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Current perspectives

Device implications of spin-transfer torques

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Abstract

This article examines spin-transfer torques from the perspective of three technological applications: hard disk drives, magnetic random access memory (MRAM), and current-tunable high-frequency oscillators. In hard disk drives, spin-transfer torques are a source of noise, and we discuss the implications spin-transfer noise will have on future sensor designs. For MRAM, we evaluate the feasibility of spin-transfer-driven switching. Finally, we discuss the possibility of GHz communication applications enabled by nanoscale spin-transfer oscillators.

keywords: GMR; TMR; MRAM; Magnetic recording; Spin transfer; Oscillators

1. Introduction

As a result of theoretical predictions [1,2] and early experimental verification [3,4] of spin-transfer torques, there has been tremendous excitement about its potential for device applications. Such excitement is natural—magnetism is widely used in commercial devices, and the spin-transfer effect provides a local means of manipulating magnetization rather than relying on the long-range effects mediated by a remote current via its Oersted field. As the other articles in this issue demonstrate, remarkable progress has been made in the area of spin-torque research over the past decade. However, spin-torque-based devices have not been introduced in the market as yet. This is not surprising. Even in the most favorable conditions, it often takes more than 10 years to commercialize new phenomena. The giant magnetoresistance (GMR) read head was first introduced in 1997 some 11 years after initial reports of GMR in the literature [5,6]. Similarly, room temperature magnetic tunneling was demonstrated in 1995 [7] and only in the last 1 or 2 years have tunneling read heads and magnetic random access memory (MRAM) cells been commercially available. Based on these examples, the commercial impact of spin torque may be expected in the near future.

High-density MRAM and current tunable high-frequency oscillators are applications for which the spin-transfer effect could find commercial viability. In this article, we will offer our perspective on these two applications, including a discussion of the key technical challenges that must be overcome before these technologies can be commercialized. In addition we will describe the detrimental impact of spin torque on GMR devices, especially on applications which require small sizes and high current densities such as next generation GMR read heads.

The basic phenomena of spin torque occur for current flowing through two magnetic elements separated by a thin non-magnetic spacer layer. The current becomes spin polarized by transmission through or upon reflection from the first magnetic layer (the reference layer) and mostly maintains this polarization as it passes through the non-magnetic spacer and enters and interacts with the second ferromagnetic layer (the free layer). This interaction leads to a change of resistance depending on the relative orientation of the magnetic layers giving rise to GMR. Commensurate with the GMR, there is a transfer of angular momentum from the polarized current to the free layer magnetization that can be described as an effective torque.

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This spin torque can oppose the intrinsic damping of the magnetic layer exciting spin waves and, for sufficient current strengths, reverse the direction of the magnetization.

In general, spin torque and GMR are intimately linked. That is, it is difficult to have one without the other. From an applications point of view, this can have significant detrimental implications in GMR-based devices. For GMR magnetic sensors and read heads, the magnetic layers are designed such that one layer is rather insensitive to an external field (the reference layer) and the second layer responds to an external field (the free layer). Implicit in these designs is that the current only monitors the relative angle of the magnetization of the two layers (via the GMR effect and change in resistance) and only affects the magnetization via heating and the generation of Oersted fields. However, spin-torque effects couple the magnetization of the reference and free layers. As a result, the magnetic recording industry is all too familiar with spin-torque-induced excitations as a source of noise in magnetic recording head sensors. It is in these sensors where spin-torque effects are likely to have their first commercial impact, albeit negative, so we will begin by discussing the implication of spin torques on proposed GMR sensor technologies, before moving onto two applications, spin–transfer-driven MRAM and current-tunable oscillators, that are enabled by spin-torque effects.

2. Spin-torque effects in CPP-GMR sensors

Relative to applications such as MRAM, little has been published on spin-torque effects in hard disk drives. Interestingly, in addition to latches and oscillators, John Slonczewki's original (rather cryptically titled) spin-torque patent described using the spin-torque effect to write bits on the recording media in disk drives [8]. Although the spin-torque effect in theory could allow one to write bits with better resolution than can be achieved by the fields generated from the pole tip of a recording head, the challenge of making reliable electrical contact to a disk rotating at nearly 10,000 rpm beneath the head appears to make this impractical.

As mentioned in the introduction, it is spin-torque effects in the sensor that presently cause concern for the disk drive industry. As we write this paper, the hard disk drive industry is changing its sensor geometry, moving from the presently used current-in-plane (CIP) GMR sensor [9] to a current-perpendicular-to-the-plane (CPP) tunneling magnetoresistive (TMR) sensor [10]. In a CIP sensor the current flows within the film plane which is the easiest geometry to employ in a film or when the lateral size of the device is large compared to the thickness of the layers. In CPP devices, the current leads are at the top and bottom of the film stack and the current flows perpendicular to the layers. This geometry is only feasible for high resistance film stacks (e.g. magnetic tunnel junctions) or for low resistance (i.e. fully metallic) film stacks with confined lateral dimensions less than 100 nm. This transition is driven by a number of factors, which include the higher magneto-resistance ratios achievable in TMR junctions and the ease in lithographic definition. A CIP-GMR read head is shown in Fig. 1a and described in detail in Ref. [9]. The magnetic field sensitivity is derived from the GMR stack that consists of a reference layer that is relatively insensitive to external field and a free layer that responds to a field. The relative angle of the magnetization of the reference and free layers controls the resistance of the device.

In present read heads the reference layer is an antiparallel coupled Co/Ru/Co stack exchange biased by an antiferromagnetic layer. Such a reference layer structure is also used in MRAM technologies [11]. The coupling is mediated by a ~0.7 nm Ru layer whose thickness is tuned to couple the layers via an RKKY interaction [12]. The two Co layers are nearly the same thickness such that net moment of the Co/Ru/Co stack (the difference of the two layers magnetization) is small. This has two advantages. The low moment of the stack limits the dipole fields generated by the reference layer that interact with the free layer. Second, the low moment makes the reference layer react weakly to external fields as long as the fields are weaker than the antiparallel exchange coupling strength. The Co/Ru/Co net magnetization direction is maintained

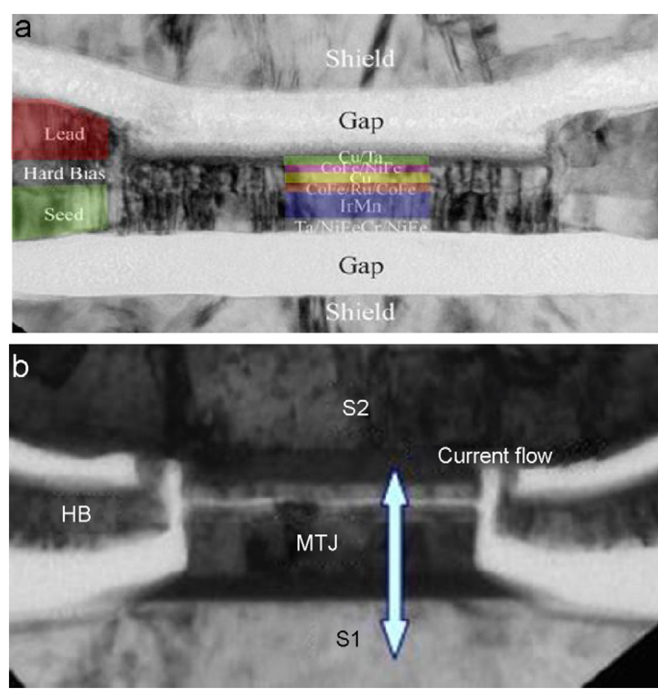

Fig. 1. (a) Transmission electron microscopy cross-section of a CIP read head sensor. False color has been added to help distinguish the various metallic layers from one another. Trackwidth is approximately 130 nm. (b) Transmission electron microscopy cross-section of a magnetic tunnel junction (MTJ) read head sensor. The bottom and top leads of the sensor are the magnetic shields *S*1 and *S*2. The sense current flows between these two leads. Alumina (bright in image) insulates the hard bias (HB) from the sensors and the shields. The tunnel barrier is the bright line approximately co-linear with the HB. The trackwidth is approximately 80 nm.