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Magnetic properties of nickel nanostructures grown in AAO membrane

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Abstract

One-dimensional nanostructures can be built by performing chemical or electrochemical reactions in the pores of a suitable host or matrix material. We have developed a method of electrodeposition of nickel nanostructures inside cylindrical pores of the anodic aluminum oxide (AAO) membranes, which provides precise control of the nanostructure height. We were able to fabricate hexagonal arrays of particles in the form of spheres, rods and long wires. Magnetization measurements of these nanostructures as function of field and temperature were carried out using a superconducting quantum-interference device magnetometer. The shape of nickel nanostructures has been investigated by field emission scanning electron microscope. The coercivity of the nickel nanostructures measured with the field perpendicular to the membrane was increasing with increasing aspect ratio of the nanostructures. These experimental values of the coercivity, varying from 200 Oe for the spherical nanodots to 730 Oe for the nanowires, are in a fair agreement with our micromagnetic modeling calculations.

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Keywords: Nickel nanodot; Nickel nanorod; Nickel nanowire; Magnetic property

Magnetic properties of magnetic nanoparticles depend on many factors such as size, shape, surface roughness and particle distribution. The particles remain single domains below certain critical size. Larger particles are multi domain and domain-wall movements contribute to the magnetization process. Magnetostatic energy of the particles is controlled by the shape and roughness of the particles. The effect of shape anisotropy on the magnetic hysteresis loops is the most pronounced for the magnetically soft particles, such as nickel or permalloy than for hard nanomagnets where magneto-crystalline anisotropy prevails. The magnetostatic interparticle interactions depend on the particle arrangement in the array and they significantly modify magnetization processes for small interparticle distances.

In the past decades, the synthesis of nanosized mag netic particles has extensively been studied because of their potential applications in information storage and biomedicine.

For example arrays of soft magnetic wires were proposed to serve as a planar separator of bio-active particles [1]. Several methods, such as wet-chemical etching, UV lithography or electrodeposition, have been developed to fabricate arrays of nanoparticles [2,3] Well-defined inorganic molecular sieves as porous host can be used to synthesize one-dimensional nanostructured magnetic material. The problem with the conventional wet-chemical preparation methods leads to a rather broad distribution in size and shape over a large area.

Because of large number of parameters affecting magnetization processes and different technologies used

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to produce arrays of nanoparticles it is difficult to conclude about the effect of the aspect ratio of the particles on their magnetic properties based on literature data. Some earlier studies include effect of a diameter of the nanowires [2] and properties of nanolithograpically patterned pillars [3].

In this paper, we describe a technology that allows fabrication of hexagonal arrays of nanostructures with fixed diameter and well-controlled height. Arrays of nickel nanostructures in the form of spheres, rods and long wires were produced by electrodeposition of nickel in AAO. The magnetization hysteresis loops and accompanying magnetic parameters evolve with the changing aspect ratio of the nanoparticles, which form the arrays.

Hexagonally ordered porous AAO was formed by anodization process as described previously [4]. The nickel nanostructures grow from the bottom of the holes, so the diameter of the nanostructure corresponds to the diameter of the template hole. In Fig. 1, the diameter of nickel nanostructures is about 100 nm. Nickel was deposited in pores by DC electrolysis in an electrolyte of the following composition: $NiCl_2 \cdot 6H_2O$.

$Ni(H_2NSO_3) \cdot 4H_2O$, boric acid and ascorbic acid. The pH value of the electrolyte was maintained at 3.5 and then the electrolysis was conducted at 20 °C, using DC current of 3–4 mA and silver counterelectrodes. By simply controlling the deposition time in the range from 5 to 15 min a variety of nickel nanostructures were fabricated as seen in Fig. 1. They had the forms of nearly spherical nanodots with the diameter of 100 and 400 nm rods and 3.4 μm long wires.

The magnetization hysteresis loops were measured using SQUID magnetometer with the field in the substrate plane (transverse to the wires) and perpendicular to the membrane, i.e. along wires or rods. The experimental results, presented in Fig. 2, show the evolution of the hysteresis loops with the increasing aspect ratio of the length–to-diameter of the particles: 1:1, 4:1 and 34:1. The most significant changes of the hysteresis loops have been observed for the field applied perpendicular to the substrate. Coercivities measured at 5 K for this configuration of the field were 200, 630 and 730 Oe, respectively, for spheres, rods and wires. Also the squareness of the loop was increasing with the increasing aspect ratio. In case of measurements with the in-plane field the shapes of the hysteresis loops were similar and the largest coercivity of 200 Oe was found for the spherical nanodots.

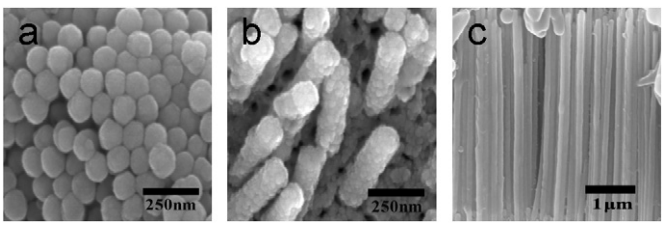

Fig. 1. The FE-SEM images of nickel: (a) nanodots, (b) nanorods and (c) nanowires after removal of the AAO templates. The diameter, length and the distance between the pores of the AAO template are 100 nm, 40 μm, and 210 nm, respectively.

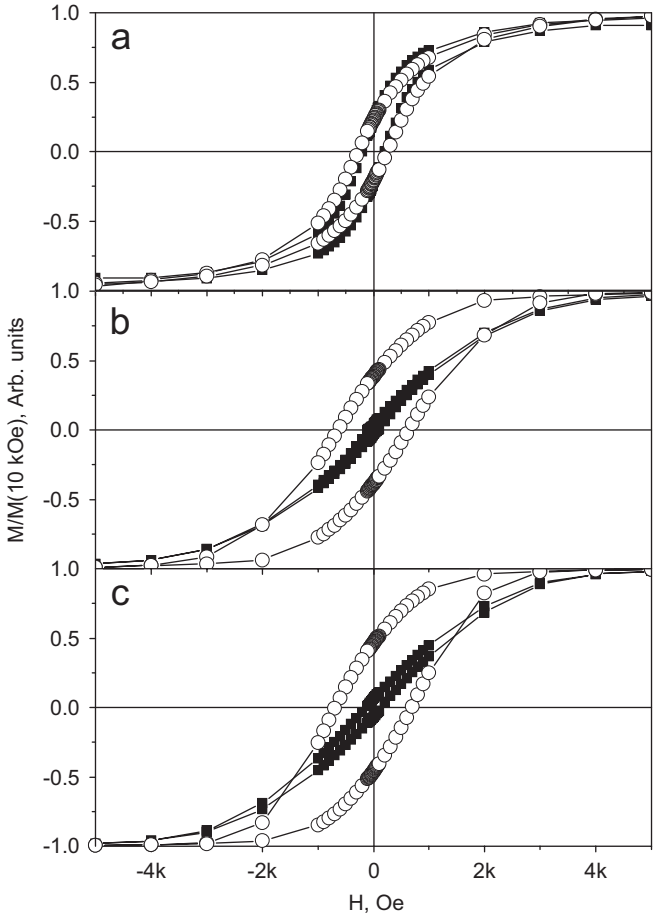

Fig. 2. Hysteresis loops for nickel: (a) nanodots, (b) nanorods and (c) nanowires measured at 5 K with the field applied parallel (-■-) and perpendicular (-○-) to the membrane plane.

The evolution of the hysteresis loops can be qualitatively understood in terms of Stoner–Wohlfarth model for magnetization rotations in the particles with uniaxial shape anisotropy. However, the quantitative analysis of the magnetization processes is far more complex in the case of nanoparticles, as indicated by micromagnetic calculations [3,5,6]. For example, magnetization reversal occurs through incoherent magnetization rotation, such as an evolution of a vortex state rather than magnetization rotation or domain-wall nucleation and domain movement, which are commonly recognized mechanisms in bulk samples. For these reasons the experimental coercivity values were significantly lower than those expected from the Stoner–Wohlfarth model. Therefore, we used micromagnetic modeling code JAMM, developed by S. Whittenburg [7], to interpret experimental hysteresis loops. The results of the micromagnetic calculations for isolated particles with different aspect ratios reproduced the evolution of the shapes of the hysteresis loops and gave reasonable agreement with the experimental values of the coercivities. However, it is worthy to mention that the measured coercivities were about 10% lower than the calculated ones and squareness of the loops was larger for theoretical curves. In addition to the aspect ratio, other

important factors, such as interparticle interactions [8], surface roughness, distributions of particle lengths and separations, can be taken into account to improve the quality of the theoretical curves fittings.

In summary, we demonstrated that it is possible to fabricate assemblies of nanoparticles with markedly different aspect ratios by varying a single-technological parameter. Magnetic properties were dominated by the shape anisotropy associated with the aspect ratio of the nanostructures.

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