Epitaxial Fe (001) micro tiling: Size and interaction effects

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The magnetic properties of 200 Å epitaxial Fe (001)/MgO (001) tiling are studied as a function of tile size and separation. For edge sizes above $\sim 3 \mu\text{m}$, the individual tiles maintain the single domain behavior while below $\sim 3 \mu\text{m}$ the tiles break into domains due to demagnetizing effects. In addition, below an inter tile separation threshold of about $0.9 \mu\text{m}$, a single tile magnetization switch provokes a reversal cascade in all the tiles; while, above this threshold, the individual tile's magnetization switches independently. In this last case, we have experimental access to the distribution of nucleation sites. Thus, we have found a clear signature of the magnetic interaction between patterned epitaxial micro tiles with in-plane magnetization. © 2000 American Institute of Physics. [S0003-6951(00)00521-0]

Magnetic properties of patterned elements are of increasing interest nowadays.¹⁻⁴ Understanding the physical properties as the magnetic material size and shape are reduced and placed in a regular array is of great importance, both fundamentally and for eventual applications as recording media and nonvolatile memories. Several studies can be found in the literature where ferromagnetic arrays of elements with high quality shape and good crystalline properties are studied.^{2,5-7} In most of these studies, the magnetic objects are placed at a large enough distance to guarantee, according to micro-magnetic simulations, that there is no interaction between them. Thus, little attention has been paid to measure and quantify the interaction between single crystal magnetic objects, that can be of crucial interest in the design and understanding of high-density magnetic circuits. In this work we study experimentally the interaction between individual single crystalline square magnetic tiles with in-plane magnetization.

The arrays of the magnetic elements are fabricated by patterning single crystal iron films. The deposition of the continuous 200-Å-thick Fe films on MgO (001) substrates is performed in a triode-sputtering system with a base pressure in the low 10^{-9} mbar range. Both the growth detailed conditions and the experimental setup used to measure the in-plane hysteresis loops by Kerr effect can be found in Ref. 8. The crystallinity and the interfaces of the films are excellent with well defined peaks in the reflection high energy electron diffraction and high and low angle x-ray diffraction

patterns.⁸ To protect them from oxidation, the Fe films are covered *in situ* with a sputtered layer of TiN or Pt with a typical thickness of 70 Å. As expected, these iron films have a well defined cubic biaxial anisotropy, with the magnetization pointing in the [100] direction but, also a small uniaxial anisotropy,⁹ most possibly related to the substrate texture that introduces an asymmetry in the switching characteristics. In all the applied field directions the remanent state is basically a single domain state.⁸ The films saturate at moderate fields of about 250 Oe when the field is applied along hard Fe [110] directions. In the following, we will discuss the influence that patterning has on these magnetic properties.

The patterning of the continuous film was carried out by conventional e-beam lithography.^{10,11} The as-deposited film is covered by a thin poly(methylmethacrylate) (PMMA) film, which is subsequently irradiated in a scanning electron microscope and developed. This PMMA layer is used as a mask in an ion beam etching procedure using Ar ions. Typically we introduced about 25% overetching in order to ensure that the continuous film was effectively separated. The trench fabricated in this way was between 350 and 400 Å in depth. All the tilings described below have the square edges parallel to the [110] directions, i.e., directions that are magnetically hard.

Both the atomic force microscopy (AFM) and the magnetic force microscopy (MFM) characterization of the fabricated structures are carried out in a commercial Park Scientific unit. One of the obtained tile structures, after all the steps described above, can be seen in the AFM image shown in Fig. 1. As observed, the trench produced by the ion bombardment using the PMMA resin as a mask is rather well defined with a depth of the order of 400 Å. Some rests of

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FIG. 1. AFM image of one of the fabricated tiling structures whose period is T , tile edge a , and tile interspacing w .

resin are still observed on the tiles' surface. To study the magnetic properties, a white light spot of about $100\text{ }\mu\text{m}$ diameter is placed within the patterned area, which is typically a square of $250\text{ }\mu\text{m}$ edge. In this way, the magneto-optic information obtained corresponds solely to the patterned area. An additional advantage of our method is the possibility of studying the effect of pattern size and separation and the effect of the orientation of the tiling with respect to the crystalline axes in the same sample, since a typical film size is of the order of 1 cm^2 .

The magnetization process as a function of the tile size for a constant tile separation w of $0.3\text{ }\mu\text{m}$ and field applied along the hard $[110]$ axis is summarized in Fig. 2(a), where the transverse Kerr effect, i.e., the magnetization component parallel to the applied field, is shown. The hysteresis loop of the continuous film is also displayed for comparison. The data in the figure correspond to two different tiling series (1st: 10 , 5 , and $2.5\text{ }\mu\text{m}$ and 2nd: 3 , 2 , and $1.5\text{ }\mu\text{m}$) fabricated in different days but on the same thin film. Figure 2(b) shows the coercive field dependence on the tile size for five different series. The first thing to note is that patterning has a very moderate effect down to a tile size of about $3\text{ }\mu\text{m}$. Below this value there is a sudden increase in coercive field. This can be attributed to the breakage of the single domain structure of the tile in several domains. As the tile size is reduced there is an increase of the in-plane demagnetizing field, and a simple estimate of the balance between the anisotropy and magnetostatic energies, without considering interactions between neighboring tiles, indicates that both energies are comparable for tiles of the order of micrometers.¹²

This breakage of the single domain structure below $3\text{ }\mu\text{m}$ is experimentally supported by preliminary MFM imaging, that shows that the magnetization distribution within the tile in this range is not uniform. It is also in good agreement with the multidomain images at the remanence obtained for the same kind of structures with typical sizes in the submicron range.^{5,13}

Previous results obtained in ultrathin Fe epitaxial dots^{14,15} have also shown an increase in the coercive field upon reduction of the dot thickness. In our case the magnetic

(a)

(b)

FIG. 2. (a) Hysteresis loops of tilings with different periods and $0.3\text{ }\mu\text{m}$ tile interspacing; (b) dependence of the coercive field on the tile edge size the dotted line is the value of the coercive field for the unpatterned Fe single crystal.

hardening is observed on reducing the lateral size of the magnetic elements under constant thickness conditions.

Actually, this hardening of the array of magnetic tiles in the micron range is strongly dependent on the interaction between tiles. The size dependence of the reversibility field, H_s , is displayed for selected series with different tile separations in Fig. 3. Also plotted in this figure, as a continuous

FIG. 3. Dependence of the reversibility field, H_s , on the tile edge size. Full circles are for different series with $0.3\text{ }\mu\text{m}$ tile interspacing while open circles are for a series with $1\text{ }\mu\text{m}$ tile interspacing. The continuous line is the demagnetizing field of an oblate ellipsoid with the aspect ratio corresponding to the measured tilings.

FIG. 4. Hysteresis loops for two different series of tilings with the same period T and different tile interspacing w . Note the increased dispersion of the coercive field as the tiles separate. $T=9\text{ }\mu\text{m}$ and (a) $w=0.3\text{ }\mu\text{m}$, (b) $w=0.9\text{ }\mu\text{m}$, (c) $w=1.5\text{ }\mu\text{m}$; $T=7\text{ }\mu\text{m}$ and (d) $w=0.3\text{ }\mu\text{m}$, (e) $w=0.9\text{ }\mu\text{m}$, (f) $w=1.5\text{ }\mu\text{m}$.

line, is the size dependence of the in-plane demagnetizing field calculated for a single oblate spheroid with the corresponding tile dimensions.¹² It can be clearly seen that it closely follows the behavior for the series of samples with inter tile distance of $1\text{ }\mu\text{m}$. As the tile separation is reduced, the saturation field also decreases, thus revealing the onset of dipolar interactions between tiles. In this case the demagnetizing field would depend on the magnetic state of adjacent tiles. If the magnetization is parallel in two tiles there will be a decrease in the internal field because part of the magnetic flux will close in the neighbor's surface. Then, the experimental fact that the patterning into tiles of these Fe thin films with in-plane magnetization has a very moderate effect for big enough tiles with low separation is explained by the magnetic interactions between adjacent tiles.

These previous results and theoretical ideas are further illustrated by selected hysteresis loops for different tile separations, shown in Fig. 4. Note that these loops represent the magnetic response of several hundred individual tiles since the area illuminated is of the order of $100\text{ }\mu\text{m}$ diameter. For $0.3\text{ }\mu\text{m}$ separation—Fig. 4(a) and Fig. 4(d)—the tiles switch simultaneously, as observed by a sharp reversal transition, while at $0.9\text{ }\mu\text{m}$ —Fig. 4(b) and Fig. 4(e)—or even much more at $1.5\text{ }\mu\text{m}$ —Fig. 4(c) and Fig. 4(f)—separations, this transition is wider for the same T value. This points to a cascade reversal for tile separation distances of $0.3\text{ }\mu\text{m}$, and, to a reversal of the tiles individually at separation distances above $\sim 0.9\text{ }\mu\text{m}$. In this geometry, with strongly reduced interactions, there must be an individual nucleation site for each tile in order to reverse its magnetization. Then, the slope of the loop at the coercive field represents the distribution of nucleation fields for our sample. It is worthwhile to point out that this behavior is actually produced by the change in the separation between tiles and not to the reduction in tile size, as smaller tiles with $0.3\text{ }\mu\text{m}$ separation also present the sharp jump at the coercive field, characteristic of strongly interacting magnetic objects [see Fig. 4(d)].

When the field is applied along the easy $[100]$ directions the observed behavior is basically the same. Below $a=3\text{ }\mu\text{m}$ demagnetizing effects break individual tiles in domains and above $w=0.9\text{ }\mu\text{m}$ the tiling magnetization processes are well described by individual noninteracting tiles.

In summary, we have fabricated Fe single crystalline thin film tiling structures by e-beam lithography and subsequent ion beam etching. The obtained structure has been studied by x-ray diffraction, scanning electron microscopy, and AFM while the magnetic properties are investigated by Kerr loops, and MFM. Both as a function of tile size and tile separation two markedly different regimes are found. They produce basically the same consequence: magnetic hardening. On one hand, as the tile size is reduced, the tiles retain the magnetic behavior of the continuous film, i.e., single domain, down to a size where the demagnetizing field breaks the tile magnetization in domains. This crossover is found at about $3\text{ }\mu\text{m}$ edge size. Above this value magnetization reversal takes place by nucleation and propagation of a single domain wall, while below this value domain walls are already present at remanence. On the other hand, for tile sizes above $3\text{ }\mu\text{m}$, as the separation between tiles increases they switch simultaneously up to a separation where they behave as independent magnetic objects and a dispersion of switching fields is measured. This crossover distance is found to be about $0.9\text{ }\mu\text{m}$.

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