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SPIN TRANSFER TORQUES IN HIGH ANISOTROPY MAGNETIC NANOSTRUCTURES

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Introduction

Spin-based electronic devices emerged in the hard disk market a little over a decade ago with the introduction of the giant magneotoresistance (GMR) read head. The basic functionality results from spin dependent scattering of polarized currents by magnetic layers separated by a non-magnetic spacer layer known as GMR for metal interlayers or tunneling magneto-resistance (TMR) for insulating spacer layers. The application of GMR in devices has sparked research in the broader field of spintronics, which relies on manipulating the spin rather than the charge of the electron via spin injection, manipulation and detection and was awarded the Nobel Prize in physics in 2007 to P. Grunberg and A. Fert [1].

While in most magnetic applications the orientations of the magnetic elements within devices are controlled by external magnetic fields, it has recently been appreciated that the relative orientations of nano-magnets can be controlled directly by the injection of spin polarized currents known as spin transfer effects. The basic phenomena of spin transfer occur for current flowing through two magnetic elements separated by a thin nonmagnetic 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 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. This spin transfer torque can exciting spin waves and reverse the direction of the free layer magnetization.

As a result of theoretical predictions by Slonczewski [2] and Berger [3] in 1996 and early experimental verification [4-6] of spin transfer torques, there has been tremendous excitement driven by a number of factors. First, spin transfer effects provide a probe of interactions between spins and magnetism and strengthen our fundamental understanding of magnetic materials [7]. These effects are described by additional terms to the traditional Landau-Lifshitz-Gilbert (LLG) equations. Thus, spin transfer links phenomena of magnetic excitations, damping, reversal, micro-magnetic configurations with spin transport [8].

A second driver for the growth of the study of spin-transfer effects is that experimental fabrication techniques have only recently been developed that allow devices to be readily made at the sub 100 nm dimensions. Such dimensions are needed for the devices to sustain high current densities. Finally, spin transfer has significant potential for novel applications for spin-based devices. Spin transfer effects provides a local means of manipulating magnetization rather than relying on the long-range effects mediated by a remote current via its Oersted field. Potential applications include spin-transfer written magnetic random access memory (MRAM) and high frequency non-linear oscillators [8] and may provide an approach for three dimensional solid state memories or magnetic logic operations.

In this report we highlight recent research on using spin-transfer torques to manipulate nano-elements having strong perpendicular magnetic anisotropy (as shown schematically in Fig. 1). In such structures the magnetic response is more strongly determined by the intrinsic properties of the materials rather than by the shape of the device. The performance of devices is less sensitive to lithography variations and is controllable by judicious engineering of materials properties. Other advantages of high anisotropy materials include: higher stability against thermal activation, more efficient coupling of the spin-current to magnetic excitations, and higher magnetic resonance frequencies. Finally, the study of spin-transfer reversal of perpendicular anisotropy elements provides insight into the magnetic reversal of patterned media elements

Theoretical background

The effects of spin-transfer on the local magnetization can be understood via the LLG equation modified to include spin-torque terms. For the case of the nanopillar where you have free and fixed magnetic layers, the dynamics of the free layer magnetization can be described by:

$$\dot{\mathbf{M}} = -\gamma \mathbf{M}\times\mathbf{H}_{eff} + \frac{\alpha}{M_S}\mathbf{M}\times\dot{\mathbf{M}} + \eta(\theta)\frac{\mu_B I}{eV}\mathbf{M}\times\left(\mathbf{M}\times\mathbf{M}_{fixed}\right) \tag{1}$$

where M and M_{fixed} are the magnetization direction of the free and fixed layers, H_{eff} is the effective field which includes the dipolar, exchange and anisotropy fields, γ is the gyromagnetic ratio, α is the damping parameter, I is the current, and V is the volume of the free layer on which the spin torque acts. $\eta(\theta)$ is the angle-dependent term that depends on the spin polarization of the current (p) and describes the spin-torque efficiency where θ is the angle between the M and M_{fixed}. The first two terms are the standard LLG equations and the third term arises from the spin-transfer interaction between two nanomagnets.

In the simplest geometry shown in Fig. 1 the applied field, M_{fixed}, and the anisotropy are along the z-axis. For a tilting of the free layer away from the z-axis, the damping term will move the magnetization back to the z-axis. When a current is applied, the spin-torque term is either parallel or anti-parallel to the damping depending on the sign of the current. For one sign of the current, the spin-torque opposes the damping, either reduces the effective damping, or for sufficient current strength can destabilize the magnetization and amplify the deviation of the magnetization. This can lead to persistent spin-waves modes or reversal of the magnetization.

The current needed to induce spin transfer reversal assuming a collinear geometry can be estimated from a stability analysis of Eq. 1. The resulting critical current is given by:

$$I_c = \left(\frac{2e}{\hbar}\right)\left(\frac{\alpha}{\eta}\right) M_s V \left(H + H_k\right) \tag{2}$$

where H is the field applied along the easy axis (also the uniaxial anisotropy direction including the dipole field from the reference layer) and H_K is the anisotropy field. For in-plane devices the current must overcome the additional additive term $2\pi M_S$ resulting from the shape anisotropy added to H_K that does not contribute to the stability of the bit against thermal fluctuations but suppresses spin-torque induced switching. This is one of the key advantages of the perpendicular geometry [9].

Magnetic nanopillars

To take advantage of the perpendicular geometry one needs materials system with perpendicular anisotropy while maintaining the other parameters such as p and α. In particular the critical current depends linearly on the H_K and α and also on the spin polarization through η. For efficient current reversal, one wants low α and high p. In general, there is a close coupling of the magnetic anisotropy, magnetic dynamics and the spin currents in these systems.

While the study of perpendicular anisotropy films is a well established field with current applications as perpendicular recording media, these materials often don't fulfill the requirements for use in magneto-electronic devices. Perpendicular anisotropy materials such as Co/Pt multilayers tend to have high α [10]. In addition, it is thought that the presence of weakly or non-magnetic Pt layers within the magnetic layers leads to high spin-orbit scattering and reduced spin polarization. We found that Co/Ni multilayers are one example of perpendicular anisotropy materials that maintains low α and high p and are the basis for the magnetic structures discussed here.

Shown in Fig. 1 is the type of structures used for spin-torque measurements [9, 11, 12]. The magnetic heterostructure is patterned into a nano-pillar sandwiched between a Cu lower lead and a Au upper lead to allow vertical spin transport through the structure. The nano-pillar device is made up of two perpendicular magnetic anisotropy layers separated by a thin Cu layer. One layer is a reference high-coercivity layer which is a $[Co/Pt]_4/[Co/Ni]_2$ multilayer. The second layer is the free layer that reverses under the action of either current or field is a [Co/Ni] multilayers. Shown in Fig. 2a is the resistance (dV/dI) versus field applied along the anisotropy axis. The layers switch in discrete jumps between the AP (high resistance) and P (low resistance) alignment with a GMR ratio of 1.0%. The coercive field of both layers has significantly increased over the continuous film values. The reference layer has a coercive field of 10 kOe and the free layer 2.65 kOe.

Shown in Fig. 2b is the resistance versus the dc current bias (I_B) in zero applied field. By cycling the current, there is hysteretic switching between the AP and P configurations. Starting from the P alignment, the free layer switches into the AP configuration for $I_C^{P\text{-}AP} = 2.7$ mA ($7.5\text{x}10^7$ A/cm^2) and switches back for $I_C^{AP\text{-}P} = -0.85$ mA ($-2.6\text{x}10^7$ A/cm^2). This demonstrates the ability of current to reverse thermally stable, high anisotropy magnetic elements.

Summary

Experiments such as the one shown in Fig. 2 have been extended to include both field and current to map out an H-I_B phase diagram [9,11, 12] and the angular dependence of reversal. These results combined with micromagnetic modeling of the free layer show that, depending on the bias current and applied field, there are regions of irreversible magnetic switching, domain formation, coherent and incoherent spin waves, or static non-uniform magnetization states. Such complex behaviors are somewhat surprising but highlight the complexity of nano-magnetic systems. A complete understanding of these phenomena will provide a clearer picture of magnetization at the nano-scale and allow the potential applications of spin-torques effects to be judged. For applications such as MRAM, lower critical currents for reversal and incorporation with magnetic tunnel junctions are needed. This requires continued research on new and improved materials and exploration of novel device architectures. While challenging the progress in understanding spin torque effects over the last decade [13] suggests there will be new phenomena discovered that drive emerging technologies.

1. E. E. Fullerton and I. K. Schuller, *The 2007 Nobel Prize in Physics: Magnetism and Transport at the Nanoscale,* ACS Nano **1**, 384 (2007).

2. J.C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).

3. L. Berger, Phys. Rev. B **54**, 9353 (1996).

4. M. Tsoi, A. G. M. Jansen, J. Bass, W. C. Chiang, M. Seck, V. Tsoi, P. Wyder Phys. Rev. Lett. **80**, 4281 (1998).

5. J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999).

6. J.A. Katine, F.J. Albert, R.A. Buhrman, E.B. Myers, D.C. Ralph, Phys. Rev. Lett. **84**, 3149 (2000).

7. D.C. Ralph and M.D. Stiles, *Spin transfer torques,* J. Magn. Magn. Mater. **320**, 1190 (2008).

8. J.A. Katine and E. E. Fullerton, *Device implications of spin-transfer torques*, J. Magn. Magn. Mater. **320**, 1217 (2008).

9. S. Mangin, D. Ravelosona, J. A. Katine, M. J. Carey, B. D. Terris and E. E. Fullerton, *Current-induced magnetization reversal in nanopillars with perpendicular anisotropy,* Nature Materials **5**, 210 (2006).

10. A. Barman, S. Wang, O. Hellwig, A. Berger, E. E. Fullerton, and H. Schmidt, *Ultrafast magnetization dynamics in high perpendicular anisotropy [Co/Pt]n multilayers*, J. Appl. Phys. **101**, 09D102 (2007).

11. D. Ravelosona, S. Mangin, Y. Henry, Y. Lemaho, J. Katine, B. Terris and E. E. Fullerton, *Current induced domain wall states in CPP nanopillars with perpendicular anisotropy*, J. Phys. D: Appl. Phys. **40** 1253–1256 (2007).

12. D. Ravelosona, S. Mangin, Y. Lemaho, J. A. Katine, B. D. Terris and E. E. Fullerton, *Domain wall creation in nanostructures driven by a spin-polarized current,* Phys. Rev. Lett. **96**, 186604 (2006).

13. For general reviews see the *Current Perspectives* sections of J. Magn. Magn. Mater. **320**, 1189 – 1311 (2008).

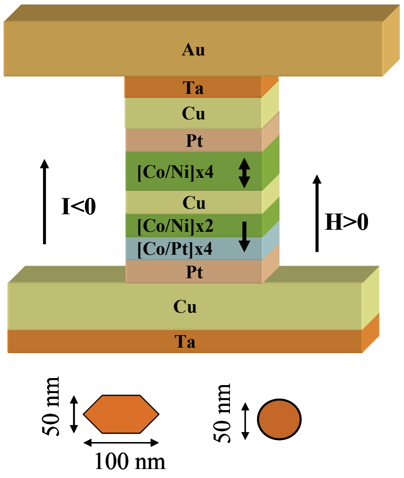

Figure 1: Schematic representation of patterned Co/Ni samples. The reference layer is a composite [Co/Pt]x4/[Co/Ni]x2 multilayer and the free layer is a [Co/Ni]x4 multilayer. The magnetization direction of the reference layer, positive field direction and the direction of electron flow for negative current are shown.

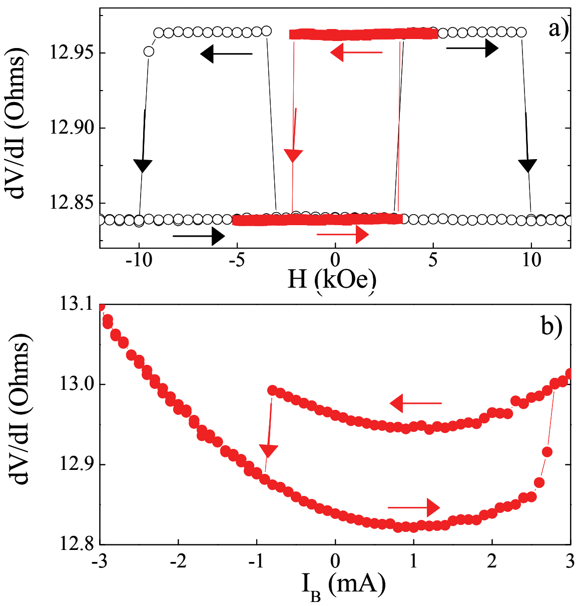

Figure 2: Transport measurements of the 50x100 nm^2 Co/Ni sample. (a) *dV/dI vs. H* for H perpendicular to the film plane. The open symbols correspond to the major loop showing discrete transitions between the P and AP states. The solid symbols are a minor loop where only the free layer reverses with the reference layer magnetization pointing down. (b) *dV/dI vs.* I_B for *H*=0 showing discrete transitions between the AP and P states.