Ferrimagnetic garnets for integrated non-reciprocal devices

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***Abstract* – Ferrimagnetic garnets are promising materials for applications in integrated non-reciprocal devices due to their low optical absorption and relatively large magneto-optical response at telecommunication wavelengths. However, their implementation into phonotic chips is rather difficult due to large lattice parameters and thermal expansion mismatch with common photonic substrates. In this talk, we present our latest progress in the growth, fabrication and characterization of various ferrimagnetic iron garnets on silicon substrates with excellent optical and magneto-optical properties expressed in terms of high Figure of Merit.**

The current situation in the field of information technology suggests the need for substantial conceptual changes. The rapid development of imaging devices with the ever-increasing resolution, progress in three-dimensional imaging, and implementation of new power consuming software tools, including artificial intelligence, start to put significant demands on improvement in the data transmission, processing and storage. Motivated by recent rapid development the attention in optical fiber communication moved towards photonic integrated circuits (PICs), which combine laser sources, modulators, and detectors on one inexpensive silicon platform using well-established and compatible silicon device processing techniques [1-6].

For their successful application, PICs would benefit from the integration of magneto-optical isolators. These isolators suppress multiple reflections between the various optical components which could destabilize the laser source, thereby reducing demands on precision manufacturing processes and increasing the efficiency of information transmission. They are taking advantage of magneto-optical phenomena which induce a non-reciprocal phase shift in a resonator (Fig. 1) or interferometer device, which avoids problems caused by the birefringence of optical waveguides.

A family of ferrimagnetic iron garnets is widely used for fabrication of discrete bulk isolators due to their excellent optical transmission and high magneto-optical response at desired optical wavelengths. However, their integration on PICs is very challenging due to their large lattice parameters and thermal expansion mismatch with conventional silicon technology. When prepared in the form of thin films, garnets

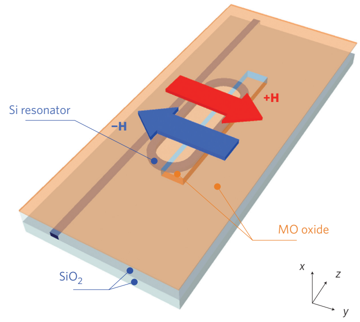

Fig. 1. Scheme of the nonreciprocal optical resonator structure [6].

usually exhibit noticeably weaker magneto-optical response than in bulk. Moreover, when conventionally deposited on silicon substrates, they exhibit negligible magneto-optical response insufficient for a functional integrated non-reciprocal element. The Figure of merit (FoM) – a ratio of Faraday rotation and absorption coefficient,

$$FoM\ [°\ dB^{-1}] = \frac{\theta_F[°\ cm^{-1}]}{\alpha\ [dB\ cm^{-1}]}, \quad (1)$$

which is commonly used for the estimation of the magneto-optical functionality is usually tens of deg/dB [6,7] in thin films compared to thousands in bulk materials [8].

In this talk, we present our recent progress in the deposition and characterization of several types of ferrimagnetic iron garnets with various compositions. A special deposition conditions and post-deposition treatment allowed us to obtain high quality garnet thin films even at silicon substrates with FoM exceeding half of bulk values.

Thin films were grown by pulsed laser deposition with a KrF laser at λ = 248 nm in oxygen atmosphere from Ce and Bi doped $Y_3Fe_5O_{12}$ (YIG) and Ce and Bi doped $Tb_3Fe_5O_{12}$ (TbIG) targets with nominal compositions. The targets were prepared by a conventional mixed oxide sintering method. The substrate was heated during the growth and rapid thermal annealing process was applied after the deposition. The samples were characterized by X-ray diffraction and vibrating sample magnetometry to check their crystallinity and magnetic

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properties. A range of different substrate temperatures and oxygen pressures were used to optimize the growth.

Optical characterization was done employing full Mueller matrix spectroscopic ellipsometer J.A. Woollam RC2 with dual rotating compensators in the spectral range from 0.7 to 6 eV in reflection geometry. At least three angles of incidence were used to acquire large enough ensemble of experimental data for the following fitting. The experimental ellipsometric data Ψ and Δ were fitted using a theoretical model of thin garnets layers on a substrate. To parametrize the dispersion of optical parameters and absorption coefficient a sum of Cody-Lorentz oscillators was used, and their parameters were fitted together with the thicknesses of the garnet layers.

Magneto-optical spectrometer with rotating analyzer was used to measure Faraday Rotation (FR) of investigated samples in the spectral range from 0.7 to 4.5 eV. The highest applied magnetic field was depending on the particular sample and was always large enough to fully saturate the sample. With the knowledge of the absorption coefficient and FR we were able to calculate FoM of particular materials and express their abilities in non-reciprocal devices.

In the growth of Bi doped YIG on Si substrates annealing of single layer Bi:YIG films did not produce a garnet phase. However an inclusion of a YIG seed layer led to crystallization into garnet phase as was previously shown for Ce:YIG [6]. Bilayers consisting of Bi:YIG with a YIG seed layer below or above the Bi:YIG were deposited and annealed [9]. FR loops of such samples at 0.8 eV are shown in Fig. 2. The amplitude of FR depends on the concentration of Bi^{3+} ions as they induce high spin-orbit coupling that increases excited state splitting and hence enhances magneto-optical effects.

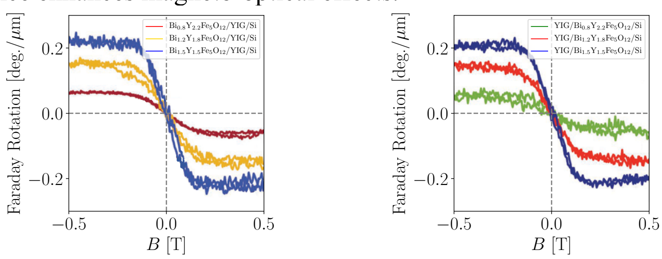

Fig. 2. FR hysteresis loops of Bi:YIG/YIG and YIG/Bi:YIG bilayers deposited on Si substrates.

Both types of bilayers exhibit similar magneto-optical properties with relatively large FR. The spectral dependence of absorption coefficient of YIG/$Bi_{0.8}$YIG and $Bi_{1.5}$/YIG bilayers is displayed in Fig 3. Both samples exhibit a decrease of absorption towards infrared region inducing high FoM as shown in Table I. The higher FoM is obtained for the sample with higher concentration of Bi^{3+} due to larger FR. The values of FoM are exceptionally large with respect to the Si substrate, which makes the bilayer deposition and following rapid thermal annealing process suitable for application purposes. It was also shown that the garnet layer grows also at waveguide sidewalls. Moreover, the YIG/BiYIG bilayer allows the magneto-optical Bi:YIG layer to be placed in direct contact with an underlying waveguide which is expected to increase optical coupling into the Bi:YIG and improve the performance of integrated optical isolators.

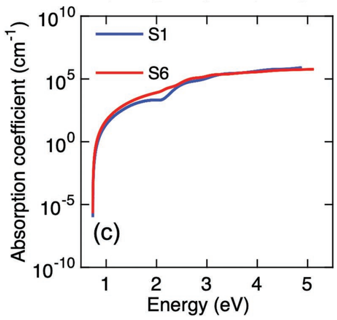

Fig. 3. Spectral dependence of absorption coefficient of YIG/$Bi_{0.8}$YIG (blue) and $Bi_{1.5}$/YIG (red) bilayers on Si substrate [9].

The growth becomes easier for the group of Ce and Bi doped TbIGs where the YIG seed layer is not necessary for the crystallization of the garnet phase. Therefore, one can obtain similar values of FoM with only single garnet layer on silicon substrate (see Table I).

TABLE I
FoM FOR DIFFERENT GARNETS GROWN ON Si SUBSTRATES

MO material and substrate	FoM [°dB^{-1}]	Reference
Y2.82Ce0.18Fe5O12 bulk	1420	[8]
CeYIG on YIG on Si substrate	38	[7]
Ce:YIG on Si substrate	21.8	[6]
YIG/Bi0.8YIG on Si substrate	397	This talk [9]
Bi1.5YIG/YIG on Si substrate	796	This talk [9]
TbIG on Si substrate	176.7	This talk [10]
$Ce_{0.25}$TbIG on Si substrate	539	This talk [10]
$Bi_{0.02}$TbIG on Si substrate	722.6	This talk [10]

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