Simulation study of new 3-terminal devices for high speed STT-RAM*

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Abstract: To improve the performance of spin transfer torque random access memory (STT-RAM), especially writing speed, we propose three modified 3-terminal STT-RAM cells. A magnetic dynamic process in the new structures was investigated through micro-magnetic simulation. The best switching speed of the new structures is 120% faster than that of the rectangular 3-terminal device. The optimized 3-terminal device offers high speed while maintaining the high reliability of the 3-terminal structure.

Key words: spin transfer torque; non-volatile memory; spin valve; micro-magnetic simulation
DOI: 10.1088/1674-4926/32/7/074007 **PACC:** 7570P; 8220W

1. Introduction

STT-RAM is one of the most competitive candidates for next generation universal memory and has been extensively studied in recent years[1−3]. The core of STT-RAM is a spin valve or a magnetic tunneling junction (MTJ) whose resistance changes according to different magnetic configurations. MTJ is taking the place of the spin valve due to its high magneto-resistance for wider memory windows[4]. However, a large critical current density J_c (10^7 A/cm^2) is the main factor for the tunneling layer (Al_2O_3 or MgO) failure in MTJ. A rectangular 3-terminal structure was proposed by Braganca to improve the reliability of STT-RAM where a spin valve is used for writing while a MTJ is used for the reading process[5]. However, the writing speed in this device is slower than that of standard STT-RAM cells because the spin valve and MTJ share a common free layer (Fig. 1(a)). Switching of the whole free layer is realized by spin torque transfer in the spin valve and then magnetization propagation. In other words, the improvement in the reliability is achieved at the cost of a longer switching time.

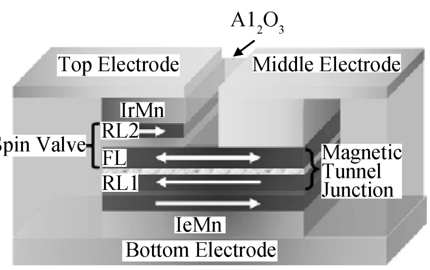
To improve the writing speed of the 3-terminal structure, we have proposed modified 3-terminal devices (Fig. 1(b)) and investigated the magnetic switching process. We carried out micromagnetic simulation to analyze the magnetic dynamic process using an object oriented micromagnetic framework (OOMMF) with a spin transfer torque term included[6].

2. Micromagnetic simulation

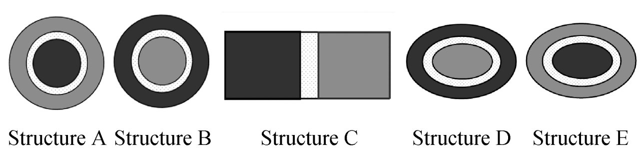
To determine whether and how much the modified structures can improve the writing speed and develop an understanding of the spin torque driven switching process in modified 3-terminal devices, we performed time-dependent micromagnetic simulation by solving the Landau–Lifshitz–Gilbert (LLG) equation using OOMMF[6]. Free layers are divided into a 3-dimensional array of cells ($5 \times 5 \times 1$ nm^3) for all structures. The material stacks of spin valve is Co (10 nm)/Cu (4 nm)/Co (2 nm).

3. Results and discussion

Magnetization evolution of free layers in different structures is shown in Fig. 2. From this, we can find that the switching times of structures A, B, C, D and E are 0.07, 0.05, 0.11, 0.08 and 0.09 ns, respectively. All of the modified structures



(a)



(b)

Fig. 1. (a) Schematic structure of the rectangular 3-terminal STT-RAM cell[5]. (b) Top view of five different 3-terminal structures; black regions are spin valves though which write current flows, gray regions are MTJs for information readout, white regions are insulating layers between spin valve and MTJ. In structure C, the pinned layer and free layer are 125×125 nm^2 and 125×250 nm^2, respectively. Areas of spin valve and MTJ in structure A, B, D, E are the same as in C.

* Project supported by the National High Technology Research and Development Program of China (No. 2009AA01A403), the Foundation for Key Program of Ministry of Education, China (No. 20091770305), and the Fok Ying-Tong Education Foundation, China (No. 114011).
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Received 16 December 2010, revised manuscript received 21 March 2011

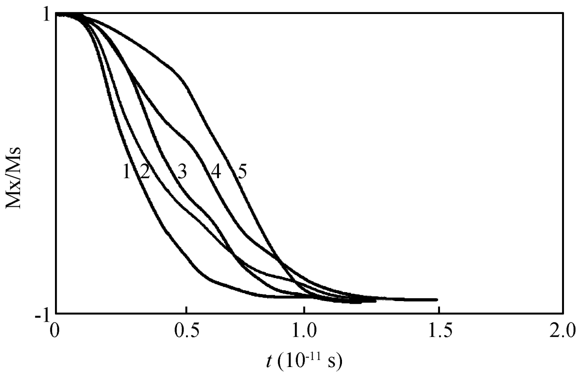

Fig. 2. Magnetization evolution of free layers (curve 1: structure B; curve 2: structure D; curve 3: structure A; curve 4: structure C; curve 5: structure E). Here, the switching time is defined as the duration needed for the magnetization of free layers being 90% reversed.

show better performance than C (the rectangular 3-terminal device).

Figures 3(a)–3(i) show the magnetic reversal process under a current density of 3.75×10^8 A/cm^2. To understand the speed improvement of these modified structures, let's take a closer look at the magnetic dynamic process in structure C (Fig. 3). Magnetization reversal in C starts with a reversal domain-like region beneath the spin valve. This reversal region then extends towards the right end of the free layer driven by exchange interaction. This process can be considered a 1-dimensional (1D) propagation of the magnetization. As for those modified structures, the exchange interacting area is circle-like. The magnetization reversal propagates in a 2D mode, which is more effective than 1D mode. In fact, the modified structures can be obtained by rotating C around different centers. That is why the modified structures switch faster than C.

It should also be noticed that structures with an outer spin valve (B, D) show higher speed than their counterparts with an inner spin valve (A, E). This implies that injection current through the center of the free layer is less efficient than that through the outer ring. From Fig. 3, we can see that in structures B and D, the local magnetization at the edge of the free layers is reversed independently. Then magnetization of the whole free layer is reversed by exchange interaction. However, this is not the case for A and E. The central region of the free layer cannot be reversed independently. From Fig. 3(d), we find an interesting phenomenon. In structure A, the magnetization far away from the center is reversed before the central region does. Note that the injected current will spread in the whole free layer no matter whether it is from the outer or inner spin valve. This implies that the outer region is easier to switch than the center under the same current. This is because the boundary conditions of the outer region differ from those of the central region. For structure E, we can find the same situation in Fig. 3(f).

From the magnetization evolution of the free layers (Fig. 3), the formation of special meta-stable domains is confirmed during switching. This is in accordance with previous research on meta-stable domain in nano-sized rings[7]. The formation of domains makes the analysis of magnetization reversal much more complicated.

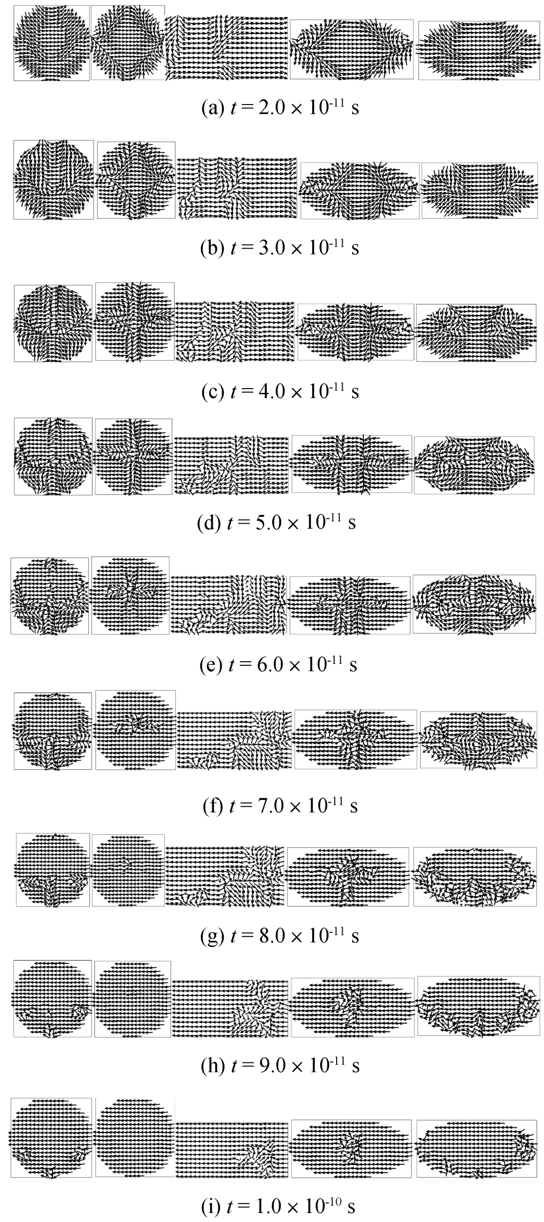

Fig. 3. Magnetization evolution during reversal from parallel to antiparallel configuration (from left to right, corresponding to structures A, B, C, D and E).

It can be found that the magnetization reversal in structure B takes the shortest time under the same current density among all structures. The reason why B is faster than D lies in the smaller shape anisotropy in B. A smaller anisotropy means a lower effective field in the LLG equation, which leads to a smaller threshold current for switching or higher speed under the same injection current density.

4. Summary

In summary, we have proposed three modified 3-terminal structures for high reliability, high speed STT-RAM. A magnetic dynamic process was investigated using OOMMF. The modified structures show better performance than the rectangular 3-terminal device (C). It is found that an outer spin valve for writing is more efficient than an inner one. The structure with an outer ring spin valve (structure B) shows the best switching performance. The writing speed of B is 120% higher than that of C. This device structure could be a solution to improved writing speed while maintaining the high reliability of a 3-terminal structure.

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