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# Light extraction enhancement of SOI-based erbium/oxygen Co-implanted photonic crystal microcavities*

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**Abstract:** $H_5$ photonic crystal (PC) microcavities co-implanted with erbium (Er) and oxygen (O) ions were fabricated on silicon-on-insulator (SOI) wafers. Photoluminescence (PL) measurements were taken at room temperature and a light extraction enhancement of up to 12 was obtained at 1.54 $\mu$m, as compared to an identically implanted unpatterned SOI wafer. In addition, we also explored the adjustment of cavity modes by changing the structural parameters of the PC, and the measured results showed that the cavity-resonant peaks shifted towards shorter wavelengths as the radius of the air holes increased, which is consistent with the theoretical simulation.

**Key words:** light extraction; erbium/oxygen co-implantation; photonic crystal microcavity; SOI; photoluminescence

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## 1. Introduction

Silicon (Si)-based light sources that are compatible with CMOS technology are highly desirable due to their low manufacturing cost relative to III/V semiconductors and because they will enable monolithic integration with electronic components on the same Si platform. However, due to their low emission efficiency, Si-based light emission has become one of the most challenging topics in group IV photonics. A Si-based light source at room temperature, especially for the 1.54 $\mu$m telecommunication band, urgently needs to be found. Er doping is a promising way because of Er's 1.54 $\mu$m electronic transition[1, 2]. By co-implanting Er with a light element such as C, H, or O, temperature quenching is reduced and a signal can be obtained at room temperature. However, the signal is still too weak for practical usage. Nevertheless, nano-resonators such as photonic crystal (PC) microcavities[3−5] can enhance the emission from these Si-based materials in a fundamentally different way compared to material engineering. Cavity-type resonators can enhance the spontaneous emission rate into the cavity mode through the Purcell effect[6, 7] and the coupling between the optical modes and the radiative ones[8, 9].

In this paper, we present the enhanced light emission of Si patterned with $H_5$-type PC microcavity structures pumped by light. The $H_5$-type cavity is a hexagon with a side size of $5a$, formed by omitting to drill a defined number of air holes, where $a$ represents the lattice constant of PC. Large light extraction enhancements, as compared to identically implanted unpatterned SOI wafers, were obtained at 1.54 $\mu$m at room temperature. Moreover, we measured and analyzed a series of samples with different structural parameters in order to verify the fundamental characteristics of a PC microcavity.

## 2. Design and fabrication

PC structures with triangular lattices of air holes were fabricated using electron beam lithography (EBL) and inductively coupled plasma (ICP) etching on SOI wafer, which had a 200 nm-thick top silicon layer and a 1 $\mu$m-thick buried oxide layer. The air holes were drilled down to the oxide layer to form 2D non-symmetric PC slab structures, as shown in Fig. 1(a). PC with moderate air filling factors, on the order of $r/a = 0.3$ was considered, where $r$ represents the radius of the air-holes, resulting in the middle of a full TE gap with frequency $a/\lambda$ around 0.3. The lattice constant $a = 470$ nm was designed for locating the 1550 nm wavelength in the middle of TE gap. Then, erbium ions were implanted at an energy of 175 keV to a dose of $7 \times 10^{13}$ at/cm$^2$ and oxygen ions were implanted at the energy of 25 keV to a dose of $4 \times 10^{14}$ at/cm$^2$. After implantation, the samples were annealed at 900 ℃ for 30 min in $N_2$ atmosphere. Several $H_5$ microcavities with air holes radius $r$ in the range from 149 to 167 nm and lattice constant $a = 470$ nm were fabricated. The scanning electron microscope (SEM) image of one sample is shown in Fig. 1(b). The structural parameters were chosen to ensure that the wavelength between 1.4 and 1.6 $\mu$m was located in the TE bandgaps of the PC.

The photoluminescence (PL) spectra were obtained using micro-Raman spectroscopy (JY HR-800). The cavities were pumped by an $Ar^+$ laser working at 488 nm, and the pump power was set to 25 mW. The pump beam was focused onto

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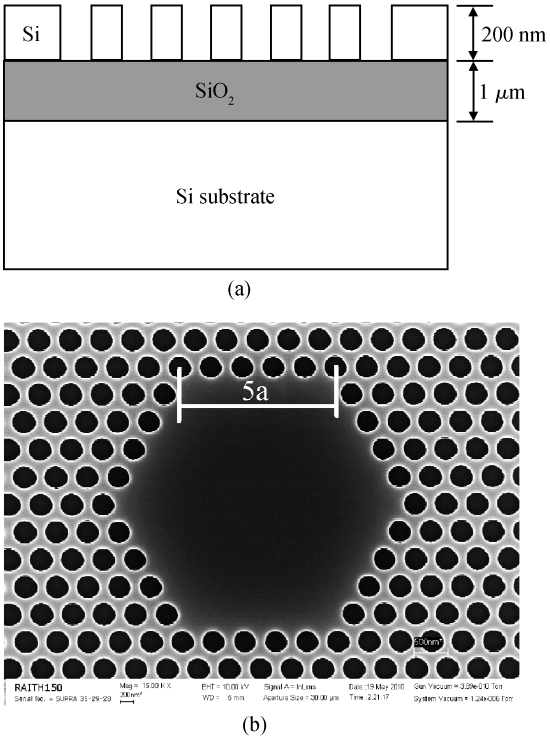

Fig. 1. (a) Sketch of PC on SOI. (b) Scanning electron microscope image of a $H_5$ microcavity.

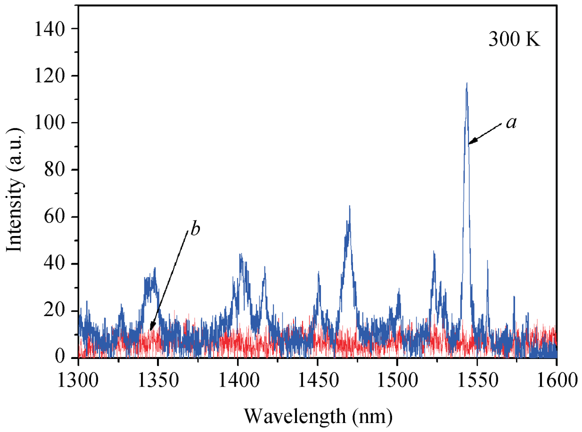

Fig. 2. Comparison of the room-temperature PL spectra of the implanted $H_5$ PC microcavity (curve $a$) and the implanted unpatterned SOI (curve $b$).

the sample by a microscope objective lens and the size of the pump spot was around 3 $\mu$m. A single InGaAs detector array cooled by liquid nitrogen was used to record the PL spectra. Characteristics for all samples were measured at room temperature.

## 3. Result and discussion

Figure 2 shows the room-temperature PL spectra of the implanted $H_5$ PC microcavity with $a = 470$ nm and $r = 149$ nm (curve $a$ in Fig. 2) and the implanted unpatterned SOI (curve $b$ in Fig. 2). The signal obtained above the complete PC structure, which is not shown in the figure, was as weak as for unpatterned SOI. The spectrum measured on the $H_5$ PC microcavity exhibited clear light emission peaks, but the peaks disappeared above both the complete PC structure and the unpatterned SOI. The results indicate that the enhanced light emission originated from the effect of the $H_5$ PC microcavity. Compared to an identically implanted unpatterned-SOI wafer, the enhancement factor is up to 12 at 1.54 $\mu$m.

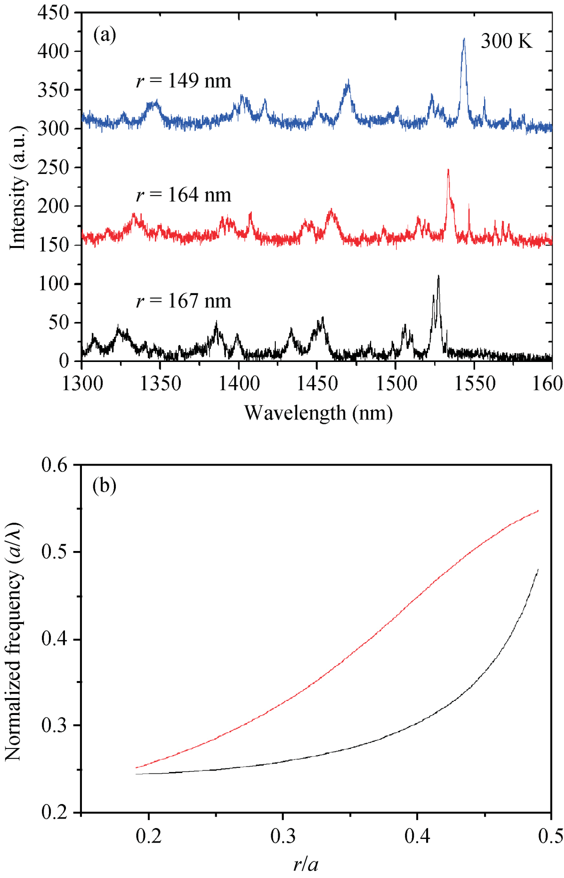

Fig. 3. (a) PL spectra for a series of $H_5$ microcavities with $a = 470$ nm. (b) PC band-edges as a function of $r/a$.

The dramatic enhancement of the photoluminescence is associated with the photonic effect. Because of the photonic bandgap, the emitted photons were confined inside the $H_5$ microcavity, and the in-plane losses were reduced. Another reason for the high light emission increase was the high electron and hole carrier densities achieved in this system. The number of electrons escaping from the $H_5$ cavity was reduced by the air holes surrounding it, and the buried $SiO_2$ barrier blocked carrier diffusion to the substrate. The high electron–hole density provided an additional scattering mechanism of the carriers to the zone center[10], thus enhancing the photoluminescence.

To this end, we explored the adjustment of cavity modes by changing the structural parameters of PC. PL spectra for a series of microcavities with air holes radius r in the range from 149 to 167 nm and $a = 470$ nm are shown in Fig. 3(a). We can see that the main peaks were at 1543.5, 1533.6 and 1527.3 nm for $r = 149$, 164, 167 nm, respectively. That is, the peak positions shifted towards shorter wavelengths as the radius of the air holes increased when the fixing lattice constant. Figure 3(b) shows the simulation of the band-edges of complete PC as a function of $r/a$. The result indicated that the band-edges shifted towards shorter wavelengths as $r/a$ increased and that the cavity mode wavelength located in the bandgap could be shifted with the band-edges, which has been well verified by the measured results.

## 4. Conclusion

We fabricated $H_5$ PC microcavities co-implanted with erbium and oxygen ions on SOI. Strong enhancements of photoluminescence intensities were observed at room temperature and the enhancement factor was up to 12 at 1.54 $\mu$m, as compared to an identically implanted unpatterned SOI wafer. The cavity modes could be adjusted by changing the radii of the air holes and the peak wavelength shifted towards shorter wavelengths as the radii increased. This system is very promising for obtaining controlled light emission at telecommunication wavelengths at room temperature.

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