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Modeling of microwave-assisted switching in micron-sized magnetic ellipsoids

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The microwave-assisted magnetization reversal is modeled in a permalloy micron-sized magnetic ellipsoid. Our simulations confirm that this process requires less field than magnetization reversal under a static field. This is due to a different reversal mode which in the case of the microwave-assisted process is always a ripple structure. During the magnetization reversal, two stages, nucleation and relaxation, are distinguished. The nucleation process is governed by spin-wave instabilities. The relaxation process is related to the domain expansion through domain-wall propagation determined by the precessional motion of magnetic moments in the center of the domain walls. As a consequence, the switching time is a complex oscillating function of the microwave frequency.

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I. INTRODUCTION

The fundamentals of fast magnetization switching constitute one of the important problems in magnetism related to technological applications.[1] Experimentally microwave-assisted (mw) switching has been reported as requiring a smaller applied field thus opening new possibilities for applications in magnetic recording and communication devices.[2–6] The mw switching process with linearly polarized excitation can be realized based, for example, on a fast magneto-optic Kerr effect setup, applying simultaneously static and microwave fields.[3,4,6,7] Another possibility to observe mw-assisted switching is given by measuring the magnetoresistance as has been done, for example, in Co stripes[8] or in NiFe magnetic tunnel junctions.[5] These experiments use relatively large (up to tens of microns) lithographically prepared magnetic elements whose dimensions do not allow the occurrence of homogeneous magnetization processes.

Differently from this, the micro superconducting quantum interference device (SQUID) experiment,[2] performed on Co nanoparticles with 20 nm diameter gives an example of a macrospin magnetization behavior. In this system nonlinear effects are clearly observed experimentally in agreement with a simple macrospin dynamical model. The behavior found in the macrospin magnetization dynamics has stimulated the technologically important proposal of microwave-assisted [or ferromagnetic resonance (FMR) assisted] magnetic recording.[9–11]

The process of understanding the underlying physics is still going on and several ideas are found in the literature. From the theoretical point of view, probably the most comprehensive understanding has been achieved in the case of one single magnetic moment.[2,10–15] In what follows we would like to mention some of the proposed mechanisms since most of them can also be partially encountered in the complex situation of nonhomogeneous magnetization reversal processes discussed in the present paper. The most frequently used one is based on a simple idea of the efficient energy transfer during excitation with frequencies close to the FMR one.[4,12] It has been also argued that excitation with a circular polarized field would be much more efficient due to the possibility to synchronize with the rotation sense of the magnetic moment.[12] Although it seems to be less efficient, synchronization is also possible with a linearly polarized field.[15] This idea remains certainly valid in a general case, however it should be noted that the notion of the FMR frequency, as corresponding to excitation of mode with zero wave vector, is not exact for micron-sized magnetic elements. Due to the minimization of the magnetostatic charges at the surfaces, even small-angle magnetization vibrations are not homogeneous[7] and the frequency spectrum depends strongly on the size and shape of the magnetic nanoelement.[16,17] Moreover, in magnetic nanoelements the frequency spectrum becomes quantized.[18,19] The second idea found in the literature is also simple: the microwave field provides a constant energy input which rises the magnetic energy of the particle up to a level higher than the saddle point of the magnetic-energy landscape.[2,5,12,15] Note that here also the thermal-activated process becomes possible.[14,20] In this sense, it can be said that the microwave field can act as an energy source which effectively decreases the energy barrier. It should be noticed here that this idea is relied on a simple picture of a two-level system which is generally not valid for a nonhomogeneous magnetization reversal scenario.

The fast mw-assisted magnetization switching process in magnetic elements is closely related to the phenomenon of precessional switching. Indeed, a small perpendicular field helps the switching to take place via the excitation of the precessional motion[21–23] due to the torque acting on the magnetization. The main problem is that with, for example, a perpendicularly applied field the magnetization continues to precess ("ringing" phenomenon) and could switch back.[24] Furthermore, it has been suggested to use a pulsed field and to tune the pulse duration to avoid multiple switching. Even the pulse shape could be optimized,[25] together with the use of two pulses with an optimized delay time.[24,26] This case again is mostly studied in the case of one magnetic moment, although micromagnetic simulations have been also widely performed in nanoelements with different shapes.[27]

The final idea which we would like to mention is that one magnetic moment under a microwave field represents a classical example of a parametrically excited nonlinear oscillator. Thus the problem is similar to the classical parametrically excited pendulum, where parametric instabilities occur varying the strength and the frequency of external oscillation. Such instabilities may be considered as precursors of the switching process. Next, in these systems nonlinear phenomena such as bifurcations and chaos[15,28,29] occur. A classical example of this is the appearance of an additional large-amplitude stationary orbit via the folding bifurcation, again studied in the case of one macrospin only.[28,29] The nonlinear phenomena lead to a complex structure of the trajectories near the separatrix, a special trajectory separating the basis of attractions of the two minima. Under the influence of external periodic force, the separatrix may become fractal so that closely situated initial conditions may lead either to switching or not.[15] This produced, for example, fractal regions of switching beyond the Stoner-Wolfarth astroid observed experimentally in micro-SQUID experiments[2] and numerically in Refs. 2, 11, 13, and 15. However, since these phenomena are complex even in the case of one magnetic moment, in a large system nonlinear phenomena are more difficult to interpret and may not lead to a clear pattern.

The reversal under oscillating fields of large-sized magnetic nanoelements was mostly studied in cases with simple magnetization reversal modes, such as domain wall,[8,30] *C* or *S* magnetization states,[31] the vortex to onion state in magnetic rings[32] or vortex-core reversal.[33,34] The enhanced mobility of domain walls with some frequencies was numerically found.[30] Experimentally, using the magnetic circular-dichroism technique in a magnetic element having a Landau pattern, the asymmetry of the domain-wall motion under a linearly polarized mw field with the drift in one direction was reported.[35] This has been explained by the entropy maximization involving the precessional excitation (the excitation of a so-called "self-trapping spin-wave mode").

As we mentioned above, most of the previous theoretical studies involve either fast switching in the macrospin case (or effectively conditions of coherent rotation) or the switching of individual objects as vortices or domain-wall structures. However, the spatial resolution of the fast Kerr experiments[3,6] requires quite large magnetic elements with not so simple and unique magnetization reversal modes. Namely, the mw-assisted switching in large systems produces a sequence of nucleation—propagation—relaxation phenomena which is the subject of the present study. We show that the overall dynamics is a complex phenomenon where some of the above mentioned processes could occur simultaneously and could play a role on different stages of the magnetization reversal.

II. MODEL

In the present work and with the aim to understand the mw-assisted switching processes in large magnetic elements,[3,6] we use a micromagnetic model to simulate the magnetization dynamics in a permalloy ellipsoid. Due to the limitation of the simulational size we used reduced dimensions of the ellipsoid: the total magnetic volume is $V = 4\ \mu\text{m} \times 2\ \mu\text{m} \times 25\ \text{nm}$. It has the same aspect ratio as in the experiment. We used the publicly available code Magpar[36] with a finite element discretization and in which we implemented the possibility to simultaneously apply dc and ac fields. The permalloy easy axis was directed parallel to the large ellipsoid axis (y axis, see Fig. 1). Initially the ellipsoid was magnetized along this axis. The dc-applied field is placed parallel to it in the opposite direction. The linearly polarized ac field with large amplitude is directed perpendicular to it (x axis). The following micromagnetic parameters were used in the simulations: anisotropy value $K = 3.31 \times 10^3\ \text{erg/cm}^3$, saturation magnetization value $M_s = 860\ \text{emu/cm}^3$ (the anisotropy field $H_K = 7.7\ \text{Oe}$), exchange parameter $A = 1.05 \times 10^{-6}\ \text{erg/cm}$, and damping parameter $\alpha = 0.012$.

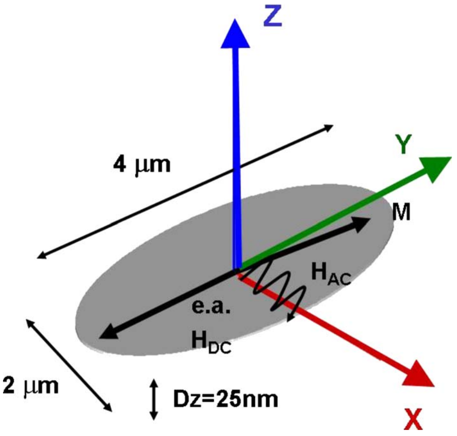

FIG. 1. (Color online) Geometry of the simulated system.

In Fig. 2 we present a hysteresis cycle for the permalloy ellipsoidal element with the field applied parallel to the easy axis direction. The coercive field is much larger than the

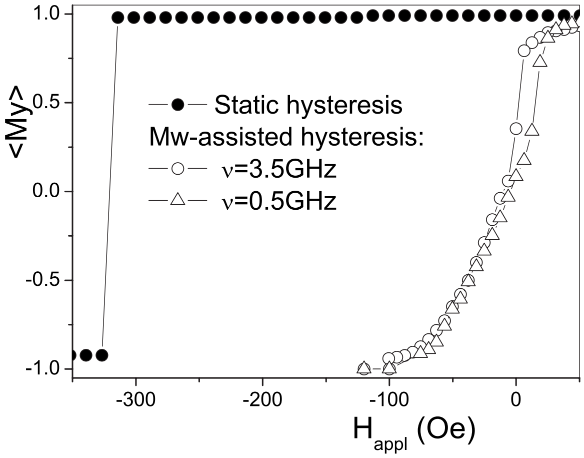

FIG. 2. Simulated descending branch of the hysteresis cycle for the permalloy ellipsoid with static applied field only (full circles) and with simultaneously applied static and mw field with $H_{ac} = 25.1\ \text{Oe}$, and two frequencies (open symbols). The dc field is applied along the long ellipsoid axis Y. The average ellipsoid magnetization $\langle M_y \rangle$ is normalized to the total saturation value.

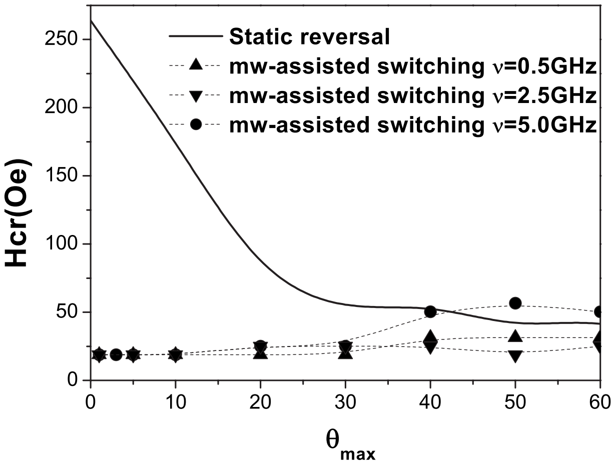

FIG. 3. Amplitude of the critical field necessary for magnetization switching as a function of the maximum field angle with the anisotropy axis for static field and microwave-assisted switching.

anisotropy field value due to the large magnetostatic shape anisotropy.

III. RESULTS

First, we model the hysteresis cycle with simultaneously applied dc and ac fields (see Fig. 2) and note the reduction in coercivity in the case of the mw-assisted switching process. The hysteresis cycle is squarelike in the former case and rounded in the latter one. To understand the coercivity reduction we model the minimum strength of the applied field required to produce the magnetization reversal in our system for different mw-field frequencies.

We notice that one of the large contributions to the coercivity reduction comes from the deviation of the magnetization direction from the y axis, following the ac field. Thus, the coercivity is reduced simply due to the fact that most of time the resulting field is applied at some angle to the easy axis. Consequently, we compare the mw-assisted switching process with the situation when a static field is applied at an angle equal to that formed during the mw-assisted case with the maximum amplitude H_{ac} of the ac field. The maximum amplitude of the critical field $H_{\mathrm{cr}}=\sqrt{H_{\mathrm{ac}}^2+H_{\mathrm{dc}}^2}$, necessary to switch the magnetization, is presented in Fig. 3 as a function of the maximum applied field angle. We use the following condition for the magnetization switching $\langle M_y\rangle<0$, where $\langle M_y\rangle$ is the average magnetization along the y direction. Our results show that even with this more fair comparison, mw-assisted switching always requires less field, except for the case of very large deviation angles and some frequencies. Therefore, the first important contribution to decrease the coercivity during the mw-assisted switching process is the deviation of field from the easy axis which leads to precessional switching. Moreover, for small field angles the results are almost independent of the ac-field frequency whose role is just to induce the precession. The results are different when strong deviations of the magnetization occur which stresses the importance of the nonlinear effects.

To illustrate the differences between the static- and mw-assisted switching processes we present the dynamical configurations during the magnetization reversal in Figs. 4 and 5. For the static process (Fig. 4) the magnetization nucleation starts with two vortices in the opposite upper and lower sides of the ellipsoid. During the irreversible jump these vortices propagate in opposite directions creating two domain walls. The propagation of these domain walls toward the left and the right sides of the ellipsoid completes the magnetization reversal.

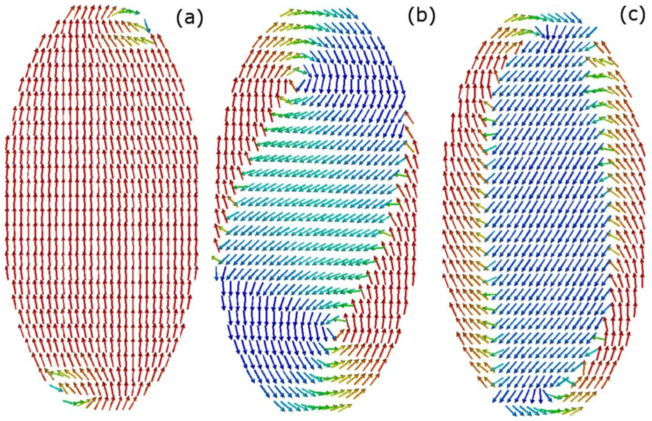

FIG. 4. (Color online) Magnetization configurations during the static-field hysteresis process at different time moments (a) initial state at the coercive field, (b) intermediate state, showing the vortices propagation, and (c) the final state at the coercive field. The field is applied at 45° with the Y axis.

Figure 5 shows the magnetization configurations during the mw-assisted switching process. The complimentary video material (see Ref. 37) illustrates the temporary dynamical evolution of the demagnetization reversal. We observe that the ellipsoid is dynamically divided into domain structures. The number of domains depends strongly on the mw frequency and may be related to the length of the spin-wave mode excited in the system. In Fig. 6 we represent an approximate number of magnetization domains nucleated during the first two nanoseconds as a function of the ac-field frequency and in the magnetization range $0.6<\langle M_y\rangle<0.8$ (normalized to the total saturation magnetization). Note that the domain size is larger in the central part of the ellipsoid than in the upper and lower sides due to the ellipsoidal form and initially grows with time (see Fig. 7). The division of the ellipsoid into domains during mw-assisted switching is experimentally confirmed by Kerr images in Ref. 6. Therefore, the mw-assisted case is characterized by a reversal mode completely different from the one appearing during the static hysteresis.

Generally speaking, the ac-driven process is complicated and involves different objects. The domains are separated by domain walls (of Néel or cross-tie types) and the magnetic moments in the center of these domain walls are constantly precessing [see Figs. 5(c) and 5(d)]. This precession is important for the domain-wall mobility. In the junctions between the domains vortices are created (see Fig. 8). Next, during the process we observe constant spinwave generation and their reflection from the ellipsoid boundaries and domain walls. Therefore, the overall process contains an interplay of several important effects, discussed earlier in the literature in

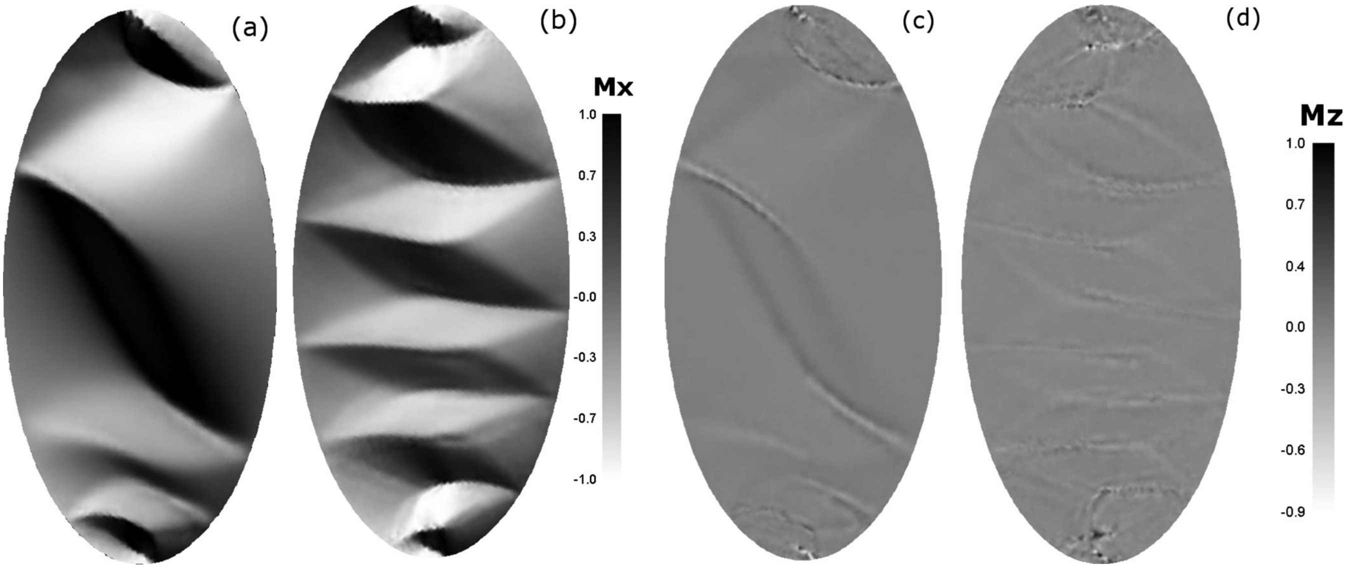

FIG. 5. Dynamical configurations: M_x (left) and M_z (right) components (gray scale) during the mw-assisted magnetization reversal for applied fields $H_{dc}=-31.41$ Oe and $H_{ac}=18.84$ Oe and for two different frequencies $\nu=1$ GHz [(a), (c)] and $\nu=6$ GHz [(b), (d)]. For the dynamics of the reversal process, see the supplemental material (Ref. 37).

more simple situations (see Sec. I). Each of them has been reported previously to be influenced by the mw field.

Figure 9 shows the dependence of the magnetization switching time in the ellipsoid on the mw frequency for several amplitudes of the ac field. We clearly observe oscillations in the switching time. Moreover there exists a region of the parameters (see Fig. 10) where the switching required more than 16 ns. To understand the phenomenon we first plot in Fig. 11 the average M_y magnetization component as a function of time. The small-period magnetization oscillations are related to the ac-field oscillations. During the switching process we can distinguish two main processes: the first one (occurring in the first 2 ns) is related to the efficiency of the magnetization nucleation in the system while the second one is related to the magnetization relaxation. Figure 11 shows that at several frequencies the magnetization reversal process started faster in its nucleation part but proceeded slower in the relaxation part.

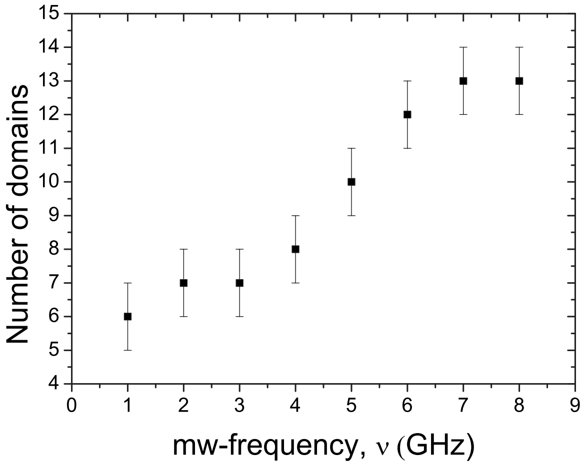

FIG. 6. Number of domains in the ellipsoid nucleated during the first two nanoseconds as a function of mw frequency for applied fields $H_{dc}=-31.41$ Oe and $H_{ac}=25.13$ Oe.

The nucleation process is associated to efficient spin-wave generation and then to spin-wave instability phenomena which is a precursor of the magnetization reversal.[38–40] The role of the ac field is to excite a spin wave with the external frequency. Because of this, the data of Fig. 6 resembles the spin-wave dispersion relation and the ripple configurations—the spin-wave modes reported in Ref. 41. However, the excited mode may be unstable for a given condition and, thus, produce instabilities and magnetization reversal. For example, we have seen that at these values of the applied field the main FMR mode is completely unstable.

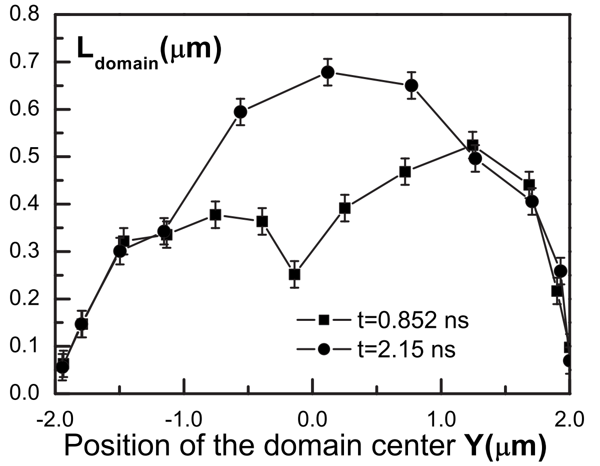

FIG. 7. Domain size in the ellipsoid along the y coordinate as a function of the position of its center for two time snapshots, corresponding to the first nucleation-expansion stage of the mw-assisted reversal processes and for $H_{dc}=-31.41$ Oe and $H_{ac}=25.13$ Oe. Note that after approximately $t>2.5$ ns the domain size expansion is suppressed.

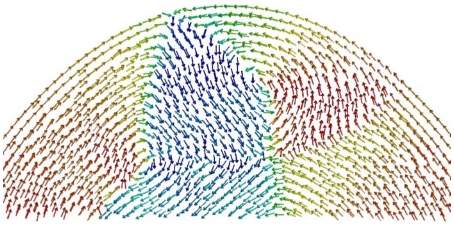

FIG. 8. (Color online) More detailed magnetization configuration in the upper part of the ellipsoid showing the occurrence of domain walls and vortices. $H_{\mathrm{dc}}=-31.41$ Oe, $H_{\mathrm{ac}}=25.13$ Oe, and $\nu=0.1$ GHz.

When we tried to excite the homogeneous mode with the magnetization antiparallel to the applied-field direction, the energy was immediately redistributed into inhomogeneous spinwaves provoking later the magnetization reversal. The excitation of these spinwaves was acting as an additional damping source leading to the magnetization reversal similar to the case of Ref. 42. In this case, the excitation with the frequencies close to FMR (around 3 GHz in Fig. 9) is the most efficient one. The first stage (several ns) is also characterized by initial expansion of the domain size, especially in the center, as seen in Fig. 7.

To illustrate the role of precession, we present in Fig. 12 the temporal evolution of the average value of the $\langle M_z^2 \rangle$ component (this value is proportional to the energy put into precession by the microwave). The first part of these curves characterizes the initial nucleation-expansion process (first 2 ns). It is clear that the energy is put efficiently into the precession with the frequency close to the main FMR mode. This is confirmed by the fast magnetization decay of the $\langle M_y \rangle$ component in Fig. 11 and the fast growth of the $\langle M_z^2 \rangle$ value in Fig. 12. This fact is consistent with the hypothesis introduced in many papers stating that for efficient switching the mw frequency should coincide with the FMR one.[4,12] In the case of magnetic elements behaving as one macrospin magnetic moment this would determine the overall switching. However, a fast nucleation is insufficient for fast magnetization switching of larger elements. Figure 12 demonstrates that for frequencies close to 6 GHz (double FMR frequency in the opposite well) the precessional energy remains constant. We note that only the magnetic moments in the centers of domain walls separating domains with opposite M_x signs (and in the vortex centers) are precessing (see Fig. 5). Thus the expansion of domain walls necessary for magnetization relaxation is dependent on the relaxation of these magnetic moments. For frequencies and time scales at which the $\langle M_z^2 \rangle$ relaxation is very slow, the energy is transferred efficiently into the precessional motion and not to the relaxation process. Consequently, the further domain expansion is extremely slow. We would like to note that this idea is in the spirit of the hypothesis introduced in Ref. 35 (self-trapping of magnetic oscillations). At the long-time scale the magnetization reversal at this stage proceeds again via additional spin-wave generation and reflection destabilizing the domain structure. Note also that the nucleation process occurs when the magnetization is antiparallel to the field direction while in the relaxation part it is parallel. Thus, the relevant frequencies are different in both cases.

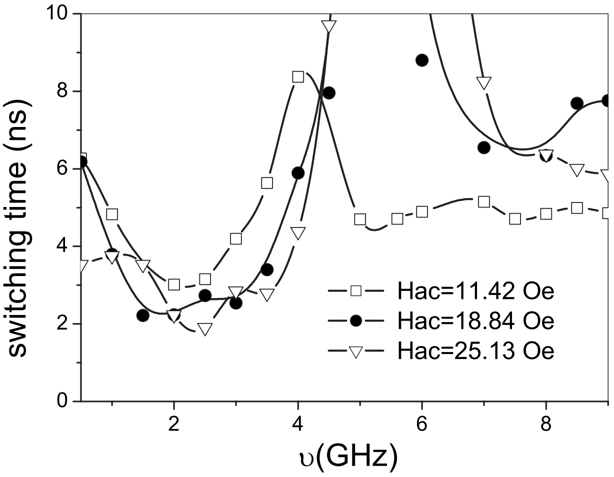

FIG. 9. Switching time of the magnetization as a function of the mw frequency for various values of the mw-field amplitude H_{ac} and $H_{\mathrm{dc}}=-31.41$ Oe

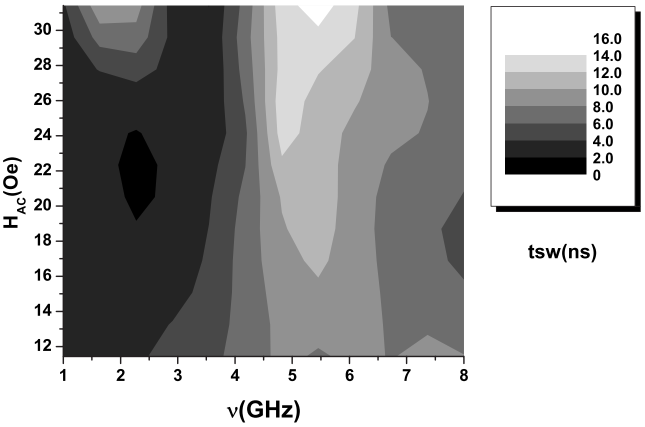

FIG. 10. Contour plot for the switching time of the ellipsoid for applied field $H_{\mathrm{dc}}=-31.41$ Oe.

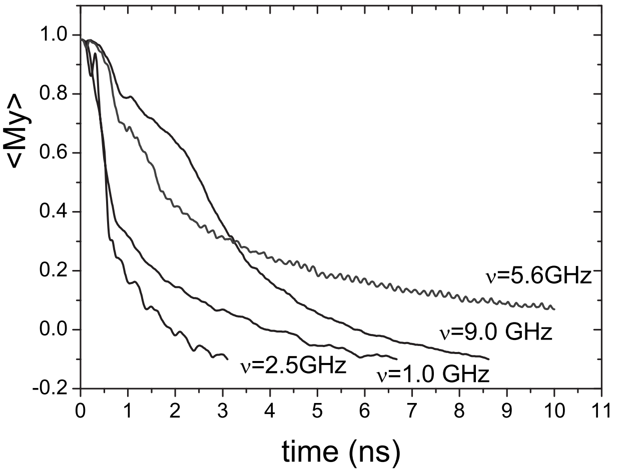

FIG. 11. Temporal evolution for the average $\langle M_y \rangle$ magnetization component (normalized to the saturation value) during the microwave-assisted switching process at $H_{\mathrm{dc}}=-31.41$ Oe and $H_{\mathrm{ac}}=25.13$ Oe.

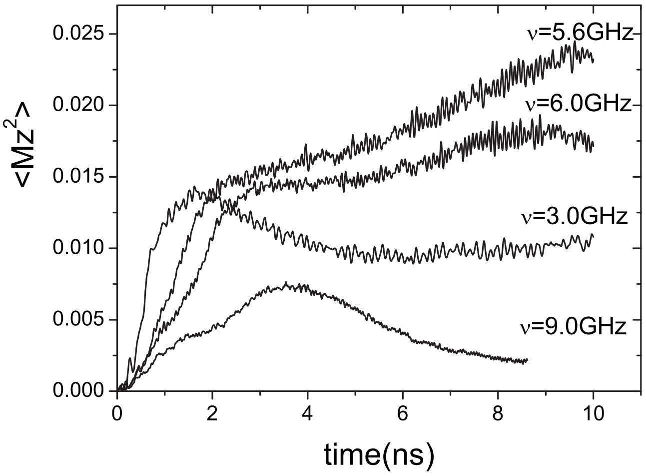

FIG. 12. Temporal evolution for the average $\langle M_z^2 \rangle$ magnetization component (normalized to the saturation value) during the microwave-assisted switching process at $H_{\mathrm{dc}}=-31.41$ Oe and $H_{\mathrm{ac}}=25.13$ Oe.

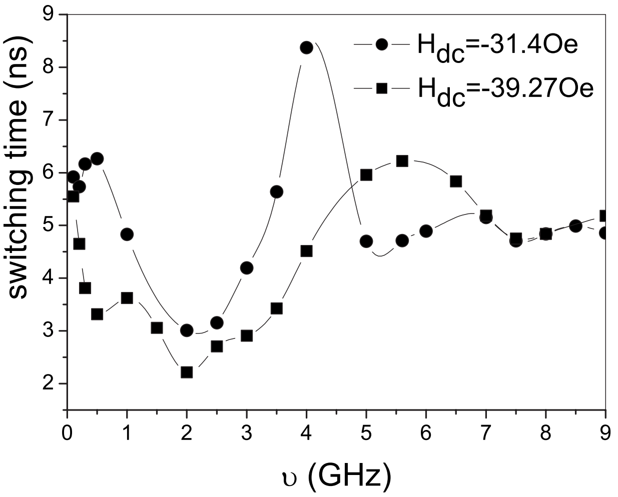

FIG. 13. Switching time of the magnetization as a function of the mw frequency for two values of the stationary field H_{dc} and the mw-field amplitude $H_{\mathrm{ac}}=25.13$ Oe.

Figure 13 shows the magnetization switching time as a function of the mw frequency for two dc-applied field values. As the applied dc field increases, the angle of the magnetization precession increases in the nucleation part of the process but decreases in the relaxation part. Larger precessional angles lead to nonlinear phenomena. Associated with larger precessional angles there is a nonlinear shift of the frequencies to smaller values.[43] This is in agreement with the results presented in Fig. 13, provided that the relevant frequencies are determined by the relaxation process. However, in Fig. 9 the frequencies are shifted to larger values with larger ac-field amplitude. This shows that the overall process is much more complicated and cannot be analyzed in terms of the FMR frequencies relevant to the switching of one magnetic moment only. In fact, different ac-frequencies excite modes with different spin-wave vector and the instabilities of them occur at different threshold amplitudes.

IV. CONCLUSIONS

Using the micromagnetic model, we have investigated the mechanism of fast magnetization switching assisted by a linearly polarized microwave field in micron-sized magnetic elements. Magnetization dynamics in these magnetic patterns is governed by nucleation-propagation-relaxation processes and is different to those of nanoscale elements behaving as one macrospin. Our simulations confirm that the microwave-assisted magnetization reversal requires a smaller field than in the process under a static applied field. The first contribution to this is the deviation of the field from the easy axis during the mw-assisted switching process. However, even when we compared the situations when the maximum-applied field angle is the same in both cases, mw-assisted switching appeared to require less field. Moreover, our results show that at small intensity of the mw-field its action is not described by the effective-field tilt. This happens due to the fact that the static- and the mw-assisted switching processes involve different reversal modes. In the first case this mode consists of the nucleation of two vortices in opposite corners, their subsequent merging and creation of two domain walls which later span the whole ellipsoid. In the second case, the reversal mode consists of a ripple structure, the external frequency being responsible for the excitation of a spin-wave mode with the corresponding ripple size. For fields below the static coercivity field, the magnetization configuration corresponds to almost homogeneous background plus excited spin-wave mode and is metastable. The amplitude of the excited spin-wave mode grows with applied field and becomes unstable, leading to magnetization reversal. Thus, the spin-wave instability mechanism[38–40] plays a major role for the fast-magnetization switching process in nanosize magnetic elements.

We have shown that the most efficient nucleation is at the FMR frequency (and its multiples). However, the magnetization reversal process after the nucleation requires also an efficient magnetization relaxation. For example, the domain growth is stimulated by the ac field. This happens due to the relaxation of precessing magnetic moments in the domain-wall center. In the spirit of the mechanism suggested in Ref. 35, for some frequencies, the relaxation process is not efficient, this happens when the mw field is coupled to the precessional motion. In this case the microwave field efficiently puts the energy into precession and not into the propagation-relaxation processes which are slowed down. As a consequence of the interplay of several mechanisms with different relevant frequencies, the switching time of magnetic elements is a complicated function of the external frequency. The above results show that the magnetization dynamics in micron-sized magnetic elements could not be analyzed as a simple FMR-related phenomenon and neither follows a direct correspondence with a spin-wave spectrum.

Finally, we would like to discuss our results in the context of available experimental data. Out results are in qualitative agreement with experimental observations. The Kerr images in Ref. 6 show the creation of ripple structures during the mw-assisted switching process in a permalloy ellipsoid. Currently there is no data available for the switching time of the magnetization in ellipsoids which could confirm the existence of the oscillations presented in Fig. 9. However, in several experimental papers on different magnetic elements we have found qualitative similarities with our results. For example, in Co bars the relaxation time observed by the fast Kerr technique showed a strong nonmonotonic behavior as a function of applied field.[7] Also in Co bars measured by the anisotropic magnetoresistance effect,[8] the authors have observed the occurrence of several resonance peaks sweeping in frequency. The microwave power input necessary for the maximum coercivity reduction was reported to be frequency dependent in the measurements of mw-assisted switching in NiFe magnetic tunneling junctions.[5] The critical field necessary for the microwave assistance was shown to be a complicated function of the mw frequency with several minima for the mw-assisted process going from vortex to onion state in magnetic nanorings.[32]

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