Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp1163-1164

# Strong suppression of scattering loss in $Er_{0.4}Y_{1.6}SiO_5$ crystalline waveguides

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## 1. Introduction

In recent years, Power consumption and signal delay in LSIs have been increasing with shrinking the process size. Hence it is difficult to increase the clock and performance speed by the further scale-down. Some new techniques for post scaling so-called "more than Moore" are desired. Si-Photonics is attracting much attention as the innovative techniques. Si-Photonics is a concept of optical inter- or intra-connection by optical waveguides in the LSI. It is thought that Si-Photonics has a potential to increase operation speeds and decrease power consumptions. However, there are several issues for realizing optical circuits in the LSI. There is no light emitting device made from Si-related materials although some devices such as waveguides, branches and resonators were fabricated and investigated.

For the light emitting devices, $Er_xY_{2-x}SiO_5$ [1] have been proposed. $Er_xY_{2-x}SiO_5$ crystals show an excellent luminescence property at a wavelength around 1.53um. Er is one of constituent elements, and there is a huge amount of optically active Er atoms in the crystal up to $10^{22}cm^{-3}$. The value is one or two order of magnitude lager than doping materials. It is clear that crystalline nature of $Er_xY_{2-x}SiO_5$ is suitable for the compact optical amplifiers and emitter devices. The crystals have been fabricated by sol-gel method, pulsed-laser deposition (PLD) [2] and sputtering techniques. We reported the quenching mechanism in $Er_xY_{2-x}SiO_5$ crystallite film prepared by the sol-gel [3]. According to our previous report, the fluorescent life time is determined by the grain size. In this method, amorphous films containing Er, Y, Si and O, were annealed for crystallization. It is thought this process leads to decrease the crystalline grain size since the nucleation occurs everywhere in the films. Another problem of the sol-gel method is quenching centers remaining in the films. For example, an –OH bond contained in the crystallites consumes energy exciting $Er^{3+}$.

In order to overcome these problems, we have attempted to utilize radical-assisted sputtering (RAS) method to form the amorphous preforms. RAS technique uses a rotatable drum as a substrate holder, and a radical source and metal targets set up independently around the drum [4]. Due to control of the drum rotation and sputtering conditions, it is possible to repeat sputtering and oxidation processes with layer-by-layer accuracy. It has been reported that the layer-by-layer process by PLD enlarges the crystalline grain [2]. RAS is suitable for fabrication of layered $Er_xY_{2-x}SiO_5$ films and its device applications, because large area and high speed layer-by-layer deposition with high uniformity is possible.

In this paper, we demonstrate Si-guide layer buried $Er_xY_{2-x}SiO_5$ crystalline waveguide [4] fabricated by RAS technique, and discuss light propagation loss in the waveguide comparing with the sol-gel waveguide.

## 2. Sample fabrication

$SiO_2$ about 1μm thick was formed on p-Si (100) substrate by wet oxidation. A 4μm width stripe groove was formed on $SiO_2$/Si substrate by UV lithography. Then, Si was evaporated about 30nm and the Si stripe was formed by lift-off method.

RAS system (Shincron, RAS-1100C) was used to prepare amorphous ErYSiO thin films on the processed substrates. Oxygen radical source and each metal target of Er, Y and Si were arranged around the drum-style substrate holder, respectively. The sputtering conditions were set up to be the Er ratio of x=0.45. In comparison, $Er_xY_{2-x}SiO_5$ (x=0.5) crystal was formed by the sol-gel method on the same structure. Consequently, the $Er_2SiO_5$ crystalline fabricated by RAS and the sol-gel layer was obtained 500nm and 250nm thickness, respectively. After deposition, the samples were annealed for crystallization at 1200 °C for 10 minutes. Then optical confinement factors of these waveguides are estimated to be 0.71 and 0.54, respectively.

The waveguides were coupled with a lensed fiber through facet. Optical pumping was performed through a lensed fiber from the left side by 1.48μm light with a pump power of 20mW. And top views of the waveguides were observed by a visible CCD for upconversion emissions and infrared camera for pumping light scattering.

## 3. Results and discussions

PL measurements were performed for two samples by using a laser diode of 655nm and power density of $30mW/mm^2$. Both samples showed the fine structure spectrum of $Er_2SiO_5$ crystal. This implies crystalline field surrounding Er atoms in both samples was almost the same. Therefore it is clear that crystalline structure of $ErYSiO_5$ is not changed by the fabrication processes.

The top views of each waveguide taken by CCD are

shown in Fig. 1. Both samples exhibit red ($^4F_{9/2}\rightarrow{}^4I_{15/2}$), green ($^2H_{11/2}$, $^2S_{3/2}\rightarrow{}^4I_{15/2}$) and blue ($^2H_{9/2}\rightarrow{}^4I_{15/2}$) emissions related to cooperative upconversion in $Er^{3+}$ ions. In case of the waveguide prepared by sol-gel(a), the light decay along the waveguide reaching to 90μm was observed. However RAS sample(b) shows intense emission stronger than another and the green light tail is 140μm long or more. These results suggest that the waveguide fabricated by RAS is efficient for light emission and low light propagation loss.

Then, we compared the upconversion emission profiles between two waveguides to reveal suppression of the light propagation loss for 1.5μm. The green light decays were fitted by using exponential function [5] and the intensity $I$ is given by,

$$I = I_0 \exp(-n\alpha\Gamma x) \qquad (1) \quad ,$$

where $\alpha$ and $\Gamma$ are the loss coefficient for 1.48μm pumping light and the confinement factor, respectively. Then $n$ corresponds to a correlation coefficient between the green emission intensity $I_g$ and the 1.48μm pumping power $P$, and the relation is given by $I_g=P^n$. Form the PL measurement of upconversion emission as a function of the pumping power, $n$ was estimated to be 1.49 [5].

The decay profile and its fitting curve of RAS sample were shown in Fig.2. Then initial flat region of the profile is due to the signal saturation of CCD. The decay coefficients $n\alpha\Gamma$ are estimated to be 185$cm^{-1}$ for RAS sample and 235$cm^{-1}$ for sol-gel sample, respectively. Accordingly, the loss coefficients $\alpha$ are 175$cm^{-1}$ for RAS sample and 295$cm^{-1}$ for sol-gel sample. It is found that the propagation loss drastically decreases by 120 $cm^{-1}$ in the RAS waveguide. The total loss is sum of the absorption of $Er^{3+}$ ions and the scattering loss. The absorption coefficient of each waveguide was almost the same because of the similar Er concentration. Therefore the reduction of loss coefficient in RAS sample is due to suppression of the scattering loss. Actually the scattering loss in the sol-gel waveguide was estimated to be about 130 $cm^{-1}$ in previous report [6]. The absorption coefficient $\alpha_{abs}$ is also given by $\sigma_{abs}N$, where $\sigma_{abs}$ and $N$ are absorption cross section and density of $Er^{3+}$ ions in $Er_xY_{2-x}SiO_5$ (x=0.45) crystal. Assuming that the scattering loss is zero, $\sigma_{abs}$ can be estimated to be $4.9\times10^{-20}$ $cm^2$ from the Er density, and this value is in good agreement with that of previous reports [1],[5]. This result also supports the scattering loss is suppressed strongly and negligible in the RAS waveguide.

## 4. Conclusions

We have demonstrated Si-guide layer buried waveguide fabricated by RAS technique. The RAS waveguide suppresses the propagation loss by 120$cm^{-1}$ in comparison with the sol-gel waveguide. The suppression corresponds to the scattering loss. The absorption cross section $\sigma_{abs}$ is estimated to be $4.9\times10^{-20}$ $cm^2$ and the scattering loss can be negligible in the RAS waveguide. We suggest that RAS technique is a good way to form $Er_xY_{2-x}SiO_5$ crystal for compact optical amplifiers and light emitting devices.

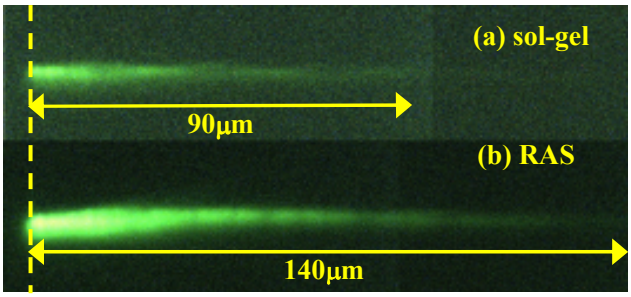


Fig.1 Upconversion emission decay behavior of two samples. The upper image is the sample fabricated by the sol-gel(a), and below is RAS(b).

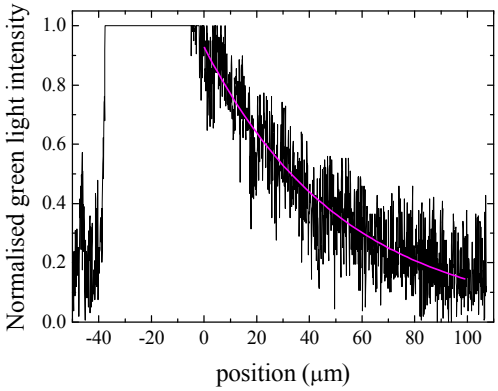


Fig.2 Green light decay and its fitting curve of RAS sample. The decay coefficient was estimated to be 185$cm^{-1}$.


## Acknowledgements

This work was supported in part by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology-Japan, and by the JSPS Core-to-core Program.


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