Silicon sensitization in rare-earth doped gain media: From Si-related defect states to Si nanocrystals

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Silicon sensitization is poised to change the landscape of rare-earth doped optical materials. Rare earth doped oxides have long been used as optical gain medium telecom wavelengths. In erbium doped fiber amplifiers, erbium ions (Er^{3+}) are excited into their first or second excited state by a pump laser, leading to gain at wavelengths near 1.53 µm as a result of stimulated emission from the first excited state to the ground state. In order to improve pump absorption, codoping with ytterbium ions is commonly used, which leads to a typical increase of the pump absorption cross-section by an order of magnitude. A much more dramatic sensitization effect was observed in Si codoped erbium doped oxides: upon incorporation of silicon nanocrystals, several research groups observed effective erbium excitation cross-sections of the order of 10^{-16} cm^2 at visible frequencies, compared to intrinsic erbium absorption cross-sections of the order of 10^{-21} cm^2. These observations imply an effective absorption cross-section enhancement of over four orders of magnitude. Such giant excitation cross-section enhancement could have significant impact on several rare-earth related optical technologies, provided the underlying science is well understood.

While it has been clearly demonstrated that silicon co-doping leads to Er sensitization, the exact role of Si nanocrystals remains an active research topic. For example, the observation of similar Er excitation cross-sections in Si doped oxides processed at widely different temperatures ranging from less than 200°C up to 1100°C suggests that Si nanocrystals are not likely the dominant Er sensitizer in these composite materials.[1] This is an important realization, since it leaves open the possibility of achieving higher sensitized Er concentrations using a vastly reduced thermal budget, a major advantage if these materials are to be used alongside conventional integrated electronic circuits. Here we discuss experimental studies carried out in recent years on various Si sensitized samples, including recent work on the emission dynamics of Si sensitized Er, revealing different excitation pathways within a single sample[2] (see Fig. 1), as well as silicon-concentration-dependent studies of the density of sensitizers, revealing optimized Si concentrations for maximizing the Er related optical gain in these materials[3] (see Fig. 2).

[1] *Excitation wavelength-independent sensitized Er^{3+} concentration in as-deposited and low temperature annealed Si-rich SiO_2 films*, Oleksandr Savchyn, Ravi M. Todi, Kevin R. Coffey, Luis K. Ono, Beatriz Roldan Cuenya, and Pieter G. Kik, Appl. Phys. Lett. **95**, 231109 (2009)

[2] *Multi-level sensitization of Er^{3+} in low-temperature-annealed silicon-rich SiO_2*, Oleksandr Savchyn, Ravi M. Todi, Kevin R. Coffey, and Pieter G. Kik, Appl. Phys. Lett. **93**, 233120 (2008)

[3] *Determination of optimum Si excess concentration in Er-doped Si-rich SiO_2 for optical amplification at 1.54 µm*, Oleksandr Savchyn, Kevin R. Coffey, and Pieter G. Kik, To be published in Appl. Phys. Lett. (2010)

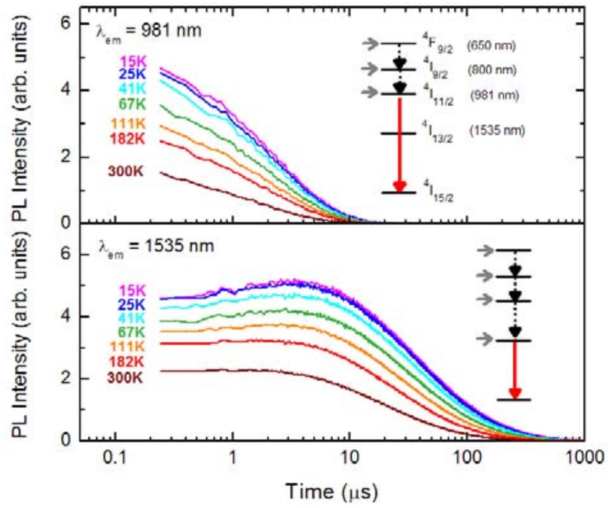

Fig. 1. (Color) Temperature dependent erbium emission dynamics after silicon sensitized pulsed excitation, showing emission from both the second excited state (top panel) and the first excited state (lower panel). The appearance of 1535 nm emission immediately after excitation indicates the presence of sensitization directly into the first excited state, while the appearance of a slow rise of the 1535 nm emission (few-µs time scale) accompanied by emission at 981 nm on a similar time scale indicates sensitization into the second excited state.

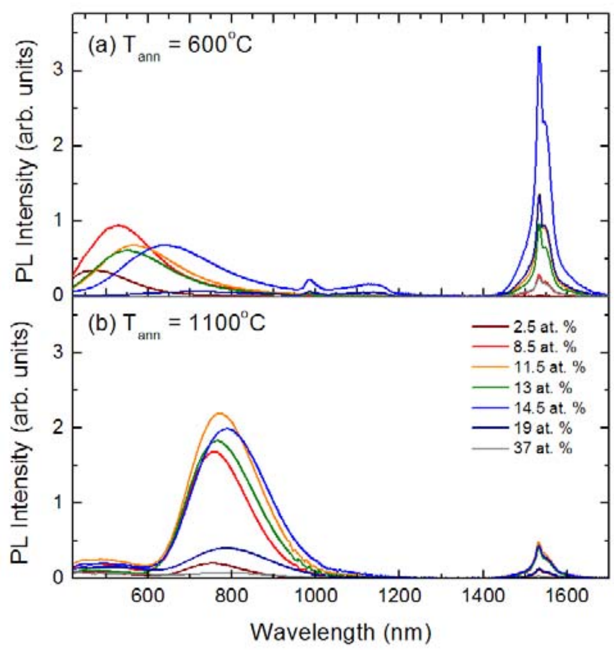

Fig. 2. (Color) Photoluminescence spectra of silicon sensitized Er doped SiO_2 for different concentrations of excess silicon, shown for two different sample processing temperatures. The low processing temperature, which does not produce Si nanocrystals, is seen to lead to stronger Er emission and broad visible emission originating related to Si-related luminescence centers. These low-temperature processed samples were also found to contain a higher concentration of sensitized Er.