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Optical amplification studies in Si nanocrystals-based waveguides prepared by ion-beam synthesis

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ABSTRACT

Light amplification has been studied in Si nanocrystals (Si-nc) based waveguides, where the active layers were obtained by ion-beam synthesis. Pump and probe measurements have been performed in both channel and rib-loaded waveguides, using short ns optical pulses from a Nd:Yag laser for pump and continuous probe signals at 650, 780 and 830 nm. The probe was quenched by carrier absorption under pumping, except at 650 nm, where a small signal enhancement was observed. On the other hand, optical amplification at 1.54 μm has been investigated in planar waveguides based on different silicates glasses codoped with Si-nc and Er, by means of the variable stripe length technique. Positive internal gain was found only in aluminium-silicates, suggesting that this can be the best host matrix for the Si-nc:Er system in order to achieve optical amplification.

1. Introduction

During the last decades, it has been demonstrated that silicon, the leading material for microelectronics, can be used to build different kinds of photonic devices (for a review see for instance Ref. [1]). Low-loss waveguides, fast modulators, power splitters and combiners, tuneable optical filters, etc. have been already demonstrated, and thus the feasibility of silicon to manipulate light. Moreover, silicon-based detectors have been fabricated with abilities to convert a light signal into an electrical one. The scientific and technological breakthrough of the actual silicon-based photonics would consist in turning silicon into an efficient light emitter in order to combine both the functionality of silicon microelectronics with ultra-fast optical data processing and transmission on a single silicon chip.

The main potentiality of Si nanostructures (Si-nc) is their ability to provide a low-loss optically active media that can be used for achieving optical gain and then open a way to a Si-based amplifier or laser. Indeed, optical gain from Si-nc-based planar waveguides has been reported [2]. However, such very encouraging results have been proved inherent to the material preparation and treatments. On the other hand, positive signal enhancement at 1.54 μm has been reported in active waveguides, where Si-nc act as a sensitizer to Er ions [3]. The inclusion of Si-nc inside an Er-doped matrix induces an increase of the Er emission efficiency. This discovery has generated a lot of interest and expectations towards the realization of an optical amplifier based on such system that will work in the strategically third optical window of the optical fibre communication.

However, several limiting factors to achieve high optical gain have been reported such as carrier absorption [4], and Auger [5] for the Si-nc system, while, in addition to those phenomena, cooperative upconversion [6], excited state absorption [7], and the low Er fraction coupled to Si-nc [8] are well-known to be the main limiting factors for the Si-nc:Er system.

In this contribution, we present an optical amplification study on Si-nc embedded in SiO_2-based waveguides and Si-nc:Er codoped silicates glasses-based planar waveguides, where the active layers have been obtained by ion implantation.

2. Si-nc active waveguides

Si-rich SiO_2 films were fabricated by Si multi-ion implantation into a thick thermal SiO_2 layer grown on a silicon substrate. Si-nc were precipitated after a thermal treatment at 1100 °C. The bottom panel in Fig. 1a represents the profiles of the Si concentrations needed to form a 0.35 μm thick core layer with 6 at% Si excess, as calculated by the SRIM2004 simulator. Rib-loaded and channel waveguides were fabricated by

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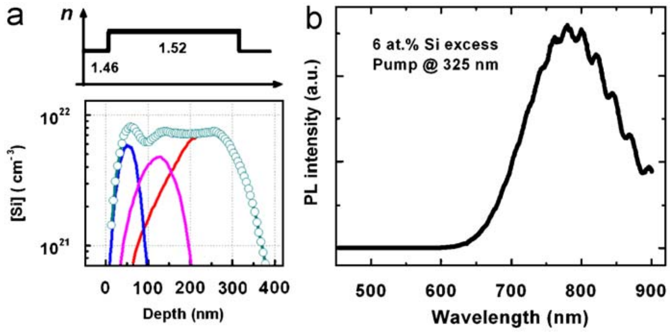

Fig. 1. (a) Si concentration and refractive index profiles of the processed waveguides, and (b) the active layer photoluminescence emission.

lithography and reactive ion etching process. The top panel in Fig. 1a represents the refractive index profile of the fabricated waveguides. A refractive index of 1.46 for the SiO_2 top and bottom cladding layers was considered, while a value of 1.54 was expected for the active Si-nc/SiO_2 layer [9]. These structures were fabricated using the same procedure as described in Ref. [10], where waveguides with an active layer of 10 at% Si excess were investigated, showing propagation losses as low as 11 dB/cm at both 633 and 780 nm wavelengths. By reducing the Si excess down to 6 at%, no degradation was found in the efficiency of the visible emission and the guiding quality of the devices. Under excitation at 325 nm from a HeCd laser, a very intense photoluminescence (PL) peaked at 780 nm was recorded from the processed layers, while defects contribution at short wavelengths was negligible, as depicted in Fig. 1b.

To investigate the PL dynamics, time-resolved (TR-PL) experiments were performed in a standard 45° configuration using 6 ns optical pulses with 10 Hz repetition rate at 355 nm of a stabilized Nd:Yag laser. The PL decays have been fitted with a stretched exponential function: $I(t) = I_0 \exp[-(t/\tau)^{\beta}]$ (see for e.g. Ref. [11]), where τ is the decay time, $I(t)$ and I_0 are the PL intensity during the decay and at $t = 0$, respectively. The stretched parameter β was found almost constant for all the data ($\beta = 0.7$). Fig. 2 reveals a strong decrease of the PL lifetime as a function of the emission energy, in good agreement with previous reports in the literature [12,13]. Quantum confinement model for the Si-nc PL emission describes well this behaviour, as the oscillator strength of the interband transitions is larger for smaller Si-nc (corresponding to higher PL emission energy).

The inset in Fig. 2 presents a comparison of two PL decays obtained at the same emission wavelength by increasing the pump energy density by two orders of magnitude. The temporal decay of the PL intensity was found independent on the pump energy density, an indication of the absence of Auger-like processes in the excitons recombination [14]. This important result allows to discard the presence of Auger process, that could significantly affect the exciton recombination dynamics, and thus the stimulated emission probability.

Time-resolved pump and probe experiments were performed by focusing the spot in a stripe (approximately 100 μm wide and 1 cm long) over the channel waveguide. A continuous probe signal was fed to the waveguides butt-coupled to a tapered fibre. The guided emission was analysed by a monochromator coupled to a streak camera. A very weak probe signal was used so that the excitons population is determined only by the pump density. It is expected with the presence of the probe signal, stimulated emission process would provide the internal optical gain needed for compensating the propagation losses. Fig. 3 shows the signal enhancement, as to say, the difference between the transmitted probe intensity in presence of the pump beam (probe on, pump

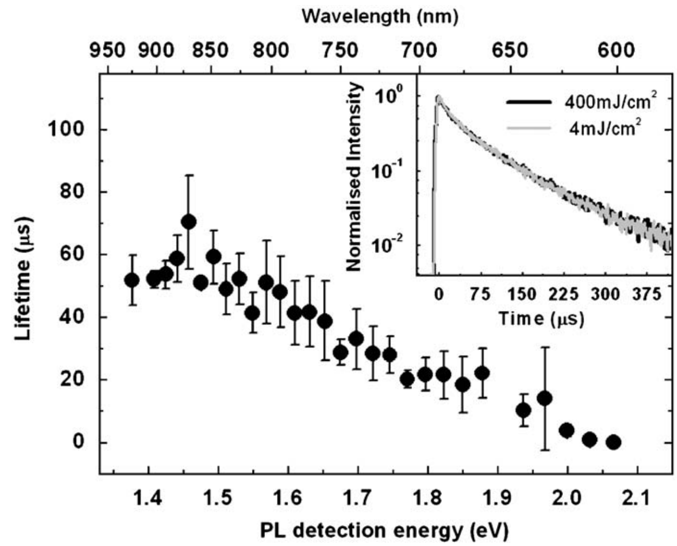

Fig. 2. Spectral dependence of the PL lifetimes. The inset reports the PL decays in normalized log scale at 780 nm for high (black) and low (grey) fluxes.

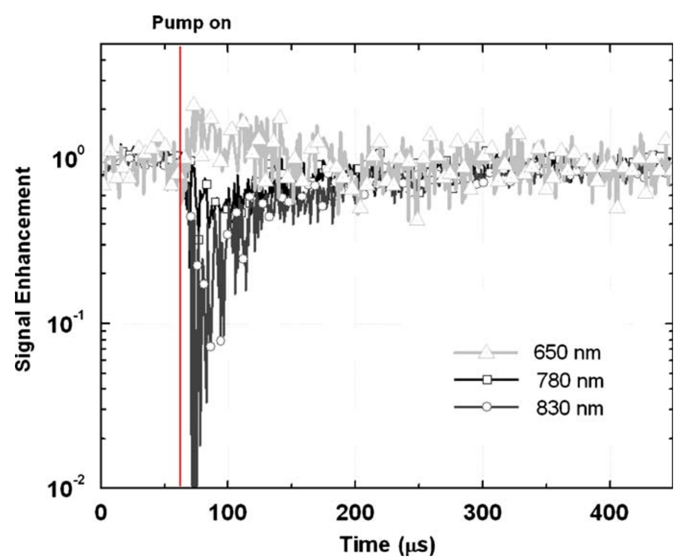

Fig. 3. Signal enhancement in log scale for different probe wavelengths. The pump energy density was fixed at 400 mJ/cm^2.

on) and the guided luminescence (probe off, pump on), normalized to the probe intensity (probe on, pump off). When the probe is tuned to 780 or 830 nm, the presence of the pump severely quenches the signal. This behaviour is consistent with the presence of carrier absorption [4], i.e. part of the excitons generated by the pump successively absorb probe photons to promote electrons to higher energetic levels in the nanocrystal conduction band. It is worth to note that there is a good agreement between the carrier absorption temporal behaviour (tens of μs) and the TR-PL measurements reported in Fig. 2, because excitons population governs both dynamics. Thus, although the suppression of non-radiative decay paths (such as Auger process) provides obvious benefits in terms of PL signal, but at the same time it increases the carrier absorption probability, since the total exciton lifetime is large.

For a probe wavelength of 650 nm, the behaviour was different and a positive signal enhancement of about 2 cm^{-1} was observed. However, it is difficult to relate this result to a stimulated