Configurational Anisotropy in Nanomagnets

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A novel magneto-optical method has been used to probe the internal magnetic energy surface in $150 \times 150 \times 15$ nm^3 square $Ni_{80}Fe_{14}Mo_5$ ("supermalloy") nanomagnets which were fabricated by electron beam lithography. A strong fourfold symmetric anisotropy field of strength 365 ± 20 Oe is found, which confirms a recent prediction of the appearance of a configurational anisotropy due to the small deviations of the magnetization from the uniform state. [S0031-9007(98)07881-8]

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Magnetism at small length scales has in recent years provided a wealth of scientific interest and potential technological applications [1]. Many of these phenomena come about by imposing a geometric restriction on the magnet which is comparable in size to some internal length scale of the magnet. A particularly interesting example of confinement in magnets occurs in the zero-dimensional limit, in which all three dimensions are on the nanometer scale. Brown's fundamental theorem [2] states that, in this case, domain formation should be entirely suppressed, and the nanomagnet must behave as a single giant spin comprising many thousands of individual atomic spins all tightly locked together by the exchange interaction. So-called single domain particles are promising candidates for high density hard disk drive data storage [3] and integrated magnetic-electronic devices [4].

The magnetic properties of bulk and thin film magnets depend critically on anisotropy [5] (dependence of energy on the magnetization direction). An understanding of anisotropy in nanomagnets is therefore essential, especially for technological applications. Assuming that the material used to fabricate the nanomagnet is intrinsically isotropic and that the nanomagnet is free from stress, magnetostatic arguments alone would suggest that the easy plane of square nanomagnets should be energetically isotropic, with the result that the in-plane magnetization direction can be changed by the smallest applied field. In a recent paper [6], however, we predicted that the small perturbations from uniform magnetization which must exist in any nonellipsoidal magnet should give rise to a strong anisotropy appearing in square nanomagnets. This was named a *configurational anisotropy,* for it has its origin in the variations of the magnetization pattern, or configuration, which arise as the mean magnetization direction is rotated within the plane [7]. We calculated that a large anisotropy field of several hundred Oe could arise which would then dominate the magnetic switching behavior.

In this Letter, we present the results of a study using magneto-optics into a $20\ \mu\text{m} \times 20\ \mu\text{m}$ array of square nanomagnets made of the soft magnetic alloy supermalloy, each of size $150 \times 150 \times 15$ nm^3, with a gap of 150 nm between nearest edges. This gap was large enough such that any magnetostatic interactions between nanomagnets were small compared to the magnetic field scale of interest. We report the first experimental verification of the presence of a strong configurational anisotropy in the square nanomagnets. The configurational anisotropy field which we have measured has a strength of 365 ± 20 Oe and has fourfold rotation symmetry.

The samples were made by high resolution electron beam lithography. A double layer of polymethylmethacrylate (PMMA), one of low molecular weight and one of high weight, were spun onto a single crystal silicon substrate. The array of squares was then exposed onto the sample in a JEOL 4000EX SEM/TEM, followed by 30 sec of development in a 1:3 solution of isobutyl methyl ketone (MIBK)/isopropyl alcohol (IPA). A 15 nm layer of $Ni_{80}Fe_{14}Mo_5$ ("supermalloy") was then deposited at a rate of 0.03 nm/sec by electron beam evaporation in an ultrahigh vacuum chamber with base pressure 4×10^{-9} mbar. The pressure during evaporation was 2×10^{-6} mbar. Ultrasonic assisted lift-off in acetone was then used to remove the magnetic film from the unexposed parts of the sample. The unpatterned film had a coercivity of ~ 2 Oe and a uniaxial anisotropy field of 6 Oe, which is induced by stray magnetic fields during growth. No evidence was found for substantial surface oxidation. The saturation magnetization was measured as 800 emu/cc. Figure 1 shows a scanning electron microscopy (SEM) micrograph of part of the finished sample.

In order to study the magnetic properties of the samples, we have designed and constructed a novel hybrid optical microscope/magneto-optical magnetometer. The sample surface can be viewed under an optical microscope while a laser spot (size $\sim 5\ \mu$m) is moved over the surface until focused on top of the nanostructure array. The reflected laser beam is then polarization analyzed in order to access the longitudinal Kerr effect, which is sensitive to the component of magnetization lying in the optical plane of incidence [8]. An electromagnet allows magnetic fields of up to 1000 Oe to be applied in the plane of the sample,

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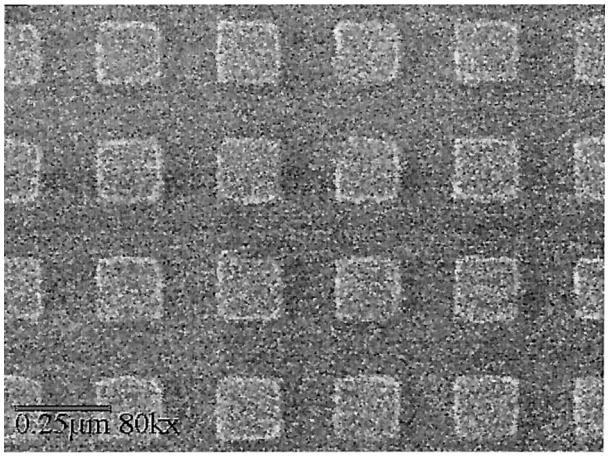

FIG. 1. A SEM micrograph of part of the finished sample.

and a small pair of air-spaced coils allows an additional small oscillating field to be applied in the plane of the sample but perpendicular to the electromagnet field. The sample can be rotated and translated.

In addition to using the magnetometer to measure conventional hysteresis loops (M-H loops), we have adopted a recently developed technique called modulated field magneto-optical anisometry (MFMA) [9] to probe the energy surface experienced by the magnetization as a function of in-plane direction. In this technique, a large and static magnetic field H is applied in the sample plane *perpendicularly* to the direction of magneto-optical sensitivity. A small transverse oscillating field H_t is then applied in the direction of magneto-optical sensitivity, in order to oscillate the magnetization about H. The measured response (referred to as the transverse susceptibility, once normalized to H_t) can be written as [9]

$$\frac{\partial \phi}{\partial H_t} \equiv \chi_t = \left(\frac{E''(\phi)}{M_s} + H \right)^{-1}, \qquad (1)$$

where ϕ is the mean magnetization direction, $E''(\phi)$ is the second derivative with respect to ϕ of the energy density surface, and M_s is the saturation magnetization. $E''(\phi)/M_s$ will be recognized as being related to the anisotropy field in the direction ϕ. Put simply, the reciprocal of the measured magneto-optical response, $1/\chi_t$, is the total internal field in the direction of the magnetization, i.e., the externally applied field H plus a term related to the effective anisotropy field coming from the internal energy surface. A powerful probe of the energy surface of the nanomagnet can thus be obtained simply by measuring $1/\chi_t$ as a function of direction and H.

There are two modes for using this probe, both of which will be used here. In the first, H is kept constant and large enough to be comparable to any internal anisotropy field. $1/\chi_t$ is then measured as a function of sample orientation. A plot of $1/\chi_t$ against in-plane orientation then describes approximately the variations of internal anisotropy field with direction.

In the second mode, use is made of the fact that there is a singularity in Eq. (1) when $H = -E''(\phi)/M_s$, leading to a maximum in the magneto-optical response χ_t. If we restrict H to being positive, then this occurs when H is directed along a magnetic hard axis [i.e., maximum in $E(\phi)$] and is equal in value to the anisotropy field. Thus, a hard axis has the characteristic signature of causing a peak in the graph of χ_t-H at some finite value of H. It can be shown that, if H is misaligned with the hard axis by more than a few degrees, then the peak in χ_t either vanishes completely or occurs at a field which is lower than the anisotropy field. The strength and direction of the hard axis can thus be located by finding the direction which maximizes the field at which the peak occurs. This second mode, although slightly more complex to understand, is a very powerful means of locating and measuring the strength of the hard axes.

Figure 2 shows the result of operating in the first mode, where $1/\chi_t$ is plotted as a function of sample orientation under a constant field $H = 660 \pm 20$ Oe (having first saturated to 1000 Oe). Conventional hysteresis loops as measured by the longitudinal Kerr effect in the direction of the applied field are also shown for two sample orientations. The most striking feature of this plot is its fourfold symmetry. There is an abrupt minimum in internal anisotropy field whenever the magnetization is parallel to one of the edges of the square nanomagnets. This is exactly as predicted by our recent theory of configurational anisotropy [6], in which the square edges should be hard axes for samples of these dimensions. An

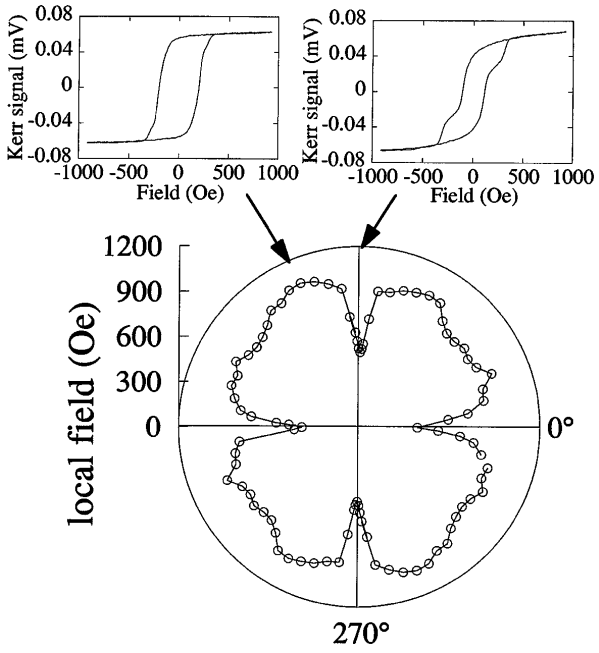

FIG. 2. A polar plot of the effective field (internal anisotropy field plus 660 Oe externally applied field) as a function of the applied field direction. $\phi = 0°$ and 90° correspond to the edges of the square nanomagnet. Data were taken in the range $\phi = 1.5°-188°$ and plotted twice to complete the circle.

estimate of the configurational anisotropy field strength can be made from the effective field at the maxima (i.e., easy axes) of Fig. 2. This is approximately 970 Oe, from which it is necessary to subtract the externally applied field strength of 660 Oe to leave an internal anisotropy field of 310 Oe. A curious feature of Fig. 2 is that the internal anisotropy field does not have its maximum when the magnetization is along the diagonals of the square. Rather, there is a small eightfold symmetric component in the energy surface which moves the maxima to either side of $\phi = 45°$. The origin of this higher order symmetry term will be discussed later.

The first experiment has established that the nanomagnets' energy surface does indeed have angular dependence and has allowed for the estimation of the strength and symmetry of its anisotropy. We now describe a second experiment in which the anisotropy strength and symmetry axes are identified more quantitatively. Figures 3 and 4 show the result of operating in the second mode, in which χ_t is measured as a function of H for different orientations of the sample. Figure 3 shows three different χ_t-H plots. Figures 3(a) and 3(c) both show peaks at finite H, indicating a nearby hard axis. Figure 3(b) has its maximum at zero field, showing this not to be a hard direction. In order to find the precise strengths of the hard axes, we have plotted in Fig. 4 the field at which the peaks occur as a function of sample orientation. One sees again a strong fourfold symmetry, with strong maxima (and, hence, strong hard axes) at $\phi = 90 \pm 2°$ and $\phi = 180 \pm 2°$, which correspond to the square edges. The fourfold anisotropy field strength is read from the heights of the maxima, and has an average value of 365 ± 20 Oe. The fourfold anisotropy term is dominant, but, in addition, there is also a small eightfold symmetric term, which is picked up as additional weak hard axes at $\phi = 45 \pm 3°$ and $\phi = 142 \pm 3°$ having an average strength of 87 Oe. The positions of these hard axes are in good agreement with the positions of the minima in Fig. 2. The shapes of the hysteresis loops which are shown in Fig. 2 are also consistent with this designation of hard axes; the loop measured at $\phi = 90°$ (right-hand side panel) shows significant rounding as the field is reduced from saturation, characteristic of hard axis loops, whereas a loop measured in between two hard axes at $\phi = 113°$ (left-hand side panel) is much squarer, characteristic of an easy axis loop.

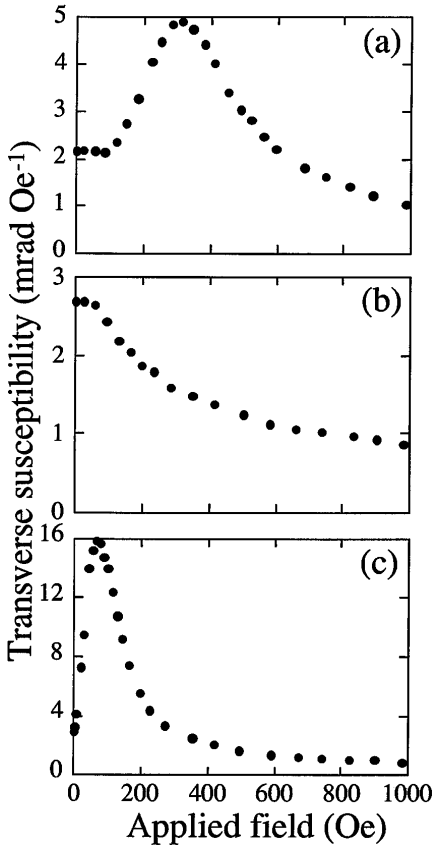

FIG. 3. Three typical χ_t-H graphs, measured with (a) $\phi = 93°$ (fourfold hard axis), (b) $\phi = 113°$ (near easy axis), and (c) $\phi = 143°$ (eightfold hard axis).

Having obtained good agreement between experiment and theory for the fourfold symmetric anisotropy term, it remains to explain the experimental observation of an unexpected eightfold symmetric component. Using the numerical micromagnetic algorithm described in our earlier work [7], we have simulated the first experiment on a square nanomagnet; a radius of curvature of 20 nm at the corners has been assumed in the simulation in order to mirror the experimental situation more closely, although this was not found to be greatly important. Figure 5 shows the result. The agreement between this simulation and the experimental results of Fig. 2 is very good, especially given that the calculation is *ab initio* and involves no free fitting parameters. In particular, the small eightfold symmetric term is clearly visible in the simulations. The analytical theory [6] which predicted the fourfold symmetry term was a first order theory; the numerical simulation is in this sense more precise and so also predicts the higher order term. In addition, the

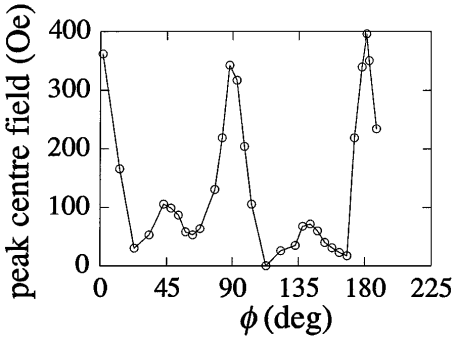

FIG. 4. The fields at which the χ_t-H peaks occurred as a function of direction. The maxima in this plot give the strengths and directions of the hard axes. $\phi = 0°$ and 90° correspond to the edges of the square nanomagnet.

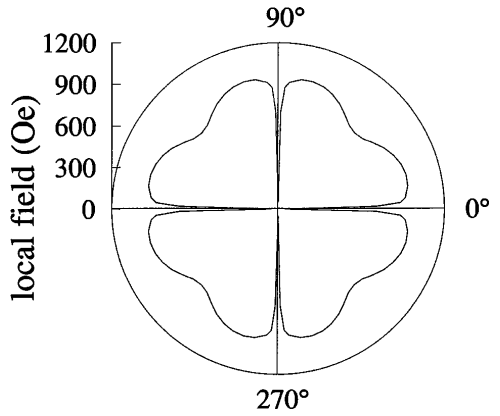

FIG. 5. A simulation of Fig. 2 using numerical micromagnetics.

estimated value of simulated configurational anisotropy implied by the heights of the maxima in Fig. 5 (951 Oe effective field which gives an internal contribution of $951 - 660 = 291$ Oe) agrees well with the experimental value of 310 Oe.

In summary, by using a novel magneto-optical method, we have mapped the internal magnetic energy surface in square nanomagnets. A strong fourfold symmetric anisotropy is found, which confirms our recent prediction of the appearance of a configurational anisotropy due to the small deviations of the magnetization from the uniform state. The anisotropy field has a strength of 365 Oe and so is comparable in strength and symmetry to the strong magnetocrystalline anisotropy field which occurs in bulk ion. We find, in addition, a weaker eightfold symmetric anisotropy which is reproduced by numerical micromagnetic simulations.

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