Synthesis and Magnetic Properties of Large-Area Arrays of Nanomagnets

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Caroline A. Ross, Associate Professor of Materials Science and Engineering, MIT
Henry I. Smith, Professor of Electrical Engineering and Computer Science, MIT

Research Areas and Objectives

This project concerns the fabrication of arrays of small magnetic particles, known as 'nanomagnets', with dimensions below 100 nm. In this size regime, particles of ferromagnetic metals such as cobalt or nickel are too small to support well-developed domain walls, but they are too large to be uniformly magnetized. They therefore exhibit interesting magnetic configurations such as magnetization vortices, and magnetic reversal occurs by non-uniform processes. Computational methods are now powerful enough to treat such particles, allowing comparisons to be made between model and experimental results. Hence, such particles provide the opportunity to test micromagnetic models, and are ideally suited for fundamental studies of magnetic interactions and switching. They also have an increasing number of uses in the rapidly developing field of magnetoelectronics, where magnetic particles can be used as data storage or logic elements. For instance, in a patterned magnetic recording medium or a magnetic random access memory (MRAM) the magnetization state of each particle can represent a single data bit. In all these applications, the need for high density storage mandates the understanding of the properties of nanoscale magnetic particles.

Our goals are: (i) to establish synthesis methods for periodic nanoparticle arrays with particle sizes in the 10 - 100 nm range, covering areas of several square centimeters;
(ii) to investigate magnetic interactions, switching and anisotropy as a function of the particle microstructure and anisotropy, and the geometry of the array; and
(iii) to design and test particle arrays for data storage applications in which each particle stores a binary bit.

Methods

This work uses interference lithography (IL) and achromatic interference lithography (AIL) to fabricate large-area nanomagnet arrays over several square cm. In each method, the interference between two laser beams is used to expose a photoresist layer with a periodic fringe pattern. A second exposure defines a grid pattern in the resist. This pattern is transferred through to an antireflective coating layer, which forms a template for definition of the magnetic array. Particle arrays have been made by etching of a pre-deposited film, by electrodeposition, or by evaporation and liftoff. The array period is 100 – 200 nm, and the magnetic particles made to date are as small as 30 nm in diameter.

This method is ideally suited to making large-area periodic nanostructures quickly and economically. In comparison, other methods for making arrays of particles of this size scale are limited to very small areas. This fabrication method gives wide latitude to the range of structures and geometries that can be created: square, oblique or rectangular arrays of cylindrical, conical, disk shape, or elliptical particles can be made with a range of interparticle spacings, with controllable magnetic moment and anisotropy. Characterization includes the measurement of the hysteresis of the arrays, the remanent states of individual particles, switching statistics within the array, the strength of interactions between particles, and superparamagnetic behavior (thermal stability). Micromagnetic modelling was carried out to understand the remanent states and switching of the particles, as well as the interactions between particles in arrays, and the results have been related to the experimental data.

Discoveries, Successes, and Innovations

We have developed a variety of methods based on IL for making nanoparticle arrays. Samples have ranged from pure nickel or cobalt to alloys such as NiCo, NiFe or CoP and to multilayer structures such as pseudo-spin valves (e.g. Co/Cu/NiFe), and have single-crystal, polycrystal, or amorphous structures. The anisotropy of the particles has been controlled by choice of particle shape, material, and microstructure. Multilayer films can be etched into dots or ellipses using special hard masks, preserving the magnetic properties of the individual layers, which is important for device applications.

Remanent magnetization states of the particles have been explored in detail. A transition occurs as a function of particle size. Larger particles show a multidomain state or a 'vortex' state with low remanence, while small particles behave as single-domain particles with high remanence. Modelling, in collaboration with F. Humphrey, shows how the transition depends on the particle geometry and composition. Good agreement between model and observed remanent states is obtained, taking the particle shape, microstructure, and crystal orientation (such as the (0001) preferred orientation in evaporated polycrystalline Co particles) into account. Thermal effects were also quantified for arrays of small particles. For 30 nm Ni pyramids, superparamagnetic behavior was observed at room temperature. Using a micromagnetic model developed by R. Chantrell, we found that magnetization reversal occurred incoherently, and identified the switching volume with the columnar grains in the nickel, demonstrating the key role of microstructure on magnetic behavior.

The switching field distribution of the particles was analysed. The particles in an array show a range of switching fields due to two effects: intrinsic variability between particles due to small differences in microstructure, shape, etc., and interactions between particles, which affect the net field experienced by each particle depending on the magnetic state of its neighbors. We were able to identify and separate these effects, which are critical in the design of any device using small magnetic elements.

More recently, we have made elliptical elements of single-layer films and pseudo-spin valve stacks of NiFe/Cu/Co. The continuous films show two distinct switching fields corresponding to the NiFe and Co layers. We patterned these films into small ellipses and found interesting changes in the magnetic properties. The switching fields of both layers increased, due to the patterning, but the NiFe now reverses at positive fields because of magnetostatic coupling to the Co. Such size- and shape-dependent behavior is of great interest in the design of high density MRAMs, and we have started to make prototype MRAM devices.

This program has included, at different times, one postdoc, five graduate students and three undergraduate students, as well as many collaborators, both US and international. It has led to over twenty-five publications and to two Ph.D. and one M.S. thesis to date.

Some Recent Publications:

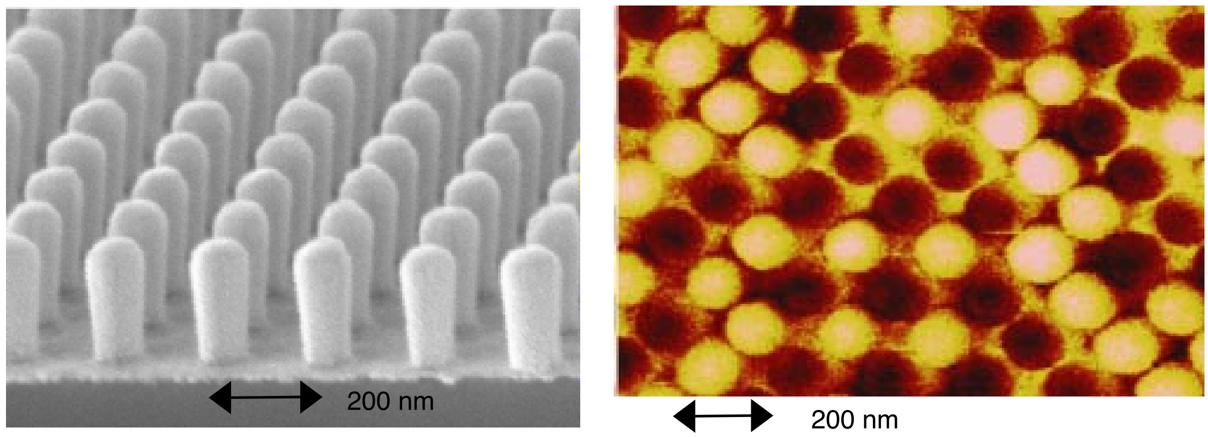
C.A. Ross, R. Chantrell, M. Hwang, M. Farhoud, T.A. Savas, Y. Hao, H.I. Smith, F.M. Ross, M. Redjdal and F.B. Humphrey, "Incoherent magnetization reversal observed in 30-nm Ni particles", Phys. Rev. B 62 14252 (2000)

C.A. Ross, M. Farhoud, M. Hwang, H.I. Smith, M. Redjdal and F.B. Humphrey, "Micromagnetic behavior of conical ferromagnetic particles", J. Appl. Phys. 89 1310-9 (2001)

F.J. Castaño, Y. Hao, S. Haratani, C.A. Ross, B. Vögeli, M. Walsh and Henry I. Smith, "Magnetic Switching in sub-100nm Patterned Pseudo Spin Valves", *in press,* IEEE Trans. Magn. (2001)

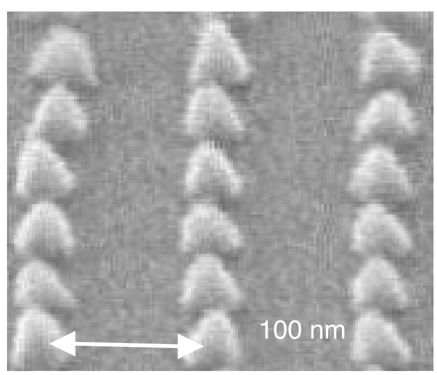
C.A. Ross, "Patterned magnetic media", Annual Review of Materials Research, *in press* (2001)

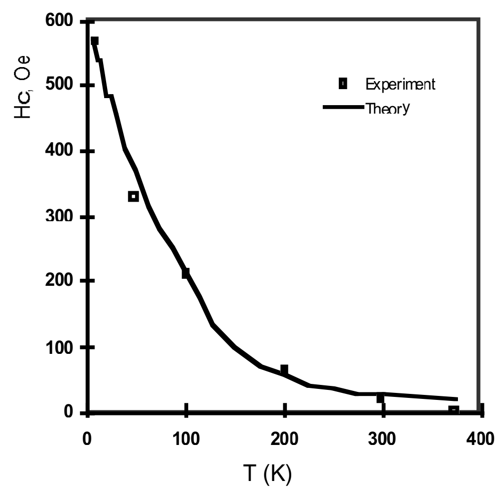
M. Hwang, M.C. Abraham, T.A. Savas, H.I. Smith, R.J. Ram and C.A. Ross "Magnetic force microscopy study of interactions in 100 nm period nanomagnet arrays", J. Appl. Phys. 87 p5108-10 (2000)
M. Hwang, M. Farhoud, Y. Hao, M. Walsh, T.A. Savas, H.I. Smith, C.A. Ross, "Major hysteresis loop modelling of two-dimensional arrays of single-domain particles", *in press,* IEEE Trans. Magn. (2000)



An array of electrodeposited Ni pillars, with diameter 90 nm, height 220 nm and period 200 nm. The magnetic image on the right shows that each pillar is magnetized 'up' (light) or 'down' (dark).

An array of conical Ni particles made by evaporation, with diameter 30 nm and period 100 nm. The magnetic properties are governed by the grain size, leading to superparamagnetic behavior at room temperature. At low temperatures the coercivity increases, agreeing with a computational model.





Hysteresis loop of an array of 80 nm x 140 nm elliptical particles made of a Co/Cu/NiFe film. The steps in the loop correspond to the separate switching of the NiFe and Co layers, which are coupled antiparallel at remanence.