Population inversion and low cooperative upconversion in Er-doped silicon-rich silicon nitride waveguide

Jee Soo Chang,[1] In Yong Kim,[1] Gun Yong Sung,[3] and Jung H. Shin[1,2,*]

[1]*Department of Physics, KAIST 335 Gwahak-ro, Yuseong-Gu, Daejeon, South Korea*
[2]*Graduate School of Nanoscience and Technology (WCU), KAIST, 335 Gwahak-ro, Yuseong-Gu, Daejeon, South Korea*
[3]*Biosensor Research Team, ETRI Daejeon 305-700, South Korea*
**jhs@kaist.ac.kr*

Abstract: Single-mode, strip-loaded silicon-rich silicon nitride (SRSN) waveguide with 11 at.% excess Si and 1.7×10^{20} cm^{-3} Er was fabricated and characterized. By using a 350 nm thick SRSN:Er core layer and a 850 nm wide SiO_2 strip, a high core-mode overlap of 0.85 and low transmission loss of 2.9 dB/cm is achieved. Population inversion of 0.73-0.75, close to the theoretical maximum, is estimated to have been achieved via 1480 nm resonant pumping, indicating that nearly all doped Er in SRSN are optically active. Analysis of the pump power dependence of Er^{3+} luminescence intensity and lifetime indicate that the Er cooperative upconversion coefficient in SRSN:Er is as low as 2.1×10^{-18} cm^3/sec.

OCIS codes: (160.5690) Rare-earth-doped materials; (230.7370) Waveguides.

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#138217 - $15.00 USD Received 16 Nov 2010; revised 24 Jan 2011; accepted 6 Apr 2011; published 18 Apr 2011

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1. Introduction

There has been a long quest to develop a Si-based light source that is compatible with the complementary metal-oxide-semiconductor (CMOS) technology for a monolithic, low-cost electro-photonic convergence [1]. Among the many diverse approaches, there has been a renewed interest in using silicon nitride (SiN), in combination with Er-doping, for such a purpose. SiN is widely used in CMOS process, and has many attractive optical properties as well. It has a high and controllable refractive index (≥2.0), enabling compact size and tight mode confinement, even when cladded with standard SiO_2 or polymers [2]. SiN is also highly transparent in the technologically important 1.5 μm region, enabling fabrication of devices such as low-loss waveguides [3,4] and high-Q resonators [5–7]. Finally, when doped with Er, SiN:Er emits light at 1.54 μm due to the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ Er^{3+} intra-4f transition [8–11], enabling fabrication and integration of light-emitting devices such as microdisk resonators [12], photonic crystals [13], and light-emitting diodes [14,15] on a Si chip.

Still, many questions remain. For instance, unlike other Er-doped thin film materials such as Al_2O_3, silicate glass, and silicates [16–19], important optical parameters such as Er^{3+} optical absorption/emission cross-sections and the cooperative upconversion coefficient (CUC) of Er in SiN have not yet been reported. The most serious question, however, is whether doped Er in SiN can be inverted at all. There have been several reports that defect removal, and possibly optical activation of Er in SiN, may be incomplete even after annealing in excess of 1100 °C [8,20,21]. Unfortunately, in oxide-based materials, such a high temperature anneals have been shown to lead to optical de-activation of Er, down to levels where population inversion is impossible, especially if excess Si is present to provide higher refractive index contrast and broad-band sensitization for Er [22–24].

#138217 - $15.00 USD Received 16 Nov 2010; revised 24 Jan 2011; accepted 6 Apr 2011; published 18 Apr 2011

As high refractive index and possibility of broadband sensitization are two important motivations for investigating Er-doped SiN, these issues need to be resolved if research into Er-doped SiN for an on-chip light source is to be meaningful. In this letter, we report on the result of fabricating and characterizing single-mode, strip-loaded silicon-rich silicon nitride (SRSN) waveguides doped with 1.7×10^{20} cm^{-3} Er and 11 at.% excess Si. Due to the presence of excess Si, some degree of sensitization is observed. However, in this paper, we will focus on the conventional, resonant pumping of Er in SRSN. We find the peak emission cross section of Er is $0.8\pm 0.02 \times10^{-20}$ cm^2 at 1536 nm. Even with a compact mode radius of 2.7 μm × 0.48 μm, a waveguide propagation loss of 2.9 ± 0.4 dB/cm at 1536 nm, which is lower than the maximum Er optical gain of 5 dB/cm, is obtained. Under resonant optical pumping at 1480 nm, a population inversion level of 0.73~0.75 out of maximum possible 0.75 is obtained, demonstrating that even with excess Si, nearly all of the doped Er is active. In addition, the CUC is determined to be as low as $\leq 2.1\times10^{-18}$ cm^3/sec, indicating that Er-doped SRSN has a high potential for applications in silicon based optical light devices and amplification.

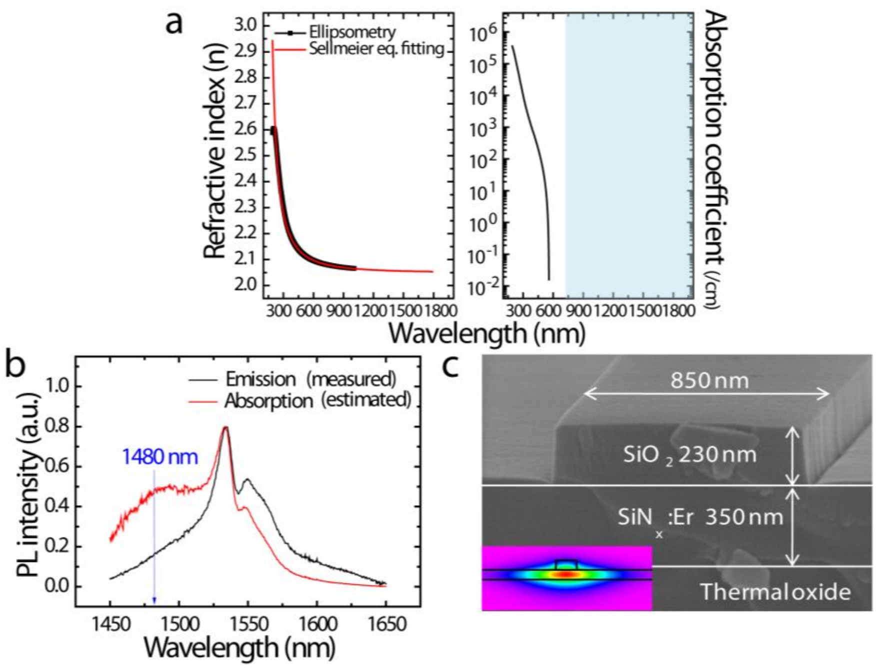

Fig. 1. (a) Refractive index of the Er doped SiN film measured by ellipsometry and fitted by the single-pole Sellmeier equation. Calculated absorption coefficient (a=4pk/l) using the extinction coefficient (k), obtained by ellipsometry. (b) Measured Er^{3+} emission spectrum and estimated absorption spectrum by the relation, $\sigma_{em}(\nu)=\sigma_{abs}(\nu)e^{(\varepsilon-h\nu)/kT}$ [25,26]. (c) SEM image of a strip-loaded SRSN:Er waveguide prior to polishing. Inset shows the calculated single TE mode profile with same parameters.

2. Sample fabrication

350 nm thick, Er doped SRSN film was deposited on a 10 μm thermal oxide wafer by the ion beam sputtering deposition (IBSD) method. High temperature annealing in flowing N_2 environment at 1100 °C for 20 min followed by hydrogenation by annealing at 650 °C for 30 min in forming gas was used to activate doped Er and passivate defects. The composition of the nitride layer was analyzed by the Rutherford backscattering spectroscopy to be 49 at. % Si, 51 at.% N, and 0.2 at.% (1.7×10^{20} cm^{-3}) Er (data not shown). Note that such a composition indicates an excess Si content of 11 at. % over stoichiometric Si_3N_4. Afterward, a 230 nm thick SiO_2 layer was deposited on top of the nitride layer, and 850 nm wide SiO_2 strips were

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fabricated by e-beam lithography and dry etching. Figure 1(a) shows the refractive index and absorption coefficient of SRSN:Er measured by ellipsometry, respectively. The refractive index of SRSN, was estimated using Sellmeier equation to be 2.055 at 1550 nm, while the absorption coefficient (α) was found to be negligible. Using the same method, refractive index of deposited SiO_2 at 1550 nm was estimated to be 1.452 (data not shown).

The room temperature photoluminescence (PL) spectrum of the SRSN:Er film is as shown in Fig. 1(b). Knowing the emission spectrum allows us to calculate the absorption spectrum by the McCumber relation [25,26]. Figure 1(c) shows a scanning electron microscope (SEM) image of a fully processed waveguide. The top surface of the waveguide and nitride layer is smooth and clean, but some sidewall roughness of the waveguide is noticeable. Shown in the inset is the calculated TE-like mode profile based on the SEM image, indicating that the waveguide is a single-mode with core-mode overlap (Γ) of 0.85.

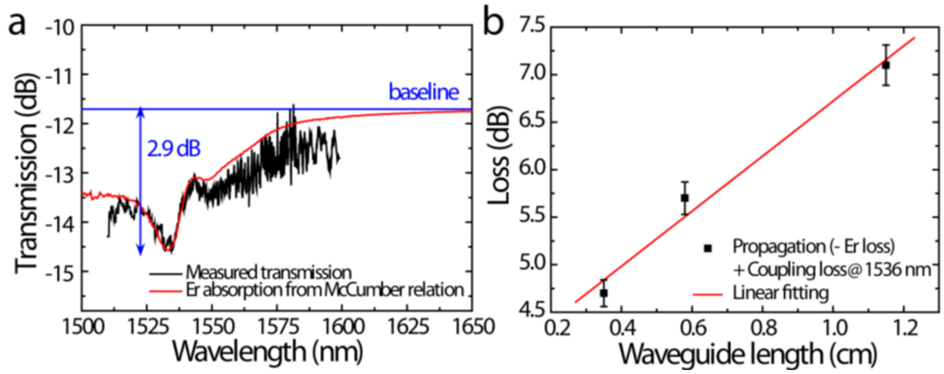

Fig. 2. (a) Measured transmission spectrum (black) of a 0.58 cm length waveguide, fitted by the absorption spectrum (red) in Fig. 1(b). Er absorption is 2.9 dB at 1536 nm. (b) A linear fitted, waveguide length dependent transmission loss without Er loss.

3. Results and analysis

Figure 2(a) shows the background-corrected transmission spectrum of a 0.58 cm long waveguide, obtained using a tunable laser, with the input polarization controlled by a polarization controller to a transverse electric-field (TE) mode. Also shown in red is the expected Er^{3+} absorption spectrum from Fig. 1(b), normalized to fit the observed transmission spectrum. We obtain a very good fit, indicating a good accuracy of the correction procedure. We observe a maximum Er^{3+} absorption loss of 2.9 dB, or 5.0 dB/cm at 1536 nm. As the Er^{3+} absorption loss is given by $a_{Er}=\sigma_{abs}\times N_{Er}\times\Gamma$ where σ_{abs} = Er absorption cross section, N_{Er} = Er concentration, and Γ = the mode overlap of Er, σ_{abs} in SRSN is estimated to be $0.8 \pm 0.02 \times 10^{-20}$ cm^2 which is slightly larger, but is still very close to, the values of $0.5\text{-}0.7\times10^{-20}$ cm^2 for Er^{3+} in oxide-based materials [16]. Given σ_{abs}, the waveguide coupling and propagation losses at 1536 nm were determined by cut-back method, as is shown in Fig. 2(b). Each data point represents the average of at least five identically prepared waveguides. Using linear fit, we obtain waveguide coupling and propagation losses of 1.9 ± 0.3 dB/facet and 2.9 ± 0.4 dB/cm, respectively.

Population inversion and optical gain was investigated by pumping the 0.58 cm long waveguide with a co-propagating 1480 nm laser diode with a maximum pump power of 40 mW/40 mW (measured in front of lensed fiber) [17]. The black, green and red lines in Fig. 3(a) show the signal transmission spectra under pump powers of 0, 5 and 40 mW, respectively. Also shown for comparison is the transmission spectra expected for various levels of population inversion [26]. Upon pumping, we clearly observe increased transmission over all wavelengths. In particular, the dip in the transmitted intensity near 1536 nm due to Er absorption first disappears, and then changes into an emission peak, indicating population

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inversion. Based on comparison with the calculated transmission spectra, we estimate the level of population inversion to be ~0.75. Figure 3(b) shows the pump-power dependent increase in transmitted signal intensity at 1536 nm in more detail. The signal enhancement saturates at 4.46 dB, corresponding to on/off gain of 7.7 dB/cm. This is much larger than the Er absorption loss of 5 dB/cm shown in Fig. 2(a), and indicates a successful achievement of an internal gain of 2.7 dB/cm, As the amplified spontaneous emission is measured to be less than −40 dBm (data not shown), this confirms that the observed on/off gain is due to population inversion and not due to mere bleaching of Er^{3+} atoms. Since absorption by Er is given by $\alpha = \sigma_{Er}(N_1\text{-}N_2)\Gamma$ [26], using the value of 0.8×10^{-20} cm^2 for σ_{Er} derived above, we calculate level of population inversion to be 0.73, in good agreement with Fig. 3(a).

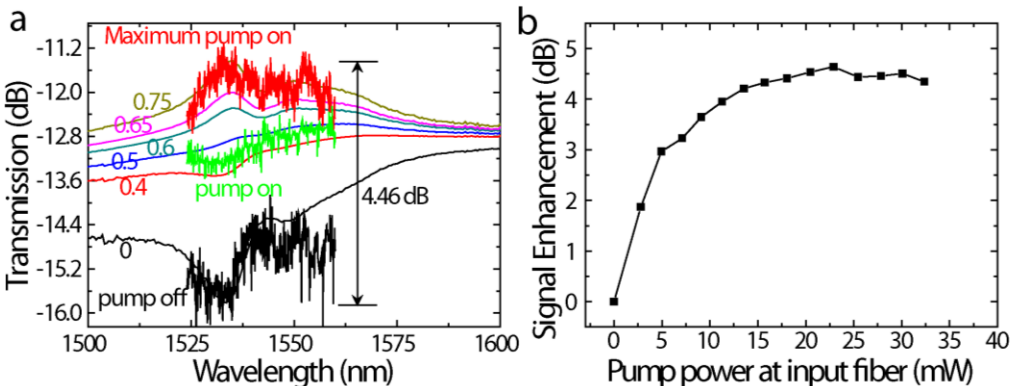

Fig. 3. (a) An absorption (black) and gain (red) spectrum with co-propagating 1480 nm laser diode (LD) pumping at 40 mW/40 mW maximum pump power. A signal enhancement of 4.46 dB is observed. The green spectrum was measured at a lower pump power, 5 mW. The colored lines are estimated transmission spectra for different inversion levels (0, 0.4, 0.5, 0.6, 0.65, 0.75). (b) The signal enhancement as a function of input pump power. Note that the pump power is measured from input fiber, and not calibrated by the waveguide-fiber coupling loss.

It should be noted, however, that due to non-zero emission cross-section of Er^{3+} at pump wavelength of 1480nm as shown in Fig. 1(b), the maximum possible inversion level is limited to $1\text{-}\sigma_{em}/\sigma_{abs}$ (=0.75) since the pump light can also lead to stimulated emission of excited Er^{3+} [28,28]. The fact that we achieve an inversion level of 0.75 is therefore demonstrates that even with 11 at. % excess Si and annealing temperature of 1100 °C, nearly all of the doped Er is active in SRSN. Still, the internal gain of 2.7 dB/cm is lower than the waveguide propagation loss of 2.9 dB/cm, so no net optical gain is yet possible. However, SiN-based resonators with Q-factors of 3×10^6, corresponding to propagation loss of 0.12 dB/cm, have already been reported [5]. Thus, with better fabrication processes, net optical gain should be achievable.

In Er-based light sources, the main factor limiting optical gain in many cases is cooperative upconversion: one excited Er^{3+} ion decays non-radiatively by exciting another excited Er^{3+} ion to a higher excited state, resulting in a net loss of an excited Er^{3+} ion [17,27–29]. A hallmark of cooperative upconversion process is the appearance of 980 nm PL due to second-excited state to ground state ($^4I_{11/2} \rightarrow {}^4I_{15/2}$) transition even when pumped at 1480 nm. However, as Fig. 4(a) shows, no such 980 nm PL could be measured from the SRSN:Er waveguides under 1480 nm pump even at pump powers sufficient to induce maximum population inversion. Furthermore, as the inset shows, the decay traces of 1536 nm Er^{3+} luminescence remains single exponential with a luminescent lifetime of 2.44 msec even when pumped at 430 mW with the 488nm line ($^4F_{7/2} \rightarrow {}^4I_{15/2}$) of an Ar laser, without the double-exponential shape with a rapid initial decay that indicates significant cooperative upconversion [17,28,29]. Taken together, Fig. 4(a) indicates that the effect of cooperative upconversion is small. Therefore, we have analyzed the 1480 nm pump power dependence of 1536 nm Er^{3+} luminescence intensity using the following equation for a 2-level model system

#138217 - $15.00 USD Received 16 Nov 2010; revised 24 Jan 2011; accepted 6 Apr 2011; published 18 Apr 2011

that has been widely used to approximate the cooperative upconversion process in the weak limit [17,26,28,29]

$$I_{Er} \propto \frac{\sigma_{abs}\phi + \sigma_{em}\phi + 1/\tau}{2CN}\{[1+\frac{4CN\sigma_{abs}\phi}{(\sigma_{abs}\phi+\sigma_{em}\phi+1/\tau)^2}]^{1/2} - 1\} \quad (1)$$

where σ_{abs}, σ_{em}, ϕ, τ, C, N is the absorption (excitation) cross section, emission cross section at 1480 nm, pump photon flux, Er^{3+} decay lifetime (measured to be 2.44 msec), CUC, and concentration of Er, respectively.

The result is shown in Fig. 4(b). The best fit is obtained with a CUC of 2.1×10^{-18} cm^3/sec. This value is among the lowest reported from an Er-doped waveguide with comparable Er concentration [27] – in fact, as the blue line shows, a reasonable fit can still be obtained even if we completely neglect the cooperative upconversion process. Such a low value of CUC is of great importance for developing Er-doped SRSN based light sources, as it indicates that population inversion can be achieved at lower pump powers, or equivalently, higher Er concentrations may be used for higher optical gain at the same given pump power.

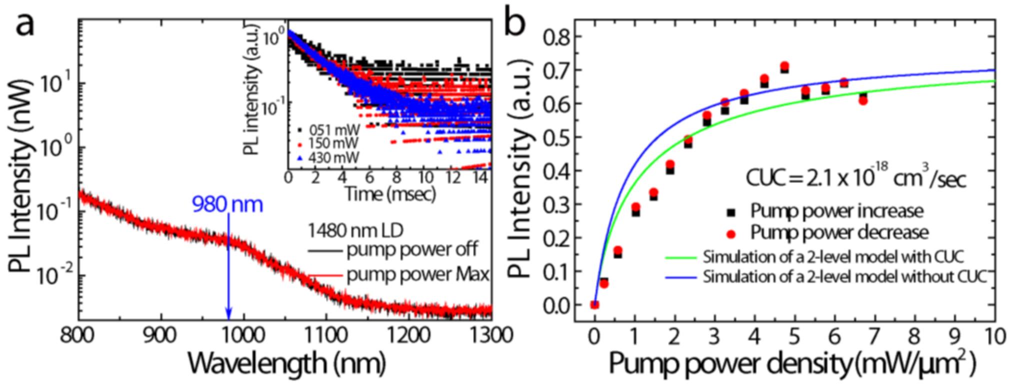

Fig. 4. (a) Photoluminescence observed by 1480 nm pumping shows no emission peak near wavelength 980 nm. (inset) Er^{3+} lifetime at 1536 nm when pumped resonantly (Ar 488 nm) with various pump powers. (b) The 1536 nm PL intensity was measured twice by increasing/decreasing the pump power. CUC of 2.1×10^{-18} cm^3/sec was derived by fitting Eq. (1) (green line). The 2-level model without CUC ($\sigma_{abs}\phi/(\sigma_{abs}\phi+\sigma_{em}\phi+1/t_{Er})$) was also calculated for comparison (blue line). The absorption/emission cross section used for calculation at 1480 nm, was 4.7×10^{-21} cm^2/1.53×10^{-21} cm^2 based on Fig. 1(b).

4. Conclusion

In conclusion,we have demonstrated fabrication and characterization of a single-mode, strip loaded SRSN:Er waveguide with 11 at.% excess Si and Er concentration, 1.7×10^{20} cm^{-3}. The SRSN:Er thin films provide peak emission cross section of $0.8\pm0.02 \times 10^{-20}$ cm^2 which is comparable to the values reported for Er^{3+} in oxide-based materials. Also, maximum achievable optical inversion of 0.75 is achieved via 1480 nm resonant pumping, with internal gain of 2.7 dB/cm. The cooperative upconversion coefficient (CUC) was 2.1×10^{-18} cm^3/sec, which is lower than the reported values for comparable Er concentration. Based on these results, we find that nearly all Er in SRSN are optically active and that population inversion is achievable at low pump power. Thus, we expect that Er doped silicon-rich silicon nitride (SRSN) thin films can be used as compact silicon based optical devices and in amplification.

Acknowledgments

This work was supported in part by the Korean Ministry of Education, Science and Technology (MEST) grant No. 2009-0087691 (BRL), 20100029255 (GRL), and the Mega Convergence R&D program of MKE (10ZC1110: Basic Research of the Ubiquitous Lifecare

Module Development). J. H. Shin acknowledges support by WCU (World Class University) program, grant No. (R31-2008-000-10071-0). J. S. Chang acknowledges support by the POSCO TJ Park Postdoctoral Fellowship.

#138217 - $15.00 USD Received 16 Nov 2010; revised 24 Jan 2011; accepted 6 Apr 2011; published 18 Apr 2011