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The room temperature deposition of high-quality epitaxial yttrium iron garnet thin film via RF sputtering

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ABSTRACT

Yttrium iron garnet (YIG) has great potential in the application of microwave devices and spintronics. However, the extremely high temperature for the growth of single crystalline YIG thin film on garnet substrate has being a barrier hindering its massive production and wide application, especially for some integrated devices which cannot bear high temperature for a long time. In this work, epitaxial single crystalline YIG thin films were successfully obtained by deposition on (111)-oriented gadolinium gallium garnet (GGG) at room temperature via RF sputtering followed by a short-time post-annealing treatment. Their structural and physical properties were carefully studied and compared with that of YIG/GGG(111) thin films deposited at high temperatures. The relatively large saturated magnetization (~120 emu/cc) and a comparable linewidth (~55 Oe) of those room-temperature-deposited YIG thin films can be achieved. This provides a viable alternative for growing YIG thin films on GGG or other garnet substrates.

1. Introduction

Ferrimagnetic yttrium iron garnet ($Y_3Fe_5O_{12}$, YIG) has attracted researchers' decades of attention for application in microwave devices and spintronics due to its relatively high Curie temperature (T_C ~ 550 K), excellent magneto-optic Kerr effect [1,2] and low magnetic loss [3–5]. Various techniques have been used to fabricate YIG thin films, such as Liquid Phase Epitaxy (LPE) [2,6], Pulsed Laser Deposition (PLD) [7–9] and Radio Frequency (RF) magnetron sputtering [10–12]. Although LPE and PLD are wellknown for growing single-crystalline thick film with high quality and high deposition rate, respectively, RF magnetron sputtering is better at producing thin film with smooth sample surface and stable stoichiometric ratio, which is more recognized by industries and suit for massive production. Previous study indicates epitaxial growth of YIG films with high quality using sputtering requires high processing temperature (above 750 °C), which hinders its wide application [13,14]. Although other growth method was applied to solve this problem, such as post-annealing process after deposition at low temperature, especially on some non-garget substrates such as silicon or quartz which could be widely used in large-scale practical production [10,12,15], there is few study to comprehensively analyze the effect of post-annealing process on YIG thin film grown on garnet substrates. It will be very important for industrial community if epitaxial YIG thin films could be massively produced on garnet substrates after being deposited at room temperature then annealed at high temperature. In this case, it will not be so critical for the choice of film-growth facility, especially for those without heater. And it will be quite efficient once large batches of films could be annealed in a furnace at the same time. Most importantly, this technique will benefit many devices which cannot stand for a long period at a relatively high temperature. In this work, epitaxial YIG thin films were grown on (111)-oriented gadolinium gallium garnet ($Gd_3Ga_5O_{12}$, GGG) substrates at room temperature by RF sputtering then annealed at high temperatures. By a series of systematical analysis of both structural and physical properties of YIG thin films prepared via different routes, we found that the physical properties of those films are comparable with that grown under high temperatures, presenting a proper way to obtain engineering desired ferrites through carefully tuning their growth conditions.

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2. Experimental section

All the YIG thin films were grown on paramagnetic (111)-oriented GGG substrate (lattice parameter a = 12.383 Å), which has a theoretically small lattice mismatch of ~0.06% compared with that of bulk YIG (lattice parameter a = 12.376 Å). The growth atmosphere was pure argon with a pressure of 0.02 mbar when YIG thin films were grown at room temperature (RT) for 8 h, followed by two different post-annealing treatments. During the annealing, these YIG thin films were kept in pure oxygen gas at 850 °C for 2 h and 10 h, respectively. And the pressure was controlled at 1.5 mbar. For comparison, YIG films were also deposited at the ambient of Ar/O_2 mixing gas (in the ratio of 1:1) with fixed deposition pressure of 0.02 mbar for 3 h. The deposition temperature varied from 700 °C to 850 °C with the interval of 50 °C in order to find the optimal growth temperature.

Afterwards, the crystallinity of both room-temperature-deposited YIG (RT-YIG) and high-temperature-deposited YIG (HT-YIG) films were examined by a high Resolution PANalytical X'pert X-ray diffractometer (HRXRD) and a Transmission Electron Microscope (TEM). Their morphologies were scanned via Atomic Force Microscopy (AFM). The ferromagnetic resonance and magnetic properties were also measured through a JES-FA200 EPR system and a Quantum Design PPMS with Vibrating Sample Magnetometer (VSM) components, respectively.

3. Results and discussion

In order to verify the crystallinity of HT- and RT-YIG thin films, θ-2θ scans, ϕ scans and RSMs by XRD were adopted. Fig. 1(a) shows the θ-2θ spectra of YIG/GGG (111) thin films grown at different high temperatures under 0.02 mbar in a certain atmosphere consisting of equal ratio of argon and oxygen. As shown in this figure, single-crystal YIG phase begins to form when the deposition temperature is increased to 750 °C, which agrees with previous studies [13,14]. The only preferred orientation is along [444] direction and its peak position shifts from $2\theta = 49.810°-50.170°$ with the increase of the growth temperature. According to previous studies by Martin L. W. etc. [16] and Wang Ying etc. [17], during a sputtering process, the substrate temperature determines the growth mode and the microstructure of thin films. The relatively high temperature contributes to the lower surface energy of substrate and relaxed strain, which can lead to high-quality epitaxial YIG thin films and less structural defects in them. The fringes can also be observed for 850°C-3h sample (deposited at 850 °C for 3 h), showing the good single-crystalline quality as well as a smooth surface, just as indicated by the AFM image, shown as the right inset in Fig. 1(a), the mean roughness of 850°C-3h film is only 0.15 nm. Its rocking curve along [444] direction is displayed in the left inset in Fig. 1(a). The full width at half maximum (FWHM) value is 0.0245°, which is quite narrow that further indicating the excellent crystallinity of YIG thin films grown on GGG (111) substrate under high temperatures.

Similarly, the diffraction peak appears at about $2\theta = 50.685°$ for RT-YIG thin films, as shown in Fig. 1(b). The angle of this peak position is higher than that of HT-YIG samples which we assumed to be caused by a relatively full strain relaxation. The preferred orientation is still along [444] direction, and the fringes can be also observed for both RT-YIG thin films. However, it can be obviously seen that the [444] diffraction peak of YIG thin film becomes

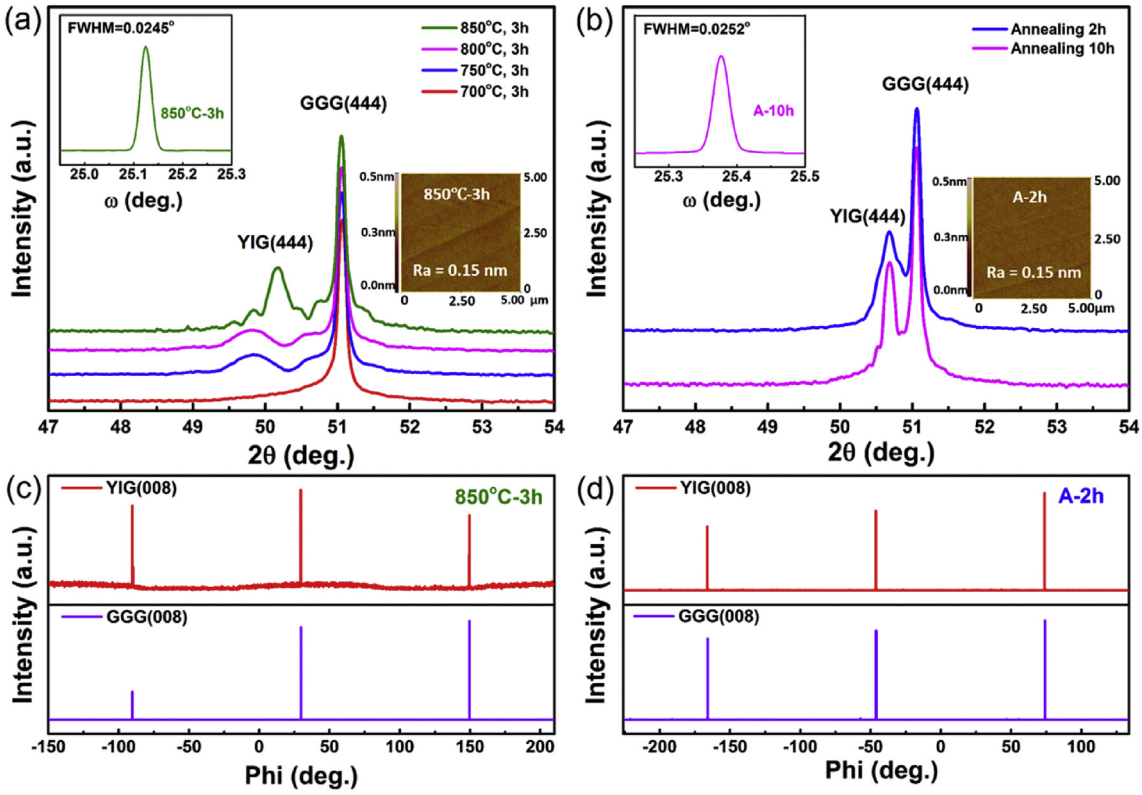

Fig. 1. The θ-2θ and Phi scan spectra of HT-YIG/GGG (111) thin films (a, c) and RT-YIG/GGG (111) thin films (b, d). The left insets in (a) and (b) show the rocking curve and FWHM value of 850°C-3h and A-10 h YIG thin films, respectively. The right insets in (a) and (b) show the morphologies of 850°C-3h and A-2h films, respectively, and the mean roughness (Ra) has been displayed on each image. The Phi scans of films (Red curves) and substrates (Purple curves) are all examined along (008) direction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)