Optical properties of erbium-implanted porous silicon microcavities

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We have used ion implantation for erbium doping of mesoporous silicon microcavities. Optically active erbium-doped microcavities with $Q$ factors in excess of 1500 have been demonstrated. We observed strong modification of the emission properties of the erbium in the microcavity with an accompanying cavity enhancement factor of 25. In addition, power- and temperature-dependent photoluminescence measurements indicate that erbium-implanted porous silicon has excitation mechanism very similar to that of erbium in a crystalline silicon host. © 2004 American Institute of Physics. [DOI: 10.1063/1.1808235]

The development of lasers and other light-emitting devices that are compatible with standard silicon wafer processing represent a key step in the realization of fully integrated optoelectronics and silicon microelectronics. Techniques used in the past in an attempt to achieve this goal involved doping silicon with rare-earth elements such as erbium or were based on silicon quantum structures such as Si/SiO$_2$ quantum wells and silicon nanocrystals embedded in silica. In a recent advancement the first silicon compatible laser was demonstrated by optically pumping whispering gallery modes in a SiO$_2$ toroidal micro-resonator doped with erbium. Surface emitting microcavity based light sources such as vertical-cavity-surface-emitting-lasers (VCSEL) offer a practical alternative for integrated optoelectronics. In addition to low lasing thresholds and high slope efficiencies, surface emitting microcavities also have full circular output beam, single longitudinal mode, and can be fabricated into integrated densely packed two-dimensional arrays. The success of the VCSEL approach is seen in the widespread use of these devices in optical communications.

One approach to fabricating silicon planar microcavities is through the use of mesoporous silicon (PSi). Using PSi, monolithically grown multilayered structures with very large refractive index modulation ($\Delta n=1.1$) in the dielectric mirrors can be readily achieved. Recent publications have shown that high quality planar PSi microcavities with $Q$ factors in excess of 7000 can be achieved by controlling the absorption and scattering losses within the structure. The ability to fabricate high $Q$-factor microcavities is an important step toward the realization of a practical microcavity laser based on silicon. In this letter we describe a method of incorporating optically active erbium ions into PSi microcavities that preserves the optical quality of the structures. The approach involves the use of ion implantation, a standard silicon processing technique, to selectively dope the cavity layer of the microcavity structure. Using this technique PSi microcavities with $Q$ factors in excess of 1500 have been fabricated, which is an order of magnitude improvement over previously published reports of erbium-doped PSi microcavities. In addition, optical characterization of the erbium-implanted devices reveals characteristics remarkably similar to erbium-doped crystalline silicon (c-Si), which is in contrast with PSi devices prepared using electrochemical doping techniques.

Erbium-doped PSi microcavities were prepared by first implanting heavily boron doped (0.005 $\Omega$ cm) $p^+$-type silicon substrate with 7.9 MeV erbium and 1.9 MeV oxygen ions to a dose of $7.7 \times 10^{13}$ and $2.5 \times 10^{14}$ cm$^{-2}$, respectively. The ion energies were chosen such that the implanted ions were deposited at a depth which coincided with the spacer layer of the microcavity. The doses were chosen to give a peak concentration of $1 \times 10^{16}$ and $7.5 \times 10^{18}$ cm$^{-3}$, respectively, which were experimentally determined to yield the maximum photoluminescence intensity from the erbium centers. After implantation samples were annealed at 600 °C for 1 h for solid phase epitaxial regrowth, which was followed by rapid thermal annealing at 800 °C for 60 s to optically activate the erbium. Rutherford backscattering measurements were done to confirm that the silicon samples recrystallized after annealing and that the erbium was implanted to the correct depth.

PSi microcavity structures were formed by progressively etching the silicon wafer in an electrolytic solution with alternating low (10 mA/cm$^2$) and high (110 mA/cm$^2$) currents, resulting in a stack of low and high porosity layers. The electrolyte comprised of a mixture of hydrofluoric acid (HF), ethanol, and water in the ratio of 0.35:0.3:0.35, which was diluted from 49% w/w HF. Samples were also fabricated at low temperature (−21 °C) to improve the uniformity of the structures and flatness of the optical interfaces. Full details of the PSi microcavity fabrication process can be found elsewhere. The microcavity structures consisted of five and six periods (bi-layers) for the top and bottom Bragg reflector, respectively, with a low porosity $\lambda/2$ cavity layer. A high porosity (low refractive index) layer was placed at the bottom of the structure to account for the high refractive index silicon substrate. PSi microcavity samples had a circular geometry with diameter of 0.7 cm. A cross-sectional scanning electron microscope (SEM) image of the erbium-implanted structure can be seen in the insert of Fig. 1. The image was taken using a Hitachi S900 SEM with a 12 kV field emission source.

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The linewidth was determined to be 1.0 nm, resulting in a cavity Q factor of 1530. The insert is a cross-sectional SEM image of the implanted structure.

FIG. 1. (a) Reflectivity spectrum of an erbium-implanted porous silicon (PSi) microcavity (solid line) and its corresponding simulation (dotted line). (b) Spatially resolved reflectivity measurement of the cavity resonance. The linewidth of the resonance is 1.0 nm resulting in a cavity Q factor of 1530. The insert is a cross-sectional SEM image of the implanted structure.

FIG. 2. Low temperature (10 K) photoluminescence measurements of an erbium-doped mesoporous silicon microcavity (solid) and an erbium-doped single PSi thin film (closed and open triangles), which has been multiplied by five times. The insert is a high-resolution spectrum of the microcavity emission used to resolve the true linewidth of the emission (3 nm).

Figure 1(a) displays the reflectivity spectrum of the erbium-doped microcavity (solid line) measured by illuminating the sample at normal incidence with a focused monochromatic beam (J/Y SPEX 1681 spectrometer) and detecting the reflected beam using a germanium detector. Through a simulation of the reflectivity spectrum (matrix transfer method) the optical properties of the structure were determined to have a porosity of 29% and thickness of 140 nm for the low porosity layers, and 76% porosity and 266 nm thickness for the high porosity layer. The layer thicknesses determined using reflectivity are also consistent with thicknesses observed in cross-sectional SEM data. At the resonance wavelength (1530 nm), the porosities of the low and high porosity layers correspond to refractive indexes of 2.7 and 1.5, respectively. The large refractive index difference $\Delta n = 1.2$ present in the mirror layers is highlighted by the very broad high reflectivity band featured in Fig. 1(a). From Monte Carlo simulations of the ion implantation we predict that the peak erbium concentration should lie at the center of the cavity layer, whilst the projected straggle of the ions $306 \text{ nm}$ is mostly confined to the cavity layer (280 nm). 11

In order to obtain a precise measure of cavity resonance linewidth an amplified spontaneous emission source coupled to a single mode optical fiber was imaged onto the sample at normal incidence, producing a spot of $<80 \mu \text{m}$ on the surface. The reflected beam was then coupled (collection angle $<0.8^\circ$) into a HP optical spectrum analyzer with a maximum resolution of 0.05 nm. This was done to restrict the line-broadening effects of both spatial inhomogeneities and large collecting angles. From these measurements the cavity resonance linewidth was determined to be 1.0 nm [Fig. 1(b)], which at 1530 nm results in a $Q$ factor of 1530. We see that in comparison with the best $Q$ factors achieved using electrochemical doping methods ($Q$ factor=130) there is a marked improvement of the optical quality of the erbium-doped structures. 3 This improvement can be attributed to two factors: First, chemical-doping techniques incorporate the active material uniformly over the entire structure including the mirrors, which increases the absorption of the quarter wave mirrors at the resonance wavelength. The above-described technique avoids this problem through the localization of the optically active material only in the cavity layer. In addition, optical activation of the rare-earth ions is achieved using high temperature annealing which tends to oxidize the PSI heavily resulting in large shifts in the optical properties of each layer, and a degradation in the microcavity reflectivity. Using ion implantation all the thermal annealing steps are done prior to the PSI fabrication and hence the PSI microcavity properties are well maintained.

Figure 2 shows a comparison of low temperature (10 K) photoluminescence (PL) spectra of erbium-doped PSI microcavity and that of a single PSI layer. The samples were excited using the 514.5 nm line of an argon ion laser (excitation power=100 mW) and the luminescence was measured via a SPEX 270M spectrometer with a liquid nitrogen cooled p-i-n germanium detector. The two distinct peaks observed in the single layer sample (1.55 and 1.6 $\mu \text{m}$) originate from transition between different multiplet states within the $^4I_{13/2}$ and $^4I_{15/2}$ levels, which have been split by the local electric field. The peak positions clearly correspond to those observed in erbium-doped c-Si that was heavily doped with boron. 12 This is distinctly different from the PL emission observed from electrochemically doped erbium in PSI, which shows a broad and featureless spectral band centered at 1.55 $\mu \text{m}$. 13 The microcavity has a significant influence on the shape of the emission spectrum: there is a strong intensity enhancement of emission at the cavity resonance and suppression at other wavelengths. Each sample was prepared using the same implantation conditions and the porosity of the single layer (29%) was matched to that of the microcavity spacer layer, such that each contained the same concentration of optically active erbium. Therefore a direct comparison of the spectra can be made in order to determine the cavity enhancement effect. On inspection of the data we find that the integrated PL intensity from the cavity is 25 times larger than that from the single layer at the resonant wavelength. The erbium emission linewidth was measured using a high resolution spectrum, with the collecting angle of the optics reduced to avoid integrating over large angles of incidence (Fig. 2 insert). The linewidth determined to be 3.0 nm, which is slightly broader than results from the reflectivity measurements ($\Delta \lambda = 1.0 \text{ nm}$) and is most likely an artifact introduced by the relatively large collecting angle (5$^\circ$) required one to obtain adequate signal to noise ratio for the measurement. The measured PL emission linewidths in these PSI structures are also an improvement on other erbium-implanted microcavities, such as silicon/silicon oxide microcavities grown by sputtering techniques. 14

The temperature- and power-dependent PL from the erbium-doped microcavities reveals important information about the nature of the luminescent centers. Figure 3(a) is an
Arterial combinations have severely limited the effective use of 
crystalline samples supports this mechanism in these PSi samples. 
The presence of heavy electrical doping in these microcavities 
saturation of erbium luminescence centers at high powers. 
recombination at intermediate excitation powers and 
tions they suggest that the PL saturation is a product of Au-
a two-step process.16 From their analysis of the rate equa-
bion recombination in crystalline silicon.

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The problems of energy backtransfer and Auger recombination 
have severely limited the effective use of c-Si as a 
host material for rare earths and has resulted in poor emission 
efficiencies. However PSi offers a possible solution to 
this problem through the use of the inherent quantum size 
effects. We propose that PSi fabricated from erbium-
implanted p-type silicon should result in erbium-doped 
nanocrystals that could be excited through alternate mecha-

nisms such as excitors bound at the nanocrystal interface. 
Erbium/silicon nanocrystal doped silica waveguides prepared 
by plasma enhanced chemical vapor deposition have already 
demonstrated gain coefficients of 7 dB cm⁻¹.17 The effective 
cavity losses in the microcavities described in this study are 
18 dB cm⁻¹ and undoped PSi microcavities with losses as 
low as 11 dB cm⁻¹ have also been demonstrated.7 With 
urther research into the compatibility of luminescent micro-
corporal silicon with erbium implantation, and improve-
ments to high quality microcavity fabrication, lasing in PSi 
microcavities may be possible.

In conclusion we have demonstrated a method for doping 
mesoporous silicon microcavities with erbium, where the 
optionally active dopants are confined to the spacer layer of 
the cavity. PSi microcavities with Q factors in excess of 1500 
were achieved using this technique. From low temperature 
photoluminescence measurements we observed strong modi-ication of the spontaneous emission spectrum of the erbium 
with a cavity enhancement of 25 times at the resonance 
well length of the microcavity. Temperature-dependent pho-
toluminescence exhibited strong thermal quenching and 
excitation-power-dependent photoluminescence measure-
ment showed saturation at high excitation powers. Both of 
these trends are characteristically similar to luminescent er-
bium centers in crystalline silicon.

The authors would like to thank G. Lerondel for many 
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FIG. 3. (a) Arrhenius plot of the temperature-dependent photoluminescence 
showing strong thermal quenching at higher temperatures. The activation 
ergy (135 meV) was determined from a fit at high temperatures (line 
connecting the data points is an aid to the eye). (b) Excitation-power-
dependent photoluminescence measurements showing a linear region at low 
excitation power and a saturation at higher powers.