Materials Science and Engineering B 223 (2017) 120–124

Contents lists available at ScienceDirect

Materials Science and Engineering B

journal homepage: www.elsevier.com/locate/mseb

Crossover between axial and radial magnetic anisotropy in self-organized permalloy nanowires

Mohamed Shaker Salem [a,*], Kornelius Nielsch [b,c]

[a] Physics Department, Faculty of Science, Cairo University, 12613 Giza, Egypt
[b] Institute of Nanostructure and Solid State Physics, University of Hamburg, Jungiusstraße 11, 20355 Hamburg, Germany
[c] Leibnitz Institute for Solid State and Materials Research (IFW), Institute of Metallic Materials, Helmholtzstraße 20, D-01069 Dresden, Germany

ARTICLE INFO

Article history:
Received 11 April 2017
Received in revised form 4 June 2017
Accepted 13 June 2017

Keywords:
Magnetic nanowires
Porous alumina
Electrodeposition

ABSTRACT

Self-organized permalloy nanowire arrays embedded in hexagonally ordered nanochannels of anodic alumina membranes were produced by electrodeposition. The dimensions of the nanowires were tuned over a wide range by controlling the dimensions of the host alumina templates. Room temperature magnetic hysteresis revealed a considerable dependence of the magnetic anisotropy of the array on the nanowire dimensions. The magnetization direction of the nanowires was found to change from axial to longitudinal direction as both the diameter and length of the wire increased. The observed behavior was ascribed to the increase in magnetostatic coupling among nanowires, as confirmed by first-order reversal curve measurements. Theoretical calculations based on a simple magnetostatic model, which considers the dipolar interaction among the wires, estimated the critical dimensions of the nanowires at which the magnetic anisotropy changes from perpendicular to longitudinal direction.

1. Introduction

Ferromagnetic nanowires have been used in a wide range of applications because of their outstanding properties. The use of magnetic nanowires in cell separation, biosensing, gene therapy, and drug delivery has been reported in the literature [1–4]. In bioseparation, nickel nanowires exhibit greater yields than magnetic polymer microsphere [5]. The high aspect ratio of the nanowires, however, provides higher sensitivity, higher capture efficiency, and faster response time than conventional sensors [6]. Another field of extremely promising applications is magnetic data storage [7]. The unique geometry of nanowires creates strong perpendicular shape anisotropy. This makes them suitable for perpendicular magnetic recording, thereby providing ultra-high density of data storage. Significant progress in areal density, defined as the number of tracks per inch multiplied by the number of bits per inch recorded on one tack, has been attained over the last 15 years because of the emergence of perpendicular recording technology [8]. In the recording process, the magnetization of a recording bit is aligned perpendicular to the recording medium. This perpendicular configuration displays several advantages over the parallel recording. The latter approach has an estimated limit of 100–200 Gbit/in^2 due to the superparamagnetic effect, which originates from thermal instability associated with further reduction in grains of the recording medium. Recently, perpendicular recording, however, was predicted to allow information densities up to around 2 Tbit/in^2 (2000 Gbit/in^2) [9].

Magnetic nanowire arrays can be grown by several routes such as chemical vapor deposition (CVD) and focused-ion-beam-induced deposition (FIBID) techniques [10,11]. Self-organized porous alumina templates provide another route to fabricate ordered magnetic nanowire arrays [12]. This is a simple inexpensive approach that can be considered an alternative to conventional lithography methods. The average pore diameter of the templates can be controlled from less than 10 nm up to 200 nm with a pore density in the range of 10^9–10^{11} [13,14]. The filling of the templates can be performed by various methods such as CVD [15]. Electrochemical deposition approach, however, is more preferred over other methods because it works under atmospheric conditions and does not require expensive equipment. Furthermore, it produces homogenous filling into high aspect ratio geometry where conventional deposition processes fail. Herein, we use the electrodeposition of permalloy into porous alumina to fabricate nanowire arrays with controlled dimensions and explore the impact of their geometry on the magnetic anisotropy. The present study focuses on permalloy nanowires because of their negligible magnetocrystalline anisotropy and magnetostriction, which make the entire magnetic anisotropy depend only on the nanowire

* Corresponding author.
E-mail addresses: mshaker@physnet.uni-hamburg.de, mohshaker78@yahoo.com (M.S. Salem).

http://dx.doi.org/10.1016/j.mseb.2017.06.008
0921-5107/

aspect ratio and the stray field of the arrays. This provides an easy control of the magnetic anisotropy in such a particular nanowire array.

2. Experimental section

Porous alumina templates with interpore distances of 500 nm were prepared by the two-step anodization of high-purity aluminum sheets in phosphoric acid under self-organized conditions. Prior to anodization, the rough surface of aluminum sheets was electropolished following a well-established technique [16]. Pore widening was performed by immersing the templates in 10 wt% phosphoric acid at 45 °C for a certain period of time. The widening rate was estimated as 5 nm/min. Permalloy nanowires were grown by pulsed electrodeposition technique [17]. The morphology, size, and composition of the nanowires were characterized by scanning electron microscopy (SEM) (Zeiss EVO-50). Further structural characterization was performed by transmission electron microscopy (TEM) (FEI TECNAI 20) and selected area electron diffraction (SAED). Samples were prepared for TEM analysis by dissolving away the aluminum oxide film in a mixed solution of phosphoric and chromic acids and placing a drop of the resulting freestanding nanowire suspension on a standard grid. Magnetic properties of the samples were investigated using superconducting quantum interference device (SQUID) (MPMS2, Quantum Design) and vibrating sample magnetometer (VSM) (VersaLab, Quantum Design) instruments.

3. Results and discussion

Fig. 1a displays the SEM image of a porous alumina template prepared by the anodization of aluminum in 1.0 wt% phosphoric acid at 195 V. The template exhibits a hexagonally arranged porous network with an average pore diameter and interpore spacing of ~150 and 500 nm, respectively. The cross-sectional view of the template after filling with permalloy is shown in Fig. 1b. The length of the nanowires was determined by controlling the total charge passed in the electrochemical deposition process. Fig. 1c shows the bright-field TEM image of a single permalloy nanowire. The image confirms the uniform diameter of the nanowire. The SAED image of this nanowire presents several sharp diffraction spots as indexed in Fig. 1d. The diffraction patterns confirmed the formation of permalloy with a fcc structure [18]. Fig. 2 displays the energy-dispersive X-ray (EDX) spectrum of a prepared nanowire array. The atomic percentages of iron and nickel in the nanowire array were 20% and 80%, respectively. This composition is typical for permalloy with a negligible magnetocrystalline anisotropy. The parameters of electrodeposition process were kept fixed, and we did not observe any change in the composition or in the crystal structure of nanowires prepared with different diameters and lengths. In our previous work, we reported a controlled change in the composition and texture of the nanowires, associated with the introduction of some variations in the parameters of the electrodeposition process [18].

Fig. 3 shows the room temperature normalized magnetic hysteresis loop with the field applied parallel and perpendicular to the wire axis *z* for two permalloy nanowire arrays having different aspect ratios. The coercive fields obtained for the 5-μm-long nanowire array with an average diameter of 150 nm were 130 and 59 Oe for the field applied perpendicular and parallel to the axis, respectively, as shown in Fig. 3a. The longitudinal saturation field was much smaller than the transverse saturation field on this nanowire array. This result indicates that the magnetization easy axis was aligned along the nanowire because of the strong shape anisotropy. This behavior is expected for high-aspect ratio nanowires embedded in weakly interacting medium. The demagnetization tensor elements of the nanowires are $N_x = N_y = 2\pi$, $N_z = 0$. This enhances the nanowire's shape anisotropy, directing the easy axis of magnetization along the long axis of the wire [19]. When the length of the nanowires was decreased to 2 μm and the average diameter was fixed, a nanowire array with an axial coercivity of

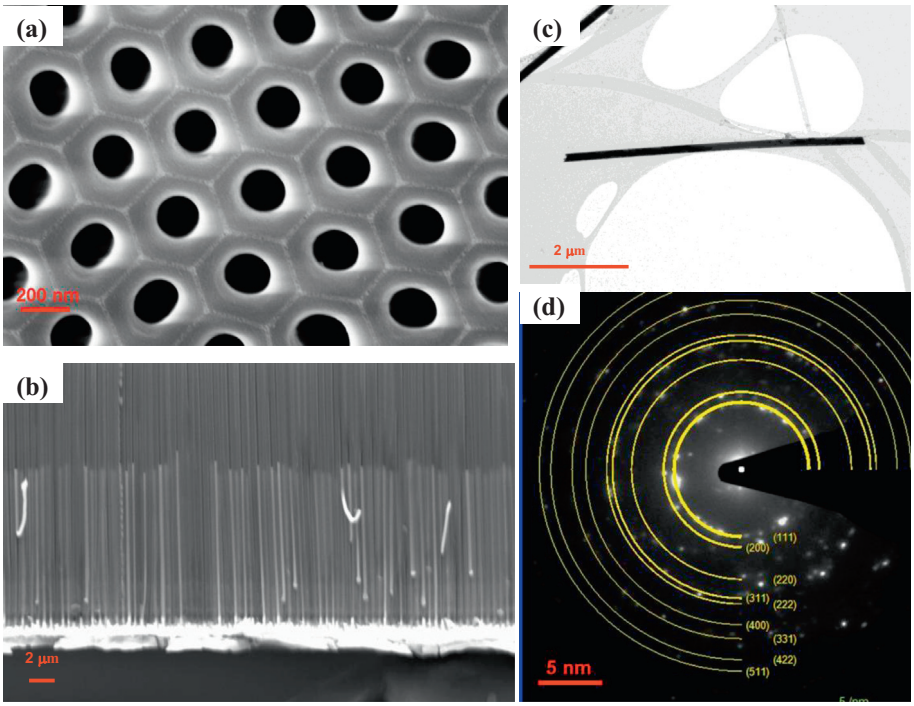

Fig. 1. (a) SEM top view image of the as-prepared permalloy nanowires (b) Cross-sectional SEM view of permalloy nanowires after the pore widening treatment. (c) TEM image of an isolated permalloy nanowire. (d) Electron diffraction (SAED) patterns of a selected area of the as-prepared nanowires.