Probing ground state in circular magnetic dots: single vs. double magnetic vortex

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Abstract – **We investigate static magnetization as a function of a magnetic field during nucleation of the magnetic vortex state in Py dots with diameter of 1000nm and with four different thicknesses varying between 15 and 50 nm. For the 50nm thick Py dots we observe direct nucleation of the single vortex state from the saturated state, while the dots with thickness equal or below 25 nm reveal formation of intermediate metastable double vortex state before entering into the single vortex ground state at small negative fields. This scenario is confirmed by micromagnetic simulations and variable field magnetic force microscopy imaging. Our simulations investigate stability of the double vortex metastable state as a function of temperature and external microwave pulses. Magnetic force microscopy was found to be a invasive imaging technique to study this kind of samples. For 20nm thick Py dots only the single vortex state is observed with commercial tips, meanwhile home made tips with lower magnetic moment were found to destroy the double vortex state during imaging process.**

1 INTRODUCTION

In the last decade the magnetic vortex state in circular magnetic dots has attracted increasing interest. This arises from the possibility of its implementation as a key element of a new type of high density storage media and the appearance of the vortex in the spin-polarized current driven spintronic devices (vortex based spin torque oscillators), as well as its possible implantation in logic operation devices [1-3]. Therefore, precise knowledge of static magnetization and magnetization topology in circular Py dots with different aspect ratio (thickness by radius) is of great importance both from fundamental and applied points of view [4]. Recent experimental and micromagnetic simulations results demonstrate the possibility of long-lived metastable states below the vortex nucleation fields, which corresponds to a double metastable vortex [5-7] in addition to the metastable single vortex, which presents the shifted vortex above the field value corresponding to the nucleation field [8].

Reducing the dots thickness may enhance pinning of the vortex core [9] and help stabilize the metastable states (S-state and double magnetic vortex (DMV) state), and to make them stable even at room temperature [5-7]. In order to better understand the dynamic response of the thin Py dots with different thicknesses, it is important to investigate the conditions for stability of the DMV metastable state which appears during the transition between saturated and single vortex ground state. Here we study experimentally and by simulations the metastable DMV state formed in 15-50 nm thick Py dots with a diameter of 1000 nm.

2 EXPERIMENTAL RESULTS

2.1 Circular Permalloy dots

Square arrays of polycrystalline Py dots with thicknesses L=50, 25, 20 and 15 nm and radii R=300 and 500 nm were fabricated using electron beam (EB) lithography and lift-off techniques. Double layer E-beam resist and highly directional electron beam evaporation allowed obtaining dots with sharp edges. The patterned area had dimensions from 2×2 to 10×10 mm^2. More details on samples growth and characterization of magnetization dynamics in single vortex state using a vector network analyzer (VNA) were published previously [4]. This paper mainly discusses static magnetic properties of Permalloy dots with thickness starting from and below 25 nm, where the metastable ground state is formed at small applied magnetic fields.

2.2 Magnetization vs. field and dot thickness

Static magnetization hysteresis loops of all Py dots arrays were measured at room temperature by using a SQUID magnetometer. The measurements were done by saturating the samples by an in-plane magnetic field of 150 mT and measuring the magnetization between -150 and 150mT with steps of 1 mT (see Figure 1). The analysis of the normalised room temperature remanence of the studied dots shows that $M(0)/M_S$ increases rapidly below 20-25 nm as can be seen in the figure. This is an indirect indication of the possible

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change of the magnetic groud state of the dots. While for single vortex ground state the remanence magnetization is expected to be small, the finite values of the remanent magnetization observed for thin dots indicate either a shifted out of center single vortex state or other metastable (S or DMV) states. Further we analyse changes in the vortex nucleation and annihilation processes with dot thickness. We define the nucleation field (H_n) as the magnetic field value at which the Py dots leave the saturated state with decreasing magnetic field by nucleating either a single or a double vortex. Correspondingly, we define the annihilation (H_a) field value as the magnetic field at which the Py dots return to the saturated state.

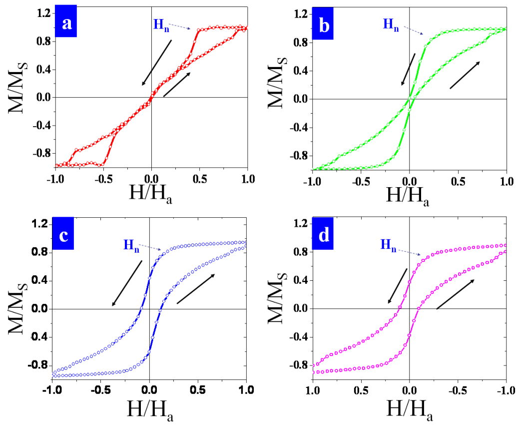

Figure 1 Hysteresis loops for the Py dot: a,b,c,d present the magnetization loops for dots with 1000nm diameter and 50, 25, 20 and 15nm thickness respectively.

Figure 2 shows that both the nucleation and saturation fields decrease with the dots thickness, most probably due to reduction of the corresponding energy barriers. Interestingly, while H_n weakly changes with decreasing thickness below 25 nm, the annihilation

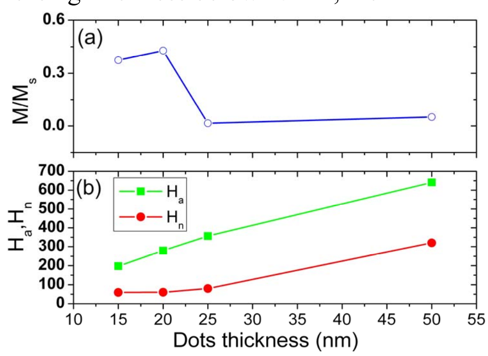

Figure 2 a) Normalized magnetization remanence $M(0)/M_S$. b) vortex nucleation and annihilation fields in Oe as a function of Py dots thickness.

field is much stronger dependent on thickness. This could be an indirect indication of the nucleation of some metastable vortex state and the annihilation from the vortex ground state.

2.3 Simulations

Let us now discuss, by using micromagnetic simulations, the possible metastable states in circular magnetic dots with a single vortex ground state.

2.3.1 Relaxation

The simulations were performed using an extension [10] on the original OOMMF code [11] that augments to the LLG equation a highly irregular fluctuating field, so the resulting equation is a stochastic differential equation of the Langevin type [12]. The micromagnetic simulations were carried out for circular Py dots with a diameter of 1035nm and thickness of 50, 25, 20 and 15nm, with simulated cell sizes of 5 x 5 x 20nm^3 and 5 x 5 x 25nm^3, $\alpha = 0.5$, $\gamma/2\pi = 2.96$ MHz/Oe, the exchange stiffness constant $A = 1.4 \times 10^{-11}$ J/m. We first saturated the dot with an in-plane magnetic field of 1000Oe, subsequently we released this field in one step, going abruptly from 1000Oe to zero field. We then tracked the energy and total magnetization of the system every 1ns and took a snapshot of the local magnetization every 10ns. To break the deterministic characteristic of OOMMF, we used a different set of random fluctuation for each run that we made.

2.3.2 Vortex core size *vs* dots thickness

In the agreement with analytical approach [13], the simulated vortex core size decreases with decreasing thicknesses (Fig.3). This makes the core in thinner dots to be more susceptible to the pinning and thus favors creation of stable metastable state.

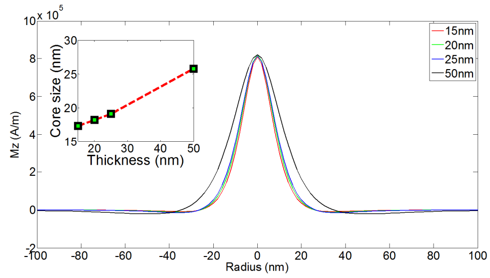

Figure 3: Numerically calculated variation of the cortex core size with dots thickness t (diameter 1036nm, cell size 2x2xt nm^3, T=0K).

2.3.3 Influence of Temperature

In Fig 4 are plotted the relative energy contributions to the total energy. These are dependent on the temperature. With for example the exchange energy this can quantitatively be understood by considering two neighbouring spins. If they are perfectly parallel the exchange energy will be low. However, at finite temperatures both spins will undergo a random shift in their orientation, caused by a random fluctuation in the effective field. This will most likely lead to an orientation of the two spins that is less parallel than before the random fluctuation, thus leading to a higher exchange energy. For the demagnetization field such tiny fluctuations on the whole play a smaller role, thus leading relatively to a higher contribution of the exchange energy to the total energy.

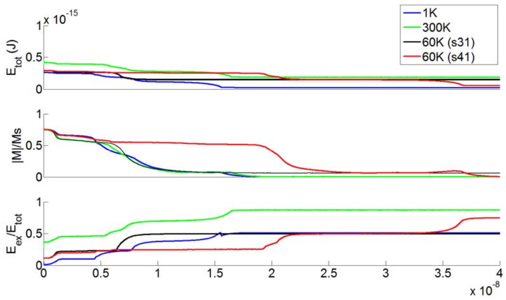

Figure 4: Relative energy contributions to the total energy vs. time for different simulated temperatures.

2.3.4. Influence of a RF drive

By applying a RF drive during the relaxation of the dot, transitions to different states can be influenced. In figure 5 is shown how a RF field couples to the dot for two orientations, parallel and perpendicular to the history field. Without the field the dot relaxes to the DMV state. This also happens with a field is applied parallel to the history field, however with the field applied in-plane perpendicular to the history field, the dot overcomes the barrier and falls to its ground state.

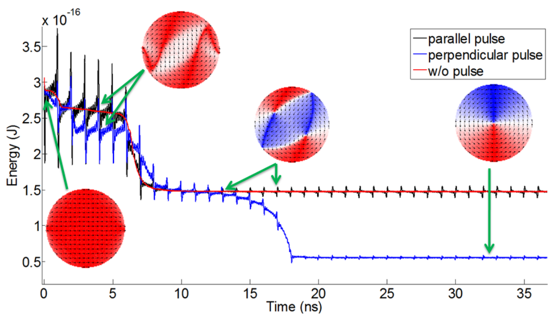

Figure 5 Relaxation of 1035x25nm dot with applied RF field that consists of a sum of sinusoidals from 1GHz to 9GHz with amplitude of 10Oe. Saturated state, S-state, DMV state vortex state respectively as indicated by the snapshots of the magnetization at the indicated time, with a color coding for Mx. (dot: 1035x25nm at 60K).

2.3.5 Simulation in the applied field (DMV)

Using the saturated dot at zero field, we apply a static magnetic in-plane field parallel to the history field (see fig 6). The resulting metastable states are of the DMV state type, but with shifted cores. Going to negative fields, thus anti-parallel to the history field, the configuration does not change much compared to that of zero field. The vortex cores get pushed away from each other to the outside of the dot. For positive fields the dot cores move the opposite way, so they cross each other before also being pushed to the outside of the dot.

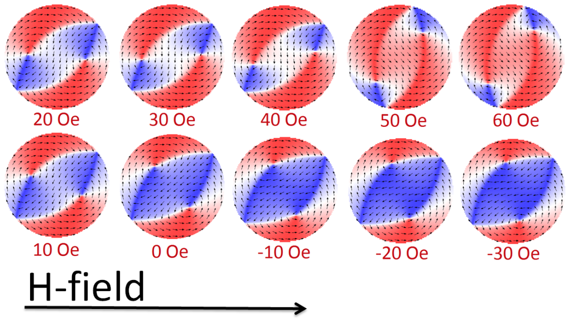

Figure 6: In-plane applied field parallel to the history field direction for dot 1035x20nm.

2.4. Magnetic force microscopy images

VFMFM (Variable Field Magnetic Force Microscopy) [14] was used to characterize the magnetic configuration of 20nm thick Py dots in remanence state and under an externally applied magnetic field. The static magnetization results (Fig.1,2) suggest formation of metastable ground state at zero field. Our images are done after the application of an in-plane field that is two times bigger than the saturation field. MFM microscopy is, especially given the sensitive nature of the metastable states quite an invasive technique. The images obtained in this way reveal that the experimentally observed magnetic configuration depends on the type of magnetic tip used. The low moment commercial tip (Nanosensors PPP-LM-MFMR), seems to modify the magnetic state of the dots substantially because it always provides single vortex images (see Fig.7a). A home made tip with lower magnetic moment however, reveals the characteristic of the DMV state in its images (Fig.7b,c). Some of the images even reveal jumps between the DMV and single vortex states during the scanning process, demonstrating the influence of the tip on the metastability of the states (see Fig.7b which shows second scan of the marked in blue area). With sufficiently large external magnetic field (18 mT) we were able to observe the shifted single vortex state (Fig. 7d). The fact that vortices shift in the opposite directions implies their opposite chirality. Figure 7e-f show simulated MFM images of the DMV (part e), S (part f) and shifted single vortex states which (in the absence of magnetic tip) are expected to depend on divergence of the magnetization [15]. Although more experiments are to be done, we believe that the observed metastable states which are effected by the MFM imaging (parts b,c), more closely resemble DMV states than S- states.

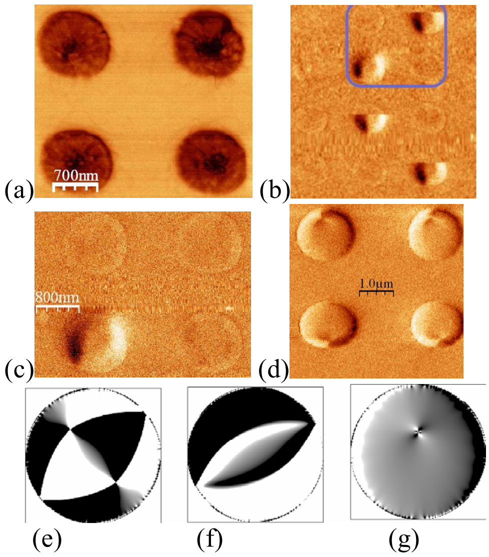

Figure 7: MFM images in zero field with commercial tip (a), with soft tip (b,c). Part (d) shows images of the shifted vortex in the field of 18 mT. Parts (e-g) present correspondingly simulated (within approach [15], in the absence of tip field) MFM images for DMV, S and shifted single vortex states.

3 DISCUSSION

The presented experimental data reveal fundamental change in the ground state of Py dots with decreasing thickness starting from and below 25nm. Micromagnetic simulations and MFM images indicate that the new remanent state in which the thinnest Py dots remain blocked at zero magnetic field, is the double vortex metastable state. While in micromagnetic simulations the DMV state survives only on the nanosecond time scale unless imperfections in the form of random fluctuations are included, our experiments, in accordance with previous observations [5-7] indicate that the metastable double vortex state is stabilized at room temperature through vortex core pinning by spatial fluctuations of the local pinning potential [9]. As long as the vortex core size decreases with decreasing dots thickness [13], enhanced vortex pinning in Py dots with thickness below 25 nm could be understood as a transition between the situation where the vortex core exceeds the typical size of the pinning centers (vortex delocalized) to the situation where the vortex core is smaller than the pinning size (localized vortex core and pinned metastable DMV state).

4 CONCLUSIONS

Measurements and simulations of magnetic properties of Py dots with thickness between 50 and 15 nm and diameter of 1000nm reveal qualitative changes in the ground state related to formation of the double vortex configuration. The transition from single vortex to metastable double vortex ground state is explained by enhancement of the vortex core pinning with reduced Py dots thickness.

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