Extended Abstracts of the 2019 International Conference on Solid State Devices and Materials, Nagoya, 2019, pp65-66

Horizontal Slot Waveguides based on Epitaxial Rare-Earth Oxide on Si

Xuejun Xu[1], Viviana Fili[1], Tomohiro Inaba[1], Takehiko Tawara[1, 2], Hiroo Omi[1, 2] and Hideki Gotoh[1]

[1] NTT Basic Research Laboratories, NTT Corporation
3-1 Morinosato-Wakamiya, Atsugi-shi
Kanagawa 243-0198, Japan
Phone: +81-46-240-3368 E-mail: xuejun.xu.xe@hco.ntt.co.jp
[2] NTT Nanophotonics Center, NTT Corporation
3-1 Morinosato-Wakamiya, Atsugi-shi
Kanagawa 243-0198, Japan

Abstract

We have epitaxially grown high quality single crystalline rare-earth oxide Gd_2O_3 and $(ErGd)_2O_3$ on silicon-on-insulator substrate and successfully demonstrated horizontal slot waveguides with strong optical confinement in these low refractive index rare-earth oxide layers. Er^{3+}-related absorption and visible frequency upconversion were also observed in the waveguides.

1. Introduction

Rare-earth (RE) ions, especially erbium (Er^{3+}), have been widely used as optical gain mediums for solid state lasers and fiber amplifiers for decades. Recently, they have also attracted great attention as being ideal solid state quantum emitters for quantum light sources [1, 2] and optical quantum memories [3, 4]. So far, however, most of these devices were made from bulk crystals or optical fibers, which are with large footprint, difficult to fabricate and impossible for large scale integration. By combining RE-incorporated materials with currently well-recognized silicon (Si) photonics platform, variety of integrated quantum optical devices can be envisioned. Single crystalline rare-earth oxide (REO), which can be epitaxially grown on Si substrate [5], are highly promising for such purpose. Furthermore, as a fundamental building block for realization of these devices, a waveguide structure, with which light is well-confined in REO, is desirable.

In this paper, we have grown high quality single crystalline REO (gadolinium oxide with and without Er incorporation, Gd_2O_3 and $(ErGd)_2O_3$) on silicon-on-insulator (SOI) substrate by molecular beam epitaxy (MBE) and experimentally demonstrated horizontal slot waveguides with strong optical confinement in low refractive index REO layers.

2. Experimental Results

To obtain high quality single crystal REO, Gd_2O_3, with lowest lattice mismatch to Si [6], was chosen as the host material. Thin layers of Gd_2O_3 and $(ErGd)_2O_3$ were grown on SOI (111) substrate by evaporating metal Gd and/or Er sources and simultaneously supplying O_2 gas flow. Streaky reflection high-energy electron diffraction (RHEED) patterns, as shown in the inset of Fig. 1(a), were maintained during the epitaxy process, indicating flat surface during growth. The final surface of REO layers was also examined by atomic force microscope (AFM), as shown in Fig. 1(a). Ultra-flat surface with root mean square (RMS) roughness as low as ~0.2 nm was obtained. Fig. 1(b) shows a typical cross-section transmission electron microscope (TEM) image of the grown samples, in which high quality single crystal and sharp interface between REO and Si could be confirmed.

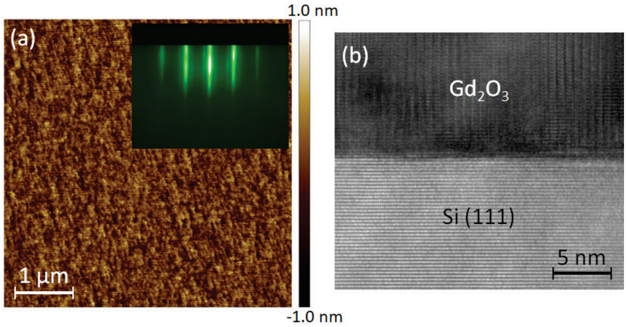

Fig. 1 (a) AFM image of Gd_2O_3 surface grown on SOI substrate. The inset shows typical RHEED pattern of Gd_2O_3 surface during MBE growth. (b) Cross-section TEM image at Gd_2O_3/Si interface.

Due to much lower refractive index of REO (around 1.6~2.0) compared with that of Si, it is difficult to confine light in the REO layers in conventional waveguide structure. Here, a rib-type horizontal slot waveguide structure was proposed, as shown in Fig. 2(a). The electric field of fundamental transverse-magnetic (TM) mode can be well confined in the low refractive index REO [7]. Furthermore, lateral optical confinement can be obtained by simply patterning the Si layer on top of REO, overcoming the difficulty for REO etching. Fig. 2(a) shows power distribution of fundamental TM mode in a horizontal slot waveguide, in which optical confinement factor of ~50% can be achieved in REO.

To realize such waveguide structure, a Si cap layer was finally grown on top of REO. To obtain flat Si surface, a low temperature (~100 °C) growth was performed, which resulted in formation of amorphous Si layer. AFM measurement show that RMS roughness is as low as ~0.4 nm. The finally grown layer stack consists of 120-nm-thick Si bottom layer (including SOI device layer), 60-nm-thick REO and 150-nm-thick Si cap layer. Based on this layer stack, straight waveguides with different widths and fiber-to-waveguide grating couplers were designed. To simplify fabrication process, the etching depth of waveguides and grating couplers were kept the same as the Si cap layer thickness. These devices were then fabricated by standard electron-beam lithography and inductively coupled plasma etching, compatible with conventional Si photonic devices. Fig. 2(b) and 2(c) show the typical scanning electron microscope (SEM) images of the fabricated waveguides and grating couplers.

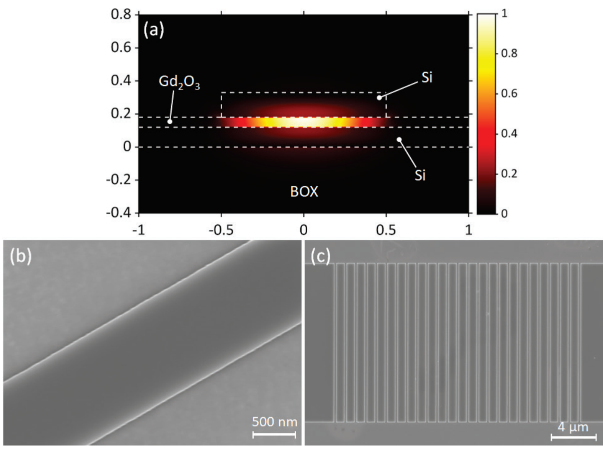

Fig. 2 (a) Power distribution (propagation direction component of Poynting vector) of fundamental TM mode in a horizontal slot waveguide. (b) and (c) are top-view SEM images of fabricated horizontal slot waveguide and grating coupler, respectively.

The light transmission of the waveguides was characterized with a tunable laser and optical component tester. The measured TM-polarized transmission spectra of 330-μm-long and 800-nm-wide waveguides (including the input and output grating couplers) based on Gd_2O_3 and $(ErGd)_2O_3$ are shown in Fig. 3(a) and 3(b), respectively. The transmission of the light through the waveguides were clearly confirmed, although the total loss is quite high. This might be attributed to (1) large coupling loss of the grating couplers due to the deviation of layer thickness from designed values, and (2) large absorption in the low temperature amorphous Si cap layer.

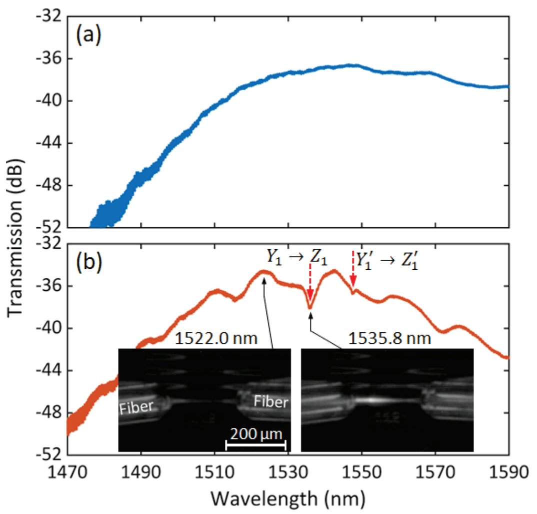

Fig. 3 (a) Transmission spectra of horizontal slot waveguides based on (a) Gd_2O_3 and (b) $(ErGd)_2O_3$. The insets in (b) are top-view microscope images of the waveguide when launching lasers with different wavelengths of 1522.0 and 1535.8 nm.

Furthermore, two additional pronounced dips could be observed at 1535.8 nm and 1547.4 nm in the transmission spectrum of $(ErGd)_2O_3$-based waveguide, while not in that of Gd_2O_3-based waveguide. They are consistent with the $Y_1 \rightarrow Z_1$ transition of Er^{3+} at C_2 site and $Y_1' \rightarrow Z_1'$ transition of Er^{3+} at C_{3i} site, respectively [8], thus corresponding to Er^{3+}-related absorption. Through launching laser with one of these transition wavelengths (1535.8 nm) into the waveguide, visible frequency upconversion light within the waveguide could be clearly seen, as shown in the inset image of Fig. 3(b). On the other hand, the upconversion light was not seen when launching laser with wavelength away from Er^{3+} transitions (1522.0 nm). This result once again verify the propagation of light in the waveguide.

3. Conclusions

High quality single crystalline REO thin films were expitaxially grown on SOI (111) substrate by MBE. Based on this material platform, horizontal slot waveguides with strong optical confinement in low refractive index REO were experimentally demonstrated, although propagation loss needs to be significantly reduced by further optimization of material growth and device design. Er^{3+}-related transitions were also observed in the waveguides from the transmission measurement results and frequency upconversion images. These results will pave the way towards realization of integrated quantum photonic devices based on rare-earth ions.

Acknowledgements

This work was partly supported by JSPS KAKENHI (No. 19H02207 and 19H02636).

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