Enhanced 1.54μm photoluminescence from Er/O-doped Si in photonic crystal double-heterostructure microcavity

Yue Wang*, Junming An and Xiongwei Hu

State Key Laboratory on Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

*wy1022@semi.ac.cn

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Abstract. Efficient enhancement of photoluminescence from Er/O-doped silicon (Si) on silicon-on-insulator (SOI) wafer in two-dimensional (2D) airbridge symmetric slab hexagonal photonic crystal (PC) gradient double-heterostructure microcavity has been demonstrated at room temperature. A single sharp resonant peak with 1541.7nm communication wavelength dominates the photoluminescence (PL) spectrum and significant PL enhancement is obtained compared to the case of identically implanted SOI wafer at pumping power of 15mW. The obvious red-shift and degraded Q-factor of resonant peak are present with the pumping power increasing, and the maximum measured Q-factor of 6284 has been achieved at pumping power of 1.5mW.

Introduction

Silicon (Si) has attracted much attention recently in the field of photonics due to its high potential for Si-based optoelectronic integration. The Si-based integrated components, such as optical modulators, light waveguide circuits, and optical detectors, have already been prepared, except for Si-based light sources.

As is well known, Si material itself is a poor light emitter due to its indirect band-gap. In last twenty years, numerous research efforts have been made to enhance light emission from Si by a variety of means, including porous Si [1], Si nanocrystals [2], Ge/Si structures [3, 4], Si with rare earth ions doping [5-7] and so on. Among the materials above-mentioned, doping Si with erbium (Er) ions is possible to obtain a radiative transition in the 4f shell of Er at the communication wavelength of ~1.54μm, which is particularly suitable for high-density Si-based optoelectronic integration. Nevertheless, light emission from Er-doped Si materials at room temperature is so weak for practical application.

Photonic crystal (PC) microcavities have the advantages of strong light-matter interaction, selectivity of wavelengths confined, high quality factor (Q-factor) and small mode volume, which can

enhance the on-resonance luminescence and suppress the off-resonance one through the Purcell effect [8] greatly. It has become a promising way to realize high-efficiency and ultra low threshold Si-based light emitter at room temperature. Among the kinds of PC microcavities, the double-heterostructue microcavities based on mode-gap effect have been verified having the highest theoretical Q-factor (~10^7), which is desirable for the Purcell effect [9-11].

In the paper, we explore to enhance photoluminescence (PL) from Er/O-doped Si material in two-dimensional (2D) airbridge symmetric slab PC gradient double-heterostructure microcavity.

Device design and fabrication

Fig.1(a) shows the schematic structure of the 2D hexagonal PC gradient double-heterostructure microcavity, which is constructed by cascading five PC waveguides (PCWs) with gradient radii of air-holes adjacent to width-reduced line-defect, named PCW1~PCW5, successively. PCW1 and PCW5, and PCW2 and PCW4 are distributed symmetrically center around PCW3, respectively. The radii of air-holes adjacent to PCW1 (PCW5), PCW2 (PCW4) and PCW3 are represented as R_1, R_2 and R_3, respectively. To construct the gradient double-heterostructure microcavity based on mode-gap effect, R_3 is equal to R, with the relationship of $R_1 > R_2 > R_3$ and R_2 is set to be $(R_1 + R_3)/2$, where R represents the radius of air-hole non-adjacent to the PCW. For realizing a single guided even-mode in the PC band-gap, the line-defect width W, defined as the distance between the centers of adjacent air-holes, is set to be $0.7W_0$, where $W_0=\sqrt{3}a$, represented as the width of normal line-defect, and a represents the lattice period of PC. Due to the mode-gap effect, the photons with the specific frequency can be confined strongly in the central PCW3 microcavity region which is called photon well similar to an electron quantum well structure. Then though the Purcell effect, the on-resonance luminescence will be enhanced greatly. Moreover, to obtain lager Q-factor and enhancement, the PC slab is designed as airbridge symmetric slab structure, which schematic cross-sectional diagram is shown in Fig. 1(b). The 2D finite difference time domain (FDTD) method was used to design and simulate the microcavity structure, and the parameters were set that a=400nm， R_1/a=0.32, R_2/a=0.29 and $R_3/a=R/a$=0.26, which ensured that the light with ~1.54μm wavelength could be confined in the cavity. The simulated results are shown in Fig.2. As seen from Fig.2, a single sharp resonant peak with 1543.5nm wavelength dominates the spectrum, and the resonant mode field is confined well in the cavity.

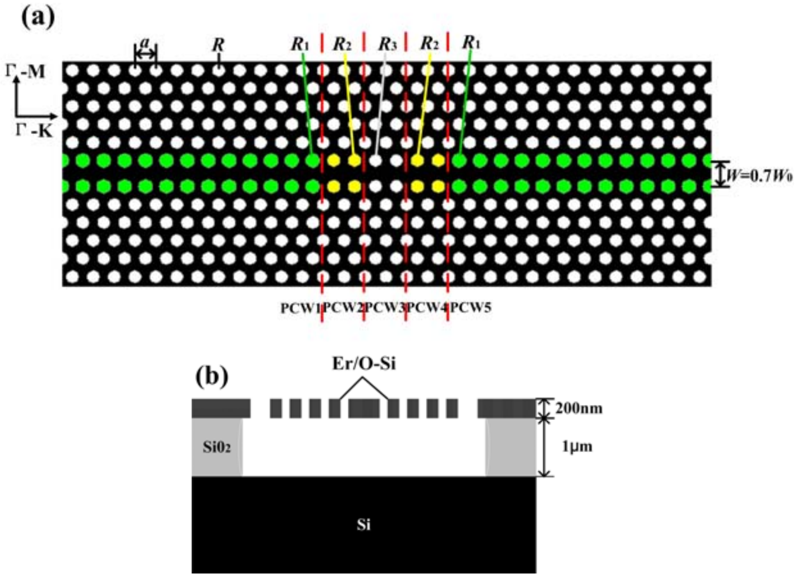

Fig.1. (a) Schematic structure diagram of the PC gradient double-heterostructure microcavity. (b) Schematic cross-sectional diagram of 2D airbridge symmetric slab PC microcavitiy.

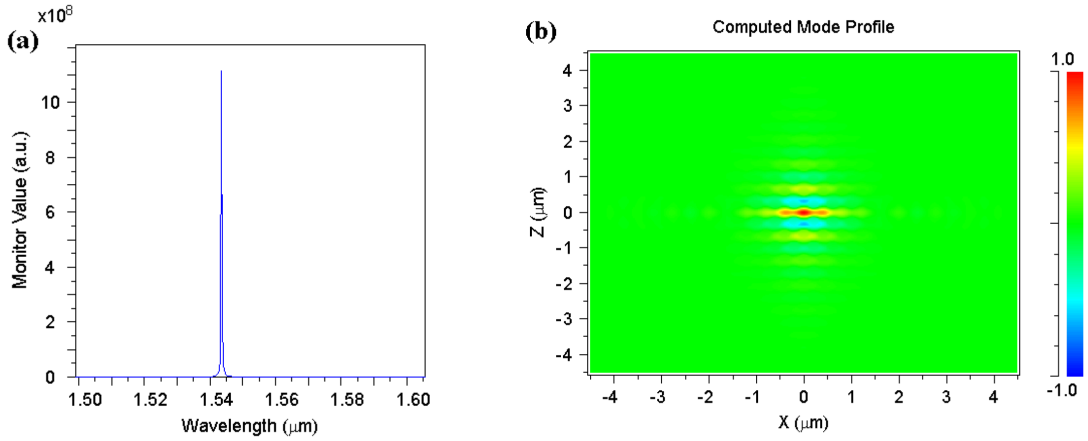

Fig.2. (a) The 2D-FDTD simulated resonant spectrum of the PC microcavity. (b) The 2D-FDTD simulated mode profile at the resonant wavelength of 1543.5nm.

In the experiment, the PC microcavity was fabricated on SOI wafer (200nm-thick top silicon, 1μm-thick buried oxide (BOX)). Firstly, Er ions were implanted at energy of 175keV to a dose of 7×10^{13} at/cm^2, and O ions were implanted at the energy of 25 keV to a dose of 4×10^{14}at/cm^2, simultaneously, to overcome temperature-quenching of Er emission. Then, the samples were annealed at 900℃ for 30 min in N_2 atmosphere to reduce implantation damage and optically activate Er ions. Thereafter, the PC microcavity was formed by electron beam lithography (EBL) and inductively coupled plasma (ICP) technologies. The air-holes were drilled down to the BOX layer and then a free-standing membrane named as airbridge symmetric slab PC structure was formed by removing the supporting BOX layer using wet chemical etching by BOE solution. Fig. 3(a) shows the scanning electron microscope (SEM) image of the fabricated PC gradient double-heterostructure microcavity. The measured PC lattice period a, the radii of air-holes R (R_3), R_2 and R_1 are 439.2nm, 114.2nm, 129.1nm and 141.4nm, respectively, which are in general accord with the designed values. Fig. 3(b) shows the SEM image of airbridge slab.

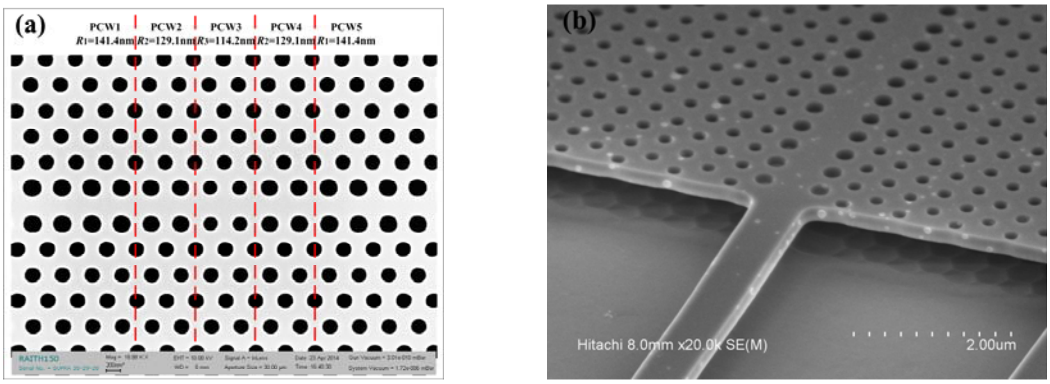

Fig.3. (a) SEM image of the fabricated PC gradient double-heterostructure microcavity. (b) SEM image of airbridge slab.

Experimental results and discussion

The micro-photoluminescence (μ-PL) measurements were performed at room temperature (T=300K) using micro-Raman spectroscopy (JY HR-800) equipped with an Ar+ laser working at 488nm, and the schematic diagram of measuring equipment is shown in Fig.4. The samples were focused and excited by the pump laser through a microscope objective lens, and the size of the spot was around 2μm. The PL signal was collected by the same lens and recorded by a single InGaAs detector array cooled down by liquid nitrogen.

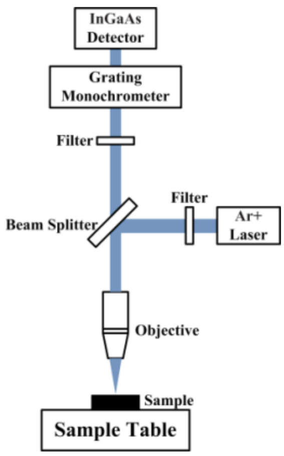

Fig. 4.The schematic diagram of μ-PL measuring equipment.

Fig.5 shows the room-temperature PL spectra of the airbridge gradient double-heterostructure microcavity and the unpatterned region on the same SOI wafer at the pumping power of 15mW, respectively. As seen from Fig.4, a single sharp resonant peak is observed at wavelength of 1541.7nm for microcavity, which suggests strong optical resonance inside the cavity. Compared to the case of identically implanted unpatterned SOI region, significant photoluminescence enhancement is achieved due to Purcell effect. The PL intensity of Er/O-doped Si is enhanced greatly at the resonant wavelength (on-resonance), but suppressed greatly at the other wavelengths (off-resonance). The full width at half maximum (FWHM) of the resonant peak is about 591pm, and according $Q=\lambda/\Delta\lambda$, Q-factor is deduced to 2609, where λ and $\Delta\lambda$ are represented as resonant wavelength and FWHM, respectively.

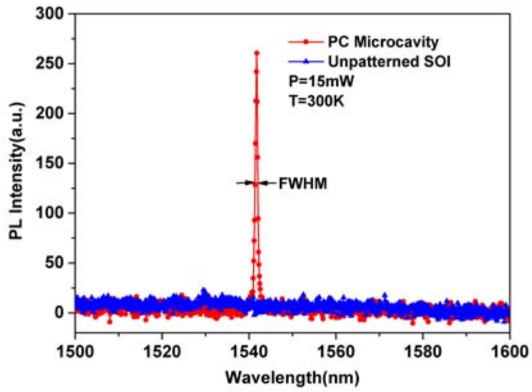

Fig. 5. Room-temperature PL spectra of the airbridge double-heterostructure microcavity and the unpatterned SOI region at the pumping power of 15mW.

In general, PCs based on compound semiconductors undergo undesirable surface-related nonradiative recombination and show strong pumping power dependence. To investigate the pumping power dependence in the airbridge cavity, PL spectra were measured as a function of pumping power. Fig.6(a) shows the dependence of PL spectrum of the cavity resonance on pumping power at room temperature. As seen from the figure, the resonant wavelength varies from 1539.5nm to 1541.7nm, and Q-factor varies from 6284 to 2609 with pumping power increasing from 1.5mW to 15mW. The observed spectral red-shift of the resonance with power increasing is correlated to the refractive index increase resulting from sample heating due to thermo-optic effect, and the Q-factor decreases with pumping power increasing due to the free-carrier absorption (FCA) of the photo-generated carriers. Fig.6(b) shows the magnified measured and Lorentz fitted graphs of the PL spectra for the resonant modes of airbridge cavity at the pumping power of 1.5mW. The resonant wavelength is 1539.5nm, and the FWHM is about 245pm, corresponding to the Q-factor of 6284. These results indicate that free-carrier absorption of photo-generated carriers has a big influence on the Q-factor of the PL resonance, and intrinsic Q-factor should be measured under extremely low pumping power in PL method.

Summary

In conclusion, we designed and fabricated 2D airbridge symmetric slab hexagonal PC gradient double-heterostructure microcavities with Er/O-doped Si as light emitters on SOI wafer, and significant enhanced 1.54μm photoluminescence is observed at room temperature. The obvious red-shift and degraded Q-factor of resonant peak are present with the pumping power increasing, and the maximum measured Q-factor of 6284 has been achieved at pumping power of 1.5mW. The results reported here prove that the combination of PC gradient double-heterostructure microcavity and Er/O-doped Si is a promising way to realize high-efficiency and high-Q Si-based light emitters operating at room temperature, which has great research and application potential in Si-based optoelectronics integration. Further improvements can be achieved by optimizing the structure, such as higher collection efficiency, electrically-pumped structures and so on.

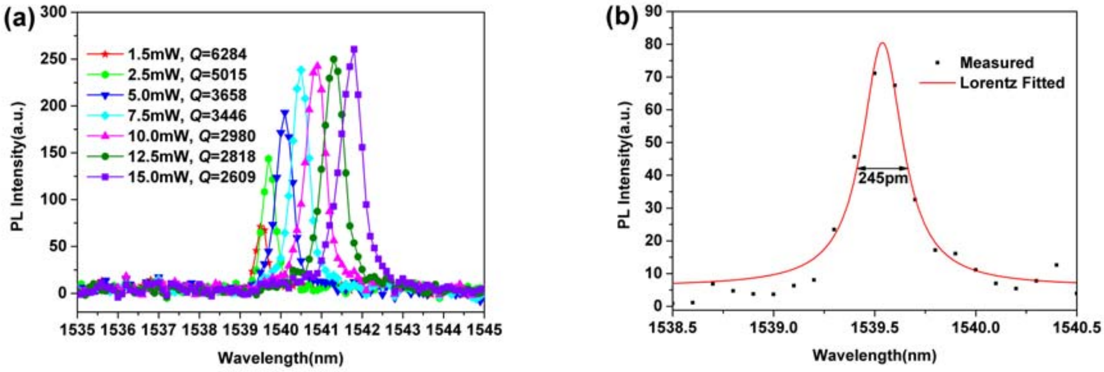

Fig. 6. (a)The dependence of PL spectrum of the cavity resonance on pumping power at room temperature. (b) The magnified measured and Lorentz fitted graphs of the PL spectrum for the cavity mode at the pumping power of 1.5mW.

Acknowledgments

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