STT-MRAM in Perpendicular Magnetic Anisotropy: Recent Overview and Outlook

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ABSTRACT: STT-MRAM is a kind of magnetic memory based on spin-transfer torque with advantages such as non-volatility, fast access, etc. This article first gives a general introduction to its background, followed by the principle structure of its basic cell, and introduces some recent advances after 2017 (especially about perpendicular magnetic anisotropy). It is divided into three areas: (1) the properties of the material itself, with more in-depth use of material properties (2) structural optimization (3) improvements in regulation. Finally, the paper briefly mentions the latest technologies in industry and gives a certain outlook, that STT-MRAM has great advantages in combating harsh environments due to its non-volatile nature, and can be used in a wide range of military and aerospace applications.

1. INTRODUCTION

In recent years, 5G (5th General Communication technology) has developed at a high speed, AI (artificial intelligence) technologies based on 5G, such us autonomous vehicles, have developed at a rapid pace, and the concept of IOT (Internet of Things) is gaining popularity. The resulting problem is that large amounts of data need to be processed in time and efficiently. However, according to Von Neumann architecture, the separation of memory units and processor units leads to limitations in terms of memory bandwidth size and long access time. In addition, since both conventional SRAM (Static Random Access Memory) and DRAM (Dynamite Random Access Memory) are based on CMOS (Complementary Metal Oxide Semiconductor) transistors, the smaller the size, the higher leakage of current of COMS, which means bigger power dissipation. These problems demands to be addressed urgently [1, 3].

There are many new memory research directions, among which STT (spin-transfer torque)-MRAM (magnetic random access memory) is a good alternative compared to other kinds of memories due to its many features such us access speed, power consumption, integration density, compatibility and expandability with CMOS circuits. MRAM is therefore considered to be the ideal device for the next generation of mainstream nonvolatile memories. Because of its good performance, STT-MRAM is even expected to become a general memory device, not limited to the traditional computing sector. STT (spin-transfer torque)-MRAM already has a relatively mature technology and has good prospects for development, from consumer electronics and personal computers to automotive and medical, military and space and many other fields, changing the performance of products [4, 5]. For example, in automotive applications it has higher speeds and lower power consumption than e-Flash, and has higher density than e-SRAM.

This article will first give an overview about basic concepts and existing technology in the direction of PMA (Perpendicular Magnetic Anisotropy), and finally conclude with an outlook on development directions.

2. STT-MRAM BASIC UNIT

The basic unit of STT-MRAM is the MTJ (Magnetic Tunnel Junction). The core of MTJ consists two FM (ferromagnetic) layers separated by a thin tunneling barrier layer in a sandwich structure. One of the layers is called the pinned layer or reference layer and is magnetized in a constant orientation along the Easy-Axis, while the other is called the FL (free layer) and is magnetized in two stable orientations, which is paralleled to the reference layer or antiparallel. In this case, due to the TMR (Tunnel Magnetoresistance), by adjusting the magnetization orientation of the free layer, MTJ will show two resistance states, high and low (the same direction for the low resistance state and vice versa for the high resistance state), which can be stored as "0" and "1" states of the computer [6]. At the same time, in order to obtain high performance and high density MTJs, it is necessary to increase its writing and reading speeds, improve reliability and structure.

2.1. PMA

PMA (perpendicular magnetic anisotropy) has significant advantages in improving the spin-transfer torque switching speed and storage density, and is a hot topic in

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academic research. Previously, MTJs mainly used IMA (In-Plane Magnetic Anisotropy), which faced two problems: the limitation of integrated density and the low switching speed. This is due to the magnetic eddy current, the IMA MTJ does not provide sufficient thermal barrier, and the large demagnetizing field (Hd) increases the switching current density [7, 8].

These problems is well solved by using PMA-MTJs, which directly avoid the current needed to overcome the Hd. Here follows the switching current densities expressions of PMA-MTJs [9]:

$$J_{c0\_\mathrm{PMA}} = \alpha \frac{2e}{\hbar\eta}(\mu_0 M_S)(H_{\mathrm{ext}} + H_K)t. \quad (1)$$

where α is the damping constant, e is the elementary charge, h-bar is the reduced Planck's constant, η is the spin transfer efficiency, μ0 is the permeability of vacuum, Hk is the effective anisotropy field, Ms and t are the saturation magnetization and the effective thickness of the FL respectively, and Hext is the external magnetic field. Unlike IMA-MTJs, this expression does not contain the Hd term. P-MTJs are more efficient for the same thermal energy barrier, and therefore academics are committed to further research on high-performance low-power STT-MRAMs using the PMA approach.

3. ADVANCES IN THE STUDY OF PMA

As in the above expression, the author is able to know that in order to reduce the switching current densities, solutions are sought from the above parameters, such as α which is related to the material properties, and broadly speaking optimization can be developed in three areas, (1) the properties of the material (2) the structural optimization of the MTJs (3) the improvement of the P-MTJs regulation method. The following section will therefore give a brief overview of these aspects and give some insight into the latest STT-MRAM integration process.

3.1. Materials

On the material (or structural) side, a number of changes have been made to the MTJ, such as changing the elements of the ferromagnetic metal layer and changing the barrier layer not to a single one but to a superposition of metal films with different properties. Meanwhile, the exploration of materials was reflected in several aspects, the thickness of different materials, the diffusion of atoms of different elements, the ratio of different elements, etc.

In 2017, Di Yi et al [10] found and demonstrated that significant PMA can be induced at the interface of 3d-5d TMOs (Transition metal oxides) through the study of superlattices

$$(\mathbf{La_{1-x}Sr_xMnO_3})/(\mathbf{SrIrO_3}) \quad .(2)$$

In order to achieve high TMR and high PMA performance, p-MTJs are often post-deposition annealing, where the diffusion phenomenon and its effect on the tunneling reluctance and magnetic anisotropy has been a scientific issue of great interest. Among the materials used in this direction are heavy metals such as Ta, Mo and W, which have also been extensively studied. Previous experiments on Ta as a research material have shown that Ta suffers from two drawbacks of temperature limitation and undesirable annealing state [11, 12].

In 2017, Jyotirmoy Chatterjee et al [13] investigated perpendicular storage electrodes (buffer/MgO/FeCoB/Cap) by replacing Ta with different thicknesses of W and W/Ta cap layers. In addition, the annealing stability of the storage electrodes up to 570 °C was demonstrated by using W 5/Ta 1 nm cap. After annealing at 425 °C, the TMR ratio of the p-MTJs stack d with W2/Ta 1 nm cap increases to 117%, which exceeds the thermal budget of the BEOL (back-end-of-line) process. Furthermore, the FeCoB with W cap has a lower gilbert damping constant and is more stable with annealing temperature than the Ta cap. This is due to the hardening effect of W and the ability to effectively keep B away from the MgO interface. This shows the great potential of further development of STT-MRAM for a variety of different industrial applications.

In 2018, Jing Zhang et al [14] found rare symmetry mismatch-driven PMA phenomena in perovskite/brownmillerite heterostructures. The unique effects arising from interfaces between oxides with different symmetries were obtained by varying the interface effect, which means producing interfacial reconfiguration between different oxides and orbital reconfiguration of octahedra at the interface. This principle can be extended to other combinations of TMO (transition mental oxide)s. In addition, they have identified an important phenomenon: symmetry breaking at the P/B (perovskite/brownmillerite) interface. This is worth exploring for breakthroughs in both material aspects and device design.

3.2. The PMA regulation Methods

Magnetic anisotropy is not only related to the preparation process and materials, but can also be regulated by external means. There are two popular methods commonly used, the first being the introduction of ferroelectric materials, controlled by the use of an electric field, which causes stress changes or polarization flips in the formed ferroelectric layer, so that as long as the appropriate parameters are modulated, the energy barrier can be effectively reduced and the writing performance of the MTJ improved [15, 16]. The other mean is the use of voltage control, called VCMA (voltage-controlled magnetic anisotropy) effect.

In 2017, Bin Peng et al [17] demonstrated the effect of $(Co/Pt)_3/(011)$ $Pb(Mg_{1/3}Nb_{2/3})O_3\text{-}PbTiO_3$ E-field control on PMA regulation at low and room temperatures by conditioning SRT (spin reorientation transition: many of hard magnetic materials exhibit thermally induced change of the easy direction of magnetization, SRT is used to generalize such observations) in Co/Pt multilayers. The onset temperature of the SRT is effectively suppressed to around 200 K and allows for modulation of the magnetic anisotropy field up to 1100 Oe. In addition, Non-volatile switching of PMA is quite good. The control of the electric field in multiferroic heterostructures provides new platform conditions for achieving P-MTJ formation.

In 2018 S. Zhao et al [18] implemented IL (ionic liquid) gating for self-selected orientation conversion of in Au/[DEME]+[TFSI]-/Pt/(Co/Pt)2/capacitor heterostructures at room temperature to achieve SRT control at a small voltage of 4 V, and this is quite different from normal VCMA ways. It was found that IL gating is reversible and that it has a significant effect on the SOC (spin-orbital coupling) effect through interfacial charge accumulation and limited electrochemical reactions. This demonstrates a unique IL-gated PMA with large ME (magnetoelectric) tunability and is a new idea for voltage-tunable PMA, such as the possibility of new IL transistors and memories, especially the FMIs (Ferrimagnetic insulators) which have attracted a lot of attention.

In 2018, Victor H. Ortiz et al [19] produced PMA properties over a wide range of thicknesses in epitaxial ferromagnetic insulator Eu3Fe5O12 (EuIG) and Tb3Fe5O12 (TbIG) films by pulsed laser deposition in Gd3Ga5O12. They utilized compressive in-plane strain to control PMA, and the PMA field relaxes very slowly as the ferrimagnetic insulator thickness increases. A general approach to full control the magnetic anisotropy of rare earth iron garnets by epitaxial growth using modulated strain is demonstrated.

In 2018, P. Yu et al [20] investigated the PMA properties regarding the epitaxial growth of Y3Fe5O12 (YIG) thin films. The possibility of controlling PMA was achieved by fabricating YIG films of different thicknesses (around 10nm to 40nm) in Sm3Ga5O12 (SmGG) buffered SGGG (substituted gadolinium gallium garnet substrate) sublayer and engineering different strains. However, there is a partial relaxation of strain in the perpendicular direction, which demands improvement.

4. CONCLUSIONS

To summarize, some of the recent developments in STT-MRAM are described. Compared to other non-volatile memories, STT-MRAM has significant advantages. It has the advantages of low power consumption, fast response, and long read/write availability. Based on its great potential, it has made great strides in academic research and commercial development, and as time has enhanced, STT-MRAM technology has been iterated and its performance has become increasingly superior.

For STT-MRAM devices to be optimized for development, not only in the three areas described above, but also in industrial applications such as the improvement of control of write currents can be effective in improving the performance of STT-MRAM. For instance, Renesas Electronics Corporation is demonstrating at IEDM 2021 two techniques for self-terminated writing with slope pulses and simultaneous write bit optimization, both of which significantly improve MRAM power consumption and speed. Although there are still considerable challenges in the development of STT-MRAM, through the continuous improvement of thermal stability and other aspects, STT-MRAM provides a new development possibility for computer storage and AI computing in the era of big data. STT-MRAM, as a new generation of low power product, will be fully integrated with the existing CMOS industry for hybrid development. With the investment of major IC leaders such as Samsung and TSMC, as well as pioneering companies in the MRAM field such as Everspin, it is believed that STT-MRAM, a high-capacity non-volatile memory, will partially replace SRAM and DRAM in the future and will be able to withstand the challenges of extreme environments and perform well in aerospace and other fields.

This paper is useful to a certain extent to understand the latest progress of STT-MRAM in PMA, and summarises and compares the development history and improvement direction of STT-MRAM. In the future, as STT-MRAM needs to be solved more and more, it will be used more and more in military, aerospace, automotive and other fields

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