Long-range magnetic ordering in nanofabricated artificial spin-ice arrays

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A frustrated system is one where it is not possible to satisfy every pair-wise interaction between the elements simultaneously. These systems are common throughout the physical and biological sciences including the proton disorder in water ice. Spin ice describes a similar phenomenon between the spins in certain materials such as pyrochlore(1). Artificial spin ice(2) represents a way of specifically tailoring the parameters of the individual elements so that the physics of such a frustrated system can be studied in depth.

Nanofabrication techniques present a unique opportunity to generate and study such an artificial spin ice system. Precise arrays of nanoscale magnetic elements can be fabricated over large areas into frustrated, artificial spin ice arrays. The physics of such systems can then be studied using real-space and reciprocal-space techniques. The size, spacing and even material of these magnetic elements can be easily manipulated to suit the experiment.

Using electron beam lithography and physical vapor deposition techniques, we have fabricated up to centimeter-scale artificial spin ice arrays in permalloy. The JEOL JBX6300-FS electron beam writer at the Center for Functional Nanomaterials ensures uniform, well-defined elements and high accuracy placement over very large areas. Using magnetic force microscopy, we have observed a long-range-ordered ground state for the first time in the as-grown samples(3). It has been determined from analysis of localized departures from this ground state that it is highly dependent on the thermodynamics during the initial deposition of the magnetic material by evaporation. The precision of the patterning and the material growth has lead to unprecedented magnetic ordering over areas larger than a centimeter square. Such arrays are ideal for reciprocal space studies with x-ray and neutron scattering.

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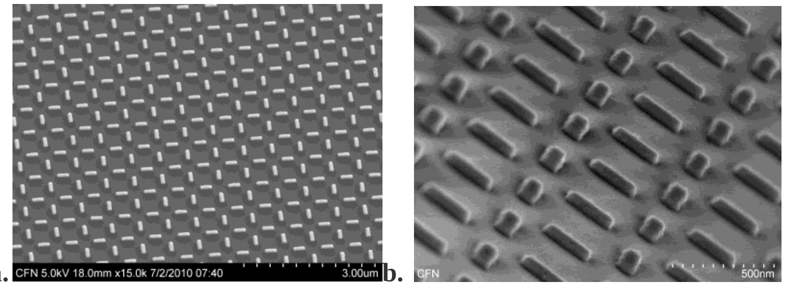

Fig. 1 Scanning electron micrographs of a portion of a centimeter-square frustrated magnet array showing both topdown (a) and tilted (b) views.

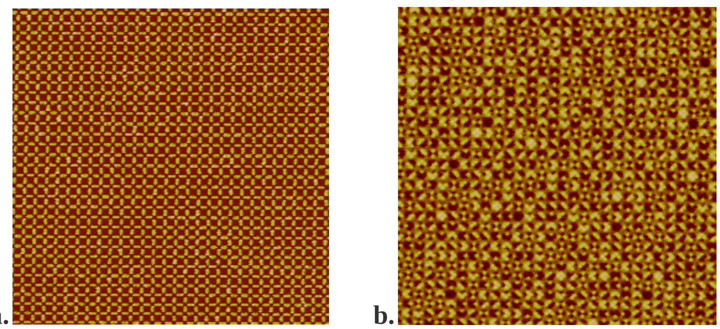

Fig. 2 Atomic force (a) and magnetic force (b) microscope images of a similar array to that shown in fig 1. The representative MFM image shows ground state ordering which is observed over the entire cm-square area.