Micromagnetic behavior of electrodeposited cylinder arrays

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Arrays of cylindrical magnetic particles have been made using interference lithography combined with electrodeposition. The cylinders are made from Ni, Co, CoP, or CoNi, with diameters of 57–180 nm, aspect ratios of 0.4–3, and array periods of 100–200 nm. The remanent states of the cylinders correspond to single-domain ''flower'' states or to magnetization vortices depending on the particle size and aspect ratio. Experimental data are in good agreement with a magnetic-state map calculated using a three-dimensional micromagnetic model, which shows the remanent state as a function of particle size and aspect ratio. The interactions between the particles, and their switching-field distribution, have been quantified.

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I. INTRODUCTION

There has been extensive interest in the magnetic properties of small (sub-100 nm) ferromagnetic particles or elements, due to their possible applications in patterned magnetic recording media and other magnetic or magnetoelectronic devices.[1,2] The magnetic behavior of such elements depends on their size relative to the magnetic exchange length $\lambda_{ex} = \sqrt{(A)}/M_s$ (expressed in cgs units), where A is the exchange constant and M_s the saturation moment. For ferromagnetic metals, λ_{ex} is typically in the range 6–20 nm. Elements of sub-100 nm dimensions are usually too small to support well-developed multidomain structures at remanence, but they are too large to be uniformly magnetized, hence their magnetization states typically contain nonuniformities such as magnetization vortices, or variations in the magnetization direction exist at their surfaces or edges. These nonuniform magnetization states lead to complex magnetic switching behavior that is not well described by the coherent rotation model. Although in some cases, agreement with coherent rotation[3] or curling[4,5] models has been obtained, generally it is found that measured switching fields are lower than model predictions[6,7] or show a different dependence on diameter,[8] the activation volume is smaller than the physical volume of the particle,[4,9–11] or switching statistics do not follow the Néel model[12] indicating a more complex magnetization reversal process. Other effects such as magnetostriction also cause deviations from the curling model.[10,13]

Computational micromagnetic models have, therefore, been used to improve understanding of both the remanent states and the switching behavior of small particles. This was initially done for the two-dimensional case of thin-film magnetic elements[14,15] but in recent years, lithography, magnetic characterization, and computational techniques have improved to the point that it is now possible to compare three-dimensional model predictions directly to experimental data gathered from individual particles or arrays of particles, revealing the effects of microstructure, edge roughness, and size variations on magnetic behavior, and giving some insight into the reversal mechanism and the effects of interactions between particles. Three-dimensional micromagnetic studies have usually concentrated on the switching behavior of single-domain particles with high aspect ratio, for instance, magnetic-tape particles[16] or particles made by electrodeposition into porous membranes or templates prepared lithographically.[7,17] Additionally, calculations of remanent states of ideal particle shapes such as cubes or cuboids have been made, as a function of size, shape, and anisotropy,[18–20] and nonuniform magnetization states in cylinders have been examined.[21–23] There have only been a few direct comparisons of computational remanence studies with experimental data.[24]

This paper presents a detailed comparison between the remanent states of arrays of low-aspect ratio cylindrical particles and a three-dimensional micromagnetic calculation. The transition between ''single domain'' and more complex remanent magnetization states deduced from hysteresis loops and magnetic images is compared with the predictions of the micromagnetic model, and good agreement is found. The interactions between particles within the array and their switching-field distributions have been quantified.

II. SAMPLE FABRICATION, STRUCTURAL CHARACTERIZATION AND MODELING

The cylinder arrays are fabricated by electrodeposition into templates made by interference lithography or achromatic interference lithography.[24–26] These methods are chosen because they are capable of exposing large area (several square centimeter) substrates with deep-submicron features in a patterning process that is much faster than electron-beam lithography. Both lithography methods rely on the interference between two laser beams to produce a fringe pattern that is used to expose a trilevel resist layer. Two perpendicular exposures are used to define a square array of holes in the

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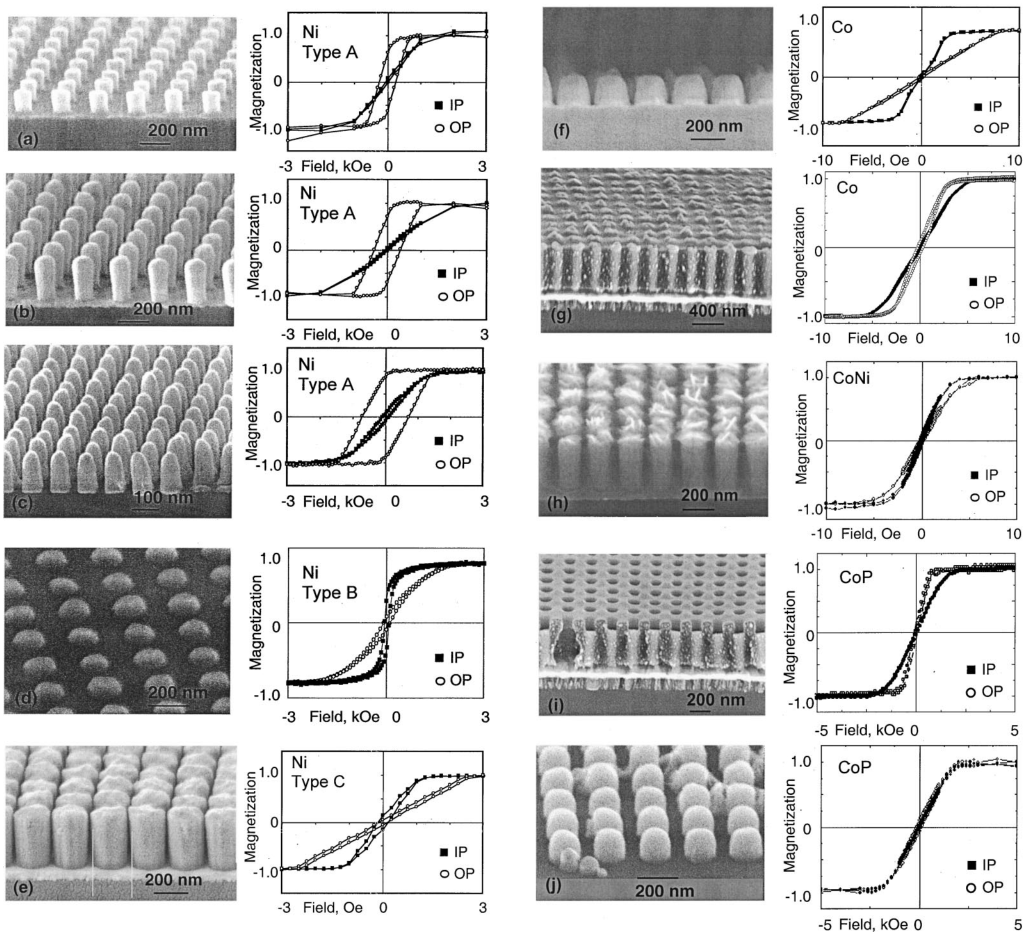

FIG. 1. Scanning electron micrographs of selected cylinder arrays of Ni, Co, CoP, and CoNi, and corresponding hysteresis loops. The field is applied either in-plane (IP, solid points) or out-of-plane (OP, open points). Additional samples are shown in Refs. 28 and 40. The magnetization is normalized to the saturation magnetization of the sample.

top resist layer. A negative resist is used for improved process latitude.[27] The hole pattern is transferred from the resist through an intermediate mask into an underlying 300–400 nm thick antireflective coating layer using reactive ion etching to give holes with straight sidewalls, which form the mold for the deposition of the cylinder arrays. The interference lithography system produces patterns with period 200 nm and above, while the achromatic-interference lithography system produces patterns with period 100 nm. The diameter of the holes in the template is controlled through the exposure dose, and was varied in the range of 0.4–0.9 times the array period.

The templates are made on silicon wafers coated with a thin evaporated conductive layer consisting of 5 nm Ti or Cr followed by 5–20 nm Au. The cylinder arrays are fabricated by electrodeposition from aqueous electrolytes as described previously.[28] Co and Ni are deposited from sulfamate electrolytes from a commercial vendor (MacDermid). CoNi pyrophosphate and CoP phosphate electrolytes were mixed from salts. The area to be electroplated, 1–10 cm^2, is defined using a tape or photoresist mask. Depositions are carried out galvanostatically, except for CoNi alloys that are deposited potentiostatically. After deposition, the antireflective coating template could be removed using an oxygen reactive ion etch to enable the cylinders to be imaged by scanning electron microscopy.

The microstructure of the samples was assessed using x-ray diffraction, transmission electron microscopy, and scanning electron microscopy. Compositions of alloys were determined by energy dispersive x-ray analysis or x-ray photoelectron spectroscopy using appropriate standards such as Co_2P powder in the case of CoP samples. Magnetic characterization was carried out using an ADE vibrating sample magnetometer or a Princeton alternating gradient magnetometer, and a Digital Instruments magnetic force microscope (MFM). Figure 1 shows representative scanning electron micrographs and hysteresis loops of several cylinder arrays. The cylinders have straight sides, with a slight taper in some cases due to an increase in the hole diameter through the thickness of the template.

Nickel samples were polycrystalline with a (111) fcc preferred orientation. From transmission electron microscopy [Figs. 2(a) and 2(b)], the as-deposited grain size was 10–20 nm, smaller than the cylinder diameter. However, annealing the smaller cylinders such as the sample shown in Fig. 1(c) during the reactive ion etch could result in recrystallization, and the final microstructure then consisted of single-crystal cylinders with occasional grain boundaries or stacking faults

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