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Dynamical switching properties and downsize scalability in Perpendicular Shape Anisotropy MTJ

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The novel Perpendicular Shape-Anisotropy Spin-Transfer-Torque Magnetic Random-Access Memory (PSA-STT-MRAM) is shown to increase the thermal stability factor Δ of the storage layer through modulation of its shape anisotropy, surpassing the scalability limitation of conventional magnetic tunnel junctions to below sub-20 nm technological nodes. However, for large aspect-ratio, the magnetization reversal becomes non-uniform and less controllable. Thus, it is necessary to reduce the total thickness of the storage layer, while keeping an appropriate Δ . We show that, making use of micromagnetic simulations, making use of a capping layer to promote an additional surface anisotropy leads to a lower thickness requirement, compatible with lower switching voltage and faster reversal. These results are backed with experimental evidence, as STT reversal is shown without field. However, this capping layer shows less efficient for very small diameters, down to 5 nm, in the limit where Δ is limited by the energy of the domain-wall created in the layer. It is shown that it would be possible to avoid this stability capping while maintaining a single PSA layer, with an induced uniaxial anisotropy.

Index Terms—Magnetic Tunnel Junction, Micromagnetics, Shape Anisotropy, Spin-Transfer-Torque

I. INTRODUCTION

SPIN-transfer-torque magnetic-random-access memories (STT-MRAM) are one of the most promising non-volatile memories. With the perpendicular magnetic tunnel junction (p-MTJ) as its main player, they offer a good compromise between non-volatility with a quasi-infinite write endurance, high speed and moderate write power consumption. Their retention time is related with the stability of the storage layer of the device, given as the ratio between the energy barrier (E_B) and the thermal energy ($k_B T$, where k_B is Boltzmann constant and T the operation temperature). Whilst limited to 20 nm diameters, MTJs with a storage layer thicker than the usual p-MTJ (values close to its diameter) further improving the scalability of MRAM to sub-20 nm nodes [1], [2]. This happens thanks to the shape anisotropy of the storage layer which now promotes a sturdy perpendicular magnetization, aiding the surface anisotropy, which strength is reduced with the area of the device. While it would be possible to maintain a large Δ at sub-10 nm diameters, the required aspect-ratio of the storage layer would promote a reversal mediated by a domain-wall nucleation and propagation, requiring larger switching current and longer write time [3]. To maintain the coherent reversal, it is necessary to reduce the total thickness of the storage layer by increasing its stability. A logic approach is to make use of a second FeCo(B)|MgO interface (as in usual p-MTJ), as a capping for the storage layer. This approach leads to an increase in total surface anisotropy energy, reinforcing the PSA and leading to thinner thicknesses with increased stability. In addition, partitioning the storage later can also avoid the formation of a domain wall [4]. Using micromagnetic simulations we show that, in addition to an increase in Δ , there is also a reduction of the switching time, due to a decrease in thickness. In addition, by keeping on relying on a single PSA layer, it is possible to use different combination of materials, such as Co which,

thanks to its higher M_s and exchange stiffness (A_{ex}), allows for thinner layers. Nonetheless, the capping stability of these devices is limited by the domain wall energy. It is shown that it is possible to create an offset in this capping by making use of a volume anisotropy in the bulk PSA-layer, which shows promise for an already established uniaxial anisotropy in Co nanowires.

II. SWITCHING DYNAMICS IN A PSA STORAGE LAYER WITH INCREASE SURFACE ANISOTROPY

We use micromagnetic simulations to investigate the stability and write speed of the storage layer. Three different regions are then defined, as shown in fig. 1 *a*). For this geometry, the surface anisotropy (k_s) is only considered in the interfaces, due to its interfacial origin. The k_s of the main barrier is kept fixed at 1.4 mJ/m², while the capping is being varied. A spin polarized current is applied to the system after relaxation and is taken in the Landau-Lifshitz-Gilbert-Slonczewski equation as a damping-like term (Γ_{STT}^{IP}):

$$\Gamma_{STT}^{IP} = -|\gamma|a_{||}V\mathbf{m} \times (\mathbf{m} \times \mathbf{m}_{RL}) \quad (1)$$

where $a_{||}$ is the STT pre-factor, V the applied voltage, \mathbf{m} the normalized magnetization vector of the storage layer and \mathbf{m}_{RL} the normalized magnetization vector of the reference layer. The STT pre-factor is taken to be only applied in the first cell layers, as it is expected to decay throughout the bulk of the storage layer.

The M_s and A_{ex} are the same throughout the thick layer, 1 MA/m and 15 pJ/m respectively. As expected, as the anisotropy is increased it is possible to reduce the thickness to achieve a similar value of stability. Thanks to this thickness decrease the switching is faster, achieving sub-10 ns reversal, as observed in fig. 1 *b*).

Based on these results we fabricate a STT-MTJ with the following magnetic stack:

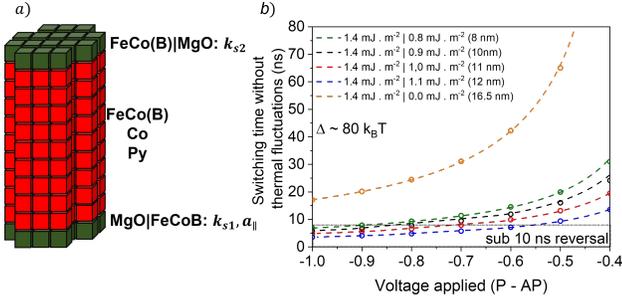


Fig. 1. a) Sketch of the storage layer. Green cubes have interfacial anisotropy. The STT effect is applied only in the first layer (through $a_{||}$). b) STT switching for increasing surface anisotropy in the capping layer with a reduced thickness for $\Delta \approx 80$.

$\text{SiO}_2/\text{Ta}(22)/\text{FeCoB}(0.8)/\text{Pt}(8)/\text{SAF}/\text{W}(0.2)/\text{FeCoB}(1)/\text{MgO}(1.25)/\text{FeCoB}(1.0)/\text{W}(0.2)/\text{FeCoB}(17)/\text{W}(0.2)/\text{FeCoB}(0.9)/\text{MgO}(1.3)/\text{FeCoB}(0.4)/\text{W}(2)/\text{Ta}(2)/\text{Ru}(10)/\text{Ta}(150)$ (nominal thicknesses in nm), where the SAF is the synthetic antiferromagnetic (composed of Co/Pt multilayers spaced by a 0.9 nm Ru). The RxA of the device is calculated by CIPT (current in-plane tunneling) to be around $7 \Omega \cdot \mu\text{m}^2$. Small diameters are reached with heavy trimming, up to 13 nm electrical diameter. Making use of the smaller thickness thanks to the MgO capping, it is possible to reverse the magnetic layer, as shown in figure 2.

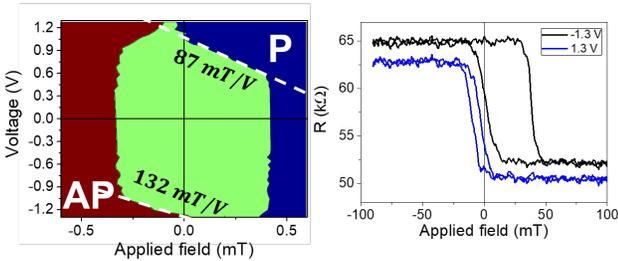


Fig. 2. (left) Phase diagram of the resistance state of the device as a function of voltage and applied field and (right) resistance field loop for two different applied voltages.

From the phase diagram is possible to extract the slope related with the STT switching (T/V), which shows values similar to the ones of usual p-MTJ. Moreover, the switching voltage can be reduced by making use of devices with smaller RxA product.

III. LIMITATION OF PSA-MTJ AT VERY SMALL NODES

Even though the use of a capping MgO proves to be enough for diameter up to 10 nm it falls short when decreasing to 5 nm and below, as we rely more on the shape anisotropy, since the contribution of the surface anisotropy drops even further. The Δ value for different bulk storage layers (NiFe, FeCo(B) and Co) with two interface contributions (1.4 mJ/m^2 and 1.0 mJ/m^2) are shown for a diameter of 5 nm and increasing thickness (so that the shape anisotropy increases the stability) in fig. 3 a). As expected, for increasing thickness (needed for the higher stability), the energy barrier does not follow a macrospin minimum energy path, but rather one of

domain-wall propagation. Thus, the energy barrier is capped by the energy of the domain-wall. A potential solution for this limiting issue is to induce an additional uniaxial anisotropy in the PSA bulk storage layer. It is shown that by increasing this term the stability increases significantly since, unlike the surface anisotropy it also scales with the thickness of the device (mJ/m^3). This substantial increase can be seen in fig. 3 b) for a Co PSA storage layer with double interface with an anisotropy increment of 0.2 MJ/m^3 . As the capping stability is increased, it is possible to reduce the total thickness of the device, which would bring forth faster reversal and lower switching current (as the diameter is being reduce and the resistance of the device is increased).

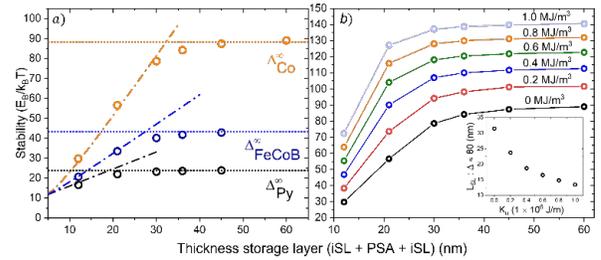


Fig. 3. a) Stability for different PSA storage layers (Py in black, FeCoB in blue and Co in yellow) for a 5 nm diameter with FeCoB double interface (1.4 mJ/m^2 and 1.0 mJ/m^2). Macrospin results shown with dashed line and limiting domain wall stability and dashed dot. Minimum energy path results shown with open circles. b) Increase in stability and upper capping limit for an incremental increase in uniaxial anisotropy in the PSA-SL, composed of Co with two interfacial FeCoB layers with surfaces anisotropy of 1.4 and 1.0 mJ/m^2 . In the inset it is shown the decrease of the thicknesses needed to achieve a stability of $80k_B T$.

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