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ScienceDirect

Ceramics International 41 (2015) 12081–12086

CERAMICS INTERNATIONAL

Fabrication and temperature dependent magnetic properties of nickel nanowires embedded in alumina templates

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Received 28 April 2015; received in revised form 29 May 2015; accepted 4 June 2015
Available online 12 June 2015

Abstract

Nickel nanowires (NWs) of 98 nm diameter and 17 micron length were fabricated by electrodeposition in anodic aluminum oxide (AAO) membranes. Structural analyses reveal that the NWs have face centered cubic (fcc) structure with preferred orientation along (111) plane. Low temperature magnetic measurements (10–300 K) show that coercivity (H_c) of nanowires increases with decreasing temperature following Kneller's law similar to the ferromagnetic nanoparticle system. In addition, the saturation magnetization follows the modified Bloch's law in the temperature range 50–300 K. However, at temperatures below 50 K there is an abrupt increase in net magnetization of the NWs that has been attributed to the presence of paramagnetic impurities in the samples that are activated at low temperatures and at high fields.

Keywords: Nickel nanowires; Electrodeposition; Coercivity; Saturation magnetization

1. Introduction

Ferromagnetic nanowires were studied extensively over the last few years because of the distinctive functionalities as compared to their bulk counterparts [1,2]. These NWs have potential applications in fundamental physics as well as in recent technologies including magnetic logic, spintronic, spin transfer torque, biomedical, and low ohmic loss devices, nanosensors, molecular electronics and solar cells [3,4]. Various methods have been employed for fabrication of metallic NWs however the template assisted is considered one of the most popular techniques. This cost effective technique can be easily established in the laboratory [5–7]. Highly ordered anodic aluminum oxide (AAO) membranes are used for fabrication of large scale magnetic NW arrays. The nanopores in AAO templates are parallel, ordered, uniform in shape and size, and are perpendicular to the surface of the templates. Moreover, the AAO templates are stable against organic solvents as well as are sustainable at high temperatures [8,9]. Electrodeposition into porous template allows the possibility to easily control various parameters independently such as inter-wire distance, diameter and length, composition and thickness of the desired NWs [10,11]. Furthermore, the microstructure of electrodeposited NWs can be tailored via deposition parameters such as temperature, pH, and concentration of electrolyte, pore diameter, and applied voltage during electrodeposition process [12,13].

Among other materials, nickel NWs have become important due to their microwave absorbing and magnetic properties for their broad range of applications that include single nanowire based functional materials and thermo electric and magneto-

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http://dx.doi.org/10.1016/j.ceramint.2015.06.025
0272-8842/

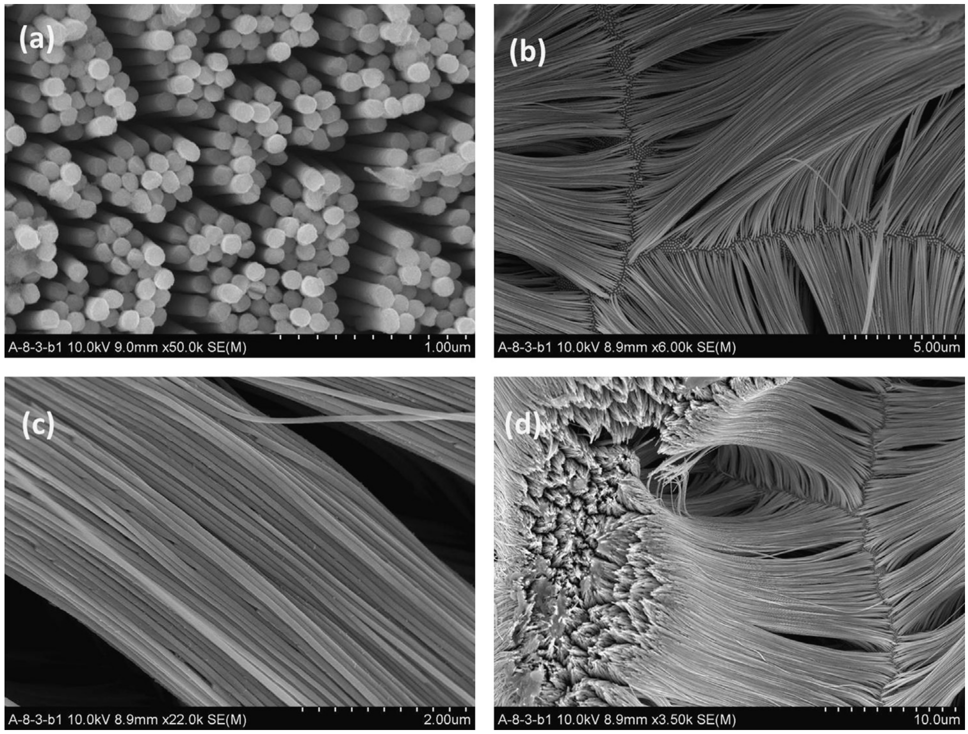

Fig. 1. (a)–(d) Scanning electron micrographs of Ni nanowires with average diameter of 98 nm and length of 17 μm.

optical devices. In case of single magnetic NW due to the shape anisotropy the magnetization direction is mostly along wire-long axis. However, when dealing with arrays of magnetic NWs, the inter-wire magnetic interactions can alter the resultant magnetic properties of the system. Many groups have studied the size dependant magnetic properties of NWs [14–16]. For magnetic recording applications the NW diameter is desired as small as possible, while for other applications such as in microwave and magneto-optical devices the NW with large diameters are favorable [17,18]. Qin et al. [15] and Han et al. [14] have reported Ni NWs with large diameters and explored their angular dependent magnetic properties in detail. Generally the small diameter NWs exhibit uniaxial anisotropy that is along the wire-long axis. While the NWs with large diameters exhibit cubic anisotropy that may be along the radial direction in the wires [19].

In the literature, many articles have been reported related to magnetic properties of Ni NWs [20–23] but still some queries remain open like how the magnetic properties (coercivity, saturation magnetization) are effected when temperature of the material goes down to few Kelvin. In this paper we report fabrication of Ni NWs by using electrochemical deposition in AAO templates and investigate the effect of low temperatures on magnetic properties of these nanowires.

2. Experimental details

The fabrication of magnetic Ni NWs was carried out by electrodeposition using anodic aluminum oxide (AAO) template, purchased from Whatman [20]. For synthesis of NWs, electrolyte was consisted of 0.12 M nickel sulfate ($NiSO_4 \cdot 6H_2O$) as a salt, 0.3 M boric acid (H_3BO_3) as the buffering agent, and deionized water as the solvent. All the chemicals used were analytical grade without any further purification. For electrical contact, one side of the template was sputter coated with copper of 200 nm thickness to make it conductive for the deposition process. Electrodeposition was carried out using three electrode cells where the sputtered conducting layer served as the working electrode, a saturated calomel electrode as the reference, and platinum sheet as the counter electrode. Electrodeposition was performed potentiostatically at a voltage of -1 V at room temperature for 60 min to obtain nickel NWs of 17 micron in length. Subsequent to fabrication, the templates containing NWs were annealed at different temperatures (i.e. 400 °C, 500 °C, 600 °C, and 700 °C) for 4 h to improve the crystallinity of the nanowires.

The structural analyses of the NWs were carried out by a scanning electron microscope (SEM) and X-ray diffraction (XRD) with Cu K_α ($\lambda = 1.540$ Å) radiation. The magnetic characterization was performed by a vibrating sample magnetometer (VSM) and a super conducting quantum interference device (SQUID) magnetometer at different temperatures under an applied magnetic field of ± 10 k Oe.

3. Results and discussion

For SEM analysis, the NWs were liberated from the templates by dissolving in 1 M NaOH solution. Fig. 1 shows the SEM images of Ni NWs. It can be seen that the NWs have an average diameter of 98 nm and length of 17 microns. The diameter of NWs was the same as the pore diameter of templates while the length was controlled by deposition time