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Fabrication and characterization of $\text{As}_2\text{S}_3/\text{Y}_3\text{Fe}_5\text{O}_{12}$ and $\text{Y}_3\text{Fe}_5\text{O}_{12}/\text{SOI}$ strip-loaded waveguides for integrated optical isolator applications

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ABSTRACT

We report two novel strategies to integrate magneto-optical oxides on oxidized silicon and SOI platforms based on strip-loaded waveguide structures. By using conventional waveguide fabrication and thin film deposition techniques, strip-loaded waveguides for magneto-optical non-reciprocal phase shift (NRPS) applications can be integrated on a silicon platform. As a demonstration, two structures, i.e. $\text{As}_2\text{S}_3/\text{Y}_3\text{Fe}_5\text{O}_{12}$ (YIG) and YIG/SOI waveguides are fabricated. Using pulsed-laser deposition followed by rapid thermal annealing, yttrium iron oxide films in which more than 95 vol.% had crystallized into the YIG phase were achieved on both substrates. The optical loss of the $\text{As}_2\text{S}_3/\text{Y}_3\text{Fe}_5\text{O}_{12}$ waveguide was characterized by a cut-back method to be ~ 10 dB/cm at 1550 nm, while the optical loss of a 450nm wide YIG/SOI waveguide was determined to be 41 dB/cm at 1550 nm by measuring the quality factor Q of a pulley-type ring resonator consisting of such waveguides. The propagation loss of polycrystalline YIG on a SiO_2/Si substrate was around 50 dB/cm at 1550 nm wavelength. The NRPS and figure of merit of both waveguides were simulated. It is suggested that a Bi:YIG or Ce:YIG layer may be integrated in these waveguide structures to achieve a higher NRPS and figure of merit for optical isolator applications. These waveguide fabrication techniques offer a compact, low cost and etch-free route for integrating magneto-optical materials on a silicon platform, which may be useful for making future integrated optical isolators and other magneto-optical components.

KEY WORDS: Integrated magneto-optical isolator, Strip-loaded waveguides, magnetic garnets, chalcogenide glass, silicon integration

1. INTRODUCTION

Magneto-optical (MO) isolators are widely used in optical systems to increase the lifetime and stability of lasers. Single crystal bismuth doped yttrium iron garnets (Bi:YIG) are used as the main component of commercial discrete optical isolators. Although this material exhibits strong Faraday rotation and low optical loss at communication wavelengths, it is difficult to integrate onto a semiconductor substrate due to several reasons. Firstly, garnets have a complex unit cell with a much larger lattice parameter compared with semiconductors (YIG: $12.376\text{\AA}$,¹ Si: $5.43\text{\AA}$, GaAs: $5.65\text{\AA}$), which precludes the possibility of heteroepitaxial growth of garnet films on a conventional semiconductor substrate. Secondly, the thermal expansion coefficient of YIG is much larger than Si, GaAs, InP or SiO_2 . Cracks can easily generate in

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crystallized YIG films on silicon when the thickness exceeds the critical value of about 100 nm.² Thirdly, crystallization of the garnet phase usually requires a high thermal budget, and impurity phases such as YFeO_3 , Fe_2O_3 and Bi_2O_3 can also precipitate during the crystallization process,³ which may cause optical scattering loss in integrated photonic devices. These factors make the fabrication of high optical quality magnetic garnet films and also optical isolators on semiconductor substrates very difficult.

In the past decade, progress has been made both for integrating magnetic garnets and exploring new silicon-compatible magneto-optical materials. By using rapid thermal annealing, Stadler et al. significantly reduced the thermal budget for YIG crystallization.⁴ Meanwhile, they reported that by pre-patterning the YIG waveguides before crystallization using wet chemical etching, cracks can be eliminated in thicker YIG waveguides.⁵ Köner et al. reported the stabilization of $\text{Bi}_3\text{Fe}_5\text{O}_{12}$ films by a crystallized YIG layer on SiO_2 substrates.⁶ These films showed pure garnet phases as well as good magneto-optical properties at visible wavelengths. On the other hand, novel magnetic oxide materials such as Co-doped CeO_2 ,⁷ Co- or Fe-doped SnO_2 ,⁸ and Fe- or Co-doped SrTiO_3 ^{9,10} show significant Faraday rotation at communication wavelengths. However, the strong optical absorption of these materials yields a low figure of merit (FOM), defined as the Faraday rotation divided by optical absorption per unit length. Controlling the valence states of the transition metal ions may decrease the optical absorption loss and increase the FOM of these materials.¹⁰

From the device point of view, two integrated isolator structures using magneto-optical oxides have been proposed. These strategies rely on non-reciprocal mode conversion (NRMC)⁵ and non-reciprocal phase shift (NRPS)¹¹ effects in magneto-optical photonic devices. NRMC is based on the same mechanism as bulk optical isolators. It is considered to be more compact than its NRPS counterpart. However, device birefringence control and optical polarizer integration are required in NRMC isolators. In contrast, NRPS devices using Mach-Zehnder (MZ) architecture are tolerant to birefringence, but they have a larger footprint compared with NRMC devices.

Despite progress in both materials and device development, several important issues need to be investigated before fabricating a practical integrated optical isolator. Firstly, the optical loss and magneto-optical properties of polycrystalline garnet have to be determined in a waveguide configuration in the near infrared wavelength range. Because pure YIG itself is highly transparent in the near-IR, grain boundary optical scattering from small amounts of amorphous or secondary phases which do not show up in x-ray diffraction measurements (XRD) can dominate the optical loss in YIG waveguides. Secondly, a simple and low cost strategy to integrate magnetic oxide waveguide structures needs to be developed. In this study, we report the integration of a polycrystalline YIG film on oxidized silicon and SOI substrates using $\text{As}_2\text{S}_3/\text{YIG}$ and YIG/SOI strip-loaded structures. The optical loss of a rapid thermal annealed YIG film was determined in both structures. Due to the index contrast between the YIG film and As_2S_3 or Si layers, high NRPS can be achieved. We simulated the NRPS and figure of merit of these waveguides based on the experimental results. We also discuss optimization of the device performance by proper optical design and incorporation of Bi/Ce:YIG polycrystalline layers in a strip-loaded waveguide structure.

2. DEVICE FABRICATION AND CHARACTERIZATION

2.1 Waveguide fabrication

A schematic diagram of the two strategies used to fabricate $\text{As}_2\text{S}_3/\text{YIG}$ and YIG/SOI strip-loaded waveguides is shown in figure 1. For the $\text{As}_2\text{S}_3/\text{YIG}$ waveguides, an 80nm yttrium iron oxide film layer was firstly deposited on an oxidized silicon substrate by pulsed laser deposition (PLD) with a Coherent COMPexPro 205 KrF (248 nm wavelength) excimer laser. The substrate temperature was kept at 500°C and the oxygen pressure was maintained at 10 mTorr during the deposition. The as-deposited film underwent rapid thermal anneal (RTA) at 850°C for 5 min under N_2 flow to promote crystallization into the YIG phase. After this step, photoresist patterns with 2 μm to 8 μm waveguide structures were formed on the crystallized YIG layer using photolithography. As_2S_3 glass films of 360 nm thickness were then thermally evaporated on the samples which were kept at room temperature. A lift-off process was carried out to form a strip-loaded waveguide structure. After that, a 2 μm thick SU-8 ($n = 1.58$, MicroChem) photoresist layer was spin-coated onto the waveguide structures and exposed under room light for 10 min as a top-cladding layer. For the YIG/SOI waveguides, SOI wafers with a device layer thickness of 220 nm and a buried oxide thickness of 3 μm were used for device fabrication. 450nm wide and 60nm thick hydrogen silsesquioxane (HSQ) resist patterns of straight waveguides and pulley-type resonators were firstly formed on the SOI substrate by electron-beam lithography. Silicon single-mode waveguides and ring resonators were then formed by reactive ion etching using a HBr plasma. After this step, an 80 nm yttrium iron oxide film layer was grown onto the silicon waveguides and resonators by PLD followed by a rapid thermal annealing process to crystallize into the YIG phase. The deposition and RTA conditions were the same as for the $\text{As}_2\text{S}_3/\text{YIG}$ waveguide fabrication.

Fig. 1 A schematic plot of the two strategies used for 1. $\text{As}_2\text{S}_3/\text{YIG}$ and 2. YIG/SOI strip-loaded waveguide fabrication

2.2 YIG film, waveguide and resonator characterization

Phase identification of the YIG films after RTA was carried out by one dimensional X-ray diffraction (1DXRD, Rigaku RU300). The magnetic hysteresis loops of these films were measured by vibrating sample magnetometry (VSM) on an ADE Technologies VSM Model 1660 at room temperature. By comparing the saturation magnetization of the polycrystalline YIG film and the saturation magnetization value of pure single crystal YIG, the crystallized volume fraction of the film was estimated. To evaluate the magneto-optical properties of these films, a 500nm YIG film was deposited on a transparent MgO substrate and crystallized by rapid thermal annealing under similar conditions. Room temperature Faraday rotation of this film at 1550nm wavelength was characterized on a custom-built apparatus with the laser beam propagating perpendicular to the film plane.

The waveguide and resonator morphologies were characterized on a Zeiss/Leo Gemini 982 SEM. Optical transmission measurements of the waveguides and resonators were performed on a Newport AutoAlign workstation in combination

with a LUNA tunable laser (optical vector analyzer, LUNA Technologies, Inc.). Waveguide end facets were formed by cleaving the substrate. Lens-tip fibers were used to couple light from the laser into and out of the devices. Reproducible coupling was achieved via an automatic alignment system with a spatial resolution of 50 nm. The optical loss of bare As_2S_3 and $\text{As}_2\text{S}_3/\text{YIG}$ waveguides with the width of 2 μm and 4 μm were characterized using the cut-back method. By simulating the confinement factor of the YIG layer, optical loss of the YIG film was calculated. For the YIG/SOI structure, the waveguide loss was determined by measuring the resonator Q factor. The optical loss of the YIG layer was also estimated by optical confinement factor simulations.

3. RESULTS AND DISCUSSION

3.1 Structure, magnetic and magneto-optical properties of polycrystalline YIG films

Figure 1 (a) shows the 1D θ -2 θ XRD spectrum of an 80nm yttrium iron oxide film deposited on an oxidized silicon wafer after rapid thermal annealing. The diffraction pattern consists of a broad diffraction feature from the amorphous SiO_2 layer and well defined diffraction peaks from crystallized YIG. No secondary phase peaks were observed in the XRD spectrum. Using Scherrer's equation,¹² we can estimate that the average YIG crystal size is about 22nm. Similar XRD patterns were also observed on YIG films deposited on SOI substrates (data not shown). The room temperature magnetic hysteresis of a crystallized YIG film is shown in figure 1 (b). The YIG film shows a saturation magnetization of 130 emu/cm^3 with an in-plane magnetic easy axis due to magnetic shape anisotropy. Comparing with the bulk magnetization value of 139 emu/cm^3 , we estimate that ~ 95 vol.% of the film has crystallized into the YIG phase. This film shows a very low in-plane saturation magnetic field of 100 Oe, which is beneficial for fabricating integrated isolators. Figure 1 (c) shows the room temperature Faraday rotation spectrum of a 500 nm polycrystalline YIG film grown on an MgO substrate. A Faraday rotation value of ~ 100 deg/cm is observed in this film, which is smaller than the bulk value of 160 deg/cm for YIG single crystals at this wavelength.¹³ This may be due to the inferior crystal quality of the RTA YIG films compared with single crystals and due to the measurement error for small rotation values at this wavelength. Notice that the saturation magnetic field of the Faraday rotation hysteresis is around 1600 Oe, which coincides with the out-of-plane saturation field value determined by VSM.

Fig.2 (a) 1D θ -2 θ XRD spectrum of an 80nm YIG film deposited on a SiO_2/Si wafer followed by rapid thermal annealing at 850°C for 5 min. (b) Room temperature in-plane (IP) and out-of-plane (OP) magnetization hysteresis loops of a crystallized YIG film on a SiO_2/Si substrate. (c) Room temperature Faraday rotation hysteresis of a 500 nm thick YIG film on a MgO substrate

3.2. Optical transmission of As₂S₃/YIG, YIG/SOI waveguides and ring resonators

As₂S₃/YIG waveguides

The cross-sectional SEM image of a 2 μm wide As₂S₃/YIG strip-loaded waveguide is shown in figure 3 (a). The waveguide consisted of a 3 μm SiO₂ bottom cladding layer ($n = 1.44$), an 80 nm YIG slab ($n = 2.2$), a 360 nm thick As₂S₃ ($n = 2.37$) channel and a 2 μm thick SU-8 top cladding layer ($n = 1.58$). The sidewalls of the As₂S₃ layer are slanted to 60°, which is due to the lift-off fabrication process.^{14, 15} The TM mode optical transmission spectrum of a 13 mm long waveguide with this structure is shown in figure 3 (b). Also shown for comparison is the transmission spectrum of a 19 mm long bare As₂S₃ channel waveguide on SiO₂/Si substrate with the same As₂S₃ channel thickness. Although shorter in length, the strip-loaded waveguide showed higher total insertion loss compared with the bare As₂S₃ channel waveguide, from the incorporation of the YIG slab. A small insertion loss variation versus wavelength is observed in both waveguides, which is attributed to multimode beating.

Fig.3 (a) Cross-sectional SEM image of a 2 μm wide As₂S₃/YIG strip-loaded waveguide. (b) TM polarization optical transmission versus wavelength of a 2 μm wide bare As₂S₃ channel waveguide and a 2 μm wide As₂S₃/YIG strip-loaded waveguide

In order to accurately determine the optical loss of the strip-loaded waveguides and the YIG films, the cut-back method was carried out to measure the insertion loss of a 2 μm wide As₂S₃ channel waveguide and a 2 μm wide and a 4 μm wide As₂S₃/YIG strip-loaded waveguide. We did not characterize the propagation loss of wider waveguides due to the stronger multi-mode beating effect. The results are shown in figure 4. The full square dots are the experimental data and the lines are linear fits to these values. The bare As₂S₃ channel waveguide showed optical loss of $5.6 \pm 0.2 \text{ dB/cm}$ at 1550 nm wavelength, which is slightly larger than but consistent with the optical loss of similar waveguides fabricated by this method.^{14, 15} The 2 μm and 4 μm wide As₂S₃/YIG waveguide showed optical losses of $9.7 \pm 0.4 \text{ dB/cm}$ and $10.6 \pm 1.0 \text{ dB/cm}$ respectively. Considering that the optical confinement factor in the YIG layer is about 11% in both waveguide structures, the propagation loss of the YIG film is calculated to be $\sim 50 \text{ dB/cm}$ ($\alpha = 11.5 \text{ cm}^{-1}$) at 1550 nm. This value is much higher than that of YIG single crystals. We expect that, although not observed in X-ray diffraction patterns, a small fraction of amorphous or secondary phases is responsible for scattering in the polycrystalline YIG film, therefore increase the material loss at near infrared wavelengths. This loss mechanism has to be reduced or compensated by materials with stronger magneto-optical properties, such as Bi/Ce:YIG, to allow the fabrication of low insertion loss optical isolators in the future.

Fig.4 Optical propagation loss of the TM mode incident light at 1550nm for (a) a 2 μm wide As_2S_3 channel waveguide (b) a 2 μm wide $\text{As}_2\text{S}_3/\text{YIG}$ waveguide and (c) a 4 μm wide $\text{As}_2\text{S}_3/\text{YIG}$ waveguide determined by the cut-back method

YIG/SOI waveguides and resonators

The top-view SEM image of a 450 nm wide YIG/SOI waveguide is shown in figure 5 (a). A crack was generated after crystallization even though the YIG film was only 80 nm thick. However the crack did not propagate through the YIG/SOI waveguide. This is because the initial area of YIG on the SOI waveguide was small. It expanded only a small area under rapid thermal annealing, which prevented the crack formation.⁷ The TM mode transmission spectra of a 6 mm long SOI and a 6 mm long YIG/SOI waveguide are shown in figure 5 (b). Both waveguides show single mode propagation characteristics, while the strip-loaded waveguide shows much higher insertion loss due to the incorporation of the YIG layer.

Fig. 5 (a) Plan-view SEM image of a 450 nm wide YIG/SOI waveguide. (b) TM polarization transmission spectrum of a bare SOI channel waveguide and a YIG/SOI waveguide

To characterize the propagation loss of the YIG/SOI waveguides, a pulley-type silicon ring resonator with a diameter of 40 μm was fabricated as shown in figure 6 (a).¹⁶ A 450 nm wide bus waveguide was designed to surround half of the circumference of the ring resonator, which provides stronger coupling between the waveguide and the resonator. The gap between the bus waveguide and the ring resonator was 300 nm. After coating the device with an 80 nm YIG layer, the transmission spectrum was measured as shown in figure 6 (b). Evenly spaced resonant peaks were observed in the TM polarization transmission spectrum, while the TE mode signals are too lossy to be measured. The resonator showed a

under-coupling to over-coupling transition upon increasing the incident light wavelength, and near-critical coupling was achieved around 1515 nm wavelength. The quality factor Q of this resonator was determined to be $\sim 10,000$ via Lorentzian peak fit in the linear scale. We can calculate the propagation loss of the YIG/SOI waveguide from the following formula.¹⁷

$$\alpha = \frac{2\pi n_g}{\lambda Q_{in}}$$

$$FSR = \frac{\lambda^2}{n_g L}$$

where λ is the resonance wavelength, Q_{in} is the intrinsic extinction ratio, n_g is the group index of the waveguide at this wavelength, α is the optical absorption coefficient, FSR is the free spectral range defined as the wavelength spacing between two adjacent resonant peaks, L is the total resonator cavity length. From the measured total quality factor Q and FSR, the optical loss of the waveguide is calculated to be 41 dB/cm at 1515nm wavelength. Comparing with the optical transmission spectrum of the straight waveguides shown in figure 5 (b) and considering a simulated confinement factor of 28% in the YIG films, the optical loss of the YIG film is estimated to be 60~70 dB/cm. This value is larger than the As_2S_3 /YIG case, which is possibly due to increased side wall roughness of the silicon waveguide during deposition and crystallization of the YIG layer.

Fig. 6 (a) Plane view SEM image of a pulley-type silicon ring resonator. (b) Measured transmission spectrum of TM polarized light in a YIG/SOI pulley type resonator

3.3 NRPS and FOM simulation of As_2S_3 /YIG and YIG/SOI waveguides

The magneto-optical performance, specifically the NRPS of these waveguides can be simulated by perturbation theory.¹⁸ The NRPS of a TM mode wave in a magneto-optical waveguide can be expressed by the following equation:^{10,18}

$$\Delta\beta^{TM} = -\frac{2\beta^{TM}}{\omega\epsilon_0 N} \iint \frac{K'' M_y}{n_0^4} H_y \partial_x H_y dx dy$$

where $\Delta\beta_{TM} = \beta^{forward} - \beta^{backward}$ is the difference in the propagation constant between forward- and backward-propagating waves. The magnetic layer is saturated along the +y direction by an external magnetic field, and the light is propagating along +z (forward) and -z (backward) directions. By varying the strip-loaded waveguide geometry, the mode profile H_y and the field gradient $\partial_x H_y$ can be controlled to yield higher NRPS and FOM in the magneto-optical waveguide. To demonstrate this, we firstly simulated the fundamental TM mode profile in the As_2S_3 /YIG and YIG/SOI waveguides by FIMMWAVE software using a wave matching method (WMM).¹⁹ From the mode profile and the experimentally measured Faraday rotation of the YIG film, we calculated the NRPS of both waveguide structures as a function of the As_2S_3 and SOI layer thickness. Also, from the measured waveguide propagation loss, we calculated the device figure of merit as a function of the As_2S_3 and SOI layer thickness, which is defined as NRPS divided by optical loss per length. The results are shown in figure 7(a) and (b) for As_2S_3 /YIG and YIG/SOI waveguides respectively. The insets are schematic diagrams of the waveguide structures used in the simulations.

First of all, we notice that the highest NRPS can be achieved at a certain thickness of the As_2S_3 or the SOI layer. This can be explained as follows: when the As_2S_3 or SOI layer is thin, the guided mode is highly confined in the YIG layer. The $\partial_x H_y$ term can be positive or negative and cancels out when integrated, which yields low NRPS. When the As_2S_3 or SOI layer is thick, the guided mode is weakly confined in the YIG layer. The H_y term is small, which also yields low NRPS. In the As_2S_3 /YIG waveguide structure, the highest FOM of 3.12 deg/dB can be achieved at a As_2S_3 layer thickness of 320 nm. However, in the YIG/SOI structure, the FOM shows smaller values and a more complex variation with SOI layer thickness. This is because the propagation loss of this waveguide is higher as measured by experiments, and part of the NRPS is canceled by the YIG film on the SiO_2 surface in this structure. An improvement in device design may be expected by etching into the SiO_2 cladding layer to decrease the optical confinement in the YIG films on the SiO_2 surface, which may lead to higher device NRPS and FOM.

Fig. 7(a) Simulated Non-Reciprocal Phase Shift (NRPS) and Figure of Merit (FOM) in (a) As_2S_3 /YIG and (b) YIG/SOI strip-loaded waveguides. The insets show the waveguide dimensions used for mode profile simulation.

In a magneto-optical Mach-Zehnder isolator, $\pm 90^\circ$ NRPS has to be achieved in its either arm in order to make an

isolator. Considering a practical MZ optical isolator with high isolation ratio and 3dB insertion loss, the FOM of the NRPS waveguide should be larger than 30 deg/dB, which is one order higher than the simulated value for the $\text{As}_2\text{S}_3/\text{YIG}$ waveguide here. The FOM can be improved by optimizing the optical transparency of the YIG layer or incorporating materials with higher Verdet constant, such as Bi/Ce:YIG, which shows more than one order higher Verdet constant compared with YIG at near infrared wavelengths. From the device fabrication point of view, both the $\text{As}_2\text{S}_3/\text{YIG}$ and the YIG/SOI waveguide structures provide a simple and low cost route to integrate magneto-optical materials on a silicon platform. An etching step is not required for the magneto-optical materials, providing better compatibility with other CMOS fabrication techniques. The $\text{As}_2\text{S}_3/\text{YIG}$ waveguide uses a continuous YIG film, which can be magnetically saturated under a small applied field of 100 Oe, whereas the YIG/SOI structure will show a much higher saturation magnetic field due to shape anisotropy when magnetized perpendicular to the waveguide direction. Nevertheless, the advantage of the YIG/SOI structure is that it directly uses silicon as the waveguide component. The silicon strip provides a large index contrast with the YIG film which yields higher NRPS and consequently shorter waveguide length to achieve optical isolation.²² Also, the YIG/SOI device structure allows epitaxial growth of novel magneto-optical materials on the SOI waveguide surface using buffer layers,¹² which provides more flexibility for materials selection. These factors need to be considered for future isolator design and fabrication. Experimental measurements of the NRPS of both waveguide structures are currently underway.

4. SUMMARY

In conclusion, we report two novel strategies to integrate magneto-optical oxides on a silicon platform with strip-loaded waveguide structures. Using conventional waveguide fabrication and thin film deposition techniques, $\text{As}_2\text{S}_3/\text{YIG}$ and YIG/SOI strip-loaded waveguides were fabricated and their optical losses were characterized by the cut-back method and with a ring resonator, respectively. The propagation loss of polycrystalline YIG film at near infrared wavelengths was evaluated based on these two waveguide structures, and was found to be much higher than YIG single crystals. It is suggested that a Bi:YIG or Ce:YIG layer may be integrated in these waveguides to achieve higher NRPS and figure of merit for optical isolator applications. These waveguide fabrication techniques provide a compact, low cost and etch-free route to integrate magneto-optical oxides and NRPS waveguides on a silicon platform, which may be useful for integrating optical isolators on semiconductor substrates.

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