Configurational anisotropy in hexagonal arrays of submicron Co elements

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The angular dependence of the in-plane magnetization reversal in hexagonally ordered Co arrays has been investigated. A sixfold anisotropy has been observed which mirrors the structural symmetry of the array. The arrays consist of polycrystalline, circular elements with constant center-to-center separation and diameters of 360 nm and below. It has been observed that the anisotropy is strongly dependent on element diameter and disappears for densely packed elements. This anisotropic coupling cannot be explained by a simple model of interacting point dipoles situated at regular lattice sites, as this predicts an isotropic interaction field for a hexagonal array. Instead, it is believed that the anisotropy arises from interactions between unsaturated regions of the elements, particularly at adjacent edges. © *2006 American Institute of Physics*.
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INTRODUCTION

A thorough understanding of the individual and collective behavior of magnetic elements in patterned arrays is needed in order to realize their potential in magnetic recording and to improve our understanding of nanomagnetism. To compete with conventional recording media, it is necessary to develop high-density arrays of noninteracting magnetic elements. A huge research effort has been put into understanding the effect of element size, shape, thickness, and microstructure on magnetic properties.[1,2] Often the elements in an array are assumed to act as independent entities with negligible interactions with their neighbors. However, stray fields arising from closely packed dots can have a significant effect on magnetic anisotropy, and hence, magnetization reversal. This is particularly true for circular, polycrystalline elements where the absence of in-plane shape and crystalline anisotropies results in a system that is dominated by interaction effects. Fourfold anisotropy has previously been observed by several groups in square arrays of circular magnetic dots.[3,4] A simple model of interacting point dipoles cannot explain this anisotropy because in a high-symmetry array, such as a square or hexagonal superstructure, point dipoles produce an isotropic magnetic field.[2] Instead it is believed that this is a configurational anisotropy[5] that arises from interactions between unsaturated regions of the elements, and which depends on the specific micromagnetic configurations of adjacent dots.[6] In this work we report the observation of sixfold in-plane anisotropy in arrays of hexagonally ordered Co elements and study its dependence on element diameter. The anisotropy is exhibited as a periodic change in coercivity and remanence repeated every 60°, echoing the structural symmetry of the arrays. Individual dots within the array are circular and polycrystalline, and hence, have no preferred easy direction in the plane. Therefore any anisotropy observed must arise from magnetostatic coupling between elements.

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EXPERIMENT

Large-area arrays of Co elements have been fabricated by etched nanosphere lithography and electrodeposition. The technique, which is described in detail elsewhere,[7] involves using a close-packed monolayer of polystyrene spheres to create antidots in a dielectric layer. The antidots are then filled with Co by electrodeposition in a Co sulfate bath. Through reactive ion etching, it is possible to control the final diameter of the electrodeposited elements. In this study we have fabricated elements with a constant center-to-center separation of 390 nm and diameters $d=210-360$ nm. The elements are of thickness 170(±20) nm. By optimizing the sphere deposition process we have produced arrays with a high degree of directional order preserved over areas of 1 cm^2.

Magnetic properties have been investigated by longitudinal magneto-optical Kerr effect (MOKE). A HeNe laser was used as an *s*-polarized light source, and a magnetic field was applied in the plane of the sample. The sample was placed in the focal plane of a 22 cm converging lens, which was used to produce a spot size of approximately 400 μm. Since the samples exhibit ordered domains over areas of 1 cm^2, this spot size ensured that the area probed was well within the ordered region. Magnetization loops were obtained for fields applied at 4° intervals in the sample plane.

Figure 1 shows magnetization loops taken 30° apart (i.e., with the field applied along and between the symmetry axes of the array) for elements with $d=360$, 270, and 210 nm. For the largest elements, and hence, the most densely packed, there is no visible dependence of the magnetization on the applied field angle. The loops exhibit a smooth reversal with a slight narrowing at fields close to zero indicating a partial flux closure state. For smaller elements, however, there is a clear change in coercivity and remanence, and a transition from hard to easy behavior as the field is rotated 30° away from a symmetry axis of the array. The loops also exhibit a steplike structure consistent with a sudden loss in the net magnetization due to the formation of magnetic vortices. Magnetization loops have been measured over the entire

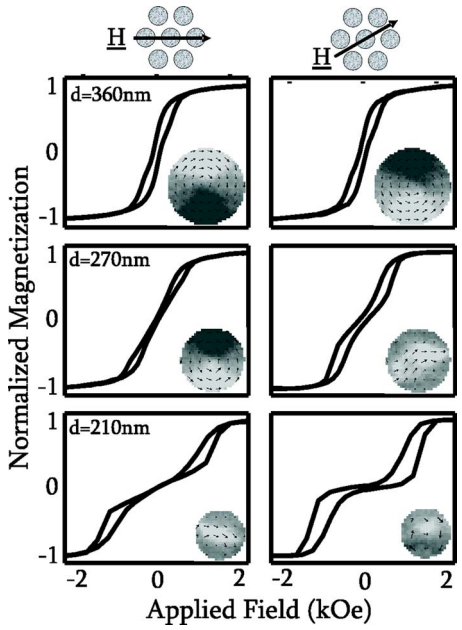

FIG. 1. Magnetization loops obtained from hexagonal arrays of Co elements using longitudinal MOKE. The field was applied along a symmetry axis of the array (left) or at 30° from the symmetry axis (right). The insets show the simulated micromagnetic configurations for an applied field close to zero after saturation along, or at 30° to, a symmetry axis.

360° range and the change from hard to easy behavior is seen to occur continuously with angle rather than by a sudden transition. Figure 2 shows the relationship between coercivity and applied field angle for an array of $d=270$ nm elements. The plot shows a striking sixfold anisotropy with an average change in coercivity of 80% between the easy and hard directions. There is also some evidence of a small uniaxial anisotropy along the 0°/180° axis. This may arise from a dislocation in the array which will reduce the interaction field along a particular direction.

DISCUSSION

We have investigated the configurational anisotropy effect for four different element diameters. The change in coercivity and remanence with the applied field angle has been used to compare the strength of the anisotropy. The largest effect was found in the 210 nm array, where a change in

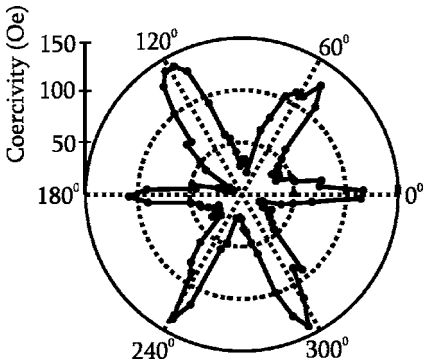

FIG. 2. Angular dependence of coercivity for a hexagonal array of $d=270$ nm elements. A sixfold anisotropy is visible which mirrors the structural symmetry of the array.

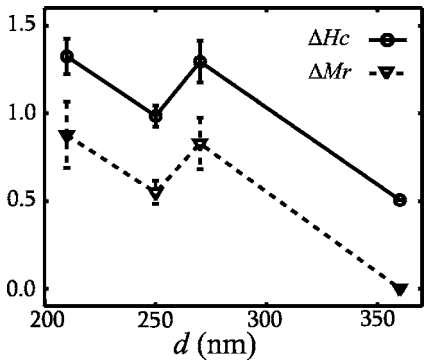

FIG. 3. Normalized change in coercivity (ΔH_c), and remanence (ΔM_r), with increasing element diameter. ΔH_c has been displaced by 0.5 units in the y direction for clarity. Note that the anisotropy is zero for the largest elements despite the reduced edge-to-edge separation.

coercivity of 270(±10) Oe and a change in normalized remanence of 0.8(±0.1) was observed between the hard and easy directions. An important point to note is that a change in element diameter results in a different aspect ratio, and hence, a change in the intrinsic value of remanence and coercivity. Hence it is necessary to compare the normalized change in these parameters when the magnetic field is applied in different directions. To calculate this change we have used the expression, $\Delta H_c=(H_{c\max}-H_{c\min})/H_{c\max}$, where ΔH_c is the normalized change in coercivity and $H_{c\max}$ and $H_{c\min}$ are the maximum and minimum coercive fields obtained along the easy and hard directions, respectively. A similar expression is used for the change in remanence, with the coercive fields replaced with the normalized remanent magnetization values. Figure 3 shows the dependence of these parameters on element diameter. The data shows a general reduction in anisotropy with an increase in element diameter. Since the center-to-center separation in all the arrays is constant, an increase in element diameter corresponds to a decrease in edge-to-edge separation. Assuming the anisotropic interaction field to be a dipolar effect originating from the unsaturated regions of individual elements, the field strength is proportional to $1/r^3$, where r is the separation between interacting regions. Clearly larger-diameter elements feel a stronger interaction field due to their closer proximity. However, it is not only the strength of the interaction field that is important, but rather its anisotropy. For larger diameters, particularly arranged in a hexagonal close-packed structure, there is a significant edge overlap of the elements when the array is viewed along an arbitrary direction. This is important since the anisotropy does not arise from point dipoles interacting at their respective lattice sites but instead from unsaturated regions of the elements, particularly at adjacent edges. It is likely that for small separations, all directions become approximately equivalent and the interaction field becomes isotropic. This would explain the observed loss of anisotropy in the 360 nm arrays, where the edge-to-edge separation is a mere 30 nm. With this reasoning, it is expected that the anisotropy should reach a maximum and then start to decrease with decreasing element diameter as the interaction field becomes too weak to be significant.

Although there is a general trend of decreasing aniso-

tropy with increasing element diameter, the exact behavior for diameters between 210 and 270 nm is not clear. At a diameter of 270 nm, there is a maximum in the coercivity and remanence values. Since this is only a single data point it is not possible to speculate its meaning with any confidence. Due to the nature of electrodeposition though, there is an uncertainty in the thickness of the elements of ±20 nm. This arises because different diameter holes result in a change in the local electric-field density at the exposed conducting regions. The deposition rate is thus affected in a way that is difficult to correct for. This uncertainty in thickness may be responsible for an anomalous data point. Further investigation is needed to clarify this point.

In an effort to further understand the anisotropy, three-dimensional micromagnetic simulations were performed using the public domain OOMMF (Ref. 8) code. A hexagonal array consisting of a single element surrounded by its six nearest neighbors was constructed and the simulated data were extracted from only the central element. Ideally, a cell size of less than the exchange length of Co (~7 nm) should be used in order to properly account for the exchange interaction. However, because of the need to simulate arrays rather than a single element, and since the elements have appreciable thicknesses, a cell size of 10 nm was chosen to allow simulations to be performed in a reasonable time scale. It was not possible to quantitatively reproduce the values of coercivity and remanence obtained from experiment using these simulations. Nevertheless, the simulated micromagnetic configurations at fields close to zero do resemble the experimentally observed behavior.

The insets of Fig. 1 show the micromagnetic configurations just above the zero field, after saturation along the easy and hard directions. For the $d=360$ nm elements a vortex structure is seen for both field directions, although the chiralities are opposite. The change in chirality has not been investigated further in this work. Experimentally, a finite remanence was measured in this sample precluding the presence of a perfect vortex. In agreement with the simulation, however, the remanence exhibited no angular dependence. For the $d=270$ nm elements there is a significant difference between the two simulated configurations. With the field applied along the principal axis of the array, the element collapses into a symmetric vortex state, while with the field applied at 30° from the principal axis the element remains in a twisted state with a remanent magnetization along the field direction. This is consistent with the experimental results where an increase in coercivity and remanence was observed when the field was applied at 30° from the principal array axes. Interpretation of the micromagnetic configuration of the $d=210$ nm elements is not as straightforward. For a field applied along the symmetry axis there is no vortex structure and considerable tilting of the magnetization out of plane, indicating that the reduced aspect ratio is becoming important. In contrast, an in-plane vortex structure is formed when the field is applied at 30° from the symmetry axis. The shapes of the experimental magnetization loops for this sample suggest that a vortex or flux closure state exists in both cases. This structure is stable over a large-field range when the field is applied at 30° from a principal array axis.

CONCLUSION

In summary, we have observed the sixfold anisotropic coupling in hexagonally ordered Co arrays. A transition between hard- and easy-axis behaviors has been observed for fields applied along and subtending a symmetry axis of the array. The angular dependence of remanence and coercivity has been used to compare the strength of the anisotropy in arrays with different element diameters. The anisotropy appears to decrease with increasing element diameter, likely as a result of the element overlap that is present in a hexagonally close-packed system. Although it has not been observed in this study, it is expected that the anisotropy will reach a maximum at lower diameters and then start to decrease with decreasing element diameter as the interaction fields become progressively weaker. Further work on arrays of elements with smaller diameters is needed to confirm the presence of this turning point.

ACKNOWLEDGMENT

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