio and potential current-driving device applications if both low resistance and low critical switching current density can be achieved. Comparing with the conventional Astroid or Toggle MRAM demo devices developed in the last ten years using the magnetic field driving as shown in Fig. 9, the novel MRAM design based on STT or nanoring MTJ design using the current switching can be expected to open a new way for upgrading the possibility of fabricating the MRAM devices with high density, high performance, but low power consumption.

### IV. CONCLUSION

In conclusion, we demonstrate that the magnetization of the nanoring-shaped MTJs can be switched by a spin-polarized current. The current density of the order of \( 6 \times 10^6 \text{ A/cm}^2 \) is sufficient to switch one onion state to another in both sandwich-type NR-MTJs and spin-valve-type NR-MTJs. Our basic investigation on the NR-MTJ materials and physics offers a possible new approach for developing the MRAM devices with high density magnetic memory structures is possible. Figure 8 shows TMR ratio development of Al-O barrier based MTJs with the years using different FM material electrodes. \(^\text{24-30}\) It shows us that the Al-O barrier based NR-MTJs, combined with spin polarized current switching or magnetic field switching, will have more potential applications for designing new devices.

![FIG. 7. (Color online) A prototype 2x2 MRAM demo device based on one NR-MTJ and one transistor structure. Here the word line, also as the gate line, plays the role of addressing each bit together with the cross bit line.](Image)

![FIG. 8. (Color online) Development of Al-O barrier based MTJs with the years using different FM materials.](Image)
cells, enhanced thermal stability, and reduced power consumption. Such NR-MTJs together with current-switching mechanism also can be used in the magnetic logic designs.

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