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Multi-bits memory cell using degenerated magnetic states in a synthetic antiferromagnetic reference layer

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ABSTRACT

We newly developed a magnetic memory cell having multi-bit function. The memory cell composed of a perpendicularly magnetized magnetic tunnel junction (MB-pMTJ) and a synthetic antiferromagnetic reference layer. The multi-bit function is realized by combining the freedom of states of the magnetic free layer and that in the antiferromagnetically coupled reference layer. The structure of the reference layer is (FeB/Ta/$[Co/Pt]_3$)/Ru/($[Co/Pt]_6$); the top and the bottom layers are coupled through Ru layer where the reference layer has two degrees of freedom of a head-to-head and a bottom-to-bottom magnetic configuration. A four-state memory cell is realized by combination of both degrees of freedom.

The states in the reference layer however is hardly detected by the total resistance of MB-pMTJ, because the magnetoresistance effect in the reference layer is negligibly small. That implies that the resistance values for the different states in the reference layer are degenerated. On the other hand, the two different states in the reference layer bring different stray fields to the free layer, which generate two different minor loop with different switching fields.

Therefore, the magnetic states in the reference layer can be differentiated by the two-step reading, before and after applying the appropriately pulsed magnetic field which can identify the initial state in the reference layer. This method is similar to distinguishing different magnetic states in an in-plane magnetized spin-valve element. We demonstrated that four different states in the MB-pMTJ can be distinguished by the two-step read-out. The important feature of the two-step reading is a practically large operation margins (large resistance change in reading) which is equal to that of a single MTJ. Even though the two-step reading is a destructive method by which 50% of the magnetic state is changed, this MB-pMTJ is promising for high density non-volatile memory cell with a minor cost of operation speed.

1. Introduction

Enhancement of the capacity of memory is an inevitable demand for modern computing system. In general, there are two major ways to enhance the capacity. One is to minimize the size of the memory cell itself. The other is to use a multi-level cell technology. For spin-transfer-torque MRAM (STT-MRAM), a magnetic tunnel junction with perpendicular magnetization (p-MTJ) is suitable to minimize the cell size while keeping sufficient retention time [1,2]. On the other hand, the conventional multi-level cell approach has also been demonstrated using a p-MTJ cell whose structure is a simply stacked two MgO-MTJs on one memory cell [3]. In the conventional multi-level MTJ cells, however, it is extremely difficult to have practically large operation margins. The operation margin is defined as the window in resistance range to distinguish the state of memory cell, for both read-out and writing due to cell-to-cell variations. Note that even in a single-level STT-MRAM, securing the operation margins is not technologically easy. Here, we propose a new concept of multi-bits p-MTJ (MB-pMTJ) cells using degenerated magnetic states. This concept is novel version of the sensing scheme for four magnetic state in a pseudo-spin valve GMR element [4,5]. Although the reading process is destructive, it can provide us operation margins comparable to those of single-level MRAM cells.

2. Structure and magnetic property of Multi-bit pMTJ

We have developed an MB-pMTJ which can be operated under ultralow-voltage with a so-called synthetic antiferromagnetic (SyAF) reference layer structure [2]. The main structure of the MB-pMTJ is shown in Fig. 1. FeB/Ta/FeB layer is the magnetic free layer

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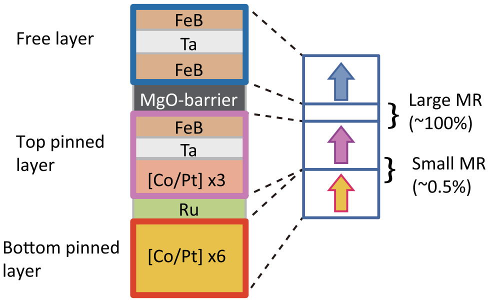

Fig. 1. Schematic diagram of structure of MB-pMTJ. The reference layer is composed of two perpendicularly magnetic layers antiferromagnetically coupled through Ru layer at low bias fields.

(storage layer) and (FeB/Ta/[Co/Pt]$_3$)/Ru/([Co/Pt]$_6$) is the magnetic reference layer. Large tunnel magnetoresistance (TMR) effect appears across the MgO barrier with magnetoresistance (MR) ratio of about 100%. On the other hand, the MR ratio across the Ru layer in the reference layer is negligibly small (about 0.5%). Therefore the magnetic configuration in the reference layer (antiparallel or parallel) could not be easily detected from the overall resistance. The resistance area product (RA) value of the MB-pMTJ was $2.3\ \Omega\mu^2$. We fabricated an MB-pMTJ with the junction size of about 120 nm diameter circle, and the resistance at the parallel state was about $200\ \Omega$. This MB-pMTJ can be switched by DC pulse whose amplitude was less than 200 mV.

Fig. 2 shows an example of the MR loops of the pMTJ. The magnetic field was applied perpendicularly to the MTJ stack. Major loop (a) indicates that the antiferromagnetic (AF) configuration is stable at lower magnetic fields (less than several hundred Oe) in both directions. This implies that the reference layer could maintain different magnetic configurations at the zero magnetic field. In other words, this MB-pMTJ has an additional degree of freedom in the configuration. To verify the existence of the different magnetic configurations, we measure minor loops of the MB-pMTJ with different initial magnetic fields of ±8000 Oe. Because a different magnetic configuration in the reference layer exerts a different stray field to the free layer, which results in a different switching field showing degenerated minor loops. The two different Minor loops (b, c) are clearly observed, and indicates that different magnetic configurations coexist at zero magnetic field. At a magnetic field of −3300 Oe on Minor loop 1 (3260 Oe on Minor loop2), the magnetic configuration of the reference layer changes from ferromagnetic configuration to antiferromagnetic configuration. By applying a magnetic field smaller (larger) than the field we can switch from Minor loop 1 to Minor loop 2 (from Minor loop 2 to Minor loop 1). We successfully switched between two Minor loops by applying the field of ±3500 Oe.

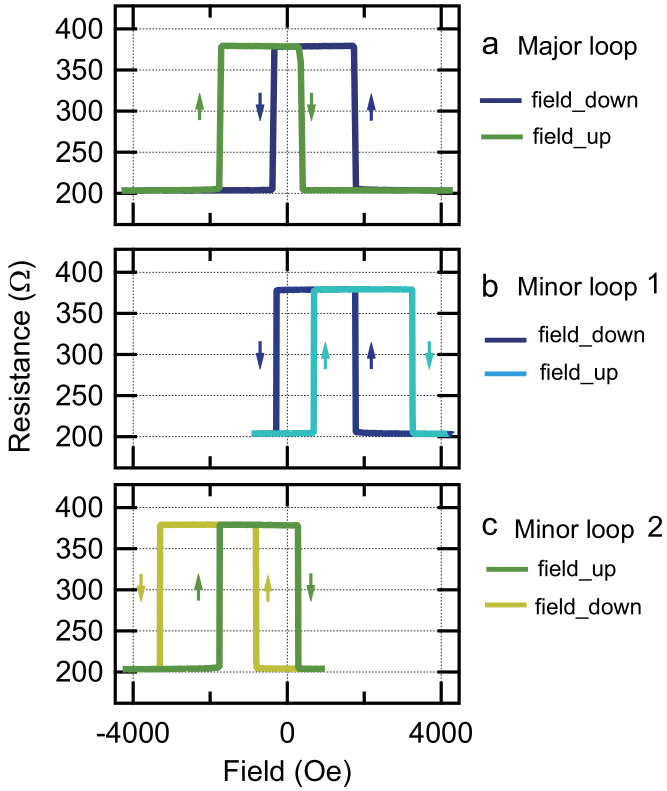

Fig. 2. Magnetoresistance curves of MB-pMTJ. (a) Major MR-loop, (b) Minor MR-loop 1, and (c) Minor MR-loop 2. In the measurement of major MR-loop, the field was swept from 8000 Oe down to −8000 Oe, and back to 8000 Oe. In the measurement of minor MR-loops (b) and (c), the field was swept from 4000 Oe down to −1000 Oe, and back to 4000 Oe for loop (b), and from −4000 Oe up to 1000 Oe, and back to −4000 Oe for loop (c).

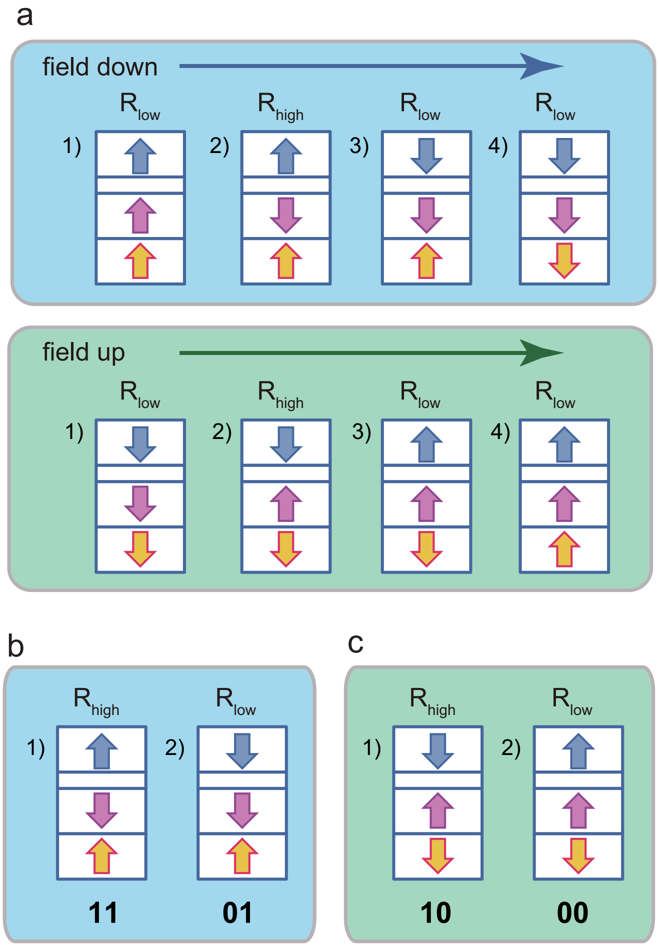

Fig. 3. Schematic illustration of magnetic-state transition of MB-pMTJ based on the results obtained from the MR loops of Fig. 2: (a) Major loop, (b) Minor loop 1, and (c) Minor loop 2. In Major loop, the magnetic state changes 3 times for both directions of field down and field up, and four different magnetic states are stable at zero field. In Minor loop 1 and loop 2, two different states coexist in the same resistance states (R_{high} and R_{low}). These four states at zero field can be assigned to 4 bits data as shown by the 2-digits binary number in the picture of Minor loop 1 and loop 2.

Detailed magnetic switching processes for the MR loops are explained in Fig. 3. When a large field is applied to the MB-pMTJ, all magnetic layers are aligned to the same direction, and the resistance is low. By decreasing the field, firstly the middle layer switches to opposite direction, and the resistance switches to high. Therefore, two configurations of the reference layer can appear at