Er^{3+} coupled to Si nanoclusters rib waveguides

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Abstract— **Er doped nano-Si system has been optimised in terms of photoluminescence intensity and lifetime. Reduction of carrier absorption losses and increasing of the number of Er ions coupled to Si-nc (around 25%) have been achieved.**

I. Introduction

The capacity for Si nanocrystals/nanoclusters (Si-nc) to act as broad-band high-absorbing sensitizers of erbium ions (Er^{3+}) is a route to realize an Erbium Doped Waveguide Amplifier (EDWA), where the pump laser can be substituted by an high power LEDs or, even, by an electrical excitation circuit [1]. The main obstacles to achieve net optical amplification in Si-nc based EDWA are currently Carrier Absorption (CA) losses [2] and the low number of Er ions coupled to Si-nc (few %). The reason for this low number is still under discussion [3-5]. In a previous work, we have quantified the CA losses in a Si-nc multi-layer sample without Erbium [2], measuring a maximum CA loss of 2 cm^{-1} at 1535 nm at high pump photon fluxes (~ 10^{20} ph/cm^2s). Recently we have focused on eliminating the CA issue in silicon rich silica oxide (SRSO) Er-doped layers [2]. The CA induced losses are proportional to the exciton population density in Si-nc; thus to reduce the CA, a faster exciton recombination in small nanocrystals and/or a faster carrier population depletion (due, for example, to a transfer mechanism) is needed. In order to realize this we have performed an intensive sample optimization to achieve a high photoluminescence (PL) signal together with a long lifetime, maintaining a low Si excess in the sample to keep small Si-nc.

II. Experimental

The layers investigated have been fabricated by RF reactive magnetron sputtering of 2-inches SiO_2 and Er_2O_3 targets under argon-hydrogen mixture. The ability of the reactive H_2 gas to reduce the oxygen-silicon species originating from the sputtered target was used to modify the incorporation of Si excess in the layers [6]. The deposition was performed onto 2-inches silicon substrates covered by stoichiometric thermal silica of 5-μm thickness. In this work we will examine a series of samples optimized in terms of high PL emission under non-resonant pumping and long lifetime for the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er ions (some milliseconds). The optimization of PL properties of the layers has been done as a function of the main deposition parameters, among them: (i) RF power on each cathode, (ii) substrate temperature T_S, and (iii) hydrogen rate r_H. [7]

After the deposition, the layers were annealed at 910 °C during 60 min in nitrogen flow (20 sccm). PL properties were studied at room temperature under excitation by Ar laser with 476nm and 488nm lines. The optimized samples were then characterized in terms of active layer refractive index and thickness by m-line measurement [8] with visible (543, 633 nm) and infrared (1319, 1542 nm) laser sources. After the deposition of a top-cladding silica,, the slab waveguide has been dry etched to create the channel structure. The etching depth and the channel widths have been chosen in order to optimize the confinement factor Γ of the guided mode while keeping a mono-modal optical waveguide. PL excitation has been performed both pumping resonantly (488 nm) and non-resonantly (476 nm): in the first case the erbium is excited both through direct absorption (although with a lower cross section) and energy transfer from Si-nc, in the latter case the ions are excited only through the Si-nc. Note that, since the Er^{3+} effective excitation cross section through Si-nc is almost 5 order of magnitude larger than direct absorption cross section the latter process can be considered negligible.

Table 1 summarizes some of the material and optical characteristics of the samples: sample C is a reference sample [3].

Table 1. Samples material and optical main characteristics.

Sample label	Si excess [at%]	Er conc. [10^{20} ions/cm^3]	Thickness [μm]	Refr. Index n at 1.5μm	Lifetime ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) [ms]
A	5 ± 2	3.4 ± 0.2	1.2	1.52	5.7 ± 0.5
B	8.5 ± 2	3.8 ± 0.4	1	1.51	5.5 ± 0.5
C	8.5 ± 2	4 ± 0.4	1	1.52	2.2 ± 0.5

III. Results

The deposition parameters (T_S in the range of 50-250 °C and r_H from 20% to 80 %) have been varied in a systematic way to optimize the PL emission under non-resonant

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pumping and the lifetime which have been chosen as figure of merit for the material optimization. Based on these results, two optimized samples were fabricated at r_H =50 % and T_S=100 °C (sample A) and 200 °C (sample B). It is worth to note that we have been able to enhance the PL intensity by almost a factor of three and the lifetime from 2 ms to almost 6 ms with respect to the reference sample C. Morevoer, no evidence of cooperative up-conversion in Er ions was revealed during the lifetime measurements, pumping in a range of photon fluxes from 10^{16} to 10^{21} ph/cm^{2}s.

The active amplification properties of the material (internal gain *g*) have been measured by means of the Variable Stripe Length (VSL) technique [10], which consists in pumping the slab waveguide with a narrow stripe-shaped beam, obtained by focalizing the laser beam with a cylindrical lens. Figure 1 summarizes the VSL results at 1540 nm for both samples as a function of the photon flux: an opposite trend is clear. Sample B shows a net decreasing of the *g* value with increasing the pumping power, while sample A shows an increase of more or less 2 dB/cm for a similar photon flux change. In the former case induced absorption is present (CA), while the latter showing a significant reduction of the losses. This result hints towards a reduction of the magnitude of CA phenomenon in sample A with respect to sample B. This is somewhat expected due to the lower Si excess in sample A.

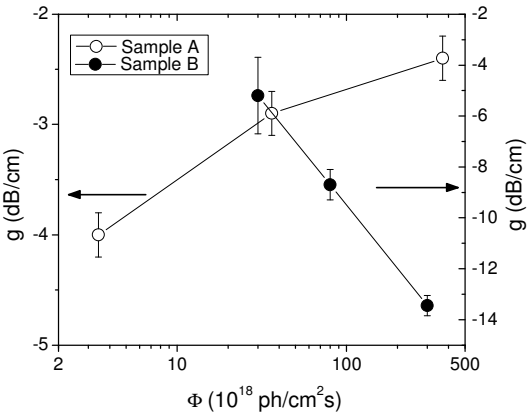

Figure 1: VSL measurements pumping at 488 nm and detecting at 1540 nm on sample A and B for three different pump photon fluxes.

Successively, the sample has been processed to get a rib-loaded waveguide. Passive and active optical behaviour have been determined by cut-back measurements and pump and probe measurements, respectively. Propagation losses (at 1600 nm) do not depend strongly on the channel widths, and show an average value of about 3.5 dB/cm with the best value of 2.6 dB/cm. It is worth to note that material losses in the non-processed layer have been found as low as 1-2 dB/cm by SES (shift excitation spot) measurements [7].

Fig. 2 reports the absorption and emission spectrum for the 5 µm wide channel. From this result we infer an absorption loss coefficient at 1535nm of about 4 dB/cm.

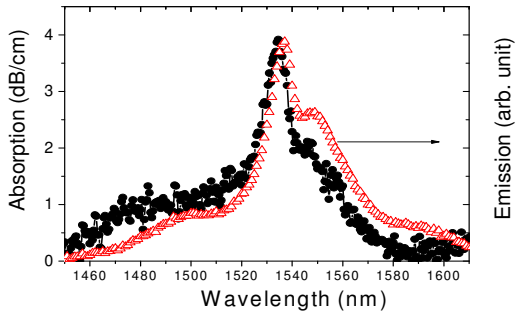

Figure 2. Absorption and emission (476nm, 1.2x10^{18} ph cm^{-2} s^{-1}) spectrum of the rib waveguide sample A (5 µm width).

Pump and probe measurements have been performed for two different probe wavelengths, respectively at Er^{3+} emission spectrum peak (1535 nm) and almost outside the emission spectrum (1610 nm). We have excited the ions pumping both non-resonant and resonant with Er^{3+} ions internal transitions (respectively λ=476 nm and λ=488 nm). Fig. 3 reports the results.

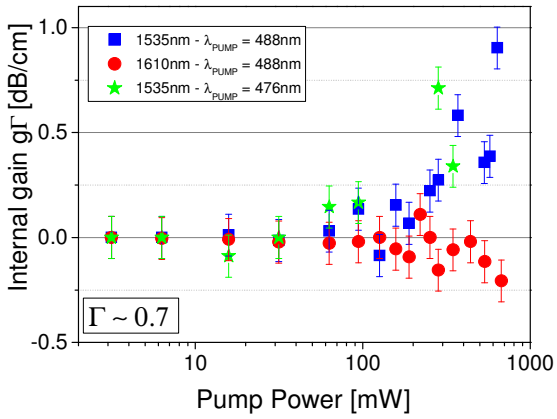

Figure 3: Pump & Probe measurements on sample A for probe wavelength of 1535 and 1600 nm.

The internal gain is almost zero within the error bars in a wide range of pumping powers (from 2 to 50 mW, i.e. 10^{19} ph/cm^{2}s). At higher powers *g* shows a positive value for the Er-gain peak wavelength probe (1535 nm) while remaining zero for the probe wavelength outside the Er emission peak (1610 nm).

Considering a confinement factor of about 0.7,, at medium photon fluxes we have measured a maximum internal gain of more than 1 dB/cm. It is worth to note that thermal oscillations effects make the measurement less reliable at higher photon fluxes. The SE for the 1610 nm probe wavelength appears to be independent from the pump photon flux, which leads us to conclude that the CA losses are negligible in this device.

By comparing the measured signal enhancement (about 1 dB/cm) with the absorption coefficient at 1535 nm

(about 4 dB/cm) we roughly estimate the percent of erbium coupled to Si-nc in our system: 25 % of optically active Er ions. This represents by far the largest improvement from the few % reported in the literature up to now. To improve this result, we have investigated the possibility of an Auger back-transfer issue, performing fast (ns) time resolved IR spectroscopic measurements.

In fact, the current interpretation for the transfer mechanism suggests an Auger-like transfer followed by a fast back transfer between excited Er^{3+} and excitons within the Si-nc, limiting to few percents the active Er^{3+} percentage that is susceptible to be excited through indirect energy transfer [4]. The dynamics of the process can be separated in two different contributions: i) one fast (ns) transfer to the first excited state of Er^{3+}, through which it is possible to excite indirectly around 50% of the Er population, followed by a fast (ns) Auger back-transfer mechanism from excited Er^{3+} to excitons in Si-nc that acts as a non-radiative quenching; ii) one slow (μs) transfer to higher Er^{3+} levels through which it is only possible to excite few percents of the Er^{3+} population.

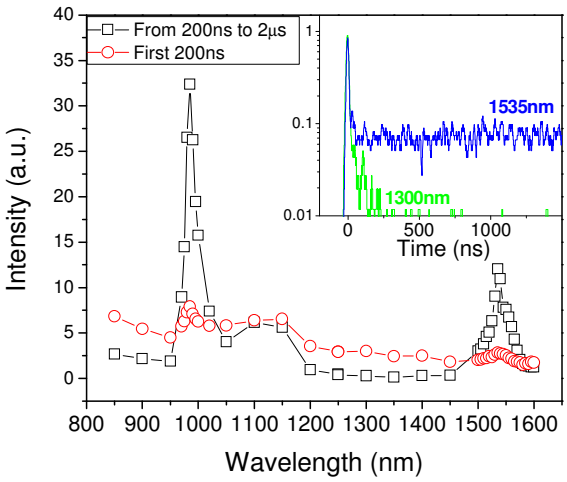

Figure 4: Time-integrated (fast - red circle, slow – black square) spectra for the sample A. The Er^{3+} spectral features are clearly visible for the slow process. Inset – Decay signal inside (1535nm) and outside (1300nm) Er^{3+} emission spectrum.

The inset of figure 4 shows the existence of two processes present in the 1.55μm emission in our samples: i) one fast (ns, rise and decay) ii) one slow (μs, rise). However, spectral analysis showed a fast decaying signal even for wavelengths outside the Er^{3+} emission spectrum. In figure 4 we show the result of integrating the fast (first 200ns) and slow (from 200ns to 2 μs) decay separately and plotted them as a function of the wavelength. Since it does not show the typical Er^{3+} spectral features, we can conclude that the fast mechanism is not associated to Er^{3+} ions emission. On the other hand, the slow part clearly reproduces the Er^{3+} emission spectra, showing both the 980nm ($^4I_{11/2} \rightarrow {}^4I_{15/2}$) and the 1.55μm ($^4I_{13/2} \rightarrow {}^4I_{15/2}$) transitions. It is worth noting that the intensity of the first transition appears higher than the second, due to the much shorter lifetime (μs compared to ms).

As a consistency check, we have performed the same measurements in samples with the same Si-nc composition but without Er^{3+}, measuring only a fast component in the IR region. We can thus conclude that in our samples no sign of Auger back transfer has been measured.

IV. Conclusions

In this work we have shown that we have been able to reduce CA induced losses in Er-doped SRSO samples both through an engineering of Si nanoclusters size (choosing opportune Si concentrations) and coupling a good percent of Er ions to Si-nc, the highest fraction up to date to our In this way one could hope to invert more than 50% of the Er ions. Moreover, we have demonstrated the absence of Auger-back transfer mechanism.

Acknowledgments

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