Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp89-90

Optical Gain in Mid-Refractive Index Contrast $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ /SiO_2 Waveguide Prepared by Radical Assisted Sputtering

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Abstract

Mid-refractive index contrast $(Er_{0.1}Y_{0.9})_2Zr_2O_7/SiO_2$ waveguide amplifier is demonstrated. Highly oriented cubic $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ crystalline thin film was prepared by radical assisted sputtering (RAS), and was with a refractive index of 2.1. Optical gain of the waveguide confined with SiO_2 clad was evaluated to be 26.9dB/cm by variable stripe length (VSL) measurements, and the value was limited by pumping power of the light source. It is also found that the characteristics of the Er ion itself dominate the gain properties.

1. Introduction

Large scale photonic integration based on silicon photonics has been developed [1]. While Si wire waveguides play an important role in silicon photonics, the high-refractive index contrast to SiO_2 clad makes low scattering loss processes difficult and causes optical nonlinearity in WDM. In order to overcome the problems, mid-refractive index contrast photonics based on SiN_x (n~2.0) waveguide and its application to 3-D photonics integration on silicon photonics platform, so-called "back-end photonics" have been proposed [2][3]. For the large scale integration, optical amplifiers are also required. In this paper, an optical gain media for mid-refractive index contrast photonics is reported.

So far we have reported $(Er_xY_{1-x})_2SiO_5$ crystalline waveguides as optical amplifiers for silicon photonics [4][5]. According to the same approach, we attempted to fabricate an $(Er_xY_{1-x})_2Zr_2O_7$ crystalline waveguide for mid-refractive index contrast photonics [6]. Layer-by-layer deposition processes are a good way to achieve high crystalline quality for the waveguide devices [5][7]. Therefore, radical-assisted sputtering (RAS) was applied to the device fabrication process[5].

2. Experiments

Cubic $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ crystalline thin film was prepared by RAS. Zr and Y/Er(10%) metal targets were used, and metal-sputtering and radical-oxidation processes were repeated alternatively with layer-by-layer accuracy of 0.26nm corresponding to d-space of the (200) plane [6]. The sample was then annealed in Ar atmosphere at 1250°C for 30min. The highly orientation was confirmed by X-ray diffraction, and the refractive index was shown to be 2.1 by ellipsometry. Details of RAS process will be described elsewhere. $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ waveguide confined with SiO_2 clad was formed on a ridge patterned SiO_2 by RAS directly. Figure 1 shows a cross-sectional SEM image of $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ waveguide. The waveguide is well confined with SiO_2 clad and has a thickness and width of 530 nm and 5 μm, respectively. Also, the corresponding optical confinement factor is approximately one.

The sharp PL emission originated from Er^{3+} ion at 1.53μm was confirmed, and the emission decay showed single exponential curve with 4.3ms. Furthermore, the edge emission from $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ waveguide was also observed. Variable stripe length (VSL) measurement then was performed to estimate the optical gain of the waveguide. A 980nm LD with a power of 1000mW was used as a pumping light source. The emitter size was 1x100μm, and a line-shaped beam pattern was acquired by expanding the beam size to 10 times using a microscope. The line-shaped pumping light was irradiated along the waveguide from top, and the irradiation length was varied by moving a shade. Edge emission of the $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ waveguide was collected with a lensed fiber, and monitored with a cooled InGaAs PD array.

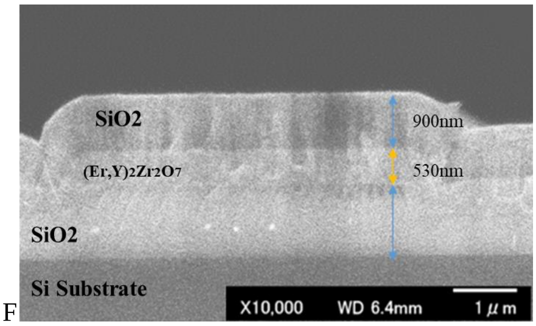

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Fig.1 Cross-sectional SEM image of $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ waveguide.

3. Results and discussions

Figure 2 (a) shows PL edge emission spectra under an excitation of 9.5kW/cm^2 as a function of irradiation length. The emission intensity increases monotonically with the irradiation length. The irradiation length L dependence of integrated PL intensity $I(L)$ is summarized as a function of excitation power in Fig. 2 (b). With increasing the excitation power, the irradiation length dependence changes to superliner from saturation behavior. This result suggests that the optical gain is obtained certainly while a short waveguide of 500µm or less.

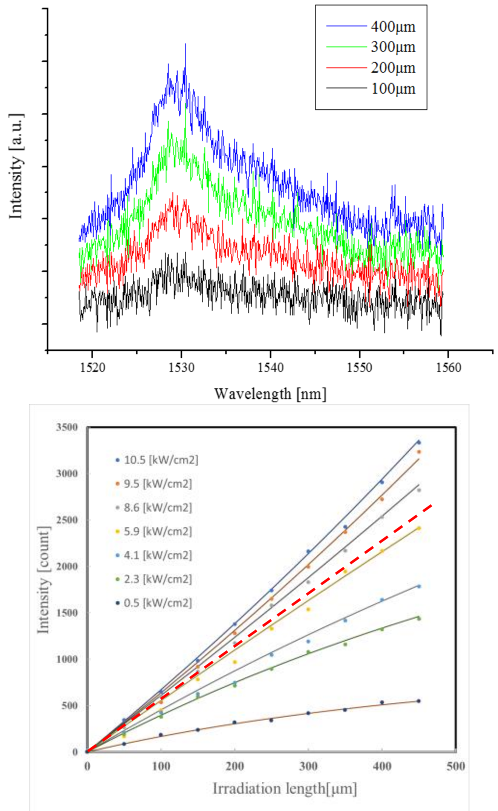

Fig. 2 Edge emission spectra as a function of the irradiation length under the excitation power of 9.5kW/cm² (a), and the irradiation length dependence of integrated PL intensity as a function of the excitation power (b).

Irradiation length dependence of the emission intensity $I(L)$ is given by

$$I(L) = \int_0^L i_0 \exp(\beta x)dx = \frac{i_0}{\beta}(\exp(\beta L) - 1) \quad (1),$$

here i_0 and β are the spontaneous emission intensity per unit length and the net gain coefficient, respectively, and these value are independent of x because of the homogeneous excitation. Note that β includes the optical confinement factor and the scattering loss of the waveguide. The fitting curves are indicated by solid lines in Fig.2 (b). A dash line in Fig. 2(b) also shows a linear relation i_0L which corresponds to β=0. The superliner behavior above the excitation power of 8.6kW/cm^2 indicates an achievement of optical gain.

In Fig. 3, the gain coefficient β estimated from the $I(L)$ curve is plotted as a function of the pumping power. β increases with the pumping power and reaches 6.2cm^{-1} at 10.5kWcm^{-2}. This gain coefficient corresponds to an optical gain of 26.9dB/cm. The pumping light at 980nm corresponds to the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ transitions of the Er^{3+} ion. The relaxation time at the second excited state $^4I_{11/2}$ is estimated to be 40µs by PL decay measurement and is fast enough to use the two level approximation. Also shown in Fig.3 is a fitting curve for the gain properties with the two level approximation.

The threshold photon flux ϕ_{th} is estimated from the fitting curve to be 3.3x10^{22}cm^{-2}s^{-1}, which is in good agreement with $(Er_xY_{1-x})_2SiO_5$ crystalline waveguide[5]. β at zero excitation on the fitting curve corresponds to the total propagation loss of 1.5µm light and is -23cm^{-1}. From this value and the total Er concentration N of 1.4x20^{21}cm^{-3}, the absorption cross section σ_{abs} of Er ion is estimated to be 1.6x10^{-20}cm^2. This value is approximately the same as Er oxide crystalline compounds such as $Er_xY_{2-x}SiO_5$ [5]. These results suggest that the characteristics of the Er ion itself dominate the gain properties. The emission cross section is considered to be almost the same as the absorption cross section σ_{abs} from the Einstein relation, and therefore the population inversion $\Delta N/N$ is estimated to be 0.28 at 10.5kWcm^{-2}. The obtained maximum gain is limited by the power of the light source. We expect gain above 50 dB/cm which corresponds to an optical gain at $\Delta N/N$=0.5.

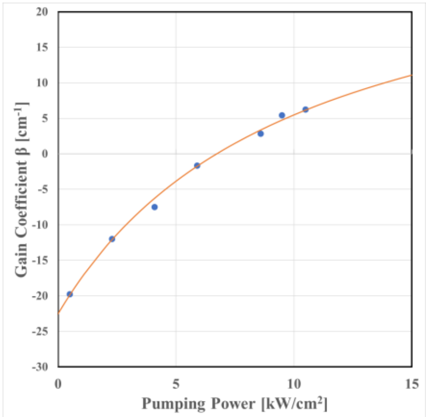

Fig.3 Optical gain property of $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ waveguide as a function of the excitation.

4. Conclusion

Highly oriented cubic $(Er_{0.1}Y_{0.9})_2Zr_2O_7$ crystalline thin film with a refractive index of 2.1 was obtained by radical assisted sputtering (RAS). By means of this process, an $(Er_{0.1}Y_{0.9})_2Zr_2O_7/SiO_2$ waveguide amplifier was proposed for mid-refractive index contrast photonics and achieved an optical gain of 26.9dB/cm. It is also found that the characteristics of the Er ion itself dominate the gain properties. Therefore, we speculate that gain above 50 dB/cm can be achieved by optimization of the device.

Acknowledgement

The authors would like to thank Prof. T. Kimura of UEC and Mr. S. Saisho of Shincron Co., LTD. for their valuable discussions and continuous encouragement.

References

[1] Handbook of Silicon Photonics, L. Vivien and L. Pavesi, eds., CRC Press, 2013.
[2] J-M. Fedeli, *et al.*, IEEE J. Sel. Top. Quantum Electron., 20(2014) 8201909
[3] K. Yamada, *et al.*, section 2 of Handbook of Silicon Photonics, L. Vivien and L. Pavesi, eds., CRC Press, 2013.
[4] H. Isshiki, *et al.*, Appl. Phys. Lett. 85 (2004) 4343.
[5] H. Isshiki, *et al.*, Photonics Research 2 (2014) A45.
[6] Hui Li, *et al.*, J. Alloys and Compounds 660 (2016)446-449.
[7] T. Kimura, *et al.*, Physica E 41 (2009) 1063.