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The effect of target rotation rate on structural and morphological properties of thin garnet films fabricated by pulsed laser deposition

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ABSTRACT

The effect of target rotation rate on the structural and morphological properties of pulsed laser deposition grown Bi:YIG garnets is investigated. The rotation rate dependence of the surface morphology and magnetic properties of the thin films were studied using atomic force microscopy combined with a magneto-optical measurement setup. The results show that decrease in the target rotation rate can also increase the roughness, the index of refraction, and the surface skewness and can decrease Faraday rotation by an order of magnitude.

1. Introduction

Bi-substituted garnet thin films have attracted much attention for magneto-optical applications such as magnetic-field sensors, optical switchers and magneto-optical isolators [1–3]. One of the best candidate techniques to fabricate garnet thin films is pulsed laser deposition (PLD) [4]. There are several factors associated with the PLD technique for fabrication of these films that have to be controlled carefully to optimize their properties. These parameters are the substrate temperature, heat treatment [5] and the frequency of substrate rotating [6]. In the past, the effects of these parameters were investigated, but the effects of target rotating frequency on the optical and magneto-optical properties of garnet films were not considered.

The surface behavior of thin films is an important factor in determining the performance of optical devices and plays an important role in all optical and magneto-optical applications of thin films. In this respect, we studied the magnetic and structural characteristics of Bi:YIG films prepared by PLD at different substrate temperatures and target rotating frequencies.

2. Experimental procedure

2.1. Target preparation

A stoichiometric target with the nominal composition of $BiY_2Fe_5O_{12}$ was fabricated from Y_2O_3, Fe_2O_3 and Bi_2O_3 powders by the mechanical alloying method and then solid state sintering at 850 °C for 10 h. The phase formations of the as-milled and annealed Garnet nano-powders were investigated by an X-ray diffractometer.

2.2. Thin film preparation

Magnetic garnet thin films have been deposited onto gadolinium gallium garnet ($Gd_3Ga_5O_{12}$) substrates using the third harmonic output from an Nd:YAG laser (355 nm, 6 ns pulse duration, 10 Hz repetition rate and laser fluence of 3 J/cm^2), which was focused on a rotating target. The resultant plasma cloud of material was condensed onto the substrate, which was positioned directly in front of the target at a distance of around 4 cm. The substrate was held at room temperature and at 600 °C for various samples. All depositions were carried out in a pure oxygen partial pressure of 60 mbar. To investigate the effect of target rotation rate, we deposited thin films of 100 nm thickness at three different rotation rates such as 72 (1.2 Hz), 150 (2.5 Hz) and 186 (3.1 Hz) round per minute (rpm).

Film composition and thickness were inferred from Rutherford backscattering spectroscopy (RBS) spectra. X-ray diffraction (XRD) scans were made to investigate the structural properties of the thin films. The magnetic hysteresis (*M–H*) loops of all the samples were recorded in parallel configuration (in-plane) using the magneto-optical Faraday rotation (FR) under AC magnetic field and polar magneto-optical Kerr rotation (MOKE) measurement. Optical microscopy and atomic force microscopy (AFM) were used to examine the surface quality of these films. Optical properties

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were measured using a UV-shimadzu spectroscope in the wavelength range 400–900 nm.

3. Results and discussion

3.1. Substrate temperature effect

The presence of garnet phase formations on the target was investigated by X-ray diffraction, with results shown in Fig. 1. To investigate the effect of substrate temperature, we deposited two Bi:YIG thin films on GGG substrate at room temperature (named as S_{11}) and at 600 °C (S_{22}). Directly after deposition, the S_{11} film was annealed at 700 °C for 2 h with rapid thermal annealing (RTA) and the S_{22} film was annealed in the deposition chamber under 200 mbar of oxygen pressure for 10 min. The XRD pattern of two samples of Bi:YIG thin films is shown in Fig. 2.

The wide angle scan shown in Fig. 2 reveals only the (444) and (888) reflections of the film and substrate that are sharper in the S_{22} sample with substrate temperature of 600 °C. From the insets of Fig. 2(b), it can be seen that the coherence length for X-rays in the film is rather long (at least 100 nm) because the film peaks are narrow [1]. The lattice constant of the film is 12.43 Å for the (444) direction and 12.37 Å for the (888) direction, which is very similar to garnet bulk lattice constant; this means that the lattice mismatch between the film and substrate is low in the growth direction. The full width at half maximum (FWHM) of the (444) film direction is 0.13° and 0.17° for the (888) direction; see the inset of Fig. 2(b) that indicates the good growth direction of (111).

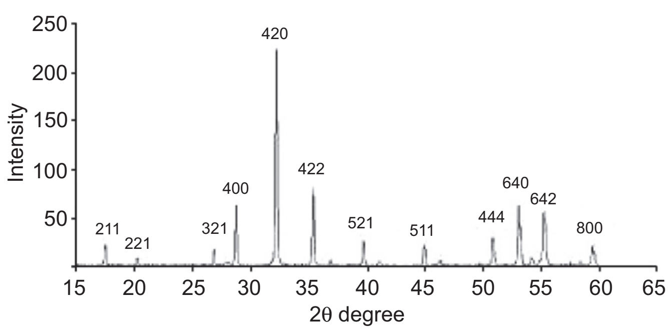

Fig. 1. XRD of Bi:YIG nano-powders used as target in the experiment.

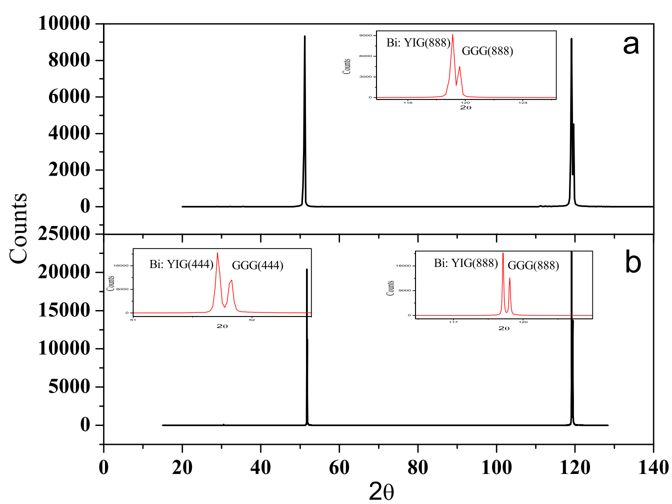

Fig. 2. XRD of Bi:YIG thin films at different substrate temperature: (a) room temperature and annealed at 700 °C and (b) with substrate temperature fixed at 600 °C.

The magnetic behavior of thin films, investigated with FR measurement, indicated that sample S_{22} provided better-quality film with higher value of magnetization and FR than S_{11}.

As mentioned above, the best structural and magnetic properties of thin films were achieved at layer with substrate temperature of 600 °C. Thus we fixed our deposition parameters and investigated the effect of target rotation rate on the properties of laser deposited thin films.

3.2. Rotation rate effect

To investigate the target rotation rate, we deposited three samples with three different frequencies (named as S_1, S_2 and S_3). The optical and mechanical properties of Bi:YIG samples were evaluated by measuring the levels of surface roughness and optical constants (n and k). The measurement results for three types of Bi:YIG films are summarized in Table 1. It can be seen that the surface roughness increases with decrease in rotation frequency, and this is confirmed in Fig. 3, which shows three-dimensional (3D) images of samples at scan rate of 1 Hz and their fast Fourier transform (FFT).

The usual application of FFT filtering is to eliminate periodic noise from uniform pattern images, such as atomic level resolution structures [7]. This is useful for the studies of surface quality with its symmetric behavior. As shown in Fig. 3(a), the FFT image is symmetric, bright and mostly confined to the region close to the origin. This indicates that the lower frequency components are of the highest intensity. This fact can be seen in Fig. 3(b) and (c), as depicted in Table 1, with asymmetric behavior and larger amount of roughness. The maximum roughness, average roughness, root mean square, root mean square value of the surface departures within the sampling area and surface skewness, which is the measure of asymmetry of surface deviations about the mean plane, all increased with decrease in rotation frequency (Fig. 4). In fact, the surface skewness can be used to describe the shape of the topography height distribution of these samples. For a Gaussian surface, which has a symmetrical shape for the surface height distribution, the skewness is zero. For an asymmetric distribution of surface heights, the skewness may be negative if the distribution has a longer tail at the lower side of the mean plane or positive if the distribution has a longer tail at the upper side of the mean plane. This parameter can give some indications of the existence of spiky features.

The increase in entropy with decrease in target rotation rate indicates that the nucleation and growth of pores are taking place spontaneously. Because of the formation of porous and rough coatings, the root mean square and average roughness values increased with decrease in target rotation rate.

On the other hand, the real and imaginary parts of refractive index of the samples were calculated from the transmittance and absorption spectra using the Kramers–Kroning relation [8].

Table 1
Optical properties and roughness of Bi:YIG thin films with different rotating frequencies.

Samples	S_1	S_2	S_3
Rotating rate	186 rpm	150 rpm	72 rpm
Maximum roughness (S_y)	74.66 nm	231.40 nm	284.56 nm
Average	39.2 nm	93.53 nm	106.38 nm
Average roughness (S_a)	5.09 nm	16.26 nm	19.23 nm
Root mean square (S_q)	7.68 nm	23.91 nm	29.48 nm
Surface skewness (S_{sk})	0.1124	0.8695	1.2361
Entropy	8.88	10.55	10.77
n	1.97	2.43	2.49
K	−0.23	−0.17	−0.05