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The influence of substrate temperature and annealing on the properties of pulsed laser-deposited YIG films on fused quartz substrate

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ABSTRACT

Yttrium iron garnet (YIG) thin films were deposited on fused quartz substrate at different substrate temperatures (T_s) varying from room temperature (RT) to 850 °C using pulsed laser deposition (PLD) technique. All the films in the as-deposited state were X-ray amorphous and non-magnetic at RT. The film deposited at RT after annealing at temperatures $T_a \geqslant 700$ °C showed both X-ray peaks and the magnetic order. The films deposited at higher T_s (500–850 °C) and then annealed at 700 °C resulted in better-quality films with higher $4\pi M_s$ value. The highest value of magnetization was for the sample deposited at 850 °C and annealed at 700 °C, which is 68% of the bulk $4\pi M_s$ value.
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1. Introduction

Ferrite thin films are considered as potential candidates for magnetic and magneto-optical recording media applications, and hence are being studied since several years [1–4]. These films require a thermal treatment either in the form of substrate heating while deposition or in the form of post-deposition annealing to optimize their properties. Even after thermal treatment the magnetic properties of the films have been reported to be different from their bulk counterparts [5–9]. Recently, there has been interest in the deposition of thin films of yttrium iron garnet (YIG) [7,9–11]. Unlike the spinel ferrites, the magnetization in these films, when deposited on fused quartz substrates using pulsed laser deposition (PLD), can even become larger than the bulk values [7]. It has, however, been shown by us that the properties of PLD YIG thin films are very much dependent on the nature of the substrate [9,11]. Single phase, YIG thin films with saturation magnetization ($4\pi M_s$) value close to that of the bulk have been grown on single-crystal $Gd_3Ga_5O_{12}$ (GGG) substrates [9]. YIG thin films when deposited on Si substrate, on the other hand, have resulted in nanocrystalline YIG mixed with orthoferrite ($YFeO_3$) phase, with lower $4\pi M_s$ value [11].

In the present paper, we present a study on the influence of thermal treatment on the evolution of structural and magnetic properties of YIG thin films deposited by PLD on fused quartz substrates.

2. Experimental details

The PLD has been employed to deposit polycrystalline YIG thin films on fused quartz substrates using a stoichiometric YIG target. The third harmonic (355 nm) of Nd:YAG (yttrium aluminum garnet) laser, with 10 Hz repetition rate and 5–6 ns pulse width, was used to ablate the target. Typical fluence of the laser beam on the target, kept at a distance of 4.5 cm from the substrate, was 2.5 J/cm^2. The depositions were carried out in pure oxygen pressure of 0.16 mbar at different substrate temperatures (T_s) varying from room temperature (RT) to 850 °C. Here, the RT means a deposition at the ambient substrate temperature in the chamber without heating or cooling the substrate. Some of the films were subjected to a post-deposition annealing (ex situ) in air for 2 h.

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The thicknesses of the films were measured by stylus profilometer and were around 200 nm. X-ray diffraction (XRD) θ– 2θ scans were made to investigate the structural properties of the thin films. Magnetic measurements were carried out at ambient temperature (298 K) using a vibrating sample magnetometer (VSM). The magnetic hysteresis (M–H) loops of all the samples were recorded in parallel configuration (in-plane), i.e. with the field applied along the film plane. The M–H loops were corrected for diamagnetic substrate contribution. The optical microscopy and the scanning electron microscope were used to examine the surface quality of these films. It was observed that films were almost free from any crack. Also, the films showed a very good adherence to the substrate, as even the ultrasonic treatment in organic solvents such as acetone and isopropyl alcohol did not peel the films off.

3. Results and discussion

The XRD of YIG thin films deposited at different T_s is shown in Fig. 1. It is seen that the films deposited in the entire T_s range (RT to 850 °C) do not show any sharp peak. The absence of sharp peaks in the as-deposited ferrite films without any substrate heating is quite common, and is related to the nanocrystalline nature of the sample. These films when examined by transmission electron microscopy (TEM) normally show clear rings with a very small grain size [12,13]. To increase the grain size to a level where XRD peaks could be observed, the films have to be subjected to a thermal treatment. This treatment can either be in the form of a substrate heating or a post-deposition annealing or a combination of both. As an example, Bohra et al. [5] observed no sharp XRD peak in the case of PLD Zn ferrite thin films on quartz substrates when deposited at RT, but peaks were observed for $T_s \geqslant 200$ °C. Similarly, Popova et al. [7] observed, in the case of PLD YIG thin films on quartz substrate, that films were devoid of any sharp XRD peaks when prepared at low T_s ($\leqslant 400$ °C), but the same could be observed for T_s above 400 °C. They deposited YIG thin films with relatively higher laser fluence (3–9 J/cm^2) and in lower oxygen pressure (0.04 mbar). Dumont et al. [14] have deposited oxygen off-stoichiometric YIG thin films on SiO_2 substrates using PLD by varying the base oxygen partial pressure between 15 and 400 mTorr. They observed that the polycrystalline single-phase YIG, with slight texture could be grown at 840 °C of substrate temperature and 30 mTorr of oxygen pressure. Sui and Kryder [15] and Dash [16], on the other hand, reported that sputter-deposited M-type barium ferrite thin films on Si substrates, and lithium zinc ferrite thin films on quartz substrate deposited at ambient substrate temperature start showing sharp XRD peaks after post-deposition annealing at or above 700 and 750 °C, respectively. In our earlier study of PLD YIG thin films on single-crystal Si(1 0 0) and GGG(1 1 1) substrates, XRD peaks were seen when films were deposited at $T_s \geqslant 600$ and 750 °C, respectively [9]. It is, therefore, quite interesting that in our present case we do not see any XRD peak even when films are deposited at T_s of 850 °C. These results clearly demonstrate that both the deposition conditions and the nature of the substrate play a vital role in the grain growth in the YIG films deposited by PLD. Moreover, just the substrate heating during deposition is not enough for the grain growth when amorphous quartz substrates are used.

In order to see if post-deposition annealing will help in the observation of XRD peaks, we annealed the RT-deposited film at temperatures (T_a) varying between 600 and 800 °C. Fig. 2(a) shows XRD of such annealed films for different T_a. As is clear from this figure, XRD peaks, indexed to single-phase YIG (standard JCPDS file no. 43-0507), were seen for $T_a \geqslant 700$ °C. It is noteworthy that the film annealed at the highest T_a of 850 °C, shows two peaks other than YIG. These additional peaks can be indexed to (1 0 0) and (1 0 1) of SiO_2. The presence of additional peaks can be because of reasons like crystallization of quartz substrate along with probable diffusion between the film and the substrate.

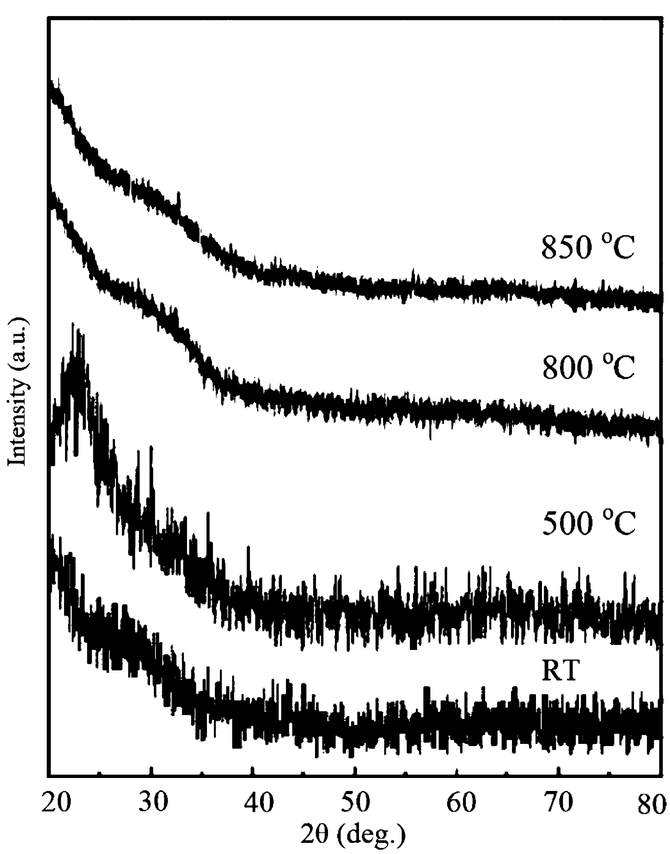

Fig. 1. XRD of YIG thin films deposited at different substrate temperatures (T_s).

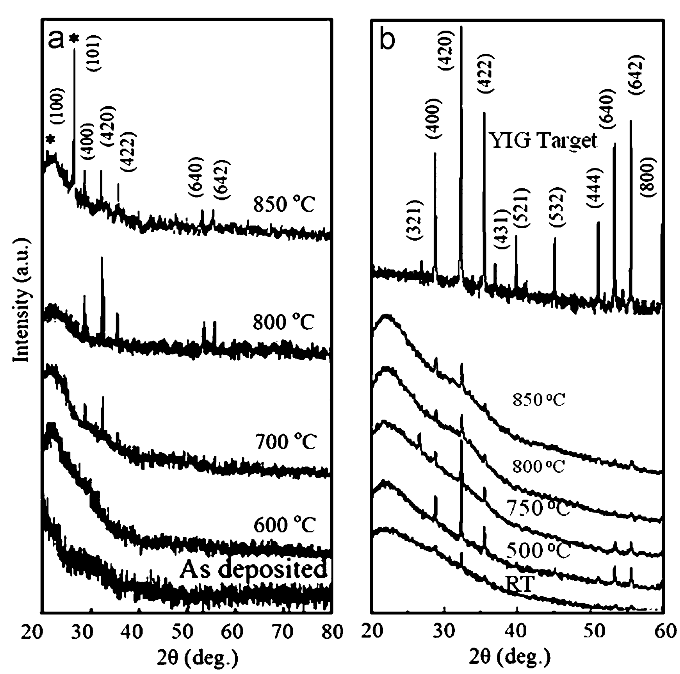

Fig. 2. XRD of YIG thin films (a) deposited at RT and annealed at different temperatures (peaks marked by '*' correspond to SiO_2) (b) XRD of YIG target and of the films deposited at different substrate temperatures and annealed at 700 °C.

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