Investigation of cerium substituted europium iron garnets deposited by Biased Target Ion Beam Deposition

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We report on the deposition, crystallization, and magnetic properties of cerium substituted europium iron garnet having the general form of $(\text{CeEu})_3(\text{FeGa})_5\text{O}_{12}$. The films were deposited on gallium gadolinium garnet and fused quartz substrates using biased target ion beam deposition at a rate of 2.7 nm/min. The Ce:EIG thin film has a composition of $\text{Ce}_{1.3}\text{Eu}_{1.7}\text{Fe}_3\text{Ga}_{1.6}\text{O}_{12}$, with 30% of the Ce in the 4+ oxidation state and the remainder as Ce^{3+} . The film exhibits the primary peaks of the garnet phase in X-ray diffraction patterns. In the visible part of the electromagnetic spectrum, the film on GGG exhibits a Faraday rotation of $3.3^\circ/\mu\text{m}$ with coercivity of 0.58 kOe whereas the film on fused quartz exhibits $1.1^\circ/\mu\text{m}$ with a coercivity of 0.8 kOe. The film on the fused quartz substrate has a saturation magnetization of 17 emu/cm^3 on at room temperature.

Index Terms— Biased target ion beam deposition, cerium substituted europium iron garnets, crystallization, magnetic and magneto-optical properties, grazing angle XRD, XPS.

I. INTRODUCTION

Magneto-optic (MO) properties of iron garnets are strongly influenced by the incorporation of a number of rare earth ions[1] into the film structure. Rare earth iron garnet (RIG) thin films have attracted significant attention within the electro-optical communication industries and are extensively used for applications in a variety of magnetic, microwave and magneto-optic devices such as optical isolators[2] and magnetic field sensors[3]. Enhancement in MO properties is due to $4f^n \rightarrow 4f^{n-1} 5d$ transitions[4]. Cerium based iron garnets are of interest for their applications in both the blue region of the visible spectrum[5] and in the infrared (IR) spectrum around 1550nm, with applications demonstrated in optical communications[6]. Incorporation of europium in iron garnets leads to large positive anisotropies[7] and increased coercivities[8]. The europium iron garnets have been reported to exhibit a rectangular hysteresis loop[9] suitable for “latched” switched applications.

Cerium substituted RIG (Ce:RIG) thin films have been fabricated using a variety of techniques, including sputtering[10-12], pulsed laser deposition[13], plasma enhanced metal organic chemical vapor deposition[4], metal organic chemical liquid deposition[4] and sol gel[14]. Our approach uses a relatively new technique known as biased target ion beam deposition (BTIBD)[15]. This is a reactive sputtering technique where an ion source is used to provide low energy ions that are accelerated via electrostatic potential towards the biased targets to generate sputtering. The deposition occurs concurrently from up to 4 metal targets simultaneously. The rate of sputtering from each target is controlled by varying the duty cycle of the applied bias. The

method has been successfully applied to $(\text{BiDy})_3(\text{FeAl})_5\text{O}_{12}$ garnets producing high quality films[16]. The primary advantage of this technique is that the garnet composition can be readily changed by controlling the relative duty cycle of the bias applied to the individual targets.

Incorporation of cerium in yttrium iron garnets (Ce:YIG) has been shown to enhance the Faraday rotation (FR) in the IR region[3, 13], due to the intra-ionic electric dipole transitions between the $4f$ and $5d$ configurations[17]. To further increase the FR there is a need to optimize the amount of cerium incorporated into the garnet[11]. In order to maintain the garnet structure, cerium substitution into the YIG should predominantly be in the form of Ce^{3+} ions. However, under most conditions used for the preparation of garnet materials the cerium is likely to be in the Ce^{4+} state and additional mechanisms need to be used to ensure the preferred Ce^{3+} oxidation state in the cerium substituted iron garnet films, using techniques like hydrolysis of alkoxides[14] and annealing techniques[12, 18] .

Discrete isolators and circulators have been made successfully using bulk magneto-optical garnets, but integration onto non-garnet substrates has been challenging due to a mismatch in lattice constant and coefficient of thermal expansion, as well as the formation of undesirable non-garnet phases. Ce:YIG ($\text{Ce}_x\text{Y}_{3-x}\text{IG}$) with $x=1$ could be grown on garnet substrates but on non-garnet substrates x has been found to be limited to 0.7 before other phases appear[19]. In this paper, we report on an investigation of high cerium doping of europium iron garnet (Ce:EIG) films on non-garnet fused quartz and lattice matched (111) oriented gallium gadolinium garnet (GGG) substrates for potential applications in the blue region of the visible spectrum. The Ce:EIG films are deposited from separate metallic targets (cerium, europium, iron and gallium) using a reactive ion beam

consisting of a controlled mixture of argon and oxygen during sputtering. This deposition technique is compatible with semiconductor substrates as the film growth takes place at low temperatures (80-120°C). The film crystallisation, surface morphology, magnetic and magneto-optical properties of the films on both substrates are examined. In this work, we suppressed the formation of Ce^{4+} using vacuum and inert atmosphere annealing and characterized the oxidation state using X-ray photoelectron spectroscopy (XPS).

II. EXPERIMENT AND SAMPLE PREPARATION

The schematic diagram of the BTIBD system is shown in Fig. 1. A low energy argon ion source is directed at the negatively biased sputtering targets. Both the negative bias and the duty cycle can be controlled to vary the deposition rate from each target thereby controlling the film composition. We found that, for a fixed negative bias of -800V, varying the pulse width alone for each target provides sufficient control. At lower bias voltage the deposition rate for some targets would be too low. The frequency of the cycle used is 71.43kHz (14μsec per full cycle), and the on time pulse width for each target is shown in Table 1. The plasma sheath that develops on the surface of the negatively biased targets accelerates positive plasma ions towards the targets and results in sputtering of the target material. If not accelerated, the low energy ions do not possess sufficient energy to produce sputtering. Oxygen is introduced to provide reactive sputtering and hence generate oxides on the substrate. The bias voltage pulse width as well as the magnitude of the negative bias is used to control the sputtering rate from the targets. The flow of argon and oxygen gases is controlled by mass flow controllers and the oxygen partial pressure (PP) control is maintained through a residual gas analyser (RGA) feedback loop.

FIG. 1 HERE

In this experiment, we grew Ce:EIG with a nominal composition of $(\text{CeEu})_3(\text{FeGa})_5\text{O}_{12}$ on fused quartz and gallium gadolinium garnet (GGG) substrates. Controlling the chemical composition of the garnet was achieved by calibrating the deposition rate of the individual metal oxides; i.e. cerium (CeO_2), europium (Eu_2O_3), iron (Fe_2O_3) and gallium (Ga_2O_3), over a range of deposition conditions. The individual metal oxides were deposited at various duty cycles and partial pressures of oxygen. The effective formula-unit (FU) flux density[16], Φ_{FU} [$\text{FU cm}^{-2}\text{s}^{-1}$], was obtained at each duty cycle. This is expressed in terms of the velocity of the moving growth surface, v_{surf} [cm s^{-1}], and FU density in the solid film, ρ_{FU} [FU cm^{-3}], and is given by:

$$\Phi_{\text{FU}} = v_{\text{surf}} \cdot \rho_{\text{FU}} \quad (1)$$

Here v_{surf} and ρ_{FU} are calculated by the relations,

$$v_{\text{surf}} = \frac{\text{final film thickness [cm]}}{\text{total deposition duration [s]}} \quad (2)$$

$$\rho_{\text{FU}} = \frac{\Phi_{\text{FU}} \cdot N_A}{\text{MW}} \quad (3)$$

where

ρ_{film} [g cm^{-3}] – macroscopic density of the film,

N_A [FU mole^{-1}] – Avagadro's number,

MW [g mole^{-1}] – gram molecular weight of the formula unit; for example Fe_2O_3 , CeO_2 etc.

Since iron oxide is the major component, about 50% in FU of the garnet, it was taken to be the rate limiting component. The PP of oxygen was set to a value that maximised the iron oxide (Fe_2O_3) growth rate, and its flux density was calculated. Taking the iron oxide flux density as a reference, the flux densities of other metal oxides are calculated and the duty cycles for each target were adjusted to generate a garnet film with the desired garnet composition $(\text{CeEu})_3(\text{FeGa})_5\text{O}_{12}$ [16]. The voltage bias and duty cycles for each target, along with sputtering conditions to obtain the Ce:EIG are shown in Table I.

TABLE 1 HERE

The average thickness of each film was measured using a Veeco Dektak 150 contact type stylus profilometer. The chemical composition of the individual metal oxide films were determined by electron microprobe analysis (EPMA) (JOEL 8530) while the composition of the garnet film was determined by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). A two stage post deposition heat treatment[12] was performed using a rapid thermal annealer (RTA ASONE-100). The first stage consisted of annealing at 750°C under vacuum for 3 minutes to suppress the Ce^{4+} oxidation state. The second annealing stage was at 875°C under nitrogen for 15 minutes to further crystallize the film and to enhance the magnetic properties. The oxidation state of cerium in as-deposited and annealed films was obtained using XPS. The X-ray diffraction (XRD) patterns were obtained using grazing angle XRD using a PANalytical EMPYREAN system. The MO properties were measured using an in-house built magneto-optical spectrometer based on the design of Kahl[20]. The magnetic properties of the film were measured at room temperature with the magnetic field parallel to the film plane using a 7 Tesla Quantum Design Magnetic Property Measurement System SQuID susceptometer and longitudinal magneto-optical Kerr effect (LMOKE) magnetometry. LMOKE magnetometry was carried out using a differential detection technique[21] utilising a HeNe laser at 632.8nm and a 1MHz balanced photo receiver pair (New Focus model 2307). The surface of the film and its roughness were characterised using optical microscopy (OLYMPUS BX 51) and atomic force microscopy (Digital Instruments D3000 SPM), respectively. The surface roughness of the sample was determined from the AFM image using the NanoScope software's (version 5.30r1¹) roughness analysis.

¹ NanoScope Software User Guide, Veeco Instruments Inc.

III. RESULTS AND DISCUSSION

A. Annealing and crystallinity

Grazing angle XRD of the as-deposited individual metal oxides and annealed Ce:EIG films on fused quartz substrates are shown in Fig. 2. The individual metal oxide films deposited by the BTBD system were polycrystalline exhibiting primary peaks of the corresponding oxides [22-25]. The broadened peaks in the XRD pattern of the as-deposited individual oxides are the result of small size of the as-deposited crystals in the polycrystalline films.

FIG. 2 HERE

Fig. 2 shows the XRD pattern of as-deposited Ce:EIG, and following each of the two annealing stages; 750°C vacuum annealing and a subsequent annealing at 875°C under nitrogen. The as-deposited Ce:EIG shows a weak broad hump around 32° which represents an amorphous film. Following annealing at 750°C under vacuum the broadened hump at 32° is replaced by a weak broad peak at 32° and another broadened hump at 28° appears. This represents the start of the crystallisation of the garnet phase. Following the second annealing at 875°C in nitrogen a number of stronger peaks consistent with the primary garnet phases (28°, 32° and 35°) appear as the sample crystallises further.

B. Surface morphology and topographical studies

The two stage post-annealed surfaces of the Ce:EIG films deposited on both fused quartz and GGG substrates where characterized using atomic force microscopy (AFM) and are shown in Fig. 3. The films prepared on GGG and fused quartz substrates have rms surface roughness (R_q) values of ~14nm (± 3 nm) and ~27nm (± 3 nm), respectively. In comparison the surface roughness of the as-deposited films was found to have a common value of ~11nm (± 3 nm) films for both substrates. Fig. 3a shows ridges and valleys formed on the surface of the film on fused quartz substrate and their spacing correlates well with surface cracks observed by optical microscopy. This is most likely due to differential thermal expansion of the film on fused quartz substrate during annealing process while no cracks were found on the sample annealed on GGG substrate.

FIG. 3 HERE

C. Chemical composition

The composition of the individual metal oxides deposited on glass substrates were CeO₂, Eu₂O₃, Fe₂O₃ and Ga₂O₃ as determined using EPMA and XRD. The chemical composition of the garnet film deposited on a fused quartz substrate, obtained using LA-ICP-MS was Ce_{1.3}Eu_{1.7}Fe₃Ga_{1.6}O₁₂, before and after annealing. Since the GGG and fused quartz substrates are placed together in the chamber, it can be assumed that the composition is the same on both substrates.

Fig. 4 shows the cerium XPS signal for the as-deposited and annealed Ce:EIG films as a function of the binding energy. The spectra presented in Fig. 4 consist of a number of overlapping peaks. Peaks labelled v_0 , v' , u_0 , u' are the peaks

corresponding to cerium in Ce³⁺ state and v , v'' , v''' , u , u'' , u''' are the peaks corresponding to cerium in Ce⁴⁺ state. The concentration of Ce³⁺, [Ce(III)] and Ce⁴⁺, [Ce(IV)] from peaks in the Ce_{3d} spectrum can be determined from the following equations[26]:

$$[\text{Ce(III)}] = \frac{\text{Ce(III)}}{\text{Ce(III)} + \text{Ce(IV)}} \quad (4)$$

$$[\text{Ce(IV)}] = \frac{\text{Ce(IV)}}{\text{Ce(III)} + \text{Ce(IV)}} \quad (5)$$

where

$$\text{Ce(III)} = v_0 + v' + u_0 + u' \text{ and} \quad (6)$$

$$\text{Ce(IV)} = v + v'' + v''' + u + u'' + u''' \quad (7)$$

represents the corresponding sums of the integrated peak areas related to the Ce³⁺ and Ce⁴⁺ XPS signals, respectively. The XPS data of the as-deposited Ce:EIG film presented in Fig. 4(a) fits closely to what is expected for CeO₂, and shows the presence of cerium in the oxidation state of Ce⁴⁺. We have performed XPS on as-deposited cerium oxide and have obtained a Ce XPS spectrum that is identical to what is shown in Fig. 4(a). In Fig. 4(a), there are small u' and v' peaks, indicating the presence of some Ce₂O₃ phase in the as-deposited Ce:EIG film. The XPS spectrum for the double-stage annealed Ce:EIG in Fig. 4(b) shows the presence of peaks corresponding to Ce³⁺ and Ce⁴⁺ and indicates that after annealing cerium is present in both Ce³⁺ and Ce⁴⁺ oxidation states. Using the equations (4-7), it is calculated that after two stage annealing the concentration of Ce³⁺ in Ce:EIG film is ~70% whereas ~30% remain in Ce⁴⁺ state. Therefore, the 1.3 formula unit (FU) of cerium in the LA-ICP-MS determined chemical composition Ce_{1.3}Eu_{1.7}Fe₃Ga_{1.6}O₁₂ has 0.9 FU of Ce³⁺ and 0.4 FU of Ce⁴⁺. By charge balancing the chemical equation, the amount of oxygen in the film is found to be ~3% less than the expected 12 FU that was previously assumed during the analysis of LA-ICP-MS results.

FIG. 4 HERE

D. Magnetic properties

A hysteresis loop of the Ce:EIG film on a fused quartz substrate is shown in Fig. 5 where the background contribution from the fused quartz substrate has been removed. The film has a coercivity of 0.8 kOe and a saturation magnetisation of 17 emu/cm³, as measured in a magnetic field of 12 kOe. SQUID magnetometry could not be used for the Ce:EIG film on the GGG substrate due to the substrate's large paramagnetic moment which obscured the signal from the film. Instead, the field-induced magnetic reversal of the Ce:EIG film was measured using LMOKE magnetometry.

FIG 5 HERE

Fig. 6 shows the normalized LMOKE signal from the film deposited on the GGG substrate as a function of field (swept at

a rate of $\sim 10^5$ Oe/s) from which a coercivity of (0.58 ± 0.01) kOe can be extracted. The coercivity of the film on the GGG substrate (measured using MOKE magnetometry; Fig. 6) is significantly smaller than the coercivity of the film on the fused quartz substrate (measured using SQUID magnetometry; Fig. 5). As such, the latter sample could not be fully saturated using existing MOKE magnetometer which has a maximum applied field of 2500 Oe.

The In Table II is a comparison of the magnetic properties of our Ce:EIG to other similar rare earth iron garnets. The substitution of europium with bismuth in the EIG tends to increase coercivity[8], which can also be observed in the Ce:EIG film reported here. Europium incorporation has reportedly also resulted in a rectangular hysteresis loop[9], however, although significant hysteresis is apparent, a purely rectangular hysteresis loop has not been observed in this work. Nevertheless, a rather high remnant magnetization (88 ± 4 % of the LMOKE signal at saturation) is observed in the LMOKE loop. The value of saturation magnetization reported in the Ce:EIG films in this study is significantly lower as compared to other literature reports (summarized in Table II), an effect which may be due to the presence of gallium in the film[5].

FIG. 6 HERE
TABLE II HERE

E. Magneto-optical properties

The magneto-optical properties of the annealed garnet deposited on fused quartz and GGG substrates are summarized in Fig. 7 – 9. Fig. 7 shows the measured percent optical transmission for the Ce:EIG films on fused quartz and GGG substrates as a function of wavelength. The optical constants namely, refractive index (n) and the extinction co-efficient (k) of the film deposited on fused quartz and GGG substrates were obtained by fitting the data in Fig. 7 with the Cauchy model including surface roughness and are shown in Fig. 8. At a wavelength of 433nm, the value of n for films on fused quartz and GGG substrates were 2.3 and 2.4, respectively. While the value of k for fused quartz and GGG substrates were 0.11 and 0.09, respectively. The reduced refractive index of the film on fused quartz as shown in Fig. 8 could be due to surface roughness [27], however the large crystallite of the film on GGG can increase the film density and raise the refractive index. The increased extinction coefficient for the film on fused quartz is due to the increased surface roughness and consequent scattering.

FIG. 7 HERE
FIG. 8 HERE

Fig. 9 shows the annealed garnet's FR spectra on both substrates, as a function of wavelength of the transmitted light. At the wavelength of 433 nm, the film deposited on GGG exhibits a FR of 3.3 $^\circ/\mu\text{m}$ whereas the film deposited on fused quartz film exhibits a FR of 1.1 $^\circ/\mu\text{m}$. Table II also shows summaries of the MO properties of various RIGs for comparison with the Ce:EIG garnet presented here. Other

garnet films grown on non-garnet substrates were found to have a FR value as high as 2.3 $^\circ/\mu\text{m}$ at a wavelength of 630 nm[28], and the films grown on garnet substrates were found to have a FR value of about 5 $^\circ/\mu\text{m}$ at the wavelength of 450 nm[29]. In comparison to these literature reports, the FR measured for our Ce:EIG film on GGG substrate is somewhat reduced, possibly due to the substitution of iron by gallium[30]. However, most garnets listed in Table II, irrespective of substrate, were analysed in the green and infra red wavelength ranges rather than near the 433 nm wavelength of interest in this study. Therefore, and as expected, the optical constants of RIG reported for a wavelength of 1550nm listed in Table II[19, 29] are lower than the values obtained at 430nm wavelength reported in this work. Overall, the optical properties of the prepared Ce:EIG films on fused quartz and GGG substrates are comparable with other RIG films prepared on similar substrates.

FIG. 9 HERE

IV. CONCLUSION

We have extensively investigated Ce:EIG films deposited on fused quartz and GGG substrates, using biased target ion beam deposition. A two stage post deposition annealing resulted in the transition of cerium from Ce^{4+} to Ce^{3+} oxidation state and crystallisation of the garnet film. Overall, the properties of the obtained Ce:EIG films on fused quartz and GGG substrates are comparable with other RIG films reported in the literature that were prepared on similar class substrates, i.e. garnet and non-garnet substrates.

One of the original aims of this work was to investigate techniques for preparation of rare earth garnets that could be integrated with conventional silicon based semiconductor processing. The biased target ion beam deposition technique itself is compatible; however the high temperatures required to crystallise the Ce:EIG and large thermal stresses generated are not compatible. In order to generate integrated magneto-optical components the thermal budget must be significantly reduced.

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In 1985-86 he was awarded an ARGC Research Fellowship and was a Member of original Networking Group in the Department of Electrical and Electronic Engineering UWA developing the QPSX technology which was subsequently standardized as IEEE 802.6. He continued to work in the communications industry and subsequently led several ASIC design teams from 1987 to 2004. He became involved in drivers for magneto-optic material and began working in 2005 as a contractor for ST Synergy Ltd (later becoming Panorama Synergy Ltd), and has worked in the magneto-optic area ever since and has several patent applications in this area.

Mariusz Martyniuk was born in Poland in 1976. He received the B.Sc. degree (hons) from the University of Toronto, ON, Canada, the M.A.Sc. degree from McMaster University, ON, Canada, and the Ph.D. degree in 2007 from The University of Western Australia, Perth, Australia.

He worked in the industry sector as an Electronics Engineer before rejoining The University of Western Australia where he is currently a Research Professor with the Microelectronics Research Group and manages the Western Australian Node of the Australian National Fabrication Facility. His primary areas of interest encompass thin-film materials and thin-film mechanics, as well as their applications in micro-electromechanical systems and optoelectronic devices.

Dr. Martyniuk's research contributions were recognized in 2008 by the award of the inaugural Australian Museum Eureka Prize (the Oscars of Australian science) for "Outstanding Science in support of Defence or National Security."

Robert C. Woodward received his B.Appl.Sc. degree in metallurgy from Curtin University, Perth, Australia, in 1987 and Ph.D. from The University of Western Australia, Perth, in 2003.

He is currently a Research Fellow in the BioMagnetics group in the School of Physics, The University of Western Australia, Perth, Australia. His research is based around understanding magnetic materials and the magnetic fields they generate, how these materials and fields interact with each other, how these interactions can be observed and characterised and finally how these interactions are used to generate tangible effects, devices and technologies.

Peter J. Metaxas received the B.Sc. (Hons.) degree from the University of Western Australia, Crawley, Western Australia, in 2004 and the Ph.D. degree in physics from the University of Western Australia and the Université Paris-Sud 11, Orsay, France, in 2009. He became a member of the IEEE in 2007.

He carried out two years of post-doctoral research at the Unité Mixte de Physique CNRS/Thales, Palaiseau, France, and has also worked at the Georgia Institute of Technology, Atlanta, USA, as a visiting scientist. Since September 2012, he has held a Research Assistant Professor position at the University of Western Australia's School of Physics, funded by an Australian Research Council Discovery Early Career Researcher Award. His primary areas of interest are spintronics and magnetic domain wall dynamics. He is author of 14 papers and one book chapter.

Dr Metaxas has been the recipient of a University of Western Australia Whitfield Fellowship, an American Australian Association Pratt Fellowship and a Marie Curie Early Stage Research Training fellowship.

John M. Dell is a Professor of electrical engineering at The University of Western Australia, Perth, Australia.

His primary areas of interest are semiconductor optoelectronics and optical MEMS devices. He has worked in both industry and academia in these fields. Work undertaken by his group on robust, low-cost microspectrometer technology has attracted funding from the US and Australian Defence Departments and more recently from the Australian Grains Research and Development Corporation. This latter funding is for the development of low-cost tools using IR spectroscopy for broad acre agriculture applications. This work is being undertaken as a collaboration between electrical engineers and soil scientists. He has several patents, over 200 journal and conference publications.

Lorenzo Faraone was born in Italy on October 26, 1951. He received the Ph.D. degree from the University of Western Australia (UWA), Perth, Australia, in 1979.

After, he worked as a Research Scientist at Lehigh University, PA (1979–1980), where he was involved in studies on MOS devices. From 1980 to 1986 he was a Member of Technical Staff at RCA Laboratories, David Sarnoff Research Center, Princeton, NJ, working on VLSI CMOS and non-volatile memory technologies, and space radiation effects in silicon-on-sapphire MOS integrated circuits. He joined the School of Electrical, Electronic and Computer Engineering at UWA in 1987, where he has held the position of Professor since 1998, and the position of Head of Department/School from 1999 to 2003. Since his arrival at UWA his research interests have been in the area of compound semiconductor materials and devices, and micro-electromechanical systems (MEMS). In particular, his interests include Mercury Cadmium Telluride materials and device technologies for infrared detector arrays, Gallium Nitride technology for ultra-violet detectors and high-speed/high-power electronics, and MEMS technologies for tuneable optical cavity infrared detectors. He currently holds more than 10 US patents, has supervised more than 25 Ph.D. student completions, and published more than 300 refereed technical papers in journals and conference proceedings.

Prof. Faraone was awarded the RCA Laboratories Individual Outstanding Achievement Award in 1983 and 1986, and the John de Laeter Innovation Award in 1997.

Fig. 1. Biased Target Ion Beam Deposition (BTIBD) system (Courtesy: 4WAVE Inc.).

Fig. 2. XRD plots of double stage annealed, single stage annealed and as-deposited Ce:EIG films on fused quartz substrates, and for Fe_2O_3 , Ga_2O_3 , CeO_2 and Eu_2O_3 films deposited on glass substrates. The patterns have been offset vertically for clarity.

Fig. 3. Surface morphology of the Ce:EIG on (a) fused quartz, and (b) GGG substrates after annealing as measured using AFM. The vertical scale is common to both images.

Fig. 4. Cerium XPS spectra in (a) as-deposited and (b) two-stage annealed Ce:EIG films on fused quartz substrates.

Fig. 5. Magnetisation versus magnetic field curve for a Ce:EIG film on a fused quartz substrate with the magnetic field applied parallel to the film

Fig. 6. Normalized LMOKE hysteresis loop (16 averages) for the Ce:EIG film on GGG with the magnetic field applied parallel to the film plane after subtraction of a linear background signal.

Fig. 7. Optical transmission spectra as a function of wavelength for the annealed Ce:EIG films deposited on fused quartz and on GGG substrates fitted using Cauchy model.

Fig. 8. Optical constants n and k as a function of wavelength for the annealed Ce:EIG films deposited on fused quartz and GGG substrates.

Fig. 9. FR spectra as a function of wavelength for the annealed Ce:EIG films deposited on fused quartz and GGG substrates.

TABLE I

BTIBD sputtering conditions used to deposit Ce:EIG

Deposition process parameters	Values / comments
Targets for deposition	cerium, europium, iron, gallium (99.99% pure)
Target ON time (14 μ sec full cycle)	Ce: 3 μ s, Eu: 5.2 μ s, Fe: 4.9 μ s, Ga: 2 μ s
Sputter gas	Argon flow at 42sccm
Process gas	Oxygen controlled by RGA set for 1×10^{-6} torr PP
Chamber pressure	Base pressure: 6.2×10^{-8} torr During deposition: $4.9\text{--}5.2 \times 10^{-4}$ torr
Substrate temperature	80–120°C
Substrate rotation rate	20 rpm
Target bias voltage	Negative bias: - 800V Positive bias: + 5V
Average thickness of the film	160nm
Deposition rate	2.67nm/min

TABLE II

Comparison of Ce:EIG films
with other RIGs

Substrate [Ref]	This report Ce:EIG		Other literature Reports							
	GGG	Fused quartz	EIG		Bi:EIG		Ce:YIG			
			Not given [31]	Ca/Mg/Zr substituted GGG [7]	Ca/Mg/Zr substituted GGG [7]	GGG[8]	GSGG [^] [29]	SOI ⁺ [19]	GGG [13]	SiO ₂ [28]
Composition	Ce _{1.3} Eu _{1.7} Fe ₃ Ga _{1.6} O ₁₂		-	Eu ₃ Fe ₅ O ₁₂	Bi _{1.3} Eu _{1.7} Fe ₅ O ₁₂	Bi ₂ Eu ₁ Fe ₅ O ₁₂	Ce ₁ Y ₂ Fe ₅ O ₁₂			
FR (°/μm) at Wavelength (nm)	3.3 at 433	1.1 at 433	-0.054 at 3250	0.27 at 510*	-2.06 at 633	1.325 at Not given	5* at 450	-0.11 at 1550	4 at 430	2.3 at 630
Optical constants at wavelength (nm)	n		-	-	-	-	2.21 at 1550	2.25 at 1550	-	-
	k		-	-	-	-	2.8×10 ⁻⁵ at 1550	8.3×10 ⁻⁵ at 1550	-	-
Coercivity (Oe)	580	800	-	-	-	1100	-	150- 250*	35	-
Saturation Magnetisation (emu/cm ³)	-	17	-	-	-	110-150	-	80-120*	100	-

[^] Gadolinium scandium gallium garnet

⁺ Silicon on insulator