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Switching and reliability issues of magnetic tunnel junctions for high-density memory device

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Abstract

Magnetoresistive random access memory (MRAM) is one of the promising universal memories, which combines the high speed of static RAM, high-density of dynamic RAM, and non-volatility of FLASH memory. However, MRAM faces several challenges prior to the appearance at the commercial market on a large scale. The most important challenge among them will be an issue, related to the magnetic switching. The conventional MRAM structures and writing methods cause several issues to be overcome for high packing density without cross-talk. Furthermore, small ferromagnetic elements will require high magnetic field, which will increase the power consumption of the devices. This article will review new writing schemes, such as thermal-assisted switching and spin-transfer switching methods. In addition, reliability characteristics and thermal stability of magnetic tunnel junctions will be presented, because ensuring the reliability of magnetic tunnel junctions emerges as an another challenging problem for the successful application of the new writing schemes to the high-density MRAM devices in the next generation.

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1. Introduction

The impressive market growth for the portable devices, such as mobile phones, PDAs, MP3 players, and digital cameras, has attracted the immense interest in the semiconductor industry, regarding on non-volatile memory technologies. The current non-volatile memory is based on the floating gate FLASH technologies because it can satisfy the mobile applications' demands for high capacity, low power consumption, small cell size, and low system cost. Although FLASH has high density and moderately fast read access time, its write mode is quite slow and its write endurance is also quite limited for many applications. Furthermore, FLASH is expected to face physical limitations for the downscaling below 45 (or less) nm technology node [1–3].

In this sense, researchers have long been searching for an alternative non-volatile memory for the FLASH memory. The fantasy of the research is to find a universal memory, which combines the high speed of static RAM, high-density of dynamic RAM, and non-volatility of FLASH memory. Magnetoresistive random access memory (MRAM) is one of the promising contenders among several emerging memory devices such as FRAM (ferroelectric RAM), PRAM (phase-change RAM), capacitorless SOI DRAM, molecular memory, and so on. The use of ferromagnetic materials as a memory element gives the MRAM the desirable property of non-volatility. Furthermore, unlike the FLASH memory, MRAM shows the

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promising characteristics of high operational speed and very little degradation of performance after a large number of write cycles.

The research on MRAM has been prompted since the observation of significant amount of tunneling magnetoresistance (TMR) at room temperature in 1995 [4,5], because most of the current MRAM technologies are based on the TMR effect in magnetic tunnel junctions (MTJs). The MTJ, which consists of two ferromagnetic layers separated by a thin insulating barrier, shows two different resistance states depending on the relative orientation of the magnetization of the constituent magnetic electrodes (parallel or anti-parallel). Conventional MRAM combines a magnetoresistive MTJ with a single-pass transistor for bit selection for a read operation and, for a write operation, an array of magnetic memory cells is located at the intersection of two perpendicular write lines, as shown in Fig. 1 [6]. To read a single bit, the transistor is turned on, bias voltage is applied to the bit, and the memory state is determined by measuring the amount of current that flows through the MTJ. Programming is achieved by passing current through the two write lines, one above (bit line) and the other below (digit line) the selected bit.

State-of-the-art MRAM faces several challenges before it can be introduced to the real semiconductor market on a large scale. One of them is related to the relative low TMR ratio, which effectively limits its read-out signal and read speed. However, TMR ratio is recently enhanced to be over 200% by replacing an amorphous Al_2O_3 tunnel barrier with a crystalline MgO barrier [7,8]. Ensuring the insulating barrier uniformity is also an extremely important challenge. Because the resistance of MTJ shows an exponential dependence in terms of the thickness of the insulating barrier, the ideal thickness for the MTJ operation is in a quite small range. A number of thin film deposition techniques are being used to achieve the level of perfection. One of the other remaining challenges is related to the switching issues. The conventional MRAM structures and writing methods is not suitable for high packing density without cross-talk. Furthermore, the driving circuits become complicate due to the magnetic-field induced write operation of the selected bit-digit line. In addition, MRAM requires a read–write operation on a small ferromagnetic element, which causes the increase of the write current and the cross-talk problems.

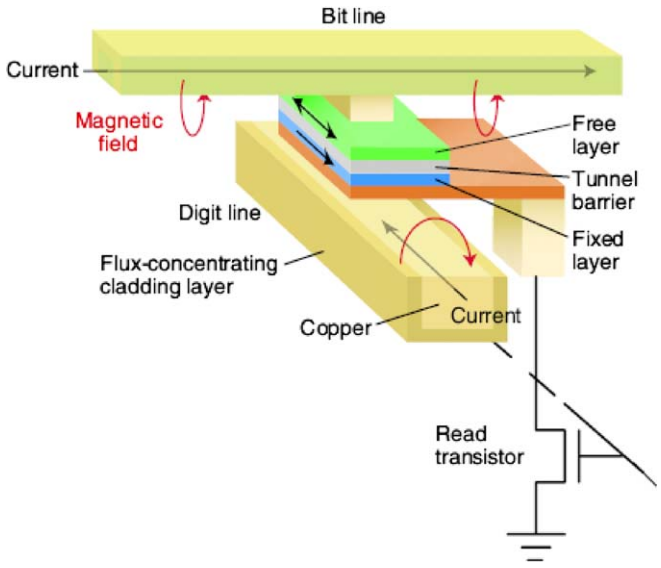

Fig. 1. Schematic picture of conventional MRAM writing scheme [6].

Because of the problems in the conventional write scheme, a number of new writing methods, such as toggle switching [6], thermal-assisted switching [9,10], spin-transfer torque switching [11,12], and local-field switching [13], have been proposed. In Section 2, the principles and possible capabilities of the new writing schemes will be presented and discussed. Particularly, the writing schemes using additional heat and spin-transfer torque will be described, because the two methods have many possible advantages and are under the intensive study. On the other hand, because the two writing schemes require high current flow through MTJs, ensuring the reliability of the tunnel barrier in MTJs under electrical stress emerges as an important challenging problem. From this point of view, the studies on the reliability characteristics and improvement of the junctions' electrical stability will be presented in Section 3.

2. New writing schemes

Conventional MRAM switching methods are using simultaneous magnetic fields generated by currents flowing in the two write lines. While the bit at the intersection of write lines switches by the combined magnetic fields, a number of bits along each write lines will be half-selected [1]. As a consequence, MRAM will suffer half-select disturbs unless the switching current deviations of the bit-to-bit is tight and the switching repeatability within a single element is ensured [14]. For higher storage densities, significant cross-talk will arise with the decrease of bit dimensions. In addition, the reduction of magnetic element's dimension may make superparamagnetism concerns of the loss of magnetic stability as a result of thermal fluctuations [15,16]. This can be easily solved either through a change in materials from magnetically soft materials to magnetically harder materials or through making the element shape more elongated to generate strong shape anisotropy fields. But, these solutions increase the switching fields of magnetic elements inevitably that require higher current density in the write lines.

To eliminate the write operation errors and lower the required switching fields, thermal-assisted switching and spin-transfer torque switching schemes were suggested.

2.1. Thermal-assisted switching

Thermal assisted storages in magnetic systems are also explored not only in MRAM technologies, but in magnetic recording technologies [17,18]. As the volume of storage