B-4-1 (Invited)
Extended Abstracts of the 2014 International Conference on Solid State Devices and Materials, Tsukuba, 2014, pp500-501

On-Chip Nonreciprocal Photonic Devices Using Magneto-Optical Oxide Thin Films

Lei Bi[1], Juejun Hu[2], Hyun Suk Kim[3], Gerald F. Dionne[3], Caroline A. Ross[3], Xiao Liang[1], Jianliang Xie[1], Longjiang Deng[1]

[1] University of Electronic Science and Technology of China
No. 4 Sec. 2 North Jianshe Road, Chengdu, China
Phone: +86-28-83201893 E-mail: bilei@uestc.edu.cn
[2]University of Delaware, Newark, DE 19716, USA
[3]Massachusetts Institute of Technology, 77 Mass. Ave., MA 02139, USA

Abstract

On-chip integration of nonreciprocal photonic devices has been a long time request for integrated photonic systems. In this report, we demonstrate nonreciprocal photonic devices monolithically integrated on a silicon platform using deposited magnetic oxide thin films. High magneto-optical (MO) figure of merit (FoM) is achieved in $SrTiO_3$ films doped with Fe or Co, as well as polycrystalline $Ce_1Y_2Fe_5O_{12}$ (CeYIG) films. A compact optical isolator based on SOI resonators is demonstrated at 1542 nm wavelength, with isolation ratio of 19.5±2.9 dB demonstrated for the fundamental TM mode.

1. Introduction

Nonreciprocal photonic devices including optical isolators and circulators are indispensible components in optical telecommunication systems. With the development of integrated photonic systems and silicon photonics, there is a strong need of monolithic on-chip integration of such devices to allow compact systems with low cost and stable performance. Although discrete nonreciprocal photonic devices have been a mature technology for several decades, integrating magneto-optical thin films on silicon, the essential material to enable nonreciprocity, has been challenging due to the material incompatibility between magnetic oxides and Si.[1] In this report, we demonstrate monolithically integrated nonreciprocal photonic devices using high figure of merit (FoM) magnetic oxide thin films on silicon. A compact on-chip optical isolator is achieved at 1542 nm wavelength.

2. MO oxide thin films with high FoM on silicon

Perovskite oxides such as $SrTiO_3$ show good lattice match with silicon and can be epitaxially grown on Si (100) surface with small lattice mismatch. Pulsed laser deposition (PLD) is used for thin film deposition on LSAT or silicon substrates. By introducing Fe or Co on the Ti sub-lattice, room temperature ferromagnetism is demonstrated in $Sr(Ti_{0.6}Fe_{0.4})O_{3-\delta}$ (STF) and $Sr(Ti_{0.7}Co_{0.3})O_{3-\delta}$(STC) thin films. The Faraday rotation and FoM of these films can be further controlled by donor or acceptor doping. A high Faraday rotation of -400 deg/cm and high FoM of 3~4 deg/dB was observed in Ga and Fe co-doped $SrTiO_3$ films.[2]

Polycrystalline garnet thin films are also good candidates of high FoM MO oxide thin films. In our study, a two step deposition strategy is carried out for Bi or Ce doped YIG deposition on silicon. Firstly, a 20 nm thick YIG film is deposited by pulsed laser deposition and rapid thermal annealing to form the crystallized garnet seed layer, then a thicker CeYIG or BiYIG layer up to 80 nm is deposited on the seed layers under substrate temperature of 600~650 °C. Figure 1a and 1b shows the XRD and AFM spectrum of a CeYIG(80 nm)/YIG(20 nm) thin film deposited on silicon. Single garnet phase and low RMS roughness of 0.92 Å have been achieved in the CeYIG films. The room temperature Faraday rotation at 1550 nm of a 500 nm thick CeYIG thin film deposited using this method is shown in figure 1c. A Faraday rotation constant of -830 deg/cm is measured at 1550 nm wavelength, which is observed to be strongly dependent on the oxygen partial pressure during CeYIG fabrication. Lower deposition oxygen partial pressure results in higher Faraday rotation, which is also observed in other reports of CeYIG thin films.[3]

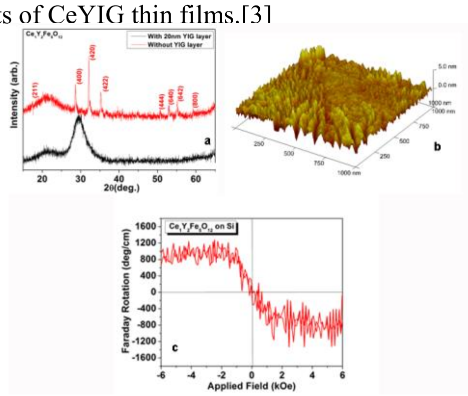

Fig. 1 (a) XRD spectrum (b) AFM morphology (c) Faraday rotation of CeYIG/YIG thin films deposited on silicon. [1]

First principle calculations based on density functional theory are carried out to explain the magneto-optical and optical properties of CeYIG. In previous studies, it has been believed that Ce^{3+} is responsible for the near infrared Faraday rotation enhancement in CeYIG thin films. From our calculation, the Ce^{3+}(4f)-Fe^{3+}(3d,tet.) electric dipole transition causes near infrared electric dipole transition at 1.2 eV and 1.8 eV respectively due to Fe^{3+} t_{2g} and e_g orbital splitting, which agreed well with experimental observations.

Introducing one oxygen vacancy into the lattice significantly stabilized the neighboring Ce valence state at 3+, whereas it also induced one Fe^{2+} ions at the tetrahedral and one at the octahedral sites respectively, which contributed to two strong optical absorption peaks at 2.0 eV and 1.5 eV. The calculated density of states (DOS) and near infrared optical absorption of $Ce_xY_{3-x}Fe_5O_{11.875}$ (one oxygen vacancy in one CeYIG unit cell) are shown in figure 2. These calculations provide guidance for further improving the magneto-optical FoM of doped YIG thin films for nonreciprocal photonic device applications.

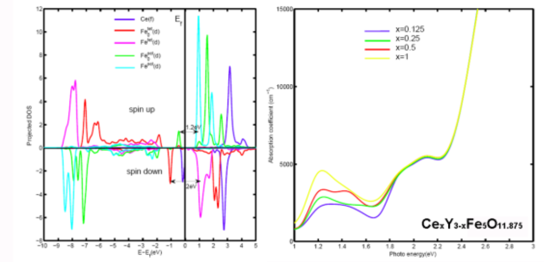

Fig. 2 Density of states (DOS) and near infrared optical absorption of $Ce_xY_{3-x}Fe_5O_{11.875}$ calculated by first principle calculations

3. Nonreciprocal photonic waveguides and resonators

Nonreciprocal photonic waveguides and resonators were fabricated on the $SrTiO_3$:Fe (STF) or CeYIG thin films using silicon or chalcogenide glass (ChG) waveguides. Figure 3a, 3b shows the optical microscope image of ChG/garnet strip-loaded photonic waveguides, and racetrack resonator using the strip-loaded waveguide structures on silicon. The ChG is thermally evaporated followed by a lift-off process to form the strip-loaded waveguide structures on CeYIG. The transmission spectrum of the racetrack resonator is shown in figure 3c. Optical loss from the CeYIG layer is estimated using the cut-back method and confinement factor simulations using FDTD method. The loss from the CeYIG layer is around 40 dB/cm. Considering the thin film Faraday rotation, this indicates a lower limit of the material FoM to be around 21 deg/dB.

4. Monolithically integrated optical isolators on silicon

An optical isolator based on nonreciprocal SOI ring resonators with CeYIG film coating is proposed and experimentally demonstrated.[4] Figure 4a shows the sketch and optical transmission spectrum of TM polarized light. The CeYIG/YIG thin film stacks are deposited on a window section of the silicon racetrack resonator with CeYIG/YIG in contact with silicon, allowing nonreciprocal optical transmission under uniaxially applied magnetic field perpendicular to the light propagation direction. A nonreciprocal phase shift (NRPS) is observed in the CeYIG/YIG/Si waveguide structure, which caused non-degeneracy of the resonance. Optical isolation is achieved in a CeYIG coated SOI racetrack resonator at around 1541 nm wavelength, with isolation ratio of 19.5±2.9 dB and insertion loss of 18.8±1.1 dB observed for the TM polarized modes. The resonator length is 290 μm, which is one order smaller than bulk optical isolators. Future development of the isolator need to consider improving the material FoM, stabilize the device temperature dependence and apply a broadband design.

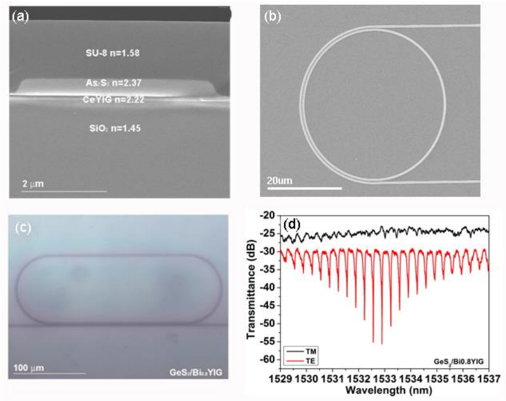

Fig. 3 (a) Cross-sectional SEM view of an As_2S_3/CeYIG waveguide (b) Top-down SEM view of a YIG/SOI ring resonator (c) Top-down optical microscope image of a GeS_2/BiYIG racetrack resonator its transmission spectrum in (d) [1]

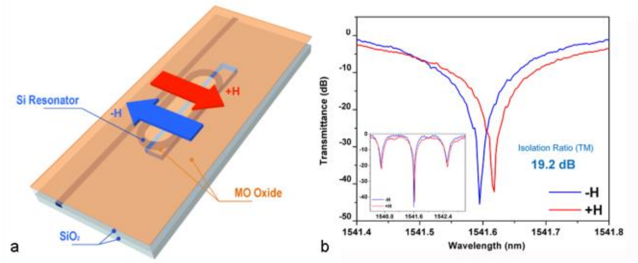

Fig. 4 (a) Schematic plot of a racetrack resonator based optical isolator on silicon. (b) TM mode isolation at around 1542 nm wavelength [4]

5. Conclusion

In conclusion, we demonstrated monolithic integration of magneto-optical oxide thin films on silicon with high FoM. Infrared optical dipole transition and influence of oxygen vacancy on the ion valence states and optical properties were calculated by density functional theory for CeYIG, which agreed very well with experimental observations. Nonreciprocal optical waveguides and resonators were monolithically fabricated on silicon using these magnetic oxide thin films. A prototype ring resonator based optical isolator was demonstrated, which showed small device footprints and high optical isolation in the near infrared wavelength range.

References

[1] Bi, L.; Hu, J.; Dionne, G. F.; Kimerling, L.; Ross, C. A. Proc. SPIE, **7941** (2011) 794105

[2] Jiang, P.; Bi, L.; Kim, D. H.; Dionne, G. F.; Ross, C. A. Appl. Phys. Lett., **98** (2011) 231909

[3] T. Goto, Y. Eto, K. Kobayashi, Y. Haga, M. Inoue and C. A. Ross, J. Appl. Phys., **113**(2013)17A939

[4] L. Bi, J. Hu, P. Jiang, D. H. Kim, G. F. Dionne, L. C. Kimerling and C. A. Ross, Nature Photonics, **5** (2011) 758