Low write-current magnetic random access memory cell with anisotropy-varied free layers

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(Received 4 August 2008; accepted 12 October 2008; published online 1 December 2008)

We propose a magnetic random access memory (MRAM) cell that utilizes field-induced switching and is applicable to high-speed memories. The MRAM cell, called the shape-varying MRAM cell, has three free layers, each having different shapes and functions, and achieves low write-current switching with high thermal stability and high external field robustness. We show analytically that one of the layers contributes to the low write-current switching and another contributes to the thermal stability. We also show the results of a micromagnetic simulation, in which write current of <0.5 mA, write time of <2 ns, energy barrier $(\Delta E/k_BT)>100$, and external field robustness of >32 Oe were obtained. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3032894]

I. INTRODUCTION

Magnetic random access memories (MRAMs) have a number of advantages such as nonvolatility, high-speed operation, unlimited read-write endurance, and high temperature operation. Among them, high-speed operation is a particularly unique attraction of MRAMs and cannot be achieved with other nonvolatile memories. Taking advantage of this, Sakimura *et al.*[1] proposed a cell circuit for high-speed application of MRAMs, in which memory elements are selected by write transistors. This enables replacement of static random access memories (SRAMs), if memory elements can be switched within a few nanoseconds. From this viewpoint, magnetic field-induced switching, not spin-transfer torque switching,[2,3] is desirable for the writing method, since magnetic reversal takes only around 1 ns.

According to Ref. 1, it is also crucial to reduce write current to less than 0.5 mA for achieving smaller cell areas than those of SRAMs. There have been many efforts to reduce the write current of MRAMs using field switching, where, in particular, write-line inserted magnetic tunnel junctions (WLIMs) (Ref. 4) are well suited to the high-speed circuits.[1] In general, achieving low write-current switching together with sufficient thermal stability and high external field robustness is difficult, and, up to now, it has not been reported that write current had been reduced to less than 0.5 mA.

In this paper, we propose a MRAM cell with field-induced switching, which can achieve low write-current switching, high thermal stability, and high external field robustness as well as high-speed operation. We first describe its structure and functions of each layer. We then derive the writing properties analytically. Finally we show numerical simulation and confirm its features quantitatively.

II. STRUCTURE

We found that a structure with plural free layers whose anisotropies are varied is effective to reduce the write current. Then, we considered that the varied anisotropies can be realized with varied shapes and proposed the following structure. Figure 1 shows a schematic illustration of an example structure. We have named the proposed MRAM cell the "shape-varying MRAM" cell. It has three magnetic layers: storage layer, top sense layer, and bottom sense layer, each of which is different in shape. These three layers correspond to the so-called free layer of a conventional MRAM. The storage layer has a relatively large aspect ratio, whereas the two sense layers have small aspect ratios and larger areas than the storage layer. This difference in shape results in a difference in anisotropy field of each layer. It should also be noted that the magnetic volume (product of the magnetization and the volume) of the storage layer has to be smaller than that of the top sense layer. Also, the sum of the magnetic volume of the storage layer and the top sense layer is balanced with that of the bottom sense layer. A tunneling barrier and a pinned layer neighbor the storage layer, forming a magnetic tunnel junction (MTJ). A conductive layer, which induces a magnetic field, is located between the top and bottom sense layers, similar to the WLIMs structure.[4] Also the conductive layer is connected to write transistors, forming the high-speed circuit structure.[1] The storage layer and the top sense layer are ferromagnetically coupled by a coupling layer, which is located between them. Also, the bottom sense layer and the other two layers are coupled in the antiparallel direction with a magnetostatic interaction. For writing, we introduce bidirectional current into the conduc-

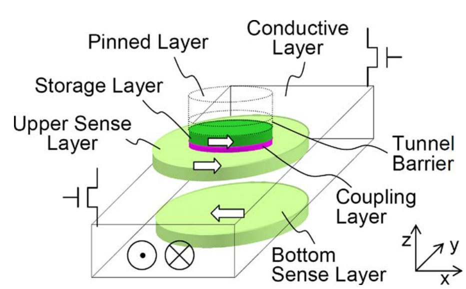

FIG. 1. (Color online) Schematic illustration of shape-varying MRAM cell.

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tive layer and apply a magnetic field to the above free layers. For reading, we utilize the tunnel magnetoresistance (TMR) effect in the MTJ.

The most important characteristic of the shape-varying MRAM cell is the division of the conventional free layer into three layers, each of which has different functions. The storage layer, having relatively large anisotropy, can maintain stored data. The top sense layer, having small anisotropy and being coupled with the storage layer, can easily reverse when sensing an applied weak magnetic field. The bottom sense layer, being antiferromagnetically coupled with the above two layers, can hold stored data from the unidirectional fields. In short, the storage layer, the top sense layer, and the bottom sense layer contribute to thermal stability, low write-current switching, and high external field robustness, respectively. Note that the essence of this cell is not basically the difference in shape but the difference in anisotropy, and the difference in shape is just a method to provide the difference in anisotropy. Incidentally, the idea of this structure is similar to that of exchange-coupled composite (ECC) media (or hard/soft stacked media),[5] which is a candidate for 1 Tb/in.^{2} recording media. Here, the storage layer and the sense layer of our proposed cell correspond to the hard and soft layers of ECC media, respectively.

III. ANALYSIS

We analyzed the writing properties of the shape-varying MRAM cell in a very simple manner. We introduced a single-domain model,[6,7] in which the magnetic moments of each layer are treated as one vector. Then, in order to understand its true nature, we considered a stack comprised of only the storage layer and the top sense layer, which have an identical shape and are coupled in the whole area. Also, we assumed that these two layers have a large difference in anisotropy field, instead of difference in shape. In these assumptions, the energy of this system when a magnetic field H is applied along the easy axis is written as

$$E = \tfrac{1}{2}H_{k1}M_1V_1 \sin^2\theta_1 - HM_1V_1\cos\theta_1 + \tfrac{1}{2}H_{k2}M_2V_2\sin^2\theta_2 - HM_2V_2\cos\theta_2 - JS\cos(\theta_1-\theta_2), \quad (1)$$

where H_{k1}, M_1, V_1, and θ_1 represent the anisotropy field, magnetization, volume, and direction of the moment from easy axis of the sense layer, H_{k2}, M_2, V_2, and θ_2 represent those of the storage layer, J represents the coupling constant between the storage layer and the sense layer (positive for ferromagnetic coupling), and S represents the area of the element. Here, magnetostatic interaction is not included and shape magnetic anisotropy is included in H_{k1} and H_{k2} for simplicity. By calculating a condition in which the $(\theta_1,\theta_2) = (\pi,\pi)$ state loses stability, we obtained the critical field H_{sw} of this system as

$$H_{sw} = \frac{H_{k1}+H_{k2}+J_1+J_2-\sqrt{(H_{k1}+H_{k2}+J_1+J_2)^2-4(H_{k1}H_{k2}+H_{k1}J_2+H_{k2}J_1)}}{2}, \quad (2)$$

where $J_1 = JS/M_1V_1$ and $J_2 = JS/M_2V_2$. To obtain more straightforward solutions, we further used the following approximation. We neglected the Zeeman energy term of the storage layer [the fourth term in Eq. (1)]. This means no field is applied to the storage layer. The validity of this approximation will be addressed later. In this case, H_{sw} becomes

$$H_{sw} = \frac{H_{k1}H_{k2}M_1M_2V_1V_2 + (H_{k1}M_1V_1 + H_{k2}M_2V_2)JS}{M_1M_2V_1V_2H_{k2} + M_1V_1JS}. \quad (3)$$

Finally, let us consider a simple case in which $J \to \infty$. Then, Eq. (3) becomes

$$H_{sw} \to H_{k1} + \frac{M_2V_2}{M_1V_1}H_{k2}. \quad (4)$$

Even though Eq. (4) was derived using a number of approximations, it expresses well one aspect of the essence of the shape-varying MRAM cell. The first term on the right side, which is the anisotropy field of the sense layer H_{k1}, is designed to be negligibly small due to its low aspect ratio. Similarly, the second term can be made smaller by reducing M_2V_2/M_1V_1. Accordingly, we can obtain a very small switching field H_{sw}.

The energy barrier was estimated as follows. We use $J \to \infty$ again. In this case, we have $\theta_1 = \theta_2$ and obtained the energy barrier ΔE as

$$\Delta E = \frac{1}{2}(H_{k1}M_1V_1 + H_{k2}M_2V_2). \quad (5)$$

This equation also expresses simply another aspect of the essence. H_{k2} is designed to be relatively large due to its large aspect ratio, thus the second term can ensure thermal stability.

As described above, the fundamental idea of our proposed cell is summarized as follows. A sufficient thermal stability is achieved by the large anisotropy of the storage layer. When a small field is applied, the sense layer, having small anisotropy, feels compelled to reverse. Here, although the storage layer, having large anisotropy, is reluctant to follow, both layers can reverse due to the ratio of the magnetic volumes. As well as these features, we can obtain a large TMR ratio with this cell. This is because we can use a material with a large anisotropy such as CoFeB for the storage layer, since this layer allows relatively large anisotropy.

Next, let us address the validity of the approximations we used. First, the approximation on the Zeeman energy of the storage layer should be valid because the Zeeman energy is much smaller than the anisotropy energy for the storage layer. As described below, it is true that the H_{k2} is around 50 Oe, whereas the applied field H is only around 5 Oe. In addition, if we take this Zeeman energy term into consideration, the switching field becomes even smaller. Second, regarding the single-domain approximation, it may not be appropriate for the present case in which the sense layer has a small aspect ratio. Accordingly, there are only qualitative facts in the obtained solution and, in order to obtain quantitative accuracy, it may be necessary to perform a numerical simulation. Third, we have not considered the bottom sense layer in the present analysis. However, a micromagnetic simulation revealed that this layer does not influence the switching field and merely increases the energy barrier and external field robustness with magnetostatic coupling. Finally, we have not taken into account the difference in shape, especially the region in the sense layer that does not overlap the storage layer. However, if we could include this effect, the switching field would be further reduced. In fact, a simulation suggested that this region can lead to the magnetic reversal because it is not affected by the burden of the storage layer.

IV. SIMULATION

We carried out a numerical simulation on the structure illustrated in Fig. 1. The magnetization (M_s), anisotropy constant (K_u), and exchange constant (A) were 8×10^5 A/m, 1×10^2 J/m^3, and 1×10^{-11} J/m for each layer. These values were set by modeling Ni–Fe. The lengths to the x and y directions of the storage layer (L_x, L_y) were $L_x=0.42$ μm and $L_y=0.24$ μm, respectively, and those of the sense layers were $L_x=0.64$ μm and $L_y=0.72$ μm, respectively. The thicknesses of the storage layer, the top sense layer, and the bottom sense layer were 1.2, 1.8, and 2.0 nm, respectively. The width and the thickness of the conductive layer were 0.64 μm and 20 nm, respectively. The coupling strength between the storage layer and the top sense layer was 1.1×10^{-5} J/m^2. We used a micromagnetic simulator based on the Landau–Lifshitz–Gilbert equation.[8] We first calculated a stable state and then applied either a current or a magnetic field to it.

We found a structure with these parameters shows the preferable properties as described above. The switching fields of the single storage layer and the single top sense layer were 48 and 6 Oe, respectively, and that of the stacked film comprising the storage layer and the top sense layer was 4.4 Oe. Even though the switching field of the storage layer is large, a very small switching field is achieved with the proposed structure. In addition, we have not clarified the reason why the switching field of the stacked film was smaller than those of the other layers, but we guess this originates from unconsidered preferable effects in our proposed structure. It is also to be noted that an excessively small coupling strength resulted in a separate reversal of the top sense layer; however, the top sense layer and the storage layer could switch simultaneously with a coupling strength of more than 2×10^{-6} J/m^2.

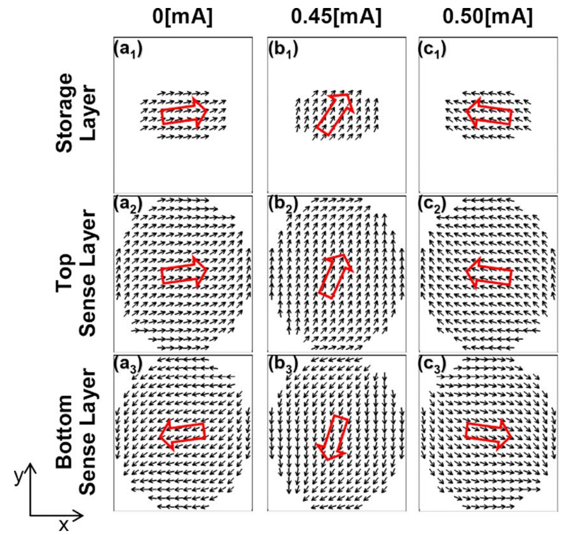

FIG. 2. (Color online) Magnetic state of each layer when a write current is introduced. (a_1)–(a_3): 0 mA. (b_1)–(b_3): 0.45 mA. (c_1)–(c_3): 0.50 mA. (a_1)–(c_1): storage layer. (a_2)–(c_2): top sense layer. (a_3)–(c_3): bottom sense layer.

Figure 2 shows the simulation results of current-induced switching. The magnetic moments of each layer do not fully switch when the write current of 0.45 mA is introduced through the conductive layer, whereas they do switch when a write current of 0.50 mA is introduced. We thus demonstrated the low write-current switching of the shape-varying MRAM cell, which is possible to replace conventional SRAMs. Furthermore, when we set the damping constant α of each layer as 0.01, we obtained a switching time of 1.8 ns. This suggests that the shape-varying MRAM cell promises very high speed operation of around 500 MHz. We also investigated the energy barrier ΔE of this system. Calculating the total energy during the reversal, which excludes the Zeeman energy, we obtained $\Delta E/k_BT$ as 106. This value is sufficient to enable 10 year retention.

In addition, we found that the obtained writing properties of the shape-varing MRAM cell were significantly superior to those of other cell structures. For example, devices with single free layer having $\Delta E/k_BT$ of as much as 100 showed a write current of more than 2 mA even though it equipped a clad layer.[9] Moreover, the WLIMs structure[4] resulted in the write current of not less than 1 mA. Thus, we concluded that the proposed structure is very promising for low current writing with high thermal stability.

Finally, we examined the external field robustness. Figure 3 shows the change in magnetic configuration when a uniform field is applied. After a magnetic field of 32 Oe was applied, the cell was restored to its initial state. When the magnetic field is applied in other directions, no changes occurred after a field, of less than 32 Oe, was removed. This indicates that this system has external field robustness of at least 32 Oe. This value is considered to be adequate for

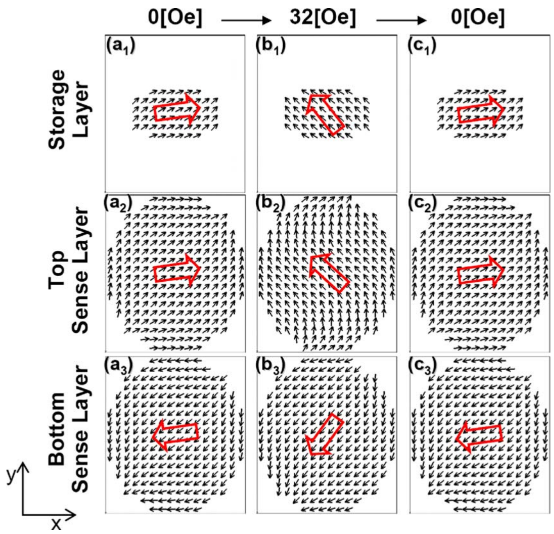

FIG. 3. (Color online) Magnetic state of each layer when an external field is applied. $(a_1)-(a_3)$: initial state. $(b_1)-(b_3)$: $H_{ex}=32$ Oe, $(c_1)-(c_3)$: final state. $(a_1)-(c_1)$: storage layer. $(a_2)-(c_2)$: top sense layer. $(a_3)-(c_3)$: bottom sense layer. Field is applied along the $-x$ direction.

practical applications. When we applied a field of more than 36 Oe along the $-x$ direction, however, the state switched to the other.

V. CONCLUSION

The shape-varying MRAM cell we proposed has a potential for high-speed applications, as a replacement for SRAMs. In short, it realizes low write-current switching, high thermal stability, and high external field robustness by dividing the conventional free layer into three magnetic layers, each of which has different anisotropies and functions. An analytical calculation described well the fundamental mechanism in which the sense layer and the storage layer contribute to the small switching field and the sufficient energy barrier, respectively. We also performed a micromagnetic simulation and verified that a write current of <0.5 mA, switching time of <2 ns, $\Delta E/k_BT>100$, and external field robustness of >32 Oe can be simultaneously achieved.

We have recently fabricated the test elements of the shape-varying MRAM cell and have obtained preferable properties, which will be addressed in detail in the near future.[10]

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