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Dipolar core-shell cells with enhanced write speed and reduced cross-talk of perpendicular shape anisotropy MRAM

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The concept of Perpendicular Shape-Anisotropy Spin-Transfer-Torque Magnetic Random-Access Memory (PSA-STT-MRAM) tackles the downsize scalability limit of conventional ultrathin magnetic tunnel junctions (MTJ) below sub-20 nm technological nodes. It is based on a thick storage layer, enhancing the thermal stability factor Δ of the device via perpendicular shape anisotropy. However, this comes at the expense of a tendency for a non-reversal mechanism, increasing the switching time and capping the stability of the device versus aspect ratio. Besides, the high aspect ratio and volume supporting thermal stability significantly increase the stray field in neighbouring bits in comparison with the conventional MTJs, in the case of dense arrays. In this work, we show that, by making use of a dipolar-coupled core-shell structure as a storage layer for the PSA-MTJ, both the reversal mechanism and stray field challenges are largely improved. We use macrospin simulations in an array to show the decrease in stray field, and micromagnetic simulations to show the faster switching times while avoiding the domain-wall limit, for a given thermal stability.

Index Terms—Magnetic Tunnel Junction, Dipolar Coupling, Stray Field, Core-Shell, Micromagnetics

I. INTRODUCTION

THE spin-transfer torque magnetic random-access memory (or STT-MRAM) is one of the most promising non-volatile memory technologies. It offers a good compromise of non-volatility with a quasi-infinite write endurance, high speed, moderate write power consumption and zero off consumption. The retention time of MRAM is related with the stability factor Δ of the device, as the ratio between the energy barrier (E_B) of the storage layer and the thermal energy ($k_B T$, where k_B is Boltzmann constant and T the operation temperature). The energy barrier in usual perpendicular magnetic tunnel junctions, made of a stack of ultrathin layers with perpendicular magnetization (p-MTJ), can be expressed as:

$$E_B = AL \left[\frac{k_s}{L} + \frac{1}{2} \mu_0 M_s^2 (N_{xx} - N_{zz}) + K_u \right], \quad (1)$$

where A is the area of the magnetic storage layer, L its thickness, k_s its surface anisotropy, μ_0 the vacuum permeability, M_s the spontaneous magnetisation saturation, N_{ii} the demagnetizing factors along the plane (xx) and out-of-plane (zz) of the storage layer and K_u the bulk uniaxial anisotropy. The latter is usually small in conventional p-MTJ, leading to a competition between the surface and shape anisotropy. For conventional p-MTJ the lateral dimensions of the storage layer is much larger than its thickness, resulting in a negative contribution of the shape anisotropy, lowering the out-of-plane stability, only promoted by surface anisotropy. Besides, the thermal stability decreases with the diameter. These effects limit the scalability of the p-MTJ to 20 nm diameters. A proposal to counter this limitation is to provide extra stability via the vertical shape anisotropy of the storage layer, by increasing its thickness. This has been proven to be effective to enhance stability at much lower diameter [1], [2]. However, for 10 nm and below, magnetisation reversal under applied voltage tends to turn to a nucleation and propagation of domain wall instead of macrospin [3], which requires larger write current and increases the write time. Thus it is necessary to

find a way cap the thickness of the PSA storage layer at no expense on its stability. One approach is to increase the surface anisotropy, via the insertion of several FeCo(B)—MgO interfaces in the storage layer [4]. In this digest we propose another approach, making use of a tubular magnetic shell around the storage layer. Using the strong dipolar coupling between both, provided by the high aspect-ratio storage layer (from now on called "core"), it is possible to couple the magnetisation of the magnetic shell antiparallel to that of the magnetic core. The stability is increased thanks to the increased effective magnetic volume, so that it is possible to reduce the thickness of the core-shell system, avoiding the domain-wall reversal and thus leading to lower-voltage and faster reversal. Moreover, as the magnetic shell is antiparallel to the core, the stray field from any given cell is reduced, enabling a denser array than in already proposed perpendicular shape anisotropy MTJ designs.

II. INCREASE OF STABILITY AND REDUCED SWITCHING TIME

We use micromagnetic simulations to investigate the thermal stability and write speed of a dipolar-coupled core-shell system. The magnetic core is considered with surface anisotropy 1.4 mJ/m² and M_s 1 MA/m. The inner diameter of the magnetic shell is spaced from the magnetic core by 1 nm, with a M_s of 0.489 MA/m and no additional anisotropy. The outer diameter of the shell is chosen to achieve the same macrospin magnetic moment for core and shell, and STT is applied only to the core. Figure 1 shows the increase in stability for a core-shell for a given thickness, which allows for a thickness reduction to achieve a given Δ . By doing so, the reversal of the magnetic core under applied voltage is faster when compared with the system without shell for a similar Δ . Fig. 2 illustrate the dynamics of switching under a voltage of -1 V, for a shell with a damping α of 0.007 and 0.1, with slightly faster switching of the core for lower α . This is attributed to how

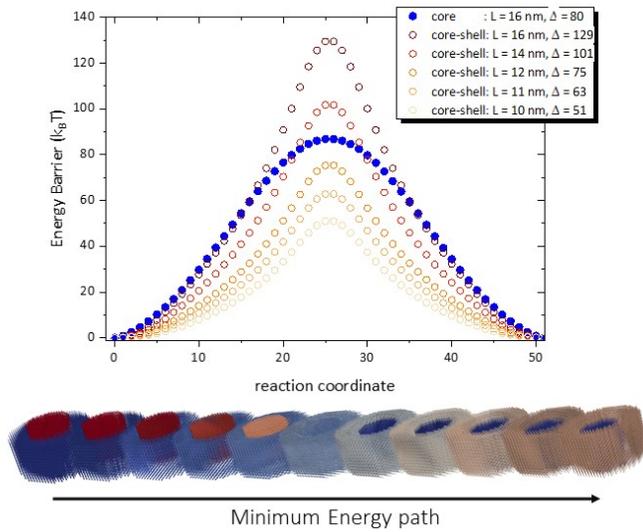


Fig. 1. Minimum energy path and associated stability factor of (filled circle) a storage layer with 14 nm diameter and 16 nm thickness and (unfilled symbols) the core-shell system (1 nm gap and inner diameter of 16 nm and outer diameter of 26 nm) for different thicknesses. The preferred energy path is shown below for the core-shell system (12 nm thickness) as a function of the reaction coordinate.

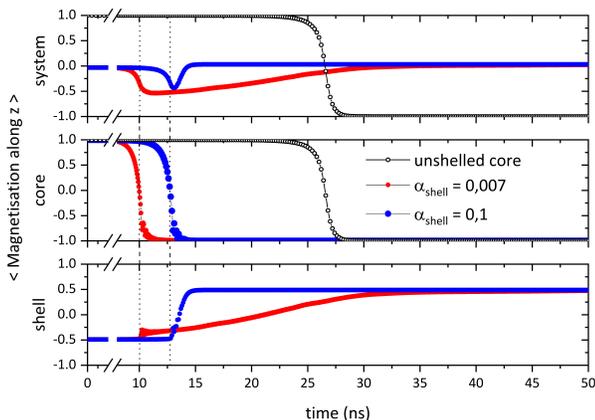


Fig. 2. Time reversal of the magnetization for the core-shell system (thickness of 12 nm, inner radius of 8 nm and outer radius of 13 nm) and isolated core without shell (thickness of 16 nm and radius of 7 nm) for different damping of the magnetic shell. The time traces of the core-shell system are separated into their isolated core and shell contributions.

fast the magnetic shell may respond to the STT excitation of the core, under the stimulus of dipolar coupling. However, this comes at the expense of a longer switching time of the shell due to precessional effects. Thus, in practice a not so small damping is beneficial, which contrasts with conventional MRAM.

III. STRAY FIELD MITIGATION

In addition to the increased stability and faster reversal, core-shell cells are a stray-field mitigation strategy for large aspect-ratio MRAM, thanks to the anti-parallel alignment of the shell such as in a synthetic antiferromagnet. We use macrospin simulations [5] to calculate what the stray field

would be on a given cell in a square array, in the two extreme cases of bit configurations, i.e., where all neighbours are up or down. We consider only 1st and 2nd neighbours, which is sufficient as dipolar fields are short-ranged in a 2D array. Figure 3 shows that, for a magnetic core with 10 nm diameter and 20 nm thickness, as the pitch falls below 50 nm, there is a strong stray field felt by a central core. Making use of a magnetic shell mitigates the stray field significantly up until the point where the shells would be in contact. This should allow to largely decrease the distributions of stability and switching voltage for different bit configurations.

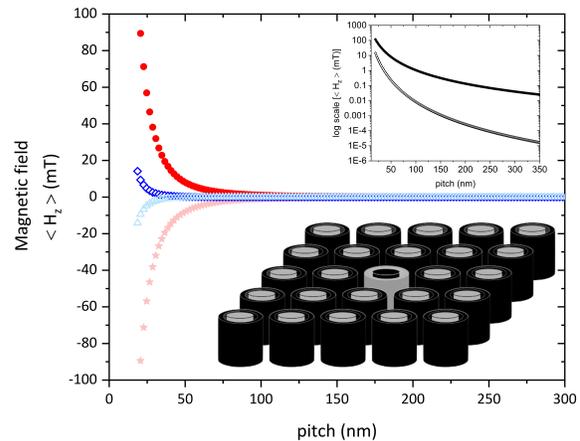


Fig. 3. Stray field created considering first and second neighbours in a central core as a function of the distance between pillars, with (unfilled symbols) and without shell (filled symbols), for different bit configurations with the central core up: all neighbours magnetisation up (stars and triangles) and all neighbours magnetisation down (square and circle). An inset shows the logarithmic scale of the dependency, while the other inset shows the schematics of a square array where the storage layer has a shell.

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