Available online at www.sciencedirect.com

SciVerse ScienceDirect

PHOTONICS AND NANOSTRUCTURES
Fundamentals and Applications

Photonics and Nanostructures – Fundamentals and Applications 10 (2012) 547–552

www.elsevier.com/locate/photonics

Ultra-large tuning of photonic modes for efficient Er-doped silicon-based emitters

L. Cavigli [a,*], A. Vinattieri [a], M. Colocci [a], D. Gerace [b], L.C. Andreani [b], A. Piana [c], D. Sanfilippo [c], A. Muscarà [c], E. Marcellino [c], D. Rodilosso [c], M.E. Castagna [c], M. Gurioli [a]

[a] *Dipartimento di Fisica e Astrofisica Università di Firenze, via Sansone 1, 50019 Firenze, Italy*
[b] *Dipartimento di Fisica "A. Volta", Università di Pavia, via Bassi 6, 27100 Pavia, Italy*
[c] *STMicroelectronics, IMS R&D, Stradale Primosole, 50, 95121 Catania, Italy*

Received 29 November 2011; received in revised form 2 April 2012; accepted 25 April 2012
Available online 5 May 2012

Abstract

We demonstrate that a gentle gas adsorption technique can be used to achieve an optimal covering of silicon-based photonic crystal slabs, leading to an unexpectedly large (up to 42 nm) shift of the resonant modes wavelength, with possibility of fine tuning. Strong enhancement (up to 30 times) of the emission band of the Er^{3+} ion into such structures is obtained. Finally, we were able to balance the adsorption and desorption processes by controlling the sample temperature, thus yielding a stable mode at the desired wavelength.

Keywords: Photonic tuning; Silicon nanostructures; Erbium

1. Introduction

In view of the long lasting goal of integrating all the optical and electronic functions on a single chip, efficient light emission in silicon-based systems and devices is one of the utmost relevant issues in nanophotonics. The combination of silicon (Si) nanostructures and Erbium (Er) doping has been pointed out as very promising due to the enhanced Er^{3+} excitation mediated by carrier capture into the Si nanoclusters [1–3]. Large improvement of the external quantum efficiency has been recently demonstrated by embedding the emitting layers into photonic crystal (PhC) systems, thus tailoring the angular emission and the radiative rate. In particular, a strong enhancement of the external emission efficiency has been obtained in silicon-on-insulator (SOI) PhC slab [4], by the existence of photonic modes at Γ with small group velocity [5–8]

A common problem in fully exploiting the synergy of nanotechnology with photonics is the spectral mismatch between photonic and material resonances. In fact, the coupling efficiency of an emitter to the modes of a PhC structure crucially depends on the ability to deterministically predict the spectral resonance of photonic systems. Unavoidable imperfections arising during the PhC fabrication spectrally detune the

* Corresponding author. Present address: Istituto di Fisica Applicata Consiglio Nazionale delle Ricerche (IFAC-CNR), Via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy.
E-mail addresses: cavigli@fi.infn.it, l.cavigli@ifac.cnr.it (L. Cavigli).

1569-4410/$ – see front matter
http://dx.doi.org/10.1016/j.photonics.2012.04.008

modes from the target wavelength. Postfabrication tuning has been realized with various methods, including digital etching [9], liquid infiltration [10,11], near field perturbation [12,13] and nano-oxidation [14]. One very simple, large (up to 5 nm) and reversible tuning method has been obtained by allowing xenon or nitrogen gas to adsorb onto a PhC slab nanocavity maintained at low temperature [15].

In this work, we demonstrate that the gas adsorption technique can be used to achieve an unexpectedly large shift of the resonant modes wavelength (up to 42 nm), which can be exploited for precise tuning of SOI PhC slab modes, yielding a strong emission enhancement of the Er^{3+} ion into a Si-based structure at the target telecommunication wavelengths around 1.5 μm. Going beyond the approaches reported in previous works, our use of a very slow gas adsorption leads to an optimal covering of the PhC slab with complete infiltration of the air pores. The consequent dielectric perturbation of the PhC modes is optimized to the maximum predicted value, which also depends on the extension of the photonic modes out of the dielectric region. By controlling the sample temperature we are also able to balance the adsorption and desorption processes, thus obtaining a stable mode at the desired wavelength.

The paper is organized as follows. In Section 2 we briefly describe our design, fabrication, and experimental tools; in Section 3 we report our experimental results and comment them, before summarizing the main conclusions of the work in Section 4.

2. Design, fabrication, and experimental methods

Active SOI waveguides were fabricated by depositing a sequence of Si (120 nm, B-doped)/SiO_2:Si-nc:Er (50 nm)/Si (120 nm, As-doped) layers on top of a 1.9 μm thick silicon dioxide layer thermally grown on a Si substrate. Silicon layers have been deposited by Low Pressure Chemical Vapor Deposition (LPCVD), while Silicon Rich Oxide (SRO), characterized by a Si excess of 43%, is grown by Plasma Enhanced Chemical Vapor Deposition (PECVD). Erbium was then introduced in SRO region by ion implantation at energy of 50 keV to a total fluence of 2.5×10^{14} ions/cm^2. The implantation energy has been chosen in order to have the projected range of the ion distribution in the center of the dielectric gate. Subsequently, a thermal annealing was performed on the device at a temperature $T = 800\,^{\circ}C$ for 30 min under nitrogen flux, with the goal of achieving the optical activation of Er^{3+} ions and the agglomeration of the Si excess in SRO films to form Si nanocrystals (Si-nc).

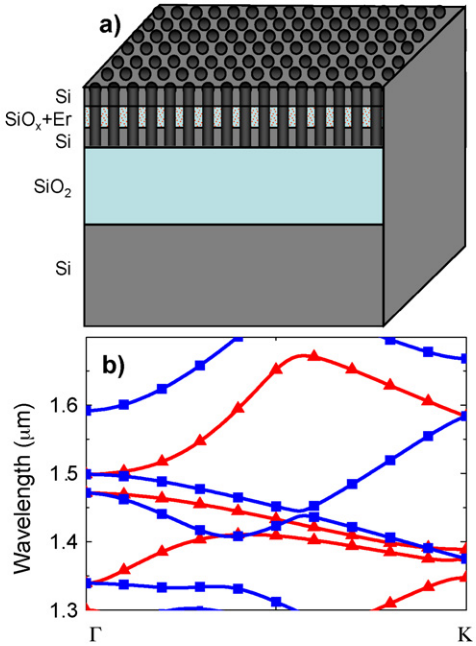

Fig. 1. (a) Scheme of the SOI PhC slab. (b) Photonic band dispersion in the case of $a = 1060$ nm around the wavelength of 1.5 μm; even (odd, respectively) states are plotted in red triangles (blue squares respectively). Around 1.5 μm we see two degenerate states at Γ (even and odd states coincide). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Two-dimensional (2D) PhC were fabricated into the SOI waveguide by means of standard electron beam lithography and reactive ion-etching techniques. The structure under consideration consists of a 2D triangular lattice of air holes; a schematic picture of the PhC is reported in Fig. 1(a). Several samples were fabricated with lattice constants varying from $a = 1000$ nm to $a = 1240$ nm in steps of 20 nm in order to provide the energy matching between the Er^{3+} emission line and a photonic mode around $\boldsymbol{k} = 0$, i.e., at the Γ point of the 2D Brillouin zone. The hole radius to lattice constant ratio, $r/a = 0.33$, was kept constant for all samples.

A guided mode expansion (GME) method [16] has been applied for the structures design. The method is based on calculating the photonic band dispersion in PhC slabs by expanding the modes of the three-layer structure (upper cladding/core/lower cladding) on the basis of guided modes of an effective planar waveguide. A typical calculation is shown in Fig. 1(b) for the PhC slab with lattice constant $a = 1060$ nm, reported for wavelengths around 1.5 μm. For the core layer we used an average refractive index to take into account the composite nature of this layer [4]. Even (odd) modes due to reflection symmetry with respect to the vertical