Preparation and characterisation of ferrimagnetic crystalline YIG thin films deposited by DC Magnetron Sputtering for magnonic research applications

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Introduction

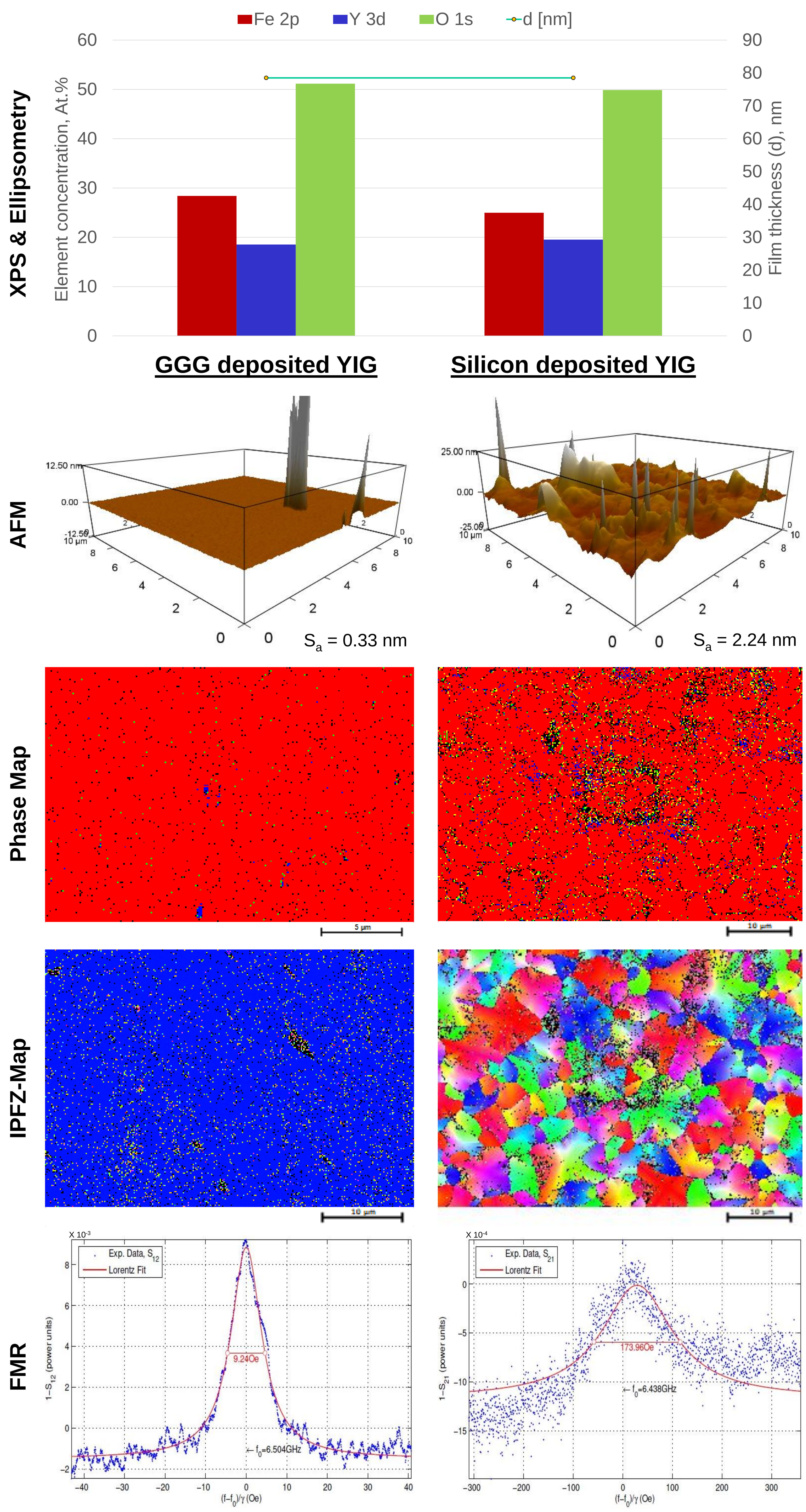
High-quality sub-100 nm-thin Yttrium Iron Garnet (YIG) films are the current state-of-the-art approach to exploring new possibilities for technological applications of spin waves in the field of magnonics. YIG, a magnetic insulator, possesses the lowest known spin-wave damping characteristics and the narrowest FMR linewidth, which makes it the most promising material for magnonic applications.

As the magnetic ordering of YIG is directly related to its crystal structure, a thin film of YIG must be made with high crystal quality to achieve desired magnetic properties, such as low damping and high saturation magnetisation. Gadolinium Gallium Garnet (GGG) substrates are usually used to deposit YIG films in magnonics research as both materials have the same crystal structure and almost the same lattice constant. Due to the high cost and difficulty in integrating GGG substrates into electronic or optical circuits, many studies have attempted other substrates such as Si/SiO_2 and MgO as an alternative for YIG deposition [1].

To date, the best YIG films have been grown via the high-temperature liquid phase epitaxy (LPE). This method is convenient for growing only thicker films. Alternatively, sputtering can be used to grow high-quality magnetic garnet thin films.

This work aimed to demonstrate the feasibility of growing high-quality sub-100 nm-thin YIG films on different substrates using a reactive DC magnetron co-sputtering method.

Results



Fabrication and Diagnostics

At room temperature, various sub-100 nm thin YIG films were deposited on silicon (100) and GGG (111) substrates via DC magnetron sputtering. The deposition parameters, such as cathode (yttrium) power and flow rate (oxygen as a reactive gas), were systematically varied in an acceptable range to tune the desired magnetic film properties. Their effects on depositing film properties were also investigated.

As-deposited YIG films resulted in an amorphous phase, so, to crystallize the material, the films were subjected to post-annealing at 850 °C, for 1 hour, in atmospheric air. Further, all the films were diagnosed according to their surface morphology, chemical composition, optical features, thickness, crystallinity, and magnetic characteristics. Several material diagnostic methods like XPS, AFM, EBSD, Ellipsometry and FMR were employed to analyze the intrinsic nature of the film material.

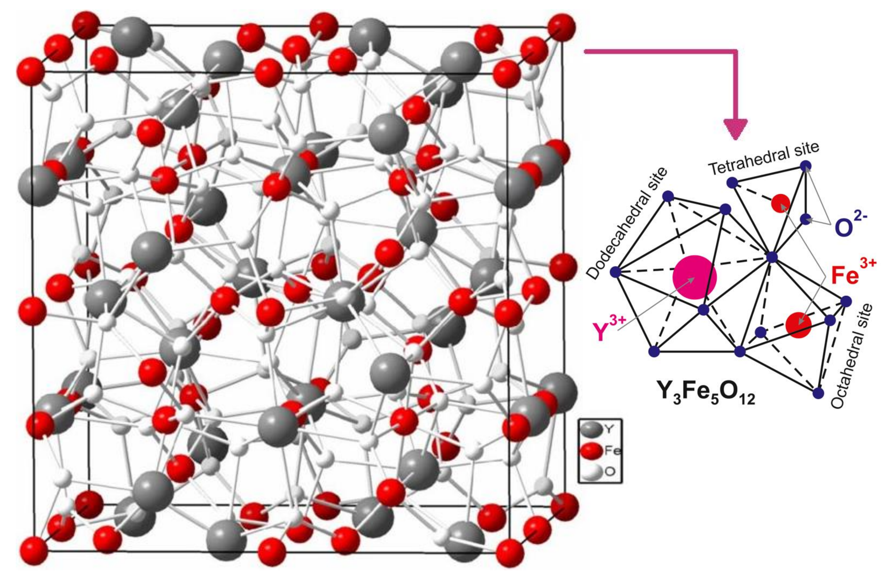


Figure 1 - *The crystallographic and atomic structure of yttrium iron garnet ($Y_3Fe_5O_{12}$) unit cell, containing three distinct sub-lattices of cations [2, 3]*

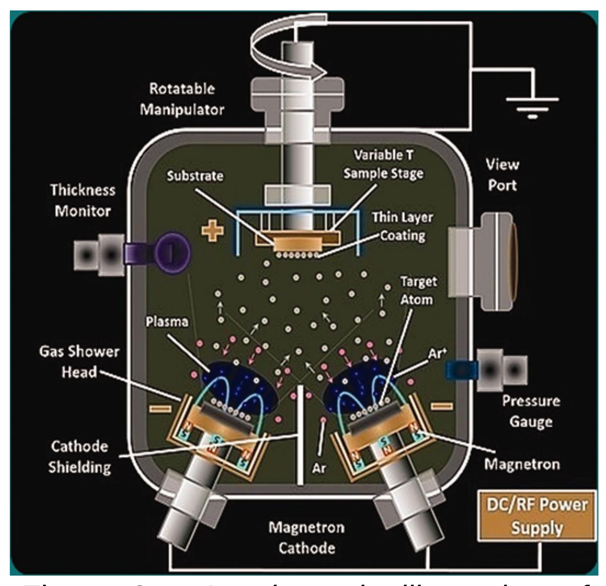


Figure 2 - *A schematic illustration of magnetron co-sputter deposition from two separated cathodes [4]*

Discussion

GGG-deposited YIG films have shown, in most cases, impressive magnetic and structural features as compared to silicon-deposited films. Post-annealed YIG/GGG was analyzed to be a monocrystalline film via EBSD with having an allover YIG phase (coloured in red) with uniformly [111] textured microstructural-crystallographic characteristics. In contrast, polycrystalline YIG with micron-sized grains can be clearly distinguished from inverse pole figure mapping of the silicon-deposited film, in which each colour represents different crystal orientations. For example, blue, red, and green represent [111], [001], and [101] crystal orientations respectively in a cubic system.

It was observed that the annealing procedure negatively affects the structural quality since the roughness of the as-deposited film on both substrates well amplifies after thermal treatment. While the GGG-deposited annealed film shows relatively smoother surface features than the silicon-deposited film.

Highly oriented post-annealed YIG crystal was grown on a GGG substrate demonstrating a small FMR linewidth (ΔH) of 9.1 Oe suggesting an LPE-like growth. While ΔH for the traditionally prepared YIG film using liquid phase epitaxy is stated to be about 1 Oe. This value is quite low among films prepared using various vapour phase epitaxy methods [5].

Conclusion and Outlook

For the first time in history, we reported growing quality YIG thin films using the DC magnetron co-sputtering method. Post-annealing procedure played a crucial role in improving structural and magnetic ordering to produce high-quality films.

A broader FMR linewidth around 174 Oe was observed for the polycrystalline YIG film deposited on a silicon wafer due to the consequence of uneven grain size distribution and random crystal orientations. The possible reason for polycrystalline YIG on silicon is that the silicon oxide layer is normally formed on the surface of the monocrystalline silicon wafer.

By studying the effects of sample preparation conditions, it was discovered that the thickness and stoichiometry of the film material can be heavily influenced by the cathode power of the sputtering target, while the roughness and optical features remain less affected. The amount of reactive gas concentration at the time of deposition inevitably affects all the above-mentioned film properties.

From a practical point of view, the overall material quality of the DC-sputtered YIG layers can be improved further, via fine-tuning of the crucial processing conditions. For instance, cathode power, reactive gas concentration and post-annealing procedure over a broad range. To deposit monocrystalline YIG directly on oxidised silicon, the undesired oxide layer could be removed using ion etching before the deposition of YIG on silicon or an additional crystalline layer could be deposited as a buffer layer such as yttrium oxide.

References:

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