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Recent developments in magneto-optic garnet-type thin-film materials synthesis

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Abstract

Magneto-optic (MO) garnets are used in a range of applications in nanophotonics, integrated optics, communications and imaging. Bi-substituted iron garnets of different compositions are the most useful class of materials in applied magneto-optics due to their excellent MO properties (large Faraday effect) and record-high MO figure of merit among all semi-transparent dielectrics. It is highly desirable to synthesise garnets which possess simultaneously a high MO figure of merit and large uniaxial magnetic anisotropy. However, the simultaneous optimization of several material properties and parameters can be difficult in single-layer garnet thin films, and it is also challenging to prepare films with high bismuth content using physical vapor deposition technologies. To meet the current challenge of developing next-generation functional MO materials, we design, develop and demonstrate the functionality of new magnetostatically-altered all-garnet multilayer heterostructures using two different garnet materials of dissimilar anisotropy types (out-of-plane and almost-in-plane). The multilayer structures possess simultaneously a high MO figure of merit and large uniaxial magnetic anisotropy together with low coercivity, if each of the layers is optimized in composition and annealed correctly. We prepare thin-film heterostructures by sandwiching a MO garnet layer with almost in-plane magnetization in-between two MO garnet layers with out-of-plane magnetization using RF sputtering. We apply customised high-temperature oven annealing processes (optimized in temperature and process durations after running many trials) for the as-deposited (amorphous) garnet multilayers to obtain the crystalline garnet phase in every layer. These structures then possess simultaneously a high optical/MO quality and low coercivity, which is very attractive for the development of magnetic photonic crystals, sensing devices and ultra-fast switches. Based on Bi-substituted ferrite garnets grown on garnet substrates, this new and unique method for the development of new magnetic materials, enables customized magnetic properties to be attained, and can be used to develop novel types of synthetic garnet materials.

Keywords: MO garnets, nanocomposites, co-sputtering, multilayer heterostructures, nanophotonics, integrated optics, magneto-photonic crystals, magneto-plasmonic crystals.

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1. Introduction

Bi-substituted iron garnets of different composition types are the most useful class of functional materials in applied magneto-optics, due to their excellent MO properties (large Faraday rotation) and record-high MO figure of merit among all semi-transparent dielectrics. These materials can possess attractive magnetic properties and high specific Faraday rotation, if the deposited layers contain a high volumetric fraction of the garnet phase with good surface quality and microstructure. Numerous research studies have been conducted to understand the relationship between the MO properties (Faraday and Kerr rotation) and the bismuth content (substitution level, the number of Bi atoms per formula unit) in each garnet-type material system. A strong dependence of Faraday rotation (FR) on the level of bismuth substitution in thin film materials has been seen in garnet films developed using liquid-phase epitaxy (LPE). The extrapolated value of the specific FR of the fully bismuth-substituted $Bi_3Fe_5O_{12}$ has been evaluated (based on these investigations) to be about 6 °/µm at the wavelength of 633 nm [1]. Recently, electron cyclotron resonance (ECR) sputtered $Bi_3Fe_5O_{12}$ films have been shown to demonstrate the specific Faraday rotation of about 8.4 °/µm at 633 nm [2, 3]. LPE films having a record-high Bi-content demonstrated a linear growth of specific Faraday rotation with increasing bismuth content, which was obtained through compositional changes from $Lu_3Fe_5O_{12}$ to $Bi_{2.4}Lu_{0.6}Fe_5O_{12}$ [4]. In order to investigate the source of such disagreements between the measured properties of highly Bi-substituted garnets and theory predictions, and also to try and increase the number of bismuth atoms per unit formula in our sputtered films, we have synthesized a range of co-sputtered nano-composite garnet-type materials. In particular, we have prepared garnet-type composite thin films by co-sputtering from two separate ceramic (oxide-mix-based) targets using either two different garnet-stoichiometry targets or a garnet-type target co-deposited with an extra oxide [5,6]. The flexibility of the co-sputtering approach has enabled many final stoichiometry variations within nano-composites by simply varying the RF power levels applied to the sputtering targets. It has also been found that an important feature of RF sputtering deposition relevant to garnet materials synthesis is the ability to transfer relatively unchanged target stoichiometries to the films grown on various substrate types (garnet or glass) which allows growth of garnet-type films with bismuth substitution levels approaching three atoms per formula unit.

In this paper, we report on the successful synthesis of several new types of high-performance MO garnet-type nano-composite and heterostructure-type materials (obtained in the form of single-layer and multilayer thin films) of potential significance in applied magneto-optics which exhibit very promising properties suggesting suitability for a wide range of applications in integrated optics such as development of next-generation magnetic photonic crystals (MPC), magneto-plasmonic crystals, MO transparencies, ultra-fast switching and sensing devices.

2. Materials synthesis and related process parameters

The synthesis of thin-film garnet-type nano-composites and fabrication of all-garnet multilayer structures required optimization of several technological processes ranging from the sputtering target stoichiometry selection, substrate-cleaning techniques, RF sputtering deposition processes to the annealing crystallization processes (which needed to be fine-tuned for crystallizing each material type).

2.1. RF magnetron co-sputtering technology

All garnet and garnet-oxide composite thin films and all-garnet multilayer heterostructures were deposited using RF magnetron sputtering in pure argon plasma. RF magnetron sputtering is an enhanced method that allows thin film deposition at low operating pressures resulting in high quality thin films [4, 7-10]. In order to deposit thin-film garnet layers onto the substrates using sputtering technology, the following parameters needed