Microwave-assisted switching of NiFe magnetic microstructures

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Abstract. We have calculated, by either macrospin analytical method or micromagnetic numerical solving, the microwave assisted switching of a small rectangular platelet as a function of the amplitude and the frequency of a microwave excitation field. The spectral analysis of this phenomenon reveals that microwave-assisted switching is optimal for a rf frequency slightly lower than the linear magnetic resonance frequency measured at low level. Similar experimental results, obtained on 100 μm-scale NiFe structures reveal the same tendency. Switching time for such a process was obtained from calculations that show that sub-nanosecond switching times require combinations of large dc (direct current) and rf (radio frequency) magnetic fields.

1. Introduction
Fast, reliable and low energy consuming magnetic switching of patterned magnetic micron or sub micron sized elements is actively studied in order to increase the performance of magnetic sensors or non volatile storage media. For example, the most used MRAM (Magnetic Random Access Memory) write process involves two perpendicular magnetic field pulses, with appropriate timing and intensity, that causes the reversal of the magnetization of the so-called free layer. Thermally Assisted Switching or TAS is also considered for overcoming the energy barrier separating the two stable magnetic states of a magnetic particle in a rapid heating / cooling cycle. These processes are time, field and temperature dependent since the reversal mechanism is based on the pass-through (or overcoming) of some energy barrier. An alternative way for assisting magnetic switching was initially proposed by Thirion et al. [1], it is Microwave Assisted Switching (MAS).
MAS consists in applying microwave excitation with a rf magnetic field perpendicular to the magnetization easy axis at the same time as a dc magnetic field. MAS procedure is cartooned in Fig. 1. It was investigated further by Nembach et al. and Pimentel et al. [2, 3] who recently reported the cancellation of the coercive field of a submillimetric (160 x 80 μm²) elliptic particle. More recently, Woltersdorf et al. [4] also reported similar results with smaller particles (down to 0.7 x 1.4 μm² elements). Both teams used Kerr effect but, due to the size difference of their magnetic microstructures, the former invoke a microwave-assisted magnetic domain nucleation mechanism, while the latter assume a coherent precession of the magnetization. The overall behavior of their systems are similar, with a maximum decrease of the switching field obtained at relatively low frequency (less than 1 GHz) and large microwave power (i.e. large rf magnetic field). This Optimal Switching Field Reduction Frequency - that we will refer to as OSFRF in the following - is in both cases assigned to some resonance frequency allowing an optimal absorption of the microwave power by the magnetic element. For applications in data storage...
technology, MAS of micro or nano elements requires a high reliability, a moderate magnetic field (in the milliTesla range) and a large speed (switching in less than 1 ns). Therefore, many efforts are done in order to validate the potential of MAS for write process in data storage.[5, 6, 7] We concentrate in this paper in the study of the influence of rf excitation on the quasistatic magnetic switching field of a small magnetic element. Our work was at the same time experimental (with the magneto-optic study of MAS in rectangular mu-Metal elements of several tens of microns length and width) and theoretical, with the modeling of smaller (micron or submicron-scaled structures). We have confirmed the existence of the OSFRF and a summary of our results is presented in table 1. This OSFRF is significantly smaller than the uniform mode resonance frequency of our samples. The purpose of the present paper is to give more details in the macrospin or micromagnetic calculations of our recently published work [8].

Table 1. Summary of the experimental and computed dynamic properties of rectangular NiFe elements: uniform mode resonance frequency ($f_{ur}$), OSFRF, static coercive field ($H_{Cstat}$) and maximum switching field reduction (this reduction is not total for experiments due to the available $H_{p,rf}$ excitation, for more details see ref. [8]).

| Patterned size | $f_{ur}$ | OSFRF | $\mu_0H_{Cstat}$ | $H_{rf}/H_{Cstat}$ | type of data |
|----------------|---------|--------|------------------|---------------------|--------------|
| 10x80x0.045 μm$^3$ | 2.1 GHz | 1.4 GHz | 0.75 mT | 0.45 | experimental |
| 20x160x0.045 μm$^3$ | 1.3 GHz | 0.8 GHz | 0.45 mT | 0.52 | experimental |
| 1.024x0.128x0.02μm$^3$ | 10.2 GHz | 7.5 GHz | 154 mT | 0.00 | macrospin |
| 1.024x0.256x0.02μm$^3$ | 7.5 GHz | 5.0 GHz | 78 mT | 0.00 | macrospin |
| 1.024x0.128x0.02μm$^3$ | 10.6 GHz | 9.0 GHz | 69 mT | 0.00 | micromagnetic |
| 1.024x0.256x0.02μm$^3$ | 7.8 GHz | 5.0 GHz | 34 mT | 0.00 | micromagnetic |

Figure 1. Configuration of the magnetization, the static and microwave magnetic fields used in MAS. The dc magnetic field is applied along the easy axis $u_x$, the rf field $h_{rf}=H_{p,rf}exp(i2\pi ft)$ is applied in plane along the hard axis $u_y$ of the NiFe parallelepiped ($l\times w\times t$).

2. Numerical modeling
2.1. Macrospin modeling
The dynamic behavior was described by Landau-Lifshitz (LL) equation[9]. The external fields are applied according to Fig. 1 with the static field $H_{dc} = H_x.u_x$ and the microwave excitation field $h_{rf} = H_{rf}cos(2\pi f_{rf}t).u_y$. $f_{rf}$ is the microwave frequency. We have integrated LL-equation over series of hysteresis loops to determine the $H_C$ dependence vs. $f_{rf}$ and $H_{rf}$. For the best coherence with experiments, we have chosen $M_S=520 \times 10^3$ A/m, and the uniaxial anisotropy term related to field-deposited NiFe alloy $K_1=245$ J/m$^3$. The demagnetizing coefficients were obtained from Aharoni’s expressions [10] for the case of rectangular platelets. As a function of the static field $H_z$ applied to the macrospin, Kittel formula was used to get the resonance frequency $f_u$ of the uniform mode. Note that the absolute sizes do not matter in macrospin approximation, the only pertinent parameter is the aspect ratio. The effect of microwave excitation on magnetic switching is shown in Fig. 2 where a minimum switching field is obtained for a rf frequency of 5 GHz, therefore lower than the resonance frequency of the system in zero field. Note that
coercive field can be cancelled for rf excitation of sufficient amplitude (typically $\mu_0 H_{p,rf}=12 \text{ mT}$ at 5 GHz). The switching time $t_R$ for this system may be shorter than 0.1 ns, in particular for large applied static fields as shown in the $t_R$ mappings of Fig. 3, for several applied static fields. However, if one wants to take advantage of the reduced static switching field - i.e., using a rf excitation with a frequency close to OSFRF and a low static field - the switching time may exceed 5 ns.

Figure 2. Coercive field mapping for the 1.024x0.256x0.02 $\mu m^3$ element obtained by macrospin computation.

Figure 3. Switching time mapping for the 1.024x0.256x0.02 $\mu m^3$ element obtained by macrospin computation.

2.2. Micromagnetic modeling

Micromagnetic computation was performed with element geometries of the same aspect ratios as the patterned NiFe films, meshed at 4x4x20 nm$^3$, the sizes of our simulated elements is 0.128x1.024 $\mu m^2$ and 0.256x1.024 $\mu m^2$. OOMMF software was used in pseudo-3D mode [11]. The same procedure as for macrospin was used and the results of coercive field and the corresponding switching time, for a parallelepiped of the same aspect ratio as the one presented in the previous section. Figures 4 and 5 illustrate our results. Note that the switching field mapping displays the same OSFRF feature (reduction of $H_C$ for 5 GHz that corresponds to an excitation frequency lower than the uniform mode resonance frequency) but it is more complex than the one of macrospin, with a secondary OSFRF obtained at low frequency ($\sim 1$ GHz). In order to better understand this behavior, we have compiled in Fig. 6 several spin structures at various steps of MAS for 1 GHz and 5 GHz. They clearly evidence two different switching modes, respectively dominated by edge domain nucleation and vortex motion at 1 GHz, and related to the excitation of a core mode and the nucleation of packed vortices for a 5 GHz excitation. Note that, at 5 GHz, very disordered spin structures appear, their time evolution is detrimental to rapid MAS process.

3. Conclusion

In conclusion, we have evidenced a significant reduction of coercive field with MAS. However, in order to reduce switching time, large magnetic fields are still required. A possible solution to minimize switching time in MAS, with a low static magnetic field, might be to take advantage of edge modes that occur at lower frequency than the uniform modes as revealed by our micromagnetic computations. One might try to use smaller nanoelements that tend to macrospin, but, unfortunately, as shown here, we also predict the need for large combinations of
fields for macrospin switching. Finally, a realistic solution might be the use of tailored magnetic field time and polarization profiles for $MAS$ that are expected to improve the switching process in terms of intensity of the field, as recently proposed by Okamoto et al. [12].

4. References
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