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Cross-over from coherent rotation to inhomogeneous reversal mode in interacting ferromagnetic nanowires

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Abstract

We have investigated the magnetization reversal mechanism and the effects of magnetostatic interaction in arrays of lithographically defined Permalloy nanowires with a fixed width of 185 nm, spacing of 35 nm and film thicknesses from 10 to 120 nm. The magnetization reversal has been investigated with vectorial Magneto-Optical Kerr Effect magnetometry. The vectorial hysteresis loops (in-plane magnetization components parallel and perpendicular to the applied field) recorded with the external field applied perpendicular to the length of the wires (hard magnetization direction), show a transition from coherent rotation to inhomogeneous reversal mode for wires' thickness above 80 nm. The effects of dipolar interactions are evidenced by the variation of the saturation field in the hard-axis hysteresis loops as a function of wires thickness. In detail, the analysis of the saturation field vs. wires thickness shows that the dipolar interactions start to play a role for wires thickness $\geqslant 20$ nm.

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1. Introduction and experimental details

The reduction of the spatial separation of elements in data storage devices is essential in order to increase the bit areal density. For this reason, the magnetostatic interaction between magnetic elements has become a crucial key as it can affect the magnetization reversal processes and the domain structures. This led to a large number of recently published papers reporting on the effect of dipolar interactions in closely packed arrays of nanometric magnets [1–6]. However, due to the technical difficulty to produce arrays of magnetic elements with a very narrow distribution of shapes, sizes and distances, often the statistical variations of these parameters can hide, at least partially, the effects of magnetostatic interactions over arrays of hundreds or thousands of elements. For instance, with electron-beam lithography, which is one of the most used nanofabrication technique, it is very difficult to produce closely packed nanoelements arrays due to proximity effects. Moreover, the writing process in electron beam lithography is serial and very slow, making the patterning of large areas very difficult. In this paper, we studied the magnetic properties and the magnetostatic interaction among closely packed nanowire in arrays fabricated using deep ultra violet (DUV) lithography and lift-off process. The advantage of this fabrication technique is that it is a parallel process and highly ordered nanowire arrays can be fabricated over a larger area as compared to currently available techniques. Various sets of permalloy ($Ni_{80}Fe_{20}$) nanowires arrays with the same wire width of 185 nm, spacing of 35 nm and film thickness (t) ranging from 10 to 120 nm were fabricated on a commercially available silicon substrate over an area of $4 \times 4\,mm^2$ using DUV lithography at 248 nm exposing wavelength. Further details of the fabrication process can be found in Ref. [7].

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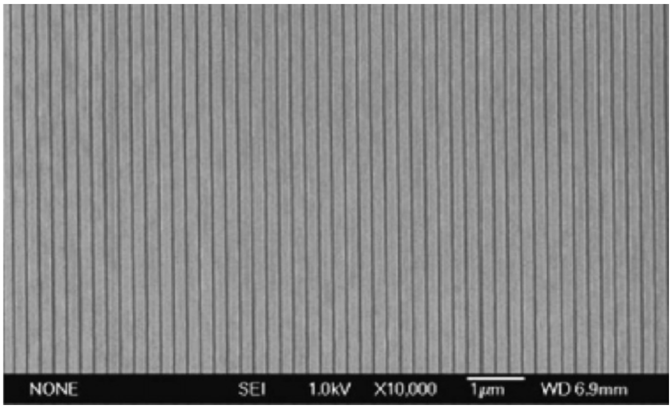

Fig. 1. Scanning electron microscopy image showing the lateral dimensions of the nanowire arrays (image taken from the 20-nm-thick wires sample).

The nanowires arrays have extremely uniform width and inter-wire spacing as demonstrated by the scanning electron microscopy micrograph of Fig. 1.

The hysteresis loops were measured using a Vectorial Magneto-Optical Kerr Effect magnetometry/microscopy (V-MOKE/μMOKE) setup, described in details in Ref. [4]. V-MOKE measurements are sensitive to both in-plane components of magnetization, parallel to the external applied field *H* (longitudinal loop) and orthogonal to it (transverse loop). Such a feature allows the reconstruction of the magnetization vector at any step of the magnetization reversal. Local hysteresis loops were recorded focusing the laser beam over a circular spot with a diameter of about 7 μm (μMOKE). With μMOKE, we can measure the hysteresis loops of about 30 wires.

2. Results and discussion

The longitudinal V-MOKE hysteresis loops recorded with the external field *H* applied parallel to the wires' length (easy magnetization direction), without focusing the laser beam, are shown in Fig. 2. No transverse magnetization component was observed in this geometry. The loops in Fig. 2 show that the coercive field is strongly dependent on the thickness of the film. In the film thickness range $10\,\text{nm} \leqslant t \leqslant 80\,\text{nm}$, there is an increase in the coercivity as the thickness increases. However, for $t = 120\,\text{nm}$, the coercivity suddenly decreases. This non-monotonic thickness dependence of the coercive field suggests that there may be a cross-over in magnetization switching mode as the thickness of the film is increased above 80 nm. To further investigate this point, in Fig. 3 the hysteresis loops recorded by applying *H* perpendicular to the wires' length (hard magnetization direction) are reported. In detail, Fig. 3 shows the in-plane magnetization components both parallel (longitudinal loops, solid line) and perpendicular (transverse loops, open dots) to *H*. In the film thickness range $10\,\text{nm} \leqslant t \leqslant 80\,\text{nm}$, we observe that the transverse component, normalized to the magnetization saturation value, reaches the maximum value of 1 at zero external field *H* while, at the same time, the longitudinal component goes to zero (viz., the magnetization in all the wires has become parallel to the wires length and is pointing along the same direction). Moreover, the longitudinal loops display a negligible hysteresis. This behavior demonstrates that, for *t* in the range 10–80 nm, the reversal takes place with a coherent rotation of the magnetization of all the wires (at $H = 0$ the magnetization is parallel to the wires length). The sense of rotation of the magnetization is determined by the slight misalignment, practically inevitable, between *H* and the wires' edges, so that even a small component of *H* along the wires length biases the rotation of the magnetization of each wire towards the same direction. In the case of $t = 120\,\text{nm}$, we observe a marked suppression of the transverse magnetization component and a modification of the shape of the longitudinal loop (viz., a reduction of the loop slope in the *H* range from −2000 to 2000 Oe). These findings indicate that the magnetization switching of the 120-nm-thick wires is no longer a coherent rotation process but it has become an inhomogeneous

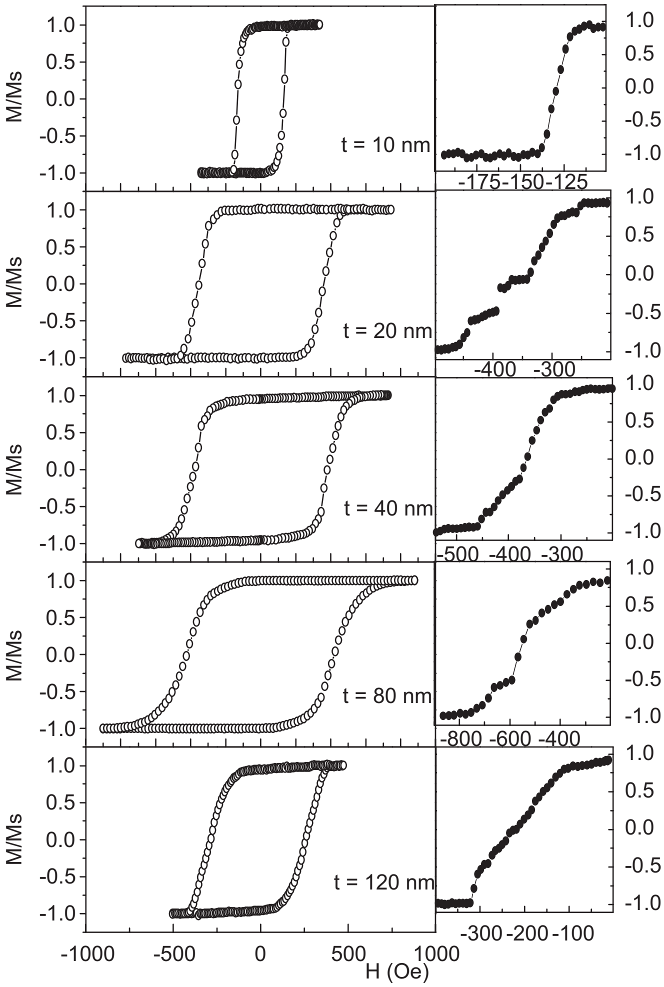

Fig. 2. Representative hysteresis loops of nanowire arrays of different thickness *t* measured with the external field *H* parallel to the wires' length. *t* curves on right side shows the portion of the hysteresis loops during the reversal from $+H$ to $-H$ recorded focusing the laser beam over a circular spot with diameter of about 7 μm.

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