Strong enhancement of Er^{3+} emission at room temperature in silicon-on-insulator photonic crystal waveguides

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We have realized silicon-on-insulator photonic crystal (PhC) waveguides with intense 1.54 μm emission at room temperature. The slabs contain a thin layer of SiO_2 with Er^{3+} doped silicon nanoclusters embedded at the center of the Si core and are patterned with a triangular lattice of holes. An enhancement by more than two orders of magnitude of the Er^{3+} near-normal emission is observed when the transition is in resonance with an appropriate mode of the PhC slab. The results are in very good agreement with calculated photonic bands and emission spectra. These findings are important for the realization of Si-compatible efficient light emitters at telecom wavelengths. *© 2006 American Institute of Physics*. [DOI: 10.1063/1.2214180]

The goal of achieving efficient light emission in Si-compatible systems is of considerable importance for the integration of photonic and electronic functions in a single chip, and it is actively pursued with a variety of approaches.[1–7] The most explored routes consist in exploiting the optical properties of silicon nanostructures[2,3] or in doping silicon with radiative centers, such as rare earths, which can be excited through electron-hole (e-h) recombination.[4] Most recently the merging of the two above-mentioned approaches, i.e. the Er doping of Si nanoclusters (nc),[5–7] has been recognized as extremely promising. In fact, optical gain[6] has been observed and room-temperature operating light emitting devices have been fabricated[7] opening the way for the future achievement of electrically driven optical amplification. One of the main problems of this system is the relatively small light extraction which, in turn, limits the external quantum efficiency. The use of a Si/SiO_2 waveguide with an Er^{3+} doped layer, coupled to a ring resonator, has been theoretically proposed to enhance luminescence efficiency.[8] As an alternative route, photonic crystals[9] (PhCs), where light propagation and confinement can be accurately tailored by a periodic modulation of the dielectric constant, offer the possibility to enhance light-matter interaction and to increase light extraction efficiency from the device.[10] Simultaneous inhibition and redistribution of light emission has been observed in III–V based two-dimensional (2D) PhCs (Ref. 11) and strong enhancement of intrinsic Si emission has been reported at low temperature in silicon-on-insulator (SOI) waveguide-embedded photonic crystals,[12] also known as PhC slabs.

In this letter we report on the realization and optical characterization of SOI PhC slabs containing a thin active layer with Er^{3+} ions and Si nc in the middle of the waveguide core. We demonstrate that strong enhancement and drastic spectral modification of the 1.54 μm emission can be obtained at room temperature, thus opening far-reaching possibilities for the realization of efficient Si-compatible light emitters for optoelectronics.

Active SOI waveguides were fabricated by depositing a core on top of a 1.9 μm thick silicon dioxide layer thermally grown on a Si substrate. The core, made of a sequence of Si(116 nm)/Si-nc:Er:SiO_2(19 nm)/Si(112 nm) layers, was realized by radio frequency confocal magnetron sputtering keeping the substrate at room temperature. The two Si layers were obtained by the sputtering of an ultrapure Si target. The Er-doped substoichiometric silicon oxide was deposited by the cosputtering of three targets, Si, SiO_2, and Er_2O_3. The Si concentration was of 37 at. % and the Er content of 3.8×10^{20} cm^{-3}, as verified by Rutherford backscattering spectrometry. After deposition the film was annealed at 900 °C for 1 h in a nitrogen atmosphere in order to induce the separation of the Si and SiO_2 phases, the formation of Si nc, and the activation of the Er^{3+} ions.

2D photonic crystals consisting of a triangular lattice of air holes were etched into the SOI waveguide by means of standard electron beam lithography and reactive ion-etching techniques. Details on the fabrication procedure can be found elsewhere.[13] A schematic picture of the waveguide is reported in Fig. 1(a) and an image of a sample surface is shown in Fig. 1(b). Several samples were fabricated with lattice constant varying from $a=1050$ nm to $a=1250$ nm in steps of 20 nm, while the hole radius to lattice constant ratio $r/a=0.33$ was kept constant for all samples. Such a fine lithographic tuning of the lattice parameter is necessary in order to assure good energy matching between the Er^{3+} emission line and a photonic mode at $\theta=0°$, i.e., at the Γ point of the 2D Brillouin zone.

Room-temperature angle-resolved photoluminescence (PL) and reflectance (R) spectra were measured in the 0.7–1 eV energy (1.77–1.24 μm wavelength) range by

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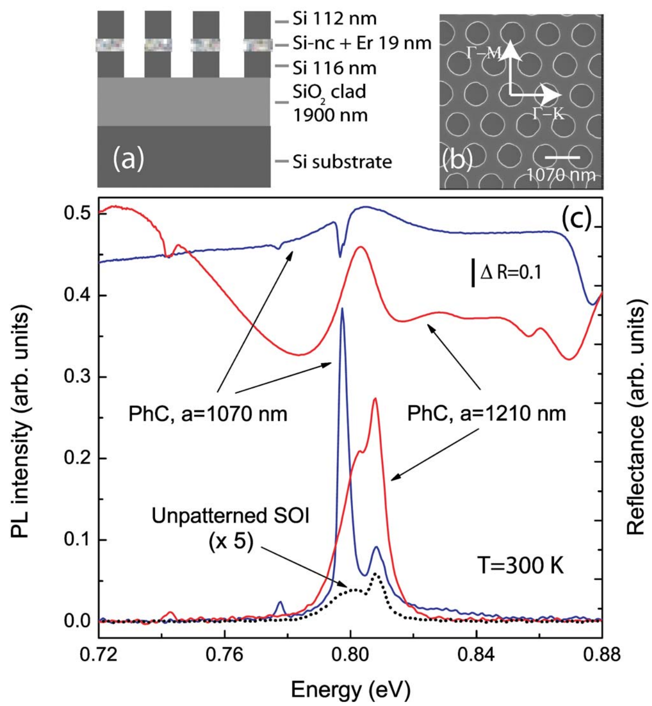

FIG. 1. (Color online) (a) Schematic illustration of the PhC slab. The active layer at the center of the Si core consists of SiO_2 with Si nc and Er^{3+} ions. (b) Scanning electron micrograph of the surface, showing the triangular lattice of air holes, for the sample with lattice constant $a=1070$ nm. (c) Room-temperature photoluminescence (PL) (bottom curves) and reflectance (R) (top curves) spectra at $\theta=0°$ of the PhC slab samples with $a=1070$ and 1210 nm and of the unpatterned waveguide.

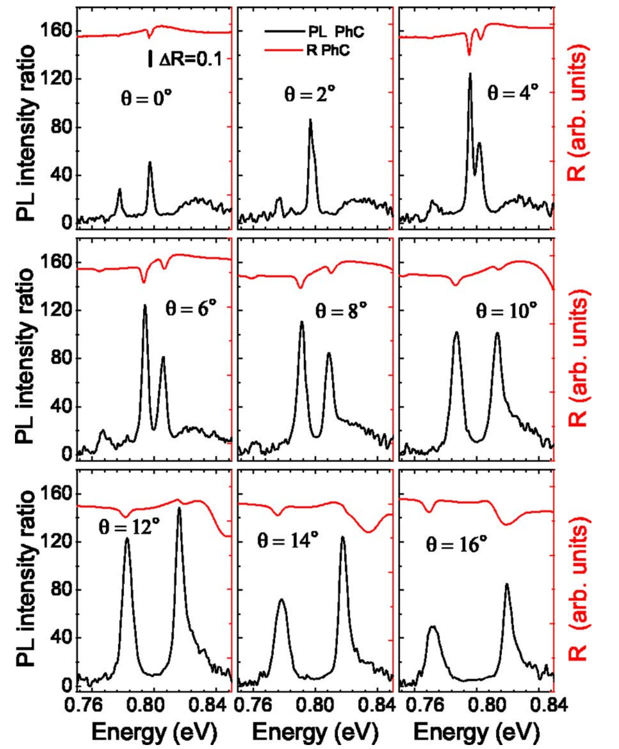

FIG. 2. (Color online) PL intensity ratios (bottom curves) and R spectra (top curves) of the 1070 nm sample at increasing values of the angle of incidence along the ΓK orientation.

means of a microreflectometer setup coupled to a Fourier-transform spectrometer (Bruker IFS66/s). An InGaAs *p-i-n* photodiode was used as a detector. Both R and PL were collected at various angles θ from the normal to the sample surface, between 0° and 16°, with an angular resolution of ±2° defined by the very small numerical aperture of the collection optics. The PL was excited using the 532 nm line of a cw Nd:YAG (yttrium aluminum garnet) laser with a power of 20 mW focused to a 100 μm spot on the sample surface.

Figure 1(c) shows the PL spectra collected at $\theta=0°$ for two PhC samples and for the unpatterned SOI waveguide. Normal incidence R spectra of PhC slabs, which show the existence of photonic modes around 0.8 eV (manifested as resonant structures[14,15]), are also reported. A strong modification of the Er^{3+} emission is observed for the PhC slabs, as compared to the unpatterned waveguide, due to the occurring of resonance conditions between the Er^{3+} transition and the photonic modes of the two PhC slabs. This is particularly evident for the sample with $a=1070$ nm, for which the $\theta=0°$ emission intensity is strongly enhanced in correspondence with the sharp structure at 0.797 eV observed in R spectra. On the other hand, the emission of the PhC sample with $a=1210$ nm is highly enhanced in intensity but its line shape is similar to that of the SOI waveguide. This can be understood by observing that for this PhC slab the intrinsic linewidth of the photonic mode at Γ, as observed in the R spectrum, is much larger and close to that of Er^{3+} emission in SiO_2. Enhancement of emission is therefore observed over the full width of Er^{3+} spectrum.

In order to search for optimal coupling conditions between Er^{3+} transitions and radiative PhC modes, we studied the angular dependence of the PL intensity around the normal direction. The results for the sample with $a=1070$ nm are shown in Fig. 2. Here we report the PL intensity ratios as obtained by dividing the PL spectrum of the PhC slab by the corresponding PL spectrum of the unpatterned SOI waveguide at the same emission angle. This yields directly the enhancement factor of emission over the investigated spectral region, i.e., the enhancement spectrum, independently of the Er^{3+} emission line shape. The enhancement spectra are characterized by a strong peak centered at 0.8 eV, which splits into two peaks for $\theta \geqslant 4°$. By increasing the angle at which the PL is collected, the splitting of the two peaks becomes more pronounced, and the enhancement of emission increases from a factor of 50 at $\theta=0°$ up to 150 at $\theta=12°$. Notice that the enhancement spectra shown in Fig. 2 are normalized to the unpatterned SOI waveguide, i.e., without considering the reduction of active material due to the PhC patterning. If the spectra are normalized to the actual emitting area (60% of total area), the enhancement of emission due to the PhC effect becomes as high as 250 for $\theta=12°$. Comparison with R spectra (also displayed in the figure) shows a very good agreement between the energy positions of the enhancement peaks and those of resonant structures in reflectance. This indicates that the emission enhancement occurs when the Er^{3+} emission is resonant with a photonic mode in the PhC slab.

To further investigate the origin of emission enhancement, we calculated the photonic band structure and the emission spectra for the PhC slab with $a=1070$ nm, as reported in Figs. 3(a) and 3(b), respectively. Expansion on the guided modes of an effective waveguide[16] and scattering matrix methods[17] have been applied for the calculations, respectively. The band diagram of the PhC slab shows the existence of a photonic mode at 0.81 eV which is degenerate at Γ and splits into two modes of opposite parities along the Γ-K di-

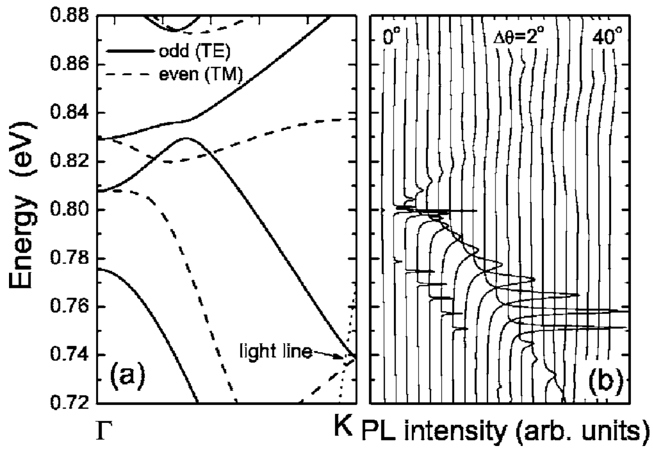

FIG. 3. Theoretical results for (a) photonic band dispersion and (b) PL spectra at increasing values of θ. The spectra have been convoluted with a Gaussian line shape with a 2×10^{-3} eV broadening.

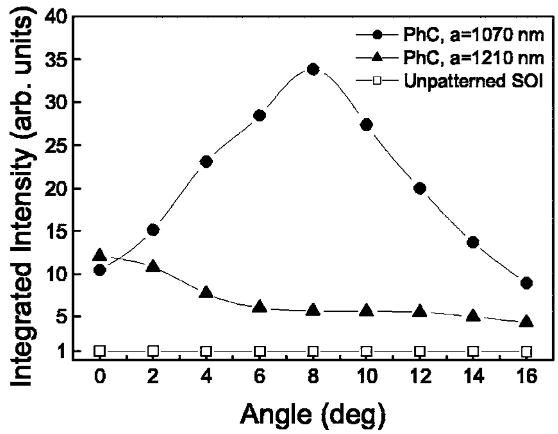

FIG. 4. Integrated (total) PL intensity of the PhC slab samples with lattice constants $a=1070$ and 1210 nm and of the unpatterned waveguide.

rection. The calculated emission is enhanced only for those energies which are in resonance with a photonic mode; they correspond closely to the peak positions in PL and to the resonant structures in R spectra. The comparison between theoretical and experimental results is very satisfactory and it clearly demonstrates that the observed enhancement of emission is indeed due to coupling of Er^{3+} emission to the radiative photonic modes of the PhC slab.

We notice that the enhancement of light emission into the vertical direction occurs in an energy region far above the 2D photonic band gap, where no truly guided photonic modes are supported by the PhC slab. Thus all photonic modes are subject to large out-of-plane diffraction and most of the light is emitted outside the slab plane. In the unpatterned slab, on the other hand, the total spontaneous emission rate $R_{\text{spon}}=R_{\text{slab}}+R_{\text{vertical}}$ is dominated by emission rate into guided modes. A change of emission lifetime can be expected,[10] however, it is not easily quantified as it depends critically on the redistribution of emission from the guided modes of the unpatterned slab into the vertical direction due to PhC patterning. Note that this mechanism is different from the one reported by Fujita *et al.*,[10] where emission in the slab is inhibited when the photon energy is within the 2D photonic band gap.

Finally we want to analyze the issue of efficient light extraction normal to the sample surface and over the whole emission range of Er^{3+} ions. Figure 4 reports on the spectrally integrated emission intensity as a function of the emission angle, for the two PhC slabs and the unpatterned SOI waveguide. The angular behavior of the integrated intensity of the SOI waveguide, which has been normalized to unity at $\theta=0°$, follows a Lambertian (cosine) law and is almost flat for small angles θ. Conversely, the PhC slab with $a=1210$ nm shows a tenfold enhanced integrated intensity at $\theta=0°$ which rapidly decreases for larger angles; on the other hand, the intensity for sample with $a=1070$ nm is characterized by 35-fold enhancement (60-fold if normalized to the active emitting area) peaked at $\theta=8°$, also rapidly decreasing for increasing angles. In both cases, most of the light is emitted at small angles around the normal direction.

In conclusion, we have realized active SOI PhC waveguides with efficient room-temperature emission at 1.54 μm. We have shown that patterning of the waveguides with a 2D PhC lattice can enhance the emission intensity of the active material by as much as 250. These results demonstrate that highly directional and efficient SOI light emitting devices can indeed be fabricated by exploiting the properties of PhC slabs.

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