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Mohammad Nur E Alam
Edith Cowan University

Mikhail Vasiliev
Edith Cowan University

Kamal Alameh
Edith Cowan University

EFFECT OF SUBSTRATE TEMPERATURE ON THE MAGNETO-OPTIC PROPERTIES OF $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ GARNET FILMS PREPARED BY RF SPUTTERING

M. NUR-E-ALAM, MIKHAIL VASILIEV AND KAMAL ALAMEH[1]

Electron Science Research Institute, Edith Cowan University, Joondalup, WA, 6027, Australia
[1]Department of Nanobio Materials and Electronics, Gwangju Institute of Science and Technology, World-Class University (WCU), Gwangju Institute of Science & Technology (GIST), Gwangju 500-712, South Korea
E-mail: m.nur-e-alam@ecu.edu.au

ABSTRACT

In this paper we present a study conducted on RF sputtered garnet films of composition type $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ prepared by using low and high substrate temperatures during the deposition process inside the vacuum chamber of sputtering system. Comparatively low coercive force is achieved in garnet films prepared at high substrate temperature of 680°C simultaneously with high MO quality and almost in-plane magnetization direction, which are the properties desired in various MO sensing, switching and imaging applications.

INTRODUCTION

Bismuth-substituted iron garnets are very well known to be the best magneto-optical (MO) materials for various applications in integrated optics and nano-photonics due to their strong MO behaviour and fast magnetization switching response [1]. A number of important application

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areas require MO thin films with very high MO quality and also low coercivity with either the in-plane-oriented easy axis of magnetization or having a strong in-plane magnetization component. Multiple variations in the material properties of garnets are required for different applications in integrated optics and in photonics, which can be engineered by adjusting the material composition, however every composition requires its own optimized deposition and annealing regimes. We were the first group that synthesized a garnet material of composition type $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ using the sputter-deposition technique and oven-annealing, and achieved films that possessed very high MO performance simultaneously with strong in-plane magnetization component and magnetically-soft switching behavior [2, 3].

In this paper, we investigate the effects of substrate temperature (used during the deposition of garnet layers using RF magnetron sputtering) on the materials properties and compare the results achieved using either "cold (250°C)" or "hot (680°C)" substrates.

FILM GROWTH AND CHARACTERIZATION

We fabricated highly Bi-substituted lutetium iron-aluminium garnet thin films (several batches from 650 nm to 1000 nm in thickness) using RF magnetron sputtering technology. The oxide-mix-based sputtering target of nominal stoichiometry $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ (prepared using 99.9% pure oxides) was used to deposit amorphous garnet-type layers onto different substrates (GGG, Corning Eagle XG and silicon) which crystallized into ferrimagnetic phase after annealing. As-deposited garnet layers were sputtered using two widely different substrate temperatures (250°C and 680°C as measured by a thermocouple sensor placed next to SiC heater) at high vacuum (1-2E^{-6} Torr), but the pure-argon (Ar) plasma was always kept at 1 mTorr. All the initially-amorphous films were crystallized using optimized annealing process within a conventional oven annealing system. The film thicknesses were monitored during the deposition processes using in-situ laser reflectometry and also re-measured after the deposition using the iterative fitting of their transmission spectra obtained with a UV/Visible spectrophotometer (Beckman Coulter DU 640 B) to the modeled transmission spectra. The measurements of Faraday rotation and hysteresis loop of Faraday rotation were performed with a well calibrated measurement setup using Thorlabs PAX polarimeter and a custom-made electromagnet. A transmission mode polarization microscope was used to observe the magnetic domain patterns in the annealed thin garnet films.

RESULTS AND DISCUSSION

Crystallized garnet films annealed using temperatures above 620°C (prepared on GGG substrates) showed the best optical and MO properties across the visible spectral region (532 nm and 635 nm polarized laser sources were used to characterize the MO performance of these garnet samples). The derived absorption spectra of samples (as-deposited and annealed) prepared onto GGG substrates using 250°C and 680°C deposition are plotted in Fig. 1. It is important to note that actual substrate surface temperatures were estimated to be about 30%

lower than these measured by thermocouple sensor, which is the likely reason that even samples grown on "hot" substrates were not crystallized in-situ.

Derivations of these absorption spectra were performed using the transmission spectra of samples and fitting software written by the second author, Dr. Mikhail Vasiliev, which correctly accounts for the effects of refractive index dispersion as well as reflection spectrum. All films (sputtered at either 250°C or 680°C) had rather low optical absorption and significantly high Faraday rotation, which led to obtaining high MO figures of merit ($2\Theta_F/\alpha$). The maximum measured values of Faraday rotation per unit film thickness of the garnet films prepared at 250 °C were very close to these obtained in films prepared at 680°C substrate temperature, but the lower absorption losses achieved in films prepared at higher temperature compared to other samples helped obtain a better MO figure of merit (42.8° at 635 nm) than that of the sample sputtered at 250°C. The best obtained values of MO quality factors of $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ garnet layers deposited onto GGG (111) substrates using 250°C and 680°C substrates temperature are shown in the inset of Fig. 1.

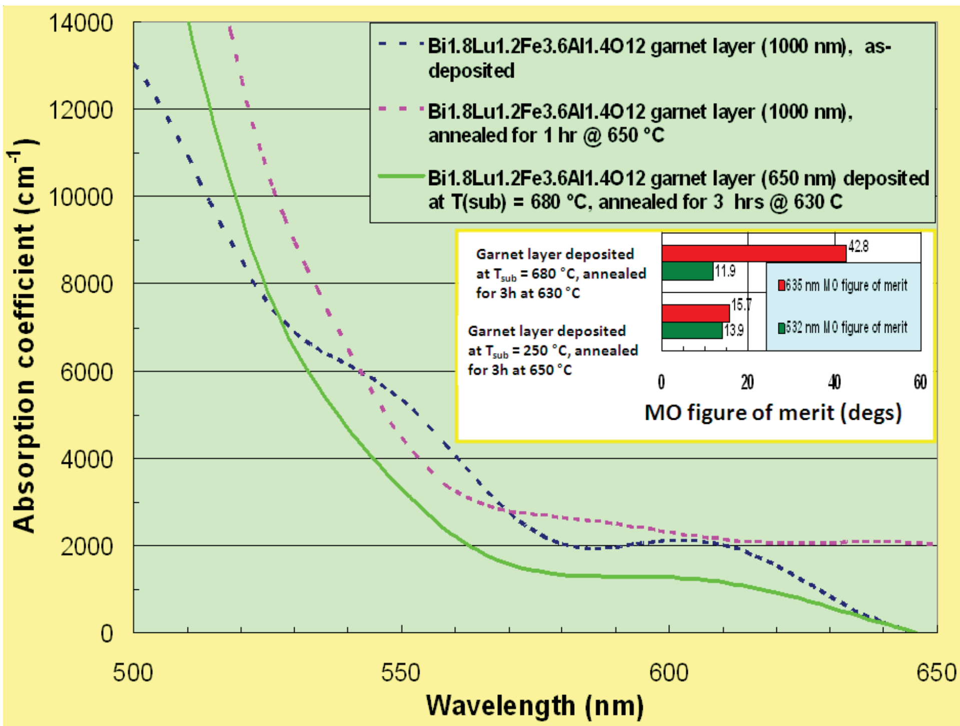

Fig. 1: Derived Absorption Spectra in Films Sputtered onto GGG Substrates using 250 °C and 680 °C Substrate Temperatures. The Values of MO Figure of Merit at 532 and 635 nm Obtained in Both Film Batches After Annealing are Shown in Inset

The magnetic films possessed very low coercive force values, as was observed during the measurements of hysteresis loop of Faraday rotation (made using a 532 nm polarized light source). Figure 2 shows the obtained hysteresis loops of specific Faraday rotation in films prepared using 250°C (green color) and also 680°C (red color) substrate temperatures. The measured coercive force values were about 45 Oe for the garnet films sputtered at 250°C and 10 (±2) Oe for the films sputtered at 680°C. Both film batches showed very strong in-plane magnetization component (weak uniaxial magnetic anisotropy), which was confirmed by the almost-linear character of their magnetization curves below the saturation observed in the measured hysteresis loops of Faraday rotation.

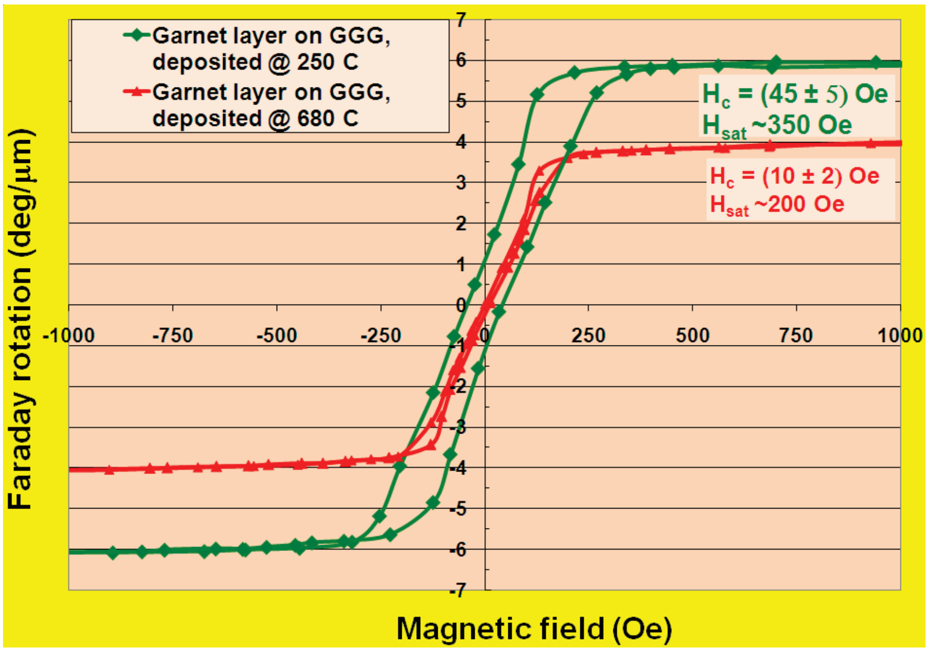

Fig. 2: Measured Hysteresis Loops of Specific Faraday Rotation at 532 nm in Sputtered $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ Garnet Films on GGG Substrates Deposited at (a) 250°C and Annealed for 1 h at 650°C, and (b) 680°C Substrate and Annealed for 3 h at 630°C.

The domain structures obtained in good-quality garnet films were observed in demagnetized samples in absence of any externally applied magnetic fields (Fig. 3 (a, b)) confirmed that the good surface quality has been achieved in the films sputtered onto GGG substrates. EDX microanalysis performed at GIST characterization labs confirmed the presence of all elements expected to be present within films (measured element concentrations in atomic % are shown Fig. 3(c)). Based on these measurement data, we derived the averaged composition of thin film to be $Bi_{1.68}Lu_{0.656}Fe_{4.294}Al_{1.184}O_{12}$ which might be expected considering the sputtering target's nominal stoichiometry and possible Bi content loss occurring during layer growth.

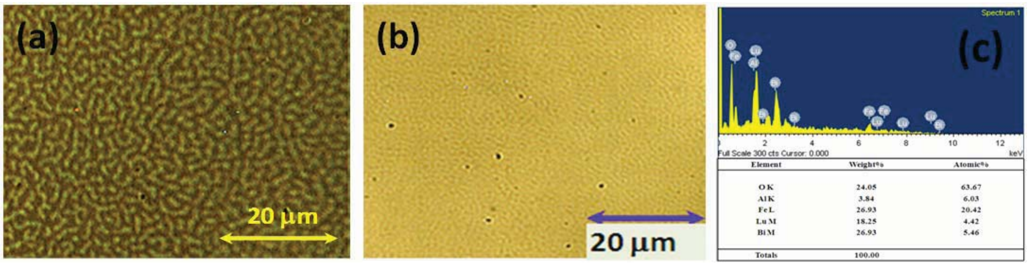

Fig. 3: Magnetic Domain Patterns Observed in Films Sputtered Onto GGG (111) at 250°C, Annealed for 1 h at 650°C (a); Deposited at 680°C and Annealed for 3 h at 630°C (b); and EDX Composition Measurement Data Obtained from Films Grown at 680°C Substrate Temperature

CONCLUSION

Magneto-optic garnet thin films of composition type $Bi_{1.8}Lu_{1.2}Fe_{3.6}Al_{1.4}O_{12}$ have been prepared using two different substrate temperatures during the deposition process and the suitable annealing process parameters for films of this type were found, leading to obtaining high quality magneto-soft thin films with excellent MO properties. Significantly low coercive forces, almost in-plane magnetization direction, and high MO performance have been observed in these garnet thin films which are attractive for MO imaging and sensing devices as well as for the future development of garnet waveguides and non-reciprocal integrated-optics components.

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