Signal enhancement improvement at 1535 nm of Si-nc: Er^{3+} waveguides

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ABSTRACT

Insertion losses, photoluminescence, and pump/probe measurements have been carried out on rib-loaded waveguides containing Er^{3+} ions coupled to Si nanoclusters (Si-nc). Evidences of partial inversion of the Er^{3+} ions excited via Si-nc are presented and discussed.

INTRODUCTION

Integrated EDWAs (Erbium-Doped Waveguide Amplifiers) on silicon substrates are fundamental elements in planar photonic circuits: many efforts are being focused in making them as compact and cheap as possible. The use of broadband efficient sensitizers for Er^{3+} ions relaxes the expensive conditions needed for the pump source and raises the performances of the optical amplifier. Within this context Si nanoclusters (Si-nc) in silica matrices have revealed as optimum sensitizers and open the route towards electrically pumped optical amplifiers [1]. Encouraging results about Er coupled Si-nc silica waveguides have been reported by Shin et al. [2,3] and Daldosso et al. [4]. However the understanding of the material system is still far to be accomplished and strong damaging processes, such as cooperative up-conversion and confined carrier absorption (CA) within the Si-nc, are to be figured out. The goal of this work is to put some light into the understanding and facing off the carrier absorption to improve the optical performances.

WAVEGUIDE FABRICATION

The waveguides have been prepared by a multi-wafers reactive magnetron co-sputtering of a pure silica target topped with Er_2O_3 pellets. The incorporation of Si excess in the film was obtained by mixing the plasma with hydrogen, owing to its ability to reduce the oxygen provided by the silica target. More details on the process can be found elsewhere [5]. First of all a 10 μm thermal SiO_2 layer was grown over the Si substrate. After the deposition of 1 μm thick Er/SRO (Silicon Rich Oxide) layer, a 1 μm thick SiO_2 cladding layer has been deposited by sputtering a SiO_2 target in pure argon plasma. Then the wafers have been annealed for different times at 900°C under pure N_2 flux to activate Er^{3+} ions, to induce the precipitation of the Si excess into nanoclusters and to improve the energy transfer between the Si-nc and the Er^{3+} ions. The annealing temperature was chosen on the basis of previous optimization studies [5]. The annealing duration has been varied between 1' and 240' in a set of samples with 7% of Si excess and $N_{Er}=4x10^{20}$ at./cm^3, as found by RBS measurements.

EXPERIMENTAL RESULTS

To figure out the effective energy transfer

1-4244-0096-1/06/$20.00 ©2006 IEEE

between Si-nc and Er ions and to evaluate the carrier absorption due to Si-nc, it is important to asses how Si-nc are forming, i. e. as a function of the annealing time. We have performed m-line measurements at 633 nm that allow us to asses the optical density of the film, i. e. the layer thickness *d* and the refractive index *n*. Then we have applied the Bruggemann approximation to get assessment about Si-nc formation by considering that the film is composed by amorphous Si-nc (900 °C are not enough to induce crystallization [5]) embedded into a matrix of sub-stoichiometric defected silica SiO_x (with x varying between 1.63 and 2 with increasing the annealing time). Figure 1 shows the results: grey line represents the Bruggeman calculation as the Si is nucleating into the nanoclusters. It can be noted that the larger x the larger the Si atoms into the nanocluster phase, reaching a situation where all the 7% Si excess is within the nanoclusters thus having x=2 in the sample annealed at the longest time (240 min). The black curve corresponds to the calculation obtained by using stoichiometric SiO_2 with n=1.457. The two curves represent two limit cases within which the formation of Si-nc as a function of the annealing time can be described. Moreover, the presence of few percents of voids that are eliminated by increasing the annealing time explains the disagreement for the short time annealed sample data with respect to the grey curve.

The Si-nc density should be independent on the annealing time, therefore the Si-nc radius increases with the annealing time, suggesting a higher role for carrier absorption.

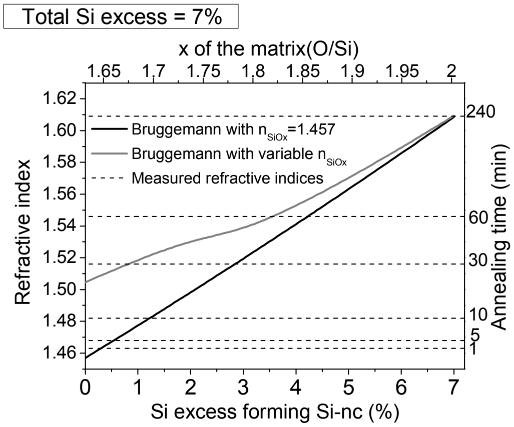

Figure 1. *Two components Bruggemann calculation by using SiO_2 with n=1.457 (black line) and the refractive indices of SiO_x as a function of x (grey line). Dashed horizontal lines correspond to the measured refractive indices.*

Optical transmission measurements have been performed to determine absorption losses and extract the absorption cross section, σ_{abs}. Once calculated the optical confinement factor and considering that all the Er ions are optically active, it is possible to extract σ_{abs}, and hence the emission cross section, $\sigma_{em}(\nu)$ (Fig. 2). It is observed that with decreasing the annealing time, $\sigma_{em}(\nu)$ increases, contrary to what expected due to the refractive index decrease ($\sigma_{em}(\nu)$ is roughly proportional to the refractive index). This is due to a change in the local environment of the Er ions. It is worth noting that σ_{em} for sample annealed at 10’ is roughly twice that of the sample annealed 60’ [6].

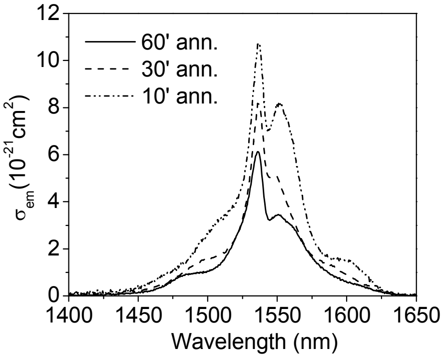

Figure 2. *Emission cross sections calculated from PL spectra at low pump power for samples annealed at 60' (solid line), 30' (dashed line) and 10' (dots).*

Amplification studies are here reported by using the signal enhancement factor SE at 1535 nm, which is the ratio of the transmitted intensity under pumping conditions (I_{PP}) to the transmitted intensity without pump (I_P). To model SE=I_{PP}/I_P, we approximate the physical system as a two levels system working in the regime of weak probes**.**

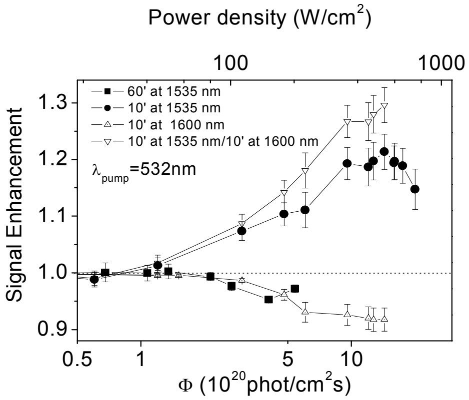

Figure 3. *SE for 1535 nm probe for sample annealed 60' (black squares) and 10' (black circles). Empty triangles are the SE measurement at 1600 nm that we take as the CA contribution for sample 10' and inverted triangles are the result of isolating the contribution of Er^{3+} from the CA absorption. The pump wavelength was 532 nm.*

As a result we have obtained, with non-resonant Er pumping a maximum SE of 1.30 (1.12 dB/cm) for the sample annealed at 10' that means an internal gain of 0.56 dB/cm (0.13 cm^{-1}) at Φ=1.4x10^{21} photon/s cm^2. In the sample annealed at 60' we do not observe any amplification because of the higher role of carrier absorption.

CONCLUSIONS

We have demonstrated that a reduction of the annealing time, while keeping constant all the other processing parameters, leads to smaller Si-nc while more Si is remained in the matrix. This has significantly improved the SE values, because of the reduction of CA and the increasing of σ_{em}.

Acknowledgements. This work is supported by EC through the projects SINERGIA and LANCER.

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