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Research articles

Magnetic domain structure and magnetic anisotropy in ferromagnetic $Y_3Fe_5O_{12}$ nanowires formed by step-edge decoration

Hyun Wook Shin *, Jong Yeog Son *

Department of Applied Physics, Kyung Hee University, Yongin 446-701, Republic of Korea

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A B S T R A C T

We investigated the ferromagnetic properties of $Y_3Fe_5O_{12}$ (yttrium iron garnet; YIG) nanowires deposited on a highly ordered pyrolytic graphite (HOPG) substrate. YIG nanowires with a diameter around 70 nm were formed on the edges of terraces of the HOPG substrate using the step-edge decoration technique and pulsed laser deposition of the YIG. The magnetic field of the YIG nanowires was investigated; a ferromagnetic hysteresis loop was observed in the direction parallel to the nanowires, whereas antiferromagnetic hysteresis loops were observed perpendicular to the nanowire growth direction. Vertical and lateral magnetic force microscopy images of the ferromagnetic YIG nanowires revealed that the magnetization directions of the nanowires were parallel to the nanowires, which showed a single ferromagnetic domain.

1. Introduction

Nanowires have been widely researched as one dimensional (1D) materials as they have physical properties different from those of three dimensional (3D) materials [1–5]. Various materials can be formed as nanowires, including metals, semiconductors, and magnetic materials, and they exhibit physical properties unique to their 1D morphology [1–5]. Metal nanowires such as copper nanowires with a diameter less than 40 nm showed electrical conductivity values much lower than those of the bulk materials because the mean free path of the metal nanowires is shorter than that in the bulk material [6,7]. Semiconductor nanowires such as Si and Ge nanowires exhibited quantized conductivities due to their low electron density and low effective mass [8,9]. Magnetic nanowires such as Fe nanowires showed the anisotropic magnetic domain parallel to the nanowires [10,11]. Similarly, magnetic nanorods showed the anisotropic magnetic domain parallel to the nanorods [12,13]. In particular, ferromagnetic nanorods arrays are currently used for the application of high density hard disk media [14].

In general, self-assembly processes for the fabrication of nanowire or nanorod arrays have used a nanotemplate-based nanowire fabrication process using anodic aluminum oxide templates and step-edge decoration using single crystal substrates with a terraced surface [15–18]. This nanotemplate-based nanowire fabrication process produces vertical nanowire or nanorod array [15–18], whereas step-edge decoration makes it possible to form horizontal nanowires or nanorods with much higher aspect ratios than those of the nanowires or nanorods fabricated using the nanotemplate-based nanowire fabrication process [15–18].

In this study, we fabricated $Y_3Fe_5O_{12}$ (yttrium iron garnet; YIG) nanowires on highly ordered pyrolytic graphite (HOPG) substrates using step-edge decoration. We measured magnetic hysteresis loops of the horizontal YIG nanowires for the magnetic fields parallel and perpendicular to the nanowires. We further observed lateral magnetic force microscopy (LMFM) and vertical MFM (VMFM) images of the YIG nanowires.

2. Experimental procedures

Ferromagnetic YIG nanowires were deposited on the terraced surface of a HOPG using an eclipse PLD method incorporated with a step-edge decoration technique. Here, a 1 in. YIG target was used for laser ablation. A frequency-tripled Nd:YAG laser (355 nm) was used for the deposition with a distance of 5 cm between the target and substrate and a laser power of 2 J/cm^2. When the base pressure was below 5×10^{-7} Torr, we started to deposit YIG nanowires at a temperature of 850 °C with an oxygen partial pressure of 100 mTorr. The repetition rate of the pulsed laser was 2 Hz and a shadow mask technique was used to block the direct YIG plume. Note that we could optimize the target-to-substrate distance and the oxygen partial pressure by monitoring the shape and dimensions of the YIG plume during the laser ablation process.

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* Corresponding authors.
E-mail addresses: seking2000@hanmail.net, jyson@khu.ac.kr (J. Yeog Son).

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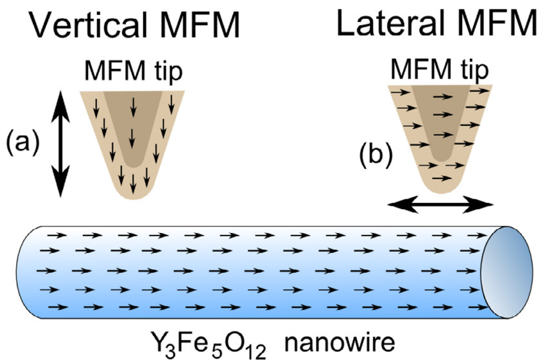

Fig. 1. Schematic of (a) vertical vibrating MFM and (b) lateral vibrating MFM used here to characterize the magnetization directions of the YIG nanowires. The magnetization direction of the MFM tip was controlled by an external magnetic field of about 0.5 T. The short and long arrows indicate the magnetization and oscillation directions of the MFM tips, respectively.

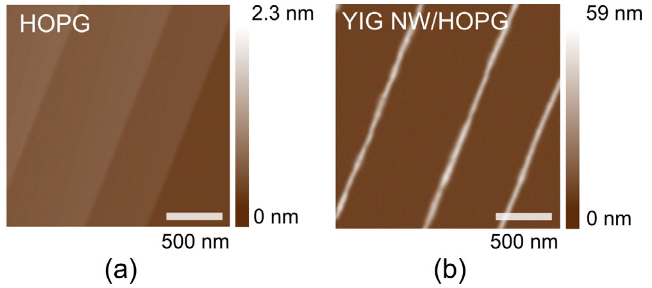

Fig. 2. (a) AFM image of the surface of a HOPG substrate where three step-edges of a terrace are clearly observed. (b) AFM image of three YIG nanowires on the three step-edges of the terrace in (a).

The interaction between the magnetization of the MFM tip for the VMFM and LMFM analyses is shown schematically in Fig. 1. When the magnetization of the MFM tip was parallel to the magnetic field of the YIG nanowires, the MFM tip experienced an attractive force, while for anti-parallel magnetization of the YIG nanowires, the MFM tip experienced a repulsive force. However, there was no force applied to the MFM tip when the magnetization of the tip was vertical to that of the YIG nanowires. Thus, the VMFM tip could not measure the magnetic force between the VMFM tip and the YIG nanowires, while this was possible using the LMFM tip. To observe the magnetic domain of the YIG nanowires, we measured the phase shift of the MFM tip obtained from the vibration of the tip in the non-contact atomic force microscopy (AFM) mode as the magnetic force measured by the MFM tip is very small. The attractive and repulsive forces between the VMFM tip and the YIG nanowires corresponded to the in-phase (bright) and out-of-phase (dark) images of the MFM data, respectively.

3. Results and discussion

Fig. 2(a) shows an AFM image of the HOPG substrate before the deposition of the YIG nanowires. All the step-edges of the terraces on the HOPG substrate showed clear contrast differences. Exposing the substrate to a pulsed laser 620 times resulted in the formation of well-aligned conformal YIG nanowires with a diameter of 70 ± 5.3 nm and thickness of 42 nm. Fig. 2(b) shows an AFM image of lateral YIG nanowires grown on each edge of a terrace on the HOPG substrate wherein the nanowires were several tens of µm long with uniform diameters. It should be noted that only YIG nanowires were formed during the fabrication processes, without any appendices such as nanoparticles or nanodots.

To investigate the crystal structure, we obtained the X-ray diffraction (XRD) pattern of the YIG nanowires on the HOPG sub-

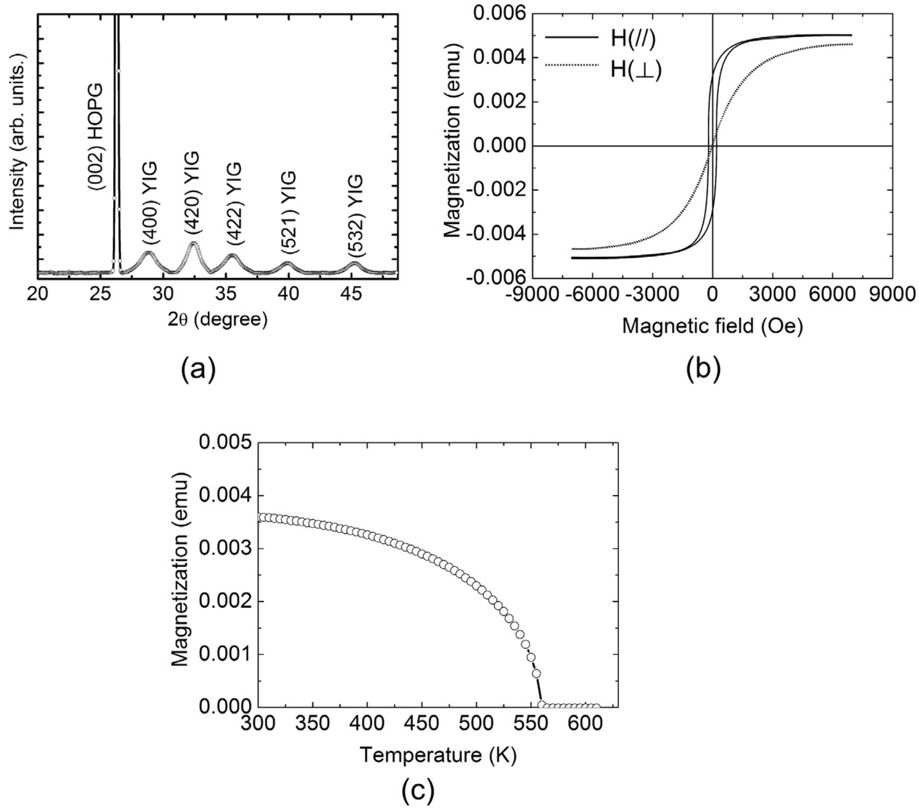

Fig. 3. (a) XRD pattern of the YIG nanowire on the HOPG substrate. (b) Hysteresis loop of the magnetization of the YIG nanowire sample perpendicular and parallel to an external magnetic field H at T = 300 K. (c) Magnetization of the YIG nanowire as a function of temperature at H = 500 eO.