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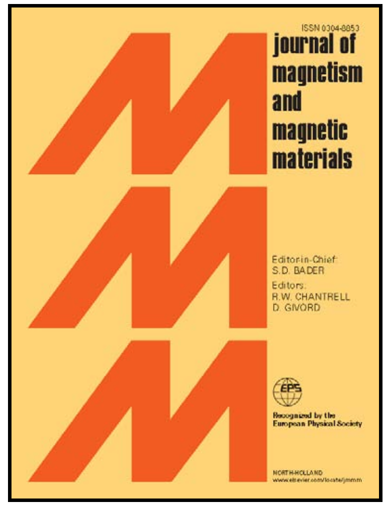

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Vortex states in soft magnets in two and three dimensions

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A B S T R A C T

The magnetization curves of arrays of near-spherical soft ferromagnetic particles are compared with those of quasi-two-dimensional dots with similar radius prepared by a rapid e-beam lithographic technique. Curves for the three-dimensional particles are anhysteretic and fit a $M(H)/M_s = \tanh(c\mu_0 H)$ law, whereas the two-dimensional arrays show irreversible segments in the first and third quadrants where the planar vortex state transforms to a collinear state by discontinuous rotation of magnetization about an axis perpendicular to the vortex axis. The additional symmetry of the spherical particle allows this rotation to occur continuously, without energy barriers due to the demagnetizing field.

1. Introduction.

The magnetization process in nanoscale magnetic elements is a topic of considerable current interest, driven by the desire to make ever-denser recording media, and smaller magnetic memory elements which can be switched quickly and efficiently.

It has long been understood that very small ferromagetic elements adopt a single-domain state [1], and that the driving force to form noncollinear or multidomain magnetic configurations is the dipole-dipole interaction, which is minimized by reducing the stray field created by the ferromagnet in surrounding space [2]. The sources of stray field can be thought of in terms of magnetic ‘charge’ created by the ferromagnet [3]. Any surface may be charged, with a magnetic charge density $\sigma_m = \mathbf{M}_s.\mathbf{e}_n$ A m^{-1}, where $\mathbf{M}_s$ is the spontaneous magnetization and $\mathbf{e}_n$ is a unit vector normal to the surface. Magnetic charge $\rho_m = -\nabla.\mathbf{M}_s$ A m^{-2} also appears in the bulk when the magnetization is nonuniform and exhibits divergence. If this were the only interaction involved, a ferromagnet would adopt a configuration where the magnetization lies everywhere parallel to the surface, and $\nabla.\mathbf{M} = 0$ in the bulk (i.e. there is no variation of magnetization along the magnetization direction). In a soft ferromagnet where magnetocrystalline anisotropy can be neglected, a conflicting requirement is to minimize the exchange interaction energy by forming a colinear structure with uniform magnetization. The characteristic scale here is the exchange length $l_{ex} = (A/\mu_0 M_s^2)^{1/2}$, which is a few nanometers in ferromagnets with a Curie point above room temperature [3]. Here A is the micromagnetic exchange constant.

It was first pointed out by Néel, that a spherical soft ferromagnetic particle will tend to adopt a vortex configuration around a major axis [4]. The result of minimizing the two energy terms in a thin flat disc is that a quasi-uniform in-plane single domain state appears at small radii (≤ 40 nm for permalloy [5]) and a vortex state with an out-of-plane singularity at the core appears for larger, submicron radii (Fig 2). The hysteresis loop for such an element is illustrated in Fig 1. There are irreversible segments in the first and third quadrants where the magnetization on one side of the vortex turns out of plane to reach saturation. These curves were first measured by Cowburn et al [5], and the vortex core was subsequently observed directly [6,7]. There have been detailed descriptions of the stable and metastable configurations appearing in ferromagnetic nanostructures, mainly based on computer simulations [8] or analytical approximations [9]. The ability to switch the vortex core from up to down along the vortex axis using pulsed fields or electric currents is a topic of great current interest [10 - 12].

The tendency of thin film elements to form vortices rather than adopt a multidomain configuration is related to the weakness of the in-plane demagnetizing field. An element with a radius to thickness ratio r/t = 5, for example, has demagnetizing factors $N_x = N_y = 0.1$ and $N_z = 0.8$ [13]. As the ratio decreases, the nanodot morphs into a cylinder or nanowire, and there is a change from in-plane to easy-axis magnetization when r/t = 0.91 [14,15]. The magnetization configuration is always influenced by sharp edges and corners, which tend to confer stability on certain non-collinear configurations [8] which produce hysteresis.

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Here we are interested in comparing the magnetization process in nanodots with that in quasi-spherical soft magnetic particles of similar size. We discuss reasons for the very different magnetization processes in these two cases.

2. Methods

Permalloy thin films of 20 nm - 40 nm thickness were deposited on silicon substrates using a Shamrock sputtering tool. Two-dimensional submicron dot arrays with different dot sizes were electron beam patterned using TOK (Tokyo Ohka Koygo Co. Ltd.) negative tone resist. The writing strategy adopted was to use pseudo-shaped beam writing, in which each dot is written by a single beam blanking event. This enabled us to produce large (1000 x 1000) magnetic dot arrays with clearly defined edges which were large enough to measure in a SQUID magnetometer. The exposed patterns were developed in 2.38 % TMAH solution and then rinsed in water. Pattern transfer was carried out by Ar^+ ion milling. The resist was removed by dipping the sample into acetone.

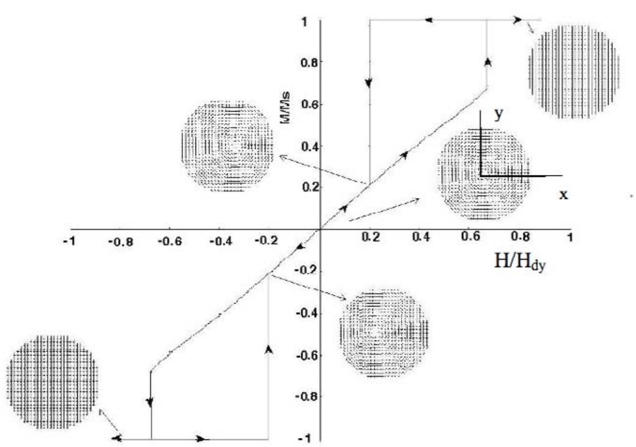

Fig. 1 Magnetization loop of a nanodot with a vortex configuration deduced by OOMMF [16] simulation. The field is applied in the *y*-direction.

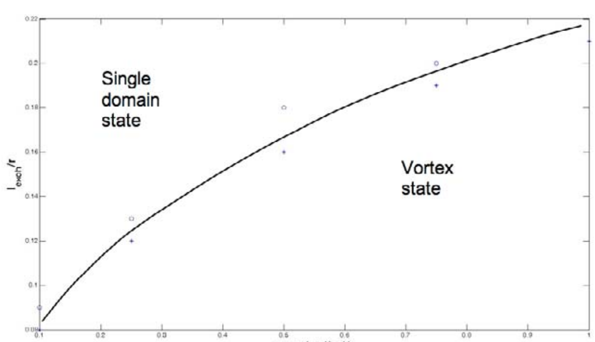

Fig. 2 Stability of single-domain and vortex states in ferromagnetic nanodots (simulation was made using OOMMF).

The submicron dot arrays were imaged by both scanning electron microscopy (Fig. 3) and atomic force microscopy (not shown). Dot arrays of 350 nm and 500 nm diameter with 3 µm spacing were produced. It is expected that there is an oxide passivation layer several nanometers thick on the surface of the dots.

Arrays of well-separated quasi-spherical iron particles on silicon were produced by a method involving etching silicon in hot KOH, described in [17]. The average particle diameter is of order 200 nm, and the average spacing is about 3 µm. These particles oxidise in ambient condition on a time scale of a week. The magnetic measurements were made on fresh samples.

3. Results and Discussion

Magnetization measurements were made using a 5 T Quantum Design superconducting quantum interference device (SQUID) magnetometer, in the temperature range 1.8 – 300 K. Magnetization curves measured with the field applied in the plane of the silicon substrate are shown in Figure 4. In the case of the dot arrays, the magnetization curves show broad hysteresis confined in the first and third quadrants. The sense of the hysteresis in the data resembles that shown in Fig. 1. The curves at 1.8 K and 300 K are practically identical.

The magnetization curves for similarly-sized three-dimensional particles are quite different. Again the curves in Fig 4b are practically identical at 1.8 and 300 K, but they exhibit no hysteresis. They are well-fitted by

$$M = M_s \tanh (c\mu_0 H) \qquad (1)$$

With c = 2.7. Similar behaviour is found in other iron particles. For instance, carbonyl iron with a 6 – 8 µm particle size follows the same law, with c = 2.1, provided the particles are well-separated by dispersing them in icing sugar to minimize dipole-dipole interactions [17]. Iron particles smaller than 200 nm dispersed in graphite behave similarly.

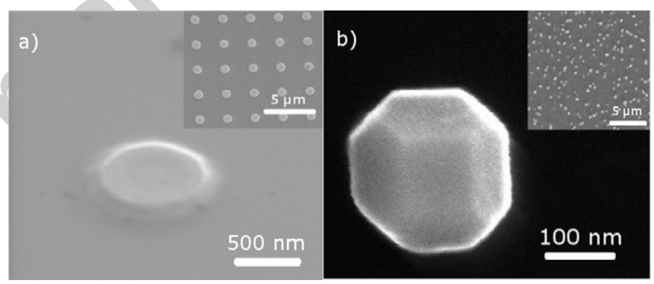

Fig. 3 a) SEM image of a 500 nm permalloy dot, and a ferromagnetic dot array with 3 µm spacing produced by e-beam lithography and b) ferromagnetic spheres on silicon prepared by an etching process [17].

The difference in behaviour illustrated in Fig. 4 has to be attributed to different magnetization processes in the two shapes of ferromagnetic particle. Some cubic magnetocrystalline anisotropy may be present in the quasi-spherical iron particles, but it is insufficient to create any hysteresis. As explained in the introduction, a spherical particle is expected to exhibit a vortex structure around a major axis, say O*z*, with the vortex core along this axis. When a field is applied along O*y*, the vortex is displaced along O*x*, as shown in Fig 1. In the two-dimensional case, the reversal of the magnetization to the right of the vortex is inhibited by the anisotropic demagnetizing field, which tries to prevent the moment from turning out of plane until the applied field reaches an appreciable fraction of M_s. No such constraint applies for a sphere. Any slice parallel to O*yz* is a circle, so the demagnetizing field will be the same whatever the orientation of the magnetization in the slice. The magnetization can therefore turn continuously in the *yz* plane in a way that is not possible in two dimensions.

4. Conclusion

There is a clear qualitative difference in the curling magnetization process between three-dimensional and two-dimensional ferromagnetic elements. The irreversibility in the latter case is associated with the last stage of magnetization reversal, which involves surmounting an energy barrier due to the large demagnetizing field as the moment turns out of plane. There is no such energy barrier in the sphere, because of the degrees of freedom afforded by the multiplicity of possible vortex axes. The anhysteretic tanh($c\mu_0H$) approach to saturation that is found empirically merits further investigation by analytical or computational methods

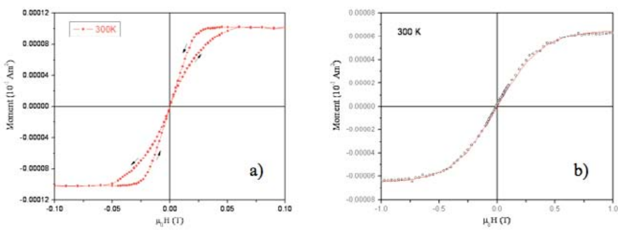

Fig. 4 Magnetization hysteresis loop measured at 300 K on an array of permalloy dots 500 nm diameter with 3 μm spacing (a) and reversible magnetization curve of quasi-spherical Fe particles of 500 nm diameter deposited on silicon. The fit (solid line) is to Eq. (1).

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References
[1] W. F. Brown, J. Appl. Phys 30 (1968) 993
[2] H. Kronmüller and M. Fähnle, *Micromagnets and the Microstructure of Ferromagnetic Solids,* Cambridge University Press, 2003
[3] J.M.D. Coey, *Magnetism and Magnetic Materials*, Cambridge University Press, (in press)
[4] L. Néel, C. R. Acad. Sci. **224** 1488 (1947)
[5] R.P. Cowburn, D K Koltsov, A O Adeyeye, M E Wellend and D M Tricker Phys. Rev Lett. 83, 1042 (1999)
[6] T. Shinjo, T, Okuno, R. Hassdorf, K.Shigeto, and T.Ono, Science 289, 930 (2000)
[7] A. Wachowiak, J. Wiebe, M. Bode, O. Pietzch, M. Morgenstren and R. Wiesendanger, Science 298 (2002) 577
[8] J.K. Ha, R. Hertel and J. Kirschner Phys. Rev. B 67 (2003) 224432
[9] K.L. Metlov and Y. Lee, Appl. Phys. Lett. 92 (2008) 112506
[10] A. Anton, Y. Otani and J. Shibata, J. Phys. Soc. Japan, 77 (2008) 03104
[11] H. Yamada, S. Kasai, Y. Nakatani, K. Kobayashi, H. Kohno, A. Thiaville and T. Ono, Nature Materials 6 (2007) 269
[12] K. Yu. Guslienko, K. S. Lee and S. K. Kim, Phys. Rev. Letters, 100 (2008) 027203
[13] M Beleggia, M D Graef, Y T Millev, D.A. Goode and G Rowlands J, Phys. D: Appl. Phys. 38(2005) 3333-3342
[14] R. I. Joseph, J. Appl. Phys. 68 (1966) 4639
[15] C. A. Ross, M. Hwang, M. Shima, J.Y. Cheng, M. Farhoud, T.A. Savas, H.I. Smith, W. Schwarzacher, F. M. Ross, M Redjdal, Phys. Rev. B 65 (2002) 144417
[16] M.J. Donahue and D.G. Porter, Interagency Report NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD (1999)
[17] P. J. Grace, M. Venkatesan, J. Alaria, J. M. D. Coey, G. Kopnov and R. Naaman, Adv. Mater. 21 (2009) 71-74.