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Efficient 1535 nm light emission from an all-Si-based optical micro-cavity containing Er\(^{3+}\) and Yb\(^{3+}\) ions

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Abstract: This work reports on the construction and spectroscopic analyses of optical micro-cavities (OMCs) that efficiently emit at ~1535 nm. The emission wavelength matches the third transmission window of commercial optical fibers and the OMCs were entirely based on silicon. The sputtering deposition method was adopted in the preparation of the OMCs, which comprised two Bragg reflectors and one spacer layer made of either Er- or ErYb-doped amorphous silicon nitride. The luminescence signal extracted from the OMCs originated from the \(4\)\(^{I_{15/2}}\)\(\rightarrow 4\)\(^{I_{13/2}}\) transition (due to Er\(^{3+}\) ions) and its intensity showed to be highly dependent on the presence of Yb\(^{3+}\) ions. According to the results, the Er\(^{3+}\)-related light emission was improved by a factor of 48 when combined with Yb\(^{3+}\) ions and inserted in the spacer layer of the OMC. The results also showed the effectiveness of the present experimental approach in producing Si-based light-emitting structures in which the main characteristics are: (a) compatibility with the actual microelectronics industry, (b) the deposition of optical quality layers with accurate composition control, and (c) no need of uncommon elements-compounds nor extensive thermal treatments. Along with the fundamental characteristics of the OMCs, this work also discusses the impact of the Er\(^{3+}\)–Yb\(^{3+}\) ion interaction on the emission intensity as well as the potential of the present findings.

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References and links


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1. Introduction

Driven by their great technological potential, optical micro-cavities OMCs (or resonators) have been the subject of intensive research. Nowadays, OMCs can be found in various applications (lasers, LEDs, sensors, etc.) and there is room for much more by either improving their efficiencies or exploring new phenomena. The simplest OMC, a Fabry-Perot-like structure, involves one spacer layer and two reflectors [1]. Following this configuration, the OMC structure not only is simple but extremely flexible in the sense that it allows to tailor its resonance wavelength, spectral line-width, and optical gain. The effective control of these characteristics, however, depends on the preparation method and properties of the materials that constitute the OMC. The choice of the most appropriate method-material for the realization of OMCs should also consider their final cost, complexity, and compatibility to existing technologies. Within this context, the use of OMCs represents a crucial step towards the achievement of all-Si-based hybrid optical-electronic devices.

Silicon and Si-based materials are well-known for their superior properties and mature processing technology [2]. Furthermore, because of their natural abundance, Si and Si-based materials constitute the fundamental basis of most electronic applications. Their limited light-emitting skills, on the other hand, inhibited the development of all-Si-based optical-electronic devices and generated certain skepticism regarding future advancement in several hi-tech fields. The scenario started to change in the 1980's with the introduction of some innovative concepts and methods giving rise to the (nowadays) well-established Si photonics [3]. One of these promising concepts is the doping of Si with rare-earth (RE) ions leading to either near-infrared or visible light emission [4,5]. The successful emission from RE-doped Si materials is noteworthy not only due to the efficient extraction of light from Si-based materials, but because triply ionized RE ions provide spectrally sharp photon radiation that is almost insensitive to temperature effects. Within the various Si–RE$^{3+}$ associations investigated so far, those involving Er$^{3+}$ ions received particular attention. Such interest was motivated by the $^{4}I_{15/2}$ → $^{4}I_{13/2}$ Er$^{3+}$-related transition (at $\sim$1535 nm) and its almost perfect match with the transmission window (C-band) of the optical fibers currently used in our telecommunications systems (for a review on the subject see, for example [6]). Moreover, the cooperative action of different RE$^{3+}$ ions was explored over the past few years with the purpose of increasing light-emitting efficiencies as well as expecting major advances in the field of solar energy conversion [7,8].

With the above ideas in mind, this work presents a comprehensive investigation of optical micro-cavities in which the spacer layers were Er- and ErYb-doped amorphous silicon nitride (a-SiN) films. The choice of a-SiN took into account its wide optical bandgap and corresponding improved Er-related light emission at $\sim$1535nm [9]. All OMCs and films were prepared by sputtering deposition and were analyzed according to their optical, compositional, and structural properties.

2. Experimental details

All samples investigated in this work were prepared by the radio frequency (13.56 MHz) sputtering method. The preparation involved the sequential deposition of a-Si and a-SiN layers – on different substrates – by using a 5 inches diameter Si target and a plasma of either
argon or nitrogen. The planar OMCs consisted of one spacer layer (a-SiN film doped with Er or with Er + Yb) sandwiched in-between two identical Bragg reflectors [Fig. 1(a)]. Each reflector, which comprised 3 pairs of alternated a-Si and a-SiN layers, was designed to be highly reflective in the ~1200–1600 nm range. Therefore, the thickness (t) and index of refraction (n at ~1535 nm) of the a-Si and a-SiN layers were: \( t_{aSi} = 95 \text{ nm}, n_{aSi} = 3.62, t_{aSiN} = 200 \text{ nm}, \) and \( n_{aSiN} = 1.94. \) For the a-SiN spacer layer, and in order to create a transmission window around 1535 nm, the thickness was 400 nm. Further information concerning the construction and main characteristics of the OMCs can be found elsewhere [10].

The doping of the OMC spacer layers was achieved by partially covering the Si target with suitable chips of metallic Er and Yb. The process is known as cosputtering and allows the production of materials with chemical compositions determined by the relative areas and sputtering yields of the elements forming the target [11]. Following this approach, the OMCs containing the spacer layer doped with Er (OMC-Er) and with Er + Yb (OMC-ErYb) were prepared by covering the Si target with 6 cm\(^2\) of Er, and with 6 cm\(^2\) of Er combined to 6 cm\(^2\) of Yb. For comparison purposes, Er- and ErYb-doped a-SiN films were also prepared with the same composition and thickness of the OMC spacer layers.

Consistent with the deposition method and conditions, all layers were amorphous as shown by Raman scattering spectroscopy [10]. The morphological aspects of the OMCs were also probed by means of scanning electron microscopy imaging (SEM-FEG) and the results confirmed the existence of a regular array of a-Si/a-SiN layers separated by well-defined interfaces [Fig. 1(b)]. The atomic composition of the samples was investigated by energy dispersive x-ray (EDX) measurements. The results indicate that the a-SiN films are almost stoichiometric ([N] ~57 at.%), homogenous, and that both Er and Yb concentrations were at the nominal doping level (clearly above the detection limits of the technique). The optical properties were investigated through transmission and reflection measurements (Perkin-Elmer \( \lambda 950 \)). Photoluminescence (PL) and photoluminescence excitation (PLE) experiments were carried out by exciting the samples with either argon ion (488.0 nm) or titanium-sapphire (900–1000 nm) laser sources with the resulting radiation being detected by either Ge or InGaAs detectors. All measurements (transmission–reflection–photoluminescence) were conducted at room temperature.

3. Experimental results

Figure 2 shows the EDX spectra of the pure and ErYb-doped a-SiN films. Because of experimental constraints, mainly those involving charging effects, the spectra were recorded
from films deposited on copper substrates. Despite the use of different substrates (copper instead of fused silica), both the doped films and the spacer layers within the OMCs were prepared during the same deposition runs and should be identical.

According to the EDX analyses, whereas the pure a-SiN film was constituted by silicon, nitrogen, and traces of oxygen (< 0.2 at.%, which can also be due to the substrate), the ErYb-doped a-SiN film also presented uniformly distributed erbium (0.4 ± 0.1 at.%) and ytterbium (0.4 ± 0.1 at.%) components. In fact, similar concentration values were obtained from a-SiN films doped with only Er or Yb (inset of Fig. 2). These numbers are consistent with the deposition method and chosen conditions and, most importantly, demonstrate the suitability of the present experimental approach in producing rather uniform RE-doped OMCs in a very controllable and reproducible manner.

The optical transmission spectra (under normal incidence) of the OMC-Er and OMC-ErYb structures are shown in Fig. 3. As can be seen, both OMCs exhibit prominent transmission windows that are located at 1510 and 1540 nm in the OMC-Er and OMC-ErYb structures, respectively. Moreover, the OMCs presented different transmission profiles below 750 nm because of the OMC-Er thermal annealing [10]. This standard procedure, when investigating RE-doped amorphous films, is intended to enhance the RE^{3+}-related light emission by suppressing non-radiative processes [12,13]. As a result of the thermal treatment, not only the Er^{3+} transitions become more pronounced [12], but the absorption edge of the a-Si layers is blue-shifted – without inducing any apparent crystallization of the OMC-Er structure [10].

The transmission windows $\lambda_T$s at 1510 nm [Fig. 3(a)] and 1540 nm [Fig. 3(b)] result from the structure adopted for the OMCs ($\lambda_T = 2 t_{\text{spacer}} n_{\text{spacer}}$ [14]) and were intentionally designed to match the $^{4}I_{13/2} \rightarrow ^{4}I_{15/2}$ optical transition [15] of the Er^{3+} ions present in the a-SiN spacer layers. The coincidence between $\lambda_T$ and the $^{4}I_{13/2} \rightarrow ^{4}I_{15/2}$ transition is illustrated in Fig. 3 by means of the optical transmission profiles of the OMCs and PL spectra of the Er- and ErYb-doped a-SiN films. In order to be comparable, the doped films were identical (composition, thickness, thermal treatment) to the Er- and ErYb-doped spacer layers present in the OMCs.

![Fig. 2. EDX survey spectra of the pure and ErYb-doped a-SiN films illustrating their main components (x-ray transitions). The copper contribution comes from the substrate. The inset is an expanded view of the EDX spectra centered at ~1.5 keV and denotes the Lβ x-ray transitions due to the presence of Er and Yb in the Er-, Yb-, and ErYb-doped a-SiN films.](image-url)
Fig. 3. Transmission spectra of OMCs in which the spacer layers were doped with (a) Er and (b) Er + Yb. The PL spectra (under 488.0 nm photon excitation) of the corresponding Er- and ErYb-doped a-SiN films were also included for comparison (notice the different vertical scales in the right-hand side). The PL signals at ~1535 and ~980 nm (with vibronic contributions up to ~1200 nm) are due to the Er$^{3+}$ and Yb$^{3+}$ ions, respectively.

Whereas 488.0 nm photons can effectively (and quasi-resonantly [5]) excite the Er$^{3+}$ ions in the a-SiN films (Fig. 3), this is not the case for the OMCs. In fact, considering the distinctive optical transmission of the OMCs, the only possibility is to excite within the ~800–1100 nm range – ideally by using photons with wavelengths $\lambda_{\text{exc}}$ that coincide with the energy levels of either Er$^{3+}$ or Yb$^{3+}$ ions. The most appropriate $\lambda_{\text{exc}}$’s were found by means of PLE measurements by observing the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition at ~1535 nm. These results are shown in Fig. 4, from which it is clear that the most appropriate $\lambda_{\text{exc}}$’s take place at ~964 and ~982 nm for the OMCs containing Er and Er + Yb, respectively. Despite such small difference, which is associated with the energy levels due to Er$^{3+}$ ($^4I_{11/2}$) and Yb$^{3+}$ ($^2F_{5/2}$) ions when inserted in the a-SiN matrix, it is clear from the spectra of Fig. 4 that the use of non-resonant $\lambda_{\text{exc}}$’s can reduce the light emission intensity by, at least, 25%.

Fig. 4. Photoluminescence excitation spectra (with light detection at ~1535 nm) of OMCs containing a-SiN spacer layers doped with Er (OMC-Er) and Er + Yb (OMC-ErYb). The spectra show that the most intense emission occurs by exciting the OMC-Er and OMC-ErYb with 964 and 982 nm photons, respectively. The inset shows the $^4I_{13/2} \rightarrow ^4I_{15/2}$ PL transition due to the Er$^{3+}$ ions present in the OMC-Er, whose intensities have been indicated in the main PLE spectrum (colored dots).
So far, we produced planar optical micro-cavities with 400 nm thick a-SiN spacer layers doped with Er and with Er + Yb. The spacer layers were inserted between two identical a-Si/a-SiN Bragg reflectors that were intended to be highly reflective in the ~1200−1600 nm range. For comparison purposes, a-SiN films doped with Er and with Er + Yb were also prepared following exactly the same experimental conditions. In order to improve the Er³⁺-related light emission, both Er-doped a-SiN film and OMC-Er structure were thermally annealed up to 750 °C. The Er³⁺-related light emission was increased by exciting the Er- and ErYb-doped OMCs and films with the optimal wavelengths. The quantitative aspects of these investigations are presented and discussed in the following.

4. Discussion

The room temperature PL spectra of the OMC-Er and OMC-ErYb structures are shown in Fig. 5. The PL spectra of the corresponding a-SiN films doped with Er and with Er + Yb are also displayed for comparison. Except for the excitation wavelength, i.e. 964 nm for the Er-doped [Fig. 5(a)] and 982 nm for the ErYb-doped [Fig. 5(b)] samples, all spectra were achieved following exactly the same conditions. Taking into consideration this fact, along with the almost identical atomic structural-compositional characteristics of the samples, the spectra of Fig. 5 indicate that: (a) compared with the Er-doped a-SiN film, the presence of Yb in the ErYb-doped a-SiN increased the Er³⁺-related 1I_{15/2}→3I_{13/2} transition (at ~1535 nm) by a factor of 4; (b) when inserted between two Bragg reflectors, i.e., in the form of an optical micro-cavity, the transition at ~1535 nm improved by a factor of 5 in the OMC-Er, and 12 times in the OMC-ErYb; (c) the Er³⁺-related transition at ~1535 nm not only became more intense in the OMCs, but also experienced a considerable line-narrowing; and (d) altogether, i.e., codoped with Yb and in the form of optical micro-cavity, the Er³⁺-related transition was augmented 48 times in a-SiN. Whereas the observed PL signal narrowing derived exclusively from the wavelength selectivity of the cavities (see the transmission curves of Fig. 3, for example), the improvement of the PL intensity at 1535 nm occurred because of the Er³⁺−Yb³⁺ interaction in conjunction with the optical amplification provided by the OMCs. Yb³⁺ ions are a two-energy level system that exhibit a large absorption cross section in the near-infrared range [15,16]. Also, around 980 nm there is considerable spectral overlapping between the 1F_{5/2} (Yb³⁺) and 5I_{11/2} (Er³⁺) energy levels, which gives rise to an efficient energy transfer from Yb³⁺ to Er³⁺ ions. Accordingly, the Er³⁺−Yb³⁺ interaction is largely explored to produce Er³⁺-related light emission either in the near-infrared or visible regions (see, for example [17], and references therein).

![Fig. 5. PL spectra of (a) OMC-Er and (b) OMC-ErYb structures. The PL spectra of the corresponding a-SiN films were also included for comparison. All measurements were performed at the very same conditions: room temperature, 45° exc.−0° detect. geometry, and by exciting the samples with either 964 nm (Er-doped) or 982 nm (ErYb-doped) photon wavelengths. Notice the multiplying factors in each spectrum.](image-url)
The observed optical amplification effect, took place because of the resonance created by the multiple reflections of the light confined between the Bragg reflectors [1]. In the case of the present OMCs, the optical amplification at the \( \sim 1535 \) nm resonance wavelength remained in the 5–12 range (Fig. 5). Another important parameter related to the optical performance of any OMC is the quality (Q-) factor. In brief, the Q-factor is given by the ratio between the resonance wavelength and its corresponding line-width. Moreover, the Q-factor is highly susceptible to characteristics such as: construction details of the OMCs (typical optical absorption of the layers, homogeneity, number of periods); photon wavelength (typical spot size, polarization); etc [1,14,18]. A rough estimate of the Q-factor of the present OMCs indicated values around 40 that, along with the achieved optical amplification, are similar to others found in literature (see, for example [19,20], and references therein).

The already discussed filtering (or wavelength selectivity) characteristic of the OMCs can be further appreciated in Fig. 6. According to the figure, the influence of the transmission windows on the PL signal of the OMC structures is clear. The spectra of Fig. 6 also show the blue-shift of the resonance wavelengths as well as the changes in the PL signal intensity as the OMCs were tilted 10\(^\circ\) from their surface perpendicular. Compared with the spectra of Fig. 5, that were achieved by adopting the 45\(^\circ\) excitation–0\(^\circ\) detection geometry, the PL spectra of Fig. 6 (35\(^\circ\) exc.–10\(^\circ\) detect.) exhibited Er\(^{3+}\)-related light emissions that shifted from 1535 to 1520 nm in the OMC-Er, and from 1536 to 1533 nm in the OMC-ErYb. The complete angular dependence of the Er\(^{3+}\) emission wavelength and intensity, by tilting the OMCs between 10\(^\circ\) and 40\(^\circ\), is shown in Fig. 7.

The angle-dependent behavior of the PL intensity (Fig. 7) can be attributed to variations in the number of 964 or 982 nm photons that effectively reach the spacer layers and/or to wave-guiding effects [10,14]. The shifts observed in the resonance wavelengths, on the contrary, had a different origin. Given the atomic-like nature of the \( ^{4}I_{15/2} \rightarrow ^{4}I_{13/2} \) Er\(^{3+}\)-related transition, its emission wavelength is centered at 1535 nm [15]. Such a value and corresponding PL spectral shape are expected to be modified only because of changes in the atomic chemical-structural environment of the Er\(^{3+}\) ions. Considering that the Er\(^{3+}\) ions surroundings (amorphous SiN) were kept unmodified, the Er\(^{3+}\) PL signal should remain constant. In spite of this, the main emission wavelength, spectral shape, and intensity of the Er\(^{3+}\)-related PL signal can be altered by the influence of external agents such as an optical micro-cavity, for example.

![Fig. 6. PL and reflection spectra of (a) OMC-Er and (b) OMC-ErYb structures. The reflection spectra were taken at 10\(^\circ\) and the PL ones under a 35\(^\circ\) exc.–10\(^\circ\) detect. geometry. The black lines reproduce the corresponding PL spectra of a-SiN films doped with Er and Er + Yb under 45\(^\circ\) exc.–0\(^\circ\) detect. geometry. All measurements were carried out at room temperature and the PL spectra were achieved under 964 nm (Er) and 982 nm (ErYb) excitation.]
The optical transmission (or reflection) properties of any OMC is determined essentially by two factors: its design characteristics (Bragg reflectors and spacer layers), and by the differences in the optical path the photons experience as they cross the OMC. When a photon hits a single layer system (index of refraction $n$ and thickness $t$), for example, the effective phase thickness $\delta$ varies with the angle of incidence such that $\delta = (2\pi nt \cos \theta)/\lambda$ [14]. As a consequence, the increase of the angle of incidence induces a blue-shift of the resonance wavelength in order to keep $\delta$ constant. At this point, it is important to remark that a similar reasoning applies for the departing photons. In the specific case of an optical micro-cavity, the presence of various layers requires the use of an effective index of refraction, defined by $n_{\text{eff}} = 2n_{\text{a-Si}}n_{\text{a-SiN}}/(n_{\text{a-Si}} + n_{\text{a-SiN}})$, that properly describes the whole OMC structure. The “new” (tilted) resonant wavelengths $\lambda_{\text{tilt}}$ can be expressed by [1]:

$$\lambda_{\text{tilt}} = \lambda_0 \cos (\theta / n_{\text{eff}}),$$

where $\lambda_0$ stands for the original (non-tilted) resonance wavelength and $n_{\text{eff}} = 2.44$ [10]. The theoretical resonance wavelengths, as provided by Eq. (1), are presented in Fig. 7. As can be seen, the agreement between the experimental and theoretical resonance wavelengths is almost perfect for the OMC-ErYb structure. In the case of the OMC-Er, on the contrary, the experimental results are $\sim 12$ nm smaller than the expected ones. Such a difference occurred because of the mismatch between the Er$^{3+}$ transition and the center of the transmission window of the OMC-Er structure [Fig. 6(a)]. Actually, the experimental results indicate that only a small portion of the Er$^{3+}$ PL signal (short-wavelength side) was enhanced by the influence of the micro-cavity, suggesting that slightly higher PL intensities could be achieved in the case of the OMC-Er. Therefore, along with the efficiency of the excitation process and wave-guiding effects, the mismatch between the light emission and transmission wavelengths can also explain the decrease of the PL intensity.

Under the present experimental conditions, it is clear that the most intense Er$^{3+}$-related PL signal was achieved just around the perpendicular of the OMC surface. On the other hand, the results also suggest that the light emission wavelengths can be tuned by almost 75 nm, i.e., from $\sim 1535$ to 1460 nm (Fig. 7).

![Fig. 7. PL results (resonance wavelength and intensity) as a function of the angle of detection – relative to the perpendicular of the sample surface. The data refer to the Er$^{3+}$-related light emission as obtained from the (a) OMC-Er and (b) OMC-ErYb structures. “Film” corresponds to the PL data of the Er- and ErYb-doped a-SiN films following the 45° exc.–0° detect. geometry. Notice the different vertical scales in the right-hand side. All measurements were carried out at room temperature and the PL spectra were achieved under 964 nm (Er) and 982 nm (ErYb) photon excitation.](image)
4. Conclusions

In summary, the present work reports on the construction and properties of optical microcavities OMCs entirely based on silicon thin films. The OMCs were formed by one spacer layer (either Er- or ErYb-doped a-SiN films) that was placed between two identical Bragg reflectors (three pairs of alternate a-Si/a-SiN films). The whole OMC structure was prepared by sputtering and was intended to present a transmission window at approx. 1535 nm. Er-, Yb-, and ErYb-doped a-SiN thin films were also prepared, following exactly the same deposition conditions, for comparison purposes. The details involving the construction, atomic composition, and optical characterization of the OMC were presented to some extent. Also, the basics of the OMCs and the mechanisms behind the Yb$^{3+}$-to-Er$^{3+}$ energy transfer were conveniently addressed.

The experimental results show that substantial improvements in the Er$^{3+}$-related PL signal were achieved by combining Er$^{3+}$ and Yb$^{3+}$ ions and by inserting the doped a-SiN spacer layers within the OMCs. In fact, compared with the Er-doped a-SiN film the Er$^{3+}$-related PL signal emitted by the OMC-ErYb was 48 times more intense. Moreover, the adoption of a 45° excitation–0° detection geometry induced no appreciable shifts in the resonance wavelength nor in the PL signal intensity. Further enhancement of the Er$^{3+}$-related light emission can be achieved by carefully choosing different Er and Yb concentrations and/or different spacer layer materials. Likewise, higher Q-factors and some improvement in the optical amplification can be achieved by increasing the number of periods and the reflectivity of the Bragg mirrors. From a practical point of view, however, our experimental approach proved to be very suitable in producing a light emitting source at ~1535 nm. More specifically, the construction of all-Si-based OMCs by the sputtering technique: (a) is perfectly compatible with the deposition of good quality thin films over relatively large areas and on almost any solid substrate, and (b) allowed the controllable insertion of doping species without the need of special elements-compounds nor complicated sample processing. Moreover, taking into consideration the amorphous nature of the Si layers, the properties of the OMCs can be customized by thermal annealing treatments. This possibility represents one additional advantage that contrasts with chemically-based methods in which extensive thermal treatments are mandatory.

Finally, the present experimental approach and results suggest the feasibility of producing efficient light-emitting materials (or structures) entirely based on Si and rare-earth ions. Furthermore, a proper combination of different Si compounds and (groups of) rare-earth ions is expected to generate customized-tunable light sources at wavelengths ranging from the ultraviolet to the infrared regions.

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