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# Experimental and computational analysis of the angular dependence of the hysteresis processes in an antidots array

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We have experimentally characterized the magnetization processes of a square array of micron sized circular antidots lithographed on a Fe(001)/GaAs film with its diagonals along the Fe magnetocrystalline easy axes (100). Both the anisotropy and the angular dependence of the magnetization reversal were measured by means of magnetooptic techniques. The coercivity of the loops along the easy and in-plane hard axes of the array increases approximately 2.5 times with respect to that measured in the continuous film region, and the first order anisotropy constant remains equal to that of bulk Fe. The magnetization reversal takes place in two steps for all the loops measured out of the easy and hard axes. We have simulated the magnetization reversal using two different micromagnetic models. In the first one, assuming that the reversal takes place fully inside the array, we have observed that the reversal nucleates at the magnetic inhomogeneities occurring at the antidot boundaries and resulting from magnetostatic energy minimization. In our second model we artificially introduced a domain wall outside the antidot region that governs the magnetization reversal showing a qualitative agreement with the angular dependence of coercivity.
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Much attention has been recently paid to the periodic patterning of magnetic films due to the fact that the control of the local morphology at the micro- and nanometric scales offers the possibility of stabilizing the magnetization distribution against either thermal or field demagnetizations beyond the limits associated with the film magnetocrystalline anisotropy.[1,2] That stabilization is based on the minimization of the dipolar energy associated with the magnetic poles present at the surfaces of the array motifs. In particular, it has been proposed[2] that the magnetization stabilization associated with arrays of nanometric antidots could make it possible to avoid the use of high magnetocrystalline anisotropy phases (as the transition metal-rare earth intermetallics) in order to implement ultrahigh density recording media.

One of the main problems raised by the patterned films is that related to the understanding of their demagnetization processes and, especially, the relationship between those processes and the array geometry and dimensions. Due to the dipolar energy minimizing structures at the antidot surfaces, the films can exhibit significant spatial inhomogeneities in the magnetic moment distribution which can largely influence the global behavior of the system and make difficult the description in simple terms of the magnetization reversal.

In this work, we present and analyze experimental data on the anisotropy and magnetization processes of an array of circular antidots. The array was produced by using x-ray lithography on a 30 nm thick Fe(001)/GaAs film grown by molecular beam epitaxy. It consisted of a square lattice of antidots with diameter $D=1$ $\mu$m, and interantidot distance $\lambda=1$ $\mu$m. covering a 0.8 mm$\times$0.8 mm region out of a 2 mm$\times$2 mm film (note that the antidot dimensions are much larger than the Fe exchange and dipolar correlation lengths). The sides of the unit cell of the array are oriented parallel to the (110) Fe film directions, i.e., the unit cell diagonals are parallel to the Fe film crystallographic easy axes. The magnetic behavior of the antidots was studied at room temperature (RT) by using a magneto-optic Kerr effect device (laser beam collimated to 0.4 mm) adapted to measure the angular dependence of the hysteresis loops and also the transverse initial susceptibility (TS). This technique yields the effective anisotropy field $H_K$ of a sample and consists of generating small amplitude magnetization oscillations in a saturated sample by simultaneously applying a large (saturating) dc field $H_{DC}$—along either the easy axis (e.a.) or the hard axis (h.a.)—and a small ac field $h_{ac}$, perpendicular to $H_{DC}$.[3]

Figure 1 shows the hysteresis loops corresponding to the antidots region and to the continuous film measured in the film plane along the e.a (a) and the hardest in-plane axis (b) of the sample. The sheet film e.a. loop is square with a reduced remanence close to 1, while the antidots e.a loop evidences a lower remanence, indicating the occurrence of a higher degree of magnetization inhomogeneity in this zone.[4] A large increase in coercivity is observed in the loops measured in the antidots region with respect to those obtained

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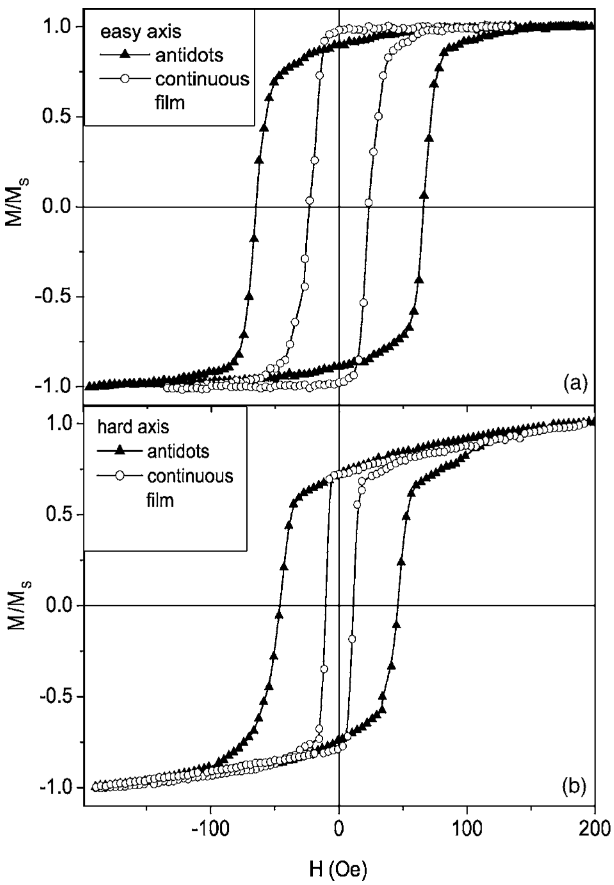


FIG. 1. Hysteresis loops measured in the continuous film and antidots regions along the easy (a) and hard (b) axes.

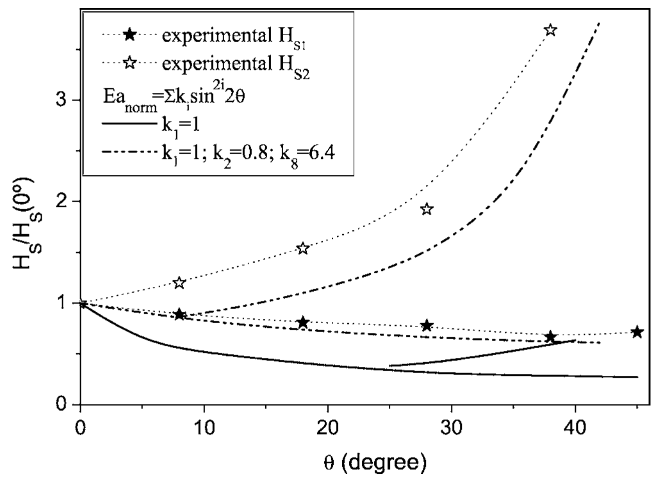


FIG. 3. Experimental and calculated (coherent rotation model) angular dependence of the switching fields of the array, normalized to $H_S(0°)$. The anisotropy energy expressions used for the calculations are normalized to the bulk anisotropy of Fe, i.e., $K_1=1$ corresponds to the first order anisotropy constant of bulk Fe (all nonspecified $K_i$ are null).

outside it. The TS measurements obtained in the array region along both the e.a. and in-plane h.a. (inset in Fig. 2) yielded an anisotropy field close to 500 Oe which, by considering the bulk Fe magnetization value, corresponds to a first order anisotropy constant value $K_1=4.3\times10^4$ J m$^{-3}$, very similar to the corresponding bulk Fe magnetocrystalline anisotropy constant. As for the angular dependence of the reversal process, the loops measured in the antidot region with the field applied along a direction at an angle $\theta$ with respect to the Fe e.a. (Fig. 2 shows the loops measured at $\theta$=0, 18, 28, and 45°) present two irreversible jumps at fields $H_{S1}$ and $H_{S2}$, with the only exceptions of those measured along the e.a. ($\theta=0°$) and the in-plane h.a. ($\theta=45°$), which present a single jump. Figure 3 shows the evolution of $H_{S1}$ and $H_{S2}$ with $\theta$: while $H_{S1}$ slowly decreases, $H_{S2}$ increases sharply with the increase of $\theta$.

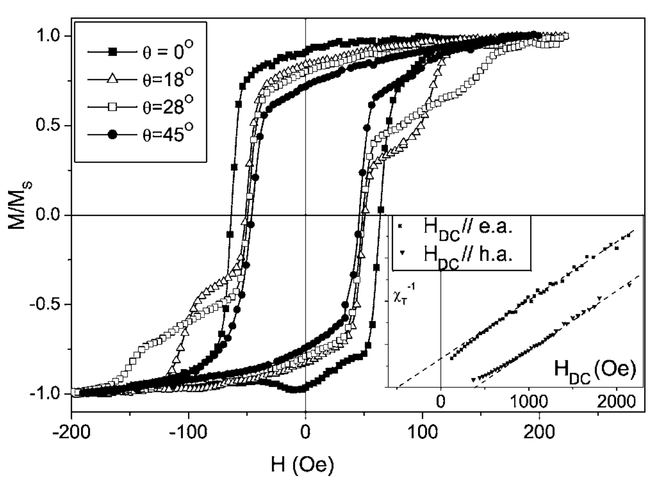


FIG. 2. Hysteresis loops measured in the antidots region with the field applied at different angles $\theta$ with respect to the e.a. The inset shows the transverse susceptibility dependence on the saturating field value $H_{DC}$.

To get a deeper insight into the mechanisms involved in the angular dependence of hysteresis we have performed micromagnetic simulations considering two different models. In both of them the computational region was discretized in a two-dimensional square mesh of 4 nm single layer units oriented with their axes at an angle of 45° with the in-plane Fe e.a. Zero boundary conditions for the magnetostatic potential were used along the $Z$ axis (assuming zero padding). The system energy was minimized by integrating a Landau–Lifshitz–Gilbert equation without the precessional term. For the dipolar contribution to the system energy the full three-dimensional (3D) magnetic potential was evaluated by means of the dynamic alternating direction implicit method.[5] In our first model we have considered an infinite array of antidots, corresponding to periodic boundary conditions along $X$ and $Y$ directions and a 2 $\mu$m $\times$ 2 $\mu$m modeled region including a circular antidot with $D=1$ $\mu$m. In this case the angular dependence of the demagnetization was governed by the occurrence of a nucleation-propagation sequence starting from the inhomogeneous magnetic moment structures present at the antidot surfaces and resulting from the magnetostatic energy minimization (see Fig. 4). The results obtained within this model show the presence of two magnetization jumps for almost all applied field angles (the exceptions are the directions close to the h.a.) and switching field values similar to those observed experimentally. However, the calculated behavior of the angular dependence of the first switching field (see Fig. 5) is qualitatively different from that experimentally observed. Our second model consists of a 4 $\mu$m $\times$ 4 $\mu$m system with a centered array of 4 $\times$ 4 antidots of diameter $D$=480 nm, separated by λ

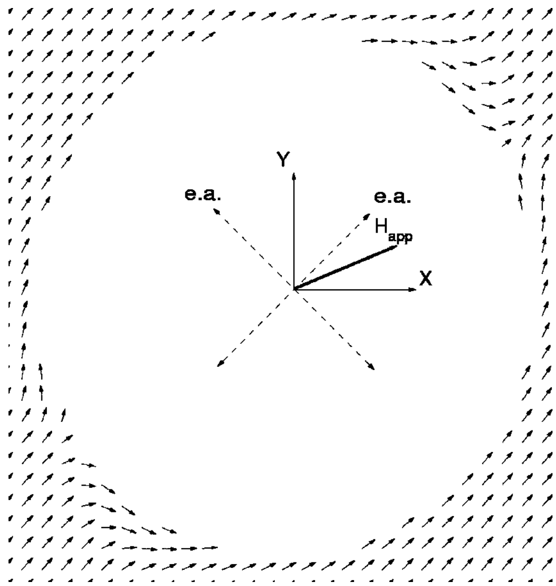


FIG. 4. The magnetization distribution at remanence calculated in the periodic array of antidots (Model I) for the external field applied at $\theta=22.5°$ and showing the occurrence of magnetic inhomogeneities at the antidot surfaces. Every arrow gives the average direction of a group of $10\times10$ moments.

=480 nm. In order to implement a more realistic approach to the experimental situation, we artificially introduced a nucleation center outside the antidots region allowing one to analyze the influence on the antidots magnetization reversal of the lower field reversal of the perimetral region. That nucleation center was implemented by assuming a triangular region, 320 nm wide, with null anisotropy located at one of the system corners. As "*a priori*" expected, in this case the hysteretic processes of the array were governed by the occurrence of a first reversed area at the reduced anisotropy region and the propagation of that reversal to the rest of the system. However, for these antidot dimensions, no pinning of the domain wall limiting the reversed and unreversed areas was observed at the antidots borders. This model also shows the angular dependence of the first switching field similar to that experimentally observed.

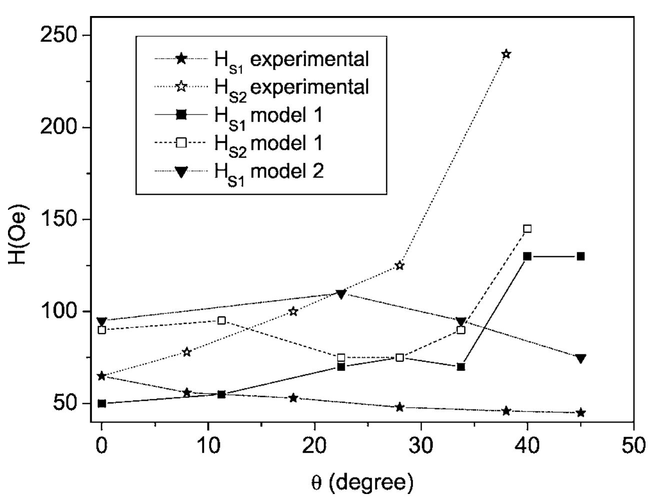


FIG. 5. Angular dependence of the switching fields in the antidots arrays simulated in two micromagnetic models in comparison to the experimentally measured values.

To discuss our results we should mention first that the observed increase of the coercivity of the lithographed region with respect to that of the continuous film can be related, as previously discussed,[1] to the fact that the antidots induce an in-plane anisotropy contribution linked to the poles present at the array motifs surface. The anisotropy is characterized by easy (hard) axes associated with the longest (shortest) interantidot distances of the array unit cell. In our case the easy axes corresponding to that contribution (i.e., the diagonals of the square) are superimposed on the magnetocrystalline easy axes thus reinforcing the film anisotropy. The TS results confirm that the patterning process preserves the original fourfold symmetry but do not show any increase of the anisotropy constant with respect to that of the bulk Fe. This can be related either to the fact that the magnetization oscillations induced during the TS measurements do not result in significant variations of the dipolar energy of the moment structures at the antidots surfaces or to the need of higher order constants to adequately describe the anisotropy energy density. The latter possibility can be checked by comparing the experimental results with those obtained for the evaluation, from a coherent rotation model, of the angular dependence of the fields at which magnetization jumps are observed. As it can be seen in Fig. 3, when the first order anisotropy constant is exclusively considered the coherent rotation model predicts (in opposition to the experimental data) the occurrence of a single jump for $\theta<22.5°$. The consideration of higher anisotropy terms yields the occurrence of two magnetization jumps from lower values of $\theta$ but do not fully reproduce the experimental behavior. From our micromagnetic models we can conclude that the reversal processes (and their angular dependence) are linked to the magnetic moment distribution inhomogeneities present in the system. Our micromagnetic simulations indicate that the hysteresis process is determined by the nucleation-propagation sequence. The results of the simulations suggest that the angular dependence of coercivity is sensitive to the type of nucleation present in the system. We have examined this process for two types of nucleations: (i) at the inhomogeneities created by the magnetostatic charges at antidot borders and (ii) at an artificially introduced null-anisotropy region outside the antidot array. We would like to point out here that in a realistic experimental situation the existing possibilities for a nucleation-propagation-pinning sequence are multiple and may be influenced by the presence of defects of different types whose nature is determined by the deposition or lithography techniques.

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