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Erbium-doped oxide for optical gain on hybrid silicon photonics platforms

(Student Paper)

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ABSTRACT

Increase of power consumption on integrated optical devices for photonic applications has encouraged material engineering to explore new materials and its properties. One of the main challenges on silicon photonics for optical applications is the hybrid integration of these materials due to the lattice mismatch imposed by silicon. In this regard, yttria-stabilized zirconia (YSZ) with a lattice parameter similar to silicon and several functional oxides has been widely studied [1]. Moreover, YSZ waveguides have demonstrated low propagation loss, and no two photon absorption (TPA). Furthermore, it is transparent from the ultraviolet to the near-infrared and exhibit good Kerr effect. It was recently demonstrated about 2 dB/cm propagation losses in waveguides etched on YSZ at a wavelength of 1380 nm [2]. In order to grow an active material as waveguide cladding, we doped YSZ with Er³⁺ ions with a wavelength emission within the C-band of telecommunication window ($\lambda=1530$ nm). In our study, we have considered Er:YSZ cladding deposited by Pulsed Laser Deposition (PLD) on a hybrid SiN_x waveguide. Moreover, we demonstrated guided emission for near-IR transitions of erbium ions under continuous-wave pump laser excitation at 1480 nm. Enhancement of Er³⁺ ion output signal at 1530nm will be discussed and explored and preliminary optical gain will be presented.

Keywords: optical gain, integrated optics, silicon platform, rare-earth, oxides, hybrid integration.

1. INTRODUCTION

The demand of new materials for more efficient photonic devices for silicon photonics has challenged material engineering to explore new functional materials and its properties comprising superconductivity, magnetism, ferroelectricity, catalytic activity, resistive switching, electro-optic effects, piezoelectricity, or optical nonlinearities, among others [3]-[5]. Hybrid integration on silicon photonics platform demand to overcome lattice constraints imposed by silicon. In this regard, material engineering has proposed and widely studied epitaxial buffer layers for high-crystalline functional oxide grown on silicon to minimize interfaces light scattering and defect density [6]. Yttria-stabilized zirconia (YSZ) is a well-known oxide used as buffer layer of functional oxides. It is widely employed as electrolytes, gas sensors and fuel cells due to its thermal and chemical stability, hardness and mechanical durability. Within the photonics field, YSZ also show promising optical properties putting this buffer oxide under the scope for photonic applications on hybrid platforms [7]-[9]. Other oxides as LiNbO₃, Al₂O₃ and Y₂O₃ [10]-[13] have already demonstrated its optic potential as light sources and optical amplifiers when doped with rare-earth ions to develop new light sources and optical amplifiers. For this purpose, low phononic materials are required to avoid non-radiative effects after doping of the host with rare earth. In order to obtain a high efficient active material, high rare-earth ion doping level is required while avoiding quenching effects and maintaining high crystallinity of the host matrix. Among the rare-earth ions, erbium is preferred for its good solubility in YSZ, as well for its emissions in the near-infrared (near-IR) range of wavelengths, making this rare-earth a perfect candidate for the development of efficient light emitting functional oxides at C-band telecommunication.

To this end, we engineered a YSZ multilayer matrix with two different Er³⁺ ion concentrations to provide a highly luminescent overlayer on top of low-loss SiN_x waveguides. Firstly, we have designed the guiding structure at two different wavelengths corresponding to the probe at 1480 nm and to the optical signal according

to the Er^{3+} transition at 1530 nm, respectively. Secondly, we optimized Er^{3+} -doped layer thickness to provide a trade-off between optical power confinement of the quasi-transverse electric (quasi-TE) mode in the passive photonic circuitry and its overlap with the active upper layer cladding. Experimentally, under a continuous-wave excitation at 980 nm wavelength and normal incidence excitation, we shown strong luminescence for the Er^{3+} transition that corresponds with the C-band wavelengths harnessed for telecom applications in silicon photonics. Moreover, we also demonstrated guided emission for both visible and near-IR transitions of erbium ions under continuous-wave pump excitation at 1480 nm.

Recently, we demonstrated a propagation loss as low as 2 dB/cm at a wavelength of 1380 nm for YSZ waveguides [14]. In this study, we demonstrated light optical gain at 1.53 μm on a hybrid photonic platform. Firstly, we have grown by means of pulsed laser deposition (PLD) technique a layer Er:YSZ on a pasive silicon nitride (SiN_x) buried on SiO_2 and we characterized this layer optically by photoluminescence (PL) at 980nm. Secondly, we proved guided emission and optical enhancement for near-IR transitions of erbium ions under continuous-wave pump excitation at 1480 nm.

2. EXPERIMENTAL DETAILS

3.1. Growth

Pulsed laser deposition (PLD) by means of a KrF excimer laser pumping at 248-nm wavelength, a fluence of 3-J/cm², and at 5-Hz repetition rate was used. Oxide deposition was carried out at high-vacuum on a stainless-steel chamber. Laser alternatively ablates 8 mol %yttria-stabilized zirconia and metallic erbium with a purity higher than 97% by using rotating ceramic targets with an incident angle of 45°. Material is deposited on a substrate placed at 50 mm from the targets on a heated holder. Substrate is heated from room temperature to 800°C at a rate of 10°C/min at an initial pressure of 10⁻⁶Torr. During deposition, constant flux of oxygen is provided to the chamber and holder is then cooled under 300 Torr oxygen at a rate of 10 °C/min.

Wafers of chemical polished 1.4 μm silicon dioxide (SiO_2) encapsulated silicon nitride (SiN_x) waveguides of 600nm height and 700nm width on a silicon platform (Fig. 1 (a)) have been developed following the STM requirements. By PLD, we deposited directly on wafer surface erbium-doped yttria-stabilized zirconia (Er:YSZ) thin films.

3.2. Optical characterization

We optically characterized Er:YSZ thin films by means of photoluminescence (PL) on a free-space optical bench using a normal incident scheme (Fig. 1 (b)). Continuous wave of Ti:Sapphire laser at a wavelength of 980-nm and power of 5-mW excites erbium ions perpendicular to the surface of the sample using a microscope objective (not guided PL). Emission and probe are perpendicularly collected by same microscope objective after excitation and focused by a convergent lens of 50-cm focal plane from the detector. Laser wavelength is filtered with a low-pass filter (1100-nm) and only erbium emission in near-IR is detected on a iHR320 spectrometer with a nitrogen-cooled-detector. Er:YSZ thin film photoluminescence (PL) emission profile shows an emission at 1530-nm wavelength corresponding to erbium ion transition $^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ (Fig. 1 (c)). A fix laser working at 1480nm (Fig. 2 (d)), cooperated with an external optical attenuator is applied as the pump source with a tunable range from 0 to 30dBm. A probe laser at 1530nm is combined with the fix laser though power splitter which output another output is guided into the integrated waveguide through grating coupler. The output power from the sample is directed to the optical spectrum analyser (OSA) for gain record. The characterization is repeated on waveguides with identical cross-section (400nm \times 600nm), with different lengths. During the signal enhancement measurements, we observed amplified spontaneous emission and strong green up-conversion in the visible range of wavelengths. After data treatment, optical gain has been studied for three waveguides of different lengths.

3. CONCLUSIONS

In this work we have demonstrated a hybrid photonic platform composed by a low-loss SiN_x waveguide cladded by an active Er:YSZ. We have deposited a thin film of Er:YSZ on SiN_x waveguides. We performed optical characterizations by PL perpendicular to the erbium-doped oxide cladding proving emission on the near-IR wavelength corresponding to erbium transition at 1530 nm. We also measured in-plane guided emission of erbium ions on the near-IR wavelengths range by butt-guide-coupling. Finally, we observed optical gain on three different length waveguides.

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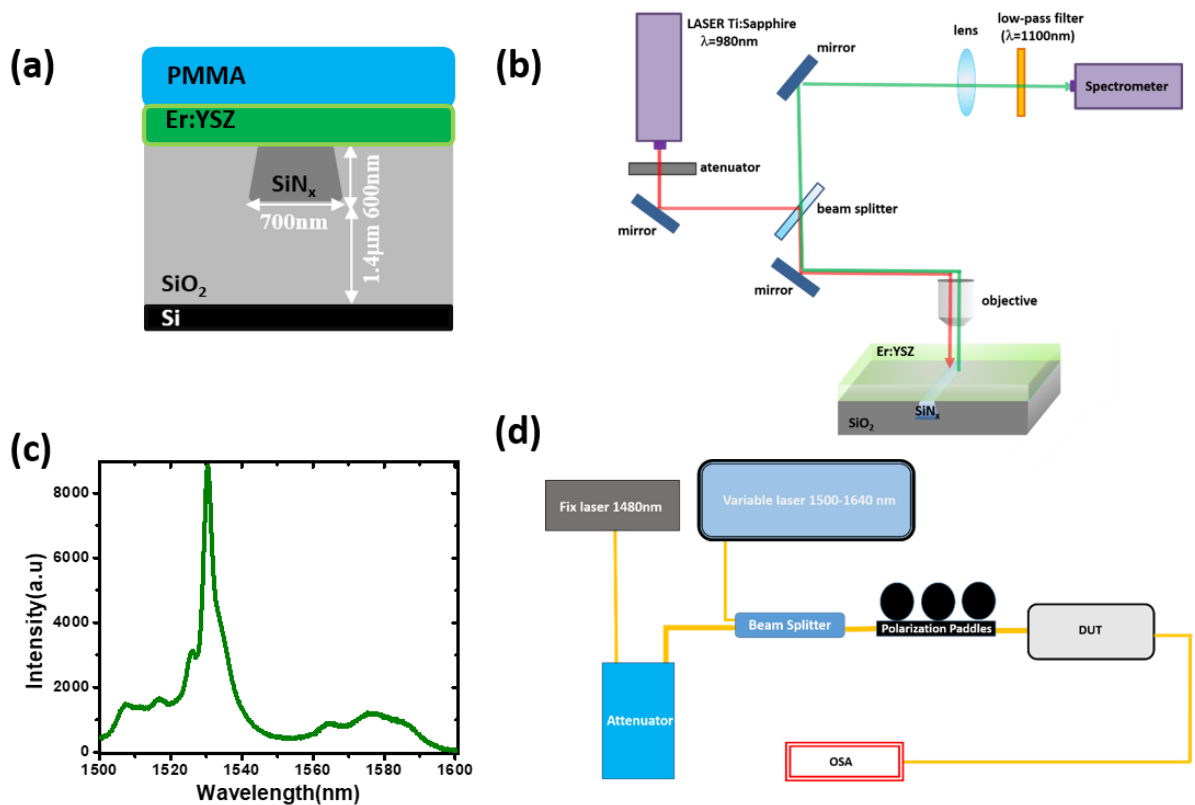


Figure 1. (a) Cross-sectional schematics views of the hybrid waveguide. (b) PL profile of erbium ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition for Er:YSZ. (c) PL setup. (d) Gain measurement setup.

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