Dipolar interaction in dense chains of submicrometric rectangular dots

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Abstract. Dense chains of rectangular dots (715x450 nm) put side by side, with interdot spacing variable in the range between about 55 and 625 nm, have been patterned by deep UV lithography, starting from a 40 nm thick permalloy film. A magneto-optical Kerr effect study, assisted by magnetic force microscopy, revealed that the magnetization inversion proceeds through the nucleation and the annihilation of two vortices, with the nucleation and annihilation fields appreciably affected by the coupling. The latter also modifies the frequency of the fundamental resonant mode of precession of the magnetization, measured by Brillouin light scattering from spin-wave. Micromagnetic simulations enabled us to account for the main features observed in the experiment.

1. Introduction

In the last years a growing interest towards arrays of submicrometric magnetic dots has been stimulated by their possible application in the field of high density magnetic recording media. As one tries to minimize the spatial separation between single elements, magnetostatic coupling becomes essential in controlling both the magnetization reversal processes and the high-frequency resonating modes of the magnetic elements [1]. Taking advantage from the dipolar coupling, Cowburn et al. [2] proposed a way to use chains of interacting nanodots to realize spin logic gates for storing and processing information. Both this fascinating applications require a deep understanding of the magnetic coupling between the elements in dense packed chains or clusters, from both the static and the dynamic point of view.

In this work we present an experimental study of the dipolar coupling in dense chains of submicrometric magnetic dots as a function of the spacing between them.

2. Experimental and micromagnetic simulations

The samples were fabricated using deep ultraviolet lithography at 248 nm exposing wavelength, starting from a Permalloy (Ni80Fe20) film, 40 nm thick, deposited on Si(100). They consisted of long chains of rectangular dots, with lateral lateral dimension 715x450 nm. In order to investigate the effect
of interdot coupling, eight different arrays of chains were produced (each array occupies an area of 0.5x0.5 mm²) having interdot spacing (s) variable between about 55 and 625 nm.

Figure 1 Experimental (points) and calculated (curves) hysteresis cycles relative to the sample with s=625 nm, for an external field applied either along the easy axis (left panel) and the hard axis (right panel) of the rectangular dots. The insets show the configuration of the magnetization within the dots. Black and white contrast correspond to the magnetization component parallel or antiparallel to the direction of H indicated by the arrow, respectively. The simulations have been performed using the Micromagus software, with periodic boundary conditions.

The experimental techniques we used to characterize our specimens are the magneto optic Kerr effect (MOKE) and the magnetic force microscopy (MFM). The former allowed us to measure the magnetization curves of the dots with an external magnetic field applied along both the easy and the hard magnetization axis of the dots. The latter gave us the possibility to visualize the magnetization configuration state of these chains of dots at remanence. Brillouin light scattering (BLS) from spin waves was then exploited (at normal incidence) to quantify the effect of dynamical dipolar coupling. Details about the experimental apparatuses are found elsewhere [3,4].

To reproduce in a satisfactory way the results of our measurements two different micromagnetic simulations packages were used, namely the commercial software MicroMagus, which permits to apply periodic boundary conditions [5], as well as the open source object oriented micromagnetic framework (OOMMF), developed by the National Institute of Standards and Technology (NIST) [6]. In both cases the discretised cell size is 5×5×20nm³.

3. Results and discussion

Fig. 1 presents the experimental and simulated magnetization curves measured on the sample with the larger interdot spacing (about 625 nm), so that the dots can be considered to a good approximation as isolated (non-interacting) entities. It can be seen that the simulated curves can satisfactorily reproduce the main features of the cycles. In particular, looking at the snapshots of the magnetization configuration reproduced in the insets, it appears that the inversion of the magnetization occurs, both for the easy and for the hard direction, through the formation of two vortices which nucleate close to one side of the dot at a field $H_N$ and then propagate in the direction perpendicular to the applied field until they annihilate at a field $H_A$. Given the different sizes of the two sides of the rectangular elements, it turns out that the evolution of the vortices markedly depends on the specific direction of the applied field. When the field is applied along the easy direction (Fig. 1, left panel) the two

Figure 2 Magnetic force microscopy image of a few dots of the sample with s=220 nm, taken at remanence after saturation along the easy axis with a field $H=1.5$ kOe.
vortices move along two well separated paths, parallel to the short side of the dot and annihilation corresponds to their expulsion from the side of the dot for a field $H_A$ around 400 Oe.

On the contrary, when the field is applied along the hard direction (Fig 1, right panel) they first tend to collide in the centre of the dot, then they repel each other and annihilate without completing the path to the side opposite to their nucleation. MFM images,[3] taken at remanence after saturating the samples along the easy axis with a field of 1.5 kOe (see Fig. 2), confirm this interpretation and show that the magnetization of the elements relaxes in a complicated domain pattern, with alternating dark and bright contrast, inside each element. Following the literature, most of the states seen in the MFM image can be interpreted as due to a double-vortex structure for the magnetization [7], even if there is the presence of a few dots which exhibit only one vortex. The observation of a prevalent double-vortex structure instead of a single-vortex, is related to the shape and the relatively large dimension of our dots. Micromagnetics simulations predict, indeed, that the number of vortices increases with the ratio between the length and the width of the dot [7,8,9].

Let us now briefly discuss the influence of dipolar coupling among the dots. Fig. 3 presents the comparison between the measured and calculated loops, for field applied along the easy direction, as a function of the interdot spacing. It can be seen that when the dots are very close to one another the transition to the vortex state is not very sharp, indicating the presence of a dispersion of the nucleation fields and of possible collective intermediate states. However, if one looks at the dependence of the value of $H_N$ on the separation $s$, it turns out that the vortices nucleation is delayed (by about a few tens of Oe) as soon as the value of $s$ is decreased from 625 nm to 55 nm. This could be surprising at first sight, since a chain of ideal single dipoles arranged side by side should prefer the antiparallel orientation, so that an anticipation of the vortex nucleation is expected at short distances. However, one should consider that in the present case there is a distortion of the magnetization at the ends of each magnetic particle (end domains), which allow the particles to reduce their magnetic energy by achieving a partial flux closure [9]. In fact, micromagnetic simulations show that the presence of end domains in closely spaced elements tends to stabilise the almost saturated state and delays the vortex formation. When the field is applied along the hard direction, as in the right panel of Fig. 1, instead, the effect of magnetostatic coupling affects mostly the annihilation field which decreases from about 700 Oe to about 450 Oe with decreasing $s$, reflecting the fact that the hard direction of the single dot becomes an easy direction for the chain of dots as a whole. As final step in the investigation of dipolar coupling, we have measured by Brillouin light scattering the resonant frequency of the spin-wave eigenmodes of the magnetization with an external field of 1 kOe applied along the easy direction of the dots. Since the angle of incidence is zero, we are studying the in-phase precession of all the dots of the array. We found that the fundamental mode, corresponding to the most intense peak in the spectra, as shown in Fig. 4, exhibit a frequency increases by 1 GHz with the separation. The physical origin of

Figure 3. Experimental (points) and calculated (curves) hysteresis cycles along the easy axis for samples with different interdot spacing $s$. The first panel show a scanning electron microscopy of the sample with $s$=55 nm.
such an effect relies on two different mechanisms. First of all, when the dots are very close to each other, the effective field felt by the precessing magnetization at the dot centre is lowered by the stray field of neighboring dots. According to our calculations, however, this effect is quite small (the decrease of the effective field at the dot centre, is about 100 Oe for s=55 nm, corresponding to a down-shift of the frequency of about 0.4 GHz) and cannot account for the whole observed frequency decrease with s. The second mechanism relies upon dynamical coupling. Due to ellipticity of precession of the magnetization vector (associated to the aspect ratio of the dots), the in-plane dynamical component of the magnetization is much larger than the out-of-plane one. Therefore it mainly contributes to the dynamic dipole stray field each dot induces in the array plane. Analogously to what observed in the case of interacting wires, the in-phase precession favours directing the force lines of the dynamic dipole field of any individual dot to the next one, so that the amplitude of magnetization precession at the edges increases, implying a smaller effective pinning of the dynamic magnetization due to coupling [4]. The profile of dynamic magnetization through the whole array becomes more homogeneous, than in the case of a small or absent coupling. As a result, the eigenfrequency shifts down, approaching the frequency of homogeneous precession of an unstructured film. Quantitatively, there is an excellent agreement between the calculated and measured frequencies, as seen in Fig. 4.

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4. References

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Figure 4 Experimental (points) and calculated (dashed line) frequency of the fundamental mode (F) as a function of the interdot spacing s. The external field H=1 kOe was applied along the easy axis of the dots. A typical spectrum, relative to the sample with s=100 nm, is shown in the inset.
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