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Tuning the magnetic properties of high aligned strontium ferrite nanowires formed in alumina template

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Ordered hexagonal array of strontium ferrite nanowires were fabricated by dip coating in alumina templates and the influence of diameter and length on the magnetic properties of high aligned nanowire arrays were studied. The diameter of nanowires, synthesized in high aspect ratios, was changed from 30 to 60 nm while maintaining the same center to center distance between them. The samples were characterized by X-ray diffraction (XRD) and field emission scanning electron microscope (FESEM) equipped with energy dispersive X-ray spectrum (EDS). Magnetic properties of nanowires were measured by a SQUID; the hysteresis loops were obtained with the applied magnetic field parallel and perpendicular to the wire axis. Magnetic properties of nanowire arrays were also investigated as a function of temperature. The Results showed that both coercivity and squareness increased with increasing wire length, while for constant center-to-center distance, coercivity decreased with increasing the diameter. Parallel anisotropy was achieved for 30 ± 4 nm diameter nanowire array having 15 ± 0.01 μm length. A curling mode of magnetization was suggested in strontium nanowires.

1. Introduction

Tuning of the magnetic properties in nanowire arrays is a topic that has attracted considerable interest due to capability of study magnetic fundamentals in low dimensional systems and potential applications mainly in high density information storage [1–4]. Magnetic nature of nanowires in high ordering give rise to outstanding properties different from the bulk, powder and even from thin film systems [5,6]. Among different methods of nanowires synthesis, such as lithography, vapor liquid solid and template base methods, the latter can deliver high-density nanowire arrays of precise parameters including length, diameter and crystallinity [7–9]. Special syntheses in alumina templates are highly cost-efficient and attractive. Template production for metal nanowires has frequently been carried out by electrodeposition into porous alumina, while complex oxide nanowires with no electrical conductivity cannot be produced by this method. Chemical based methods, in particular sol–gel, are the most common approaches in preparation of such complex oxide nanowires [10]. Sol–gel method has been improved by other techniques such as electrospinning in order to synthesize multi-cation complex oxide nanowires [11].

Researchers have investigated the influence of the size on the magnetic properties of nanowires [5]. Ferromagnetic materials such as nickel nanowires have been intensively studied in different lengths and diameters [12,13]. CoPt and FePt are the ferromagnetic materials with large anisotropy which have been investigated from fundamental and technological points of view [14,15]. Uniformly distributed nanowires can have a key role in development of magnetic evaluation of ferromagnetic and ferrimagnetic. Although various magnetic metal or metal oxides have been fabricated and characterized [9,16], limited information is available regarding the hexaferrites with one dimensional structure. Strontium ferrite is the kind of hexaferrite with magnetoplumbite structure; energy density of magneto-crystalline anisotropy constant (3.7×10^6 erg/cm^3) is comparable to that of shape anisotropy (2.5×10^3 erg/cm^3).

In the present work, we employed dip coating process to fabricate high aspect ratio strontium ferrite nanowires array in alumina templates. Such nanowires are ideal systems to study magnetization reversal and anisotropy in one dimension. Moreover, the presence of billions of wires in a single template allows the

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application of macroscopic measurement techniques, like SQUID magnetometry. Applied magnetic field was directed either parallel or perpendicular to the wires. Changing anisotropy from parallel to perpendicular was achieved via modifying the wire diameter and length. A magnetization reversal model was used to explain the experimental data. Magnetic properties of nanowire arrays were also measured at different temperatures ranging 300–10 K in order to investigate saturation magnetization and coercivity.

2. Experimental details

2.1. Fabrication of alumina templates and nanowire arrays

Samples of pure aluminum foil were degreased using 10% sodium hydroxide at 70 °C for 2 min, rinsed and immersed for 1 min in nitric acid at room temperature. The foils, then, were electropolished for 10 min in a mixture of perchloric acid and ethanol (1:5 volume ratio) to achieve a smooth surface. Double anodizing process was carried out in 0.3 M oxalic acid at a DC voltage of 40 V and temperature of 4 °C. The first anodization time was 12 h while the second one varied based on the template thickness. The samples were dipped into 0.2 M solution of $CuCl_2$ to remove the aluminum substrate.

Based on preliminary experiments, nanopores diameters were carefully widened by subsequent chemical treatment in 5 wt% phosphoric acid solution that allowed continuous increase of the pore diameter. In this way, the filling factor of nanopores within the templates could be suitably tuned. Various types of templates with nominal pore diameters of 30, 40, 50, and 60 nm in 15, 30 and 60 μm lengths were selected to study the effect of size on magnetic properties of nanowire arrays. The length of nanowires was controlled by template thickness and the extent of filling the pores during dipping process.

To prepare the synthesizing solution, appropriate amount of $Fe(NO_3)_3.9H_2O$ was dissolved in deionized water and, then, $Sr(NO_3)$ was added. After complete dissolving the salts, citric acid was added to the solution; Fe/Sr ratio of 11was selected to optimize magnetic properties based on our previous study while the ratio of cations to acid was set to 1:1. Ammonium hydroxide was used to adjust pH value of 7 in the solution to avoid dissolving of the template. The solution was subsequently evaporated at 80 ± 3 °C until a sol with desirable viscosity was achieved. Then, the templates were dipped into the sol for 2 h and gelation took place at 80 ± 3 °C in air oven. The surface of template was horizontally placed in the solution; the long synthesis time allowed complete filling of the pores by a single dipping process and the required thickness was obtained. After formation of nanowires, excess material was removed from the surface of template. It should be mentioned that removal of barrier layer was not essential in this method.

After precipitation of nanowires into the pores, the template was dried at 120 ± 3 °C and then the sample were calcinated for 30 min in air atmosphere to obtain crystalline ferrite. The heating rate was 1 °C/min to the sintering temperature, followed by 1 h annealing. Slow heating rate was selected to avoid bending of the samples. Calcination temperatures were changed from 500 to 900 °C in steps of 50 °C. It was observed that temperatures above 650 °C damaged the template by bending or breaking. During the synthesis, metallic nitrates were decomposed into metal oxides, O_2 and NO_2. The metal oxides reacted and grew within the alumina template pores to form $SrFe_{12}O_{19}$ [17]. In order to synthesize strontium powders, similar solution was used, followed by evaporation of the sol at 80 ± 3 °C to form a gel, then, heating continued until the gel was dried. Finally, the powders were calcinated at

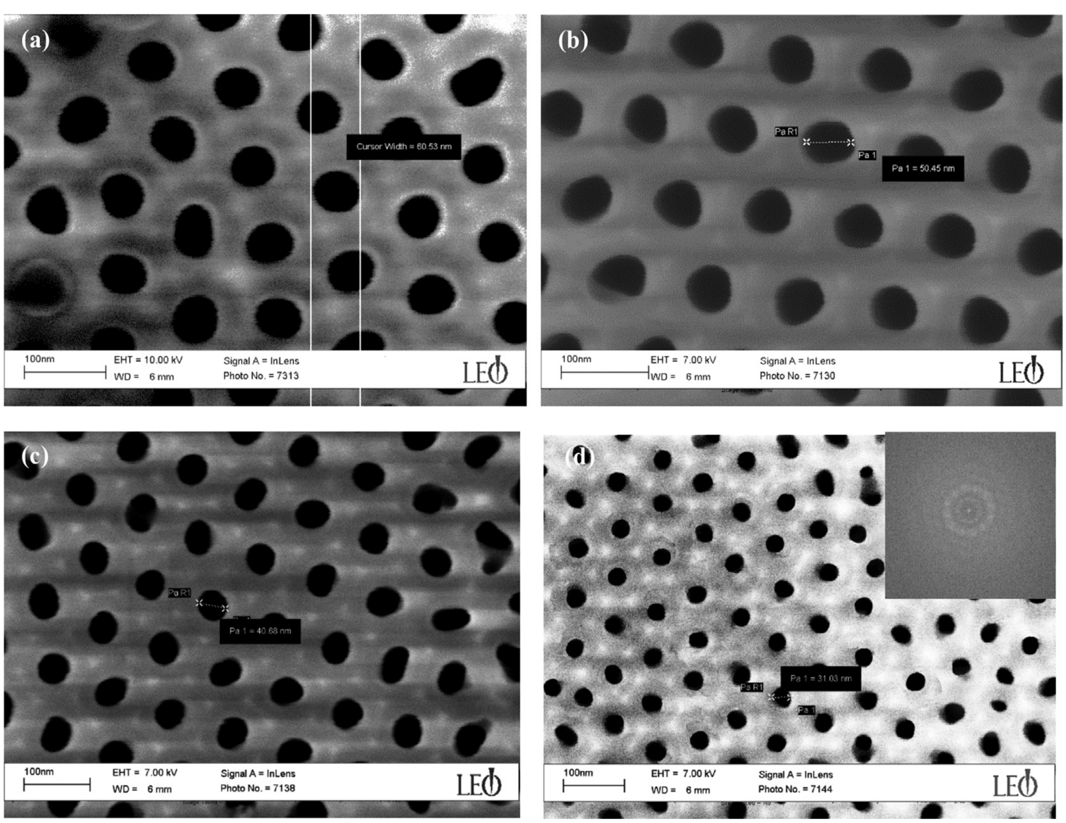

Fig. 1. FESEM images of surface of template with diameter of (a) 60, (b) 50, (c) 40 and (d) 30 nm, the insert shows fast Fourier transforms of the template.