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High Sensitivity and High Quality-Factor Silicon Photonic Crystal Resonator with Double Nanocavities for Label Free Biosensing

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Abstract

We propose a high quality factor (Q) and high sensitivity photonic crystal nanocavity-type biosensors. We show experimentally that it has high Q value of > 1x10^5 and the detection limit of the refractive index change of < 1x10^{-7} which is the best in the previous reports.

1. Introduction

Among various kind of microcavity based biosensors [1, 2], photonic crystal (PhC) biosensors have received great attention over the past several years due to their high quality factor of ~9 million [3]. A high quality (Q)-factor is advantageous in reducing the spectral noise of the sensors. In this paper, in order to obtain a high Q-factor, a label free biosensor based on PhC double nanocavity-type device is proposed. In the double nanocavity-type biosensor, the cavity resonators are placed in the center of the structure and their nearest neighbor holes radius are changed and keep them smaller than PhC air holes. Similar modification neighboring the cavity is reported to be effective to increase the Q-factor of the PhC resonator [4]. We have previously reported single cavity resonator [5] with Q~10^5, where we did not change the neighbor hole radius. The schematic of the sample structure is shown in Fig. 1. The higher Q-factor is obtained by this structure.

2. Simulation and Experiment

The finite difference time domain (FDTD) method has been used to investigate the refractive index dependence of resonant wavelength shift and the Q-factor. The simulation results with respect to hole radius neighbor to the nanocavities is shown in Fig. 2. It is recognized that the Q-factor (Q) reaches to maximum (2×10^5) when the neighbor hole radius is 65 nm (r=0.215a). The reason is thought that the suitable modification at the cavity edge leads to suppress the leaked light from the cavity [4]. Here a (=302 nm) is a period of air holes in the PhC and the radius in the normal PhC is 94 nm (0.31a). So we adopted the neighboring hole size of 65 nm. Once the geometrical parameters were defined, the samples were fabricated onto silicon on insulator (SOI) wafer. The device fabrication process is shown in Fig. 3. The SOI substrate has a top silicon layer of thickness 300 nm on a 1.1 μm buried oxide layer. A 110 nm thick oxide layer was thermally grown as an intermediate layer of pattern transfer. An electron beam (EB) sensitive photoresist, ZEP-520A was spin coated onto the oxide layer. An Elionix (ELS-G100) electron beam lithography system was used to define high resolution patterns on the resist. The patterns were then developed by xylene and iso propyl alcohol. In order to transfer this pattern into the Si layer we used reactive-ion etching (RIE) and inductively coupled plasma (ICP) using CF_4 and Cl_2 gas respectively. In a final step, wet etching by diluted hydrofluoric acid was used to remove SiO_2 mask. Scanning electron microscope images of the fabricated device is shown in Fig. 4 where the cavity hole was too big and connected to surrounding holes.

3. Results and Discussion

The experimental result of double nanocavity-type resonator at various sucrose concentrations is shown in Fig. 5 and Fig. 6 with the simulation results at different cavity hole size. The resonance spectra have shifted with changing the sucrose concentration and the shift is almost linear. The resonance peak shift is 0.21nm/(0.1% sucrose) which is almost fit to the simulation result for the cavity diameter of 450 nm. However, the diameter of actually fabricated cavity diameter is larger than 450 nm and it is connected to the surrounding holes. But still the fitting between the experiment and the simulation is good. This may accidentally happened and further deep consideration will be required. In Fig. 7 the figure of merit for resonator sensor is discussed. As explained in the figure caption $\lambda_{res}/(SQ)$, where S =$\Delta\lambda_{res}/\Delta n$, is a good index for the detection limit of refractive index change. In Table I this index is compared with other works. It is demonstrated that our device has the highest detection sensitivity within the previous reports.

4. Conclusion

The nanocavity type PhC resonateor sensor was proposed and fabricated. By adopting double cavity type and modification of the size of the neighboring hole, a large Q-factor of >10^5 was obtained. Even though the shape was different from the ideal, very good sensitivity was obtained.

Acknowledgement

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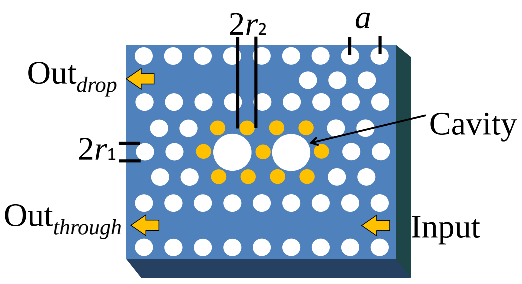

Fig. 1 Schematic of proposed double nanocavity resonator.

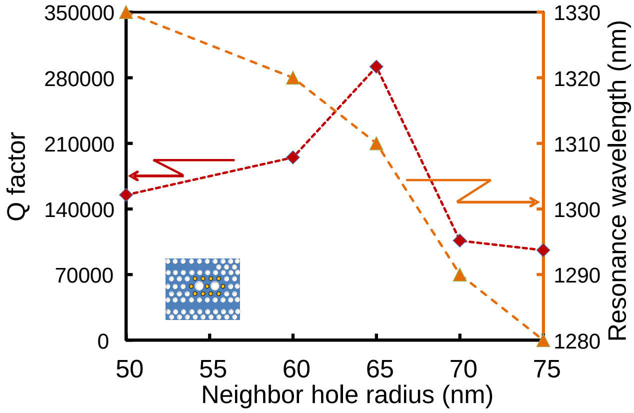

Fig. 2 Simulation results of Q- factor and resonance wavelength versus neighbor hole radius.

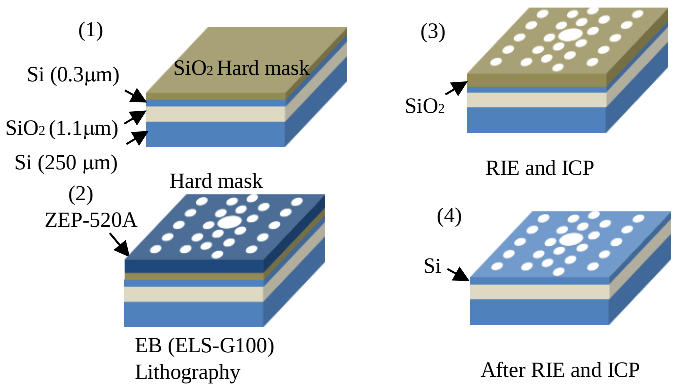

Fig. 3 Fabrication process for Si PhC resonators.

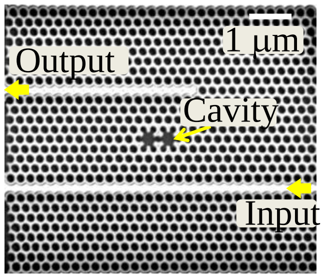

Fig. 4 SEM image of double nanocavity resonator.

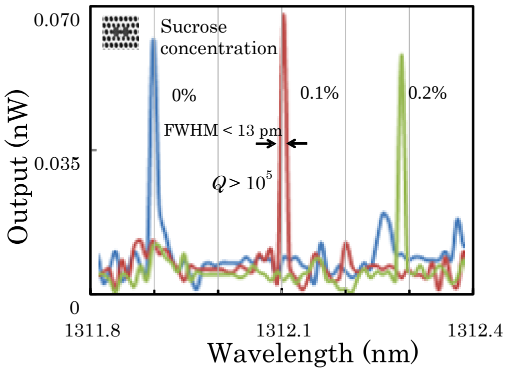

Fig. 5 Experimental result of double nanocavity Si PhC resonator for various sucrose concentrations.

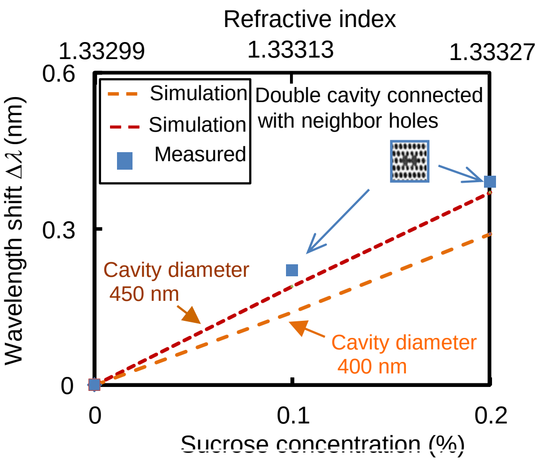

Fig. 6 Resonance wavelength shift versus sucrose concentration.

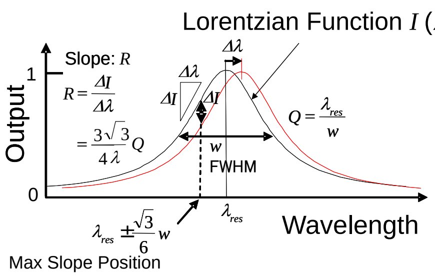

Fig. 7 Output change when the resonance curve is shifted by $\Delta\lambda_{res}$. The resonation curve is generally approximated by the Lorentzian function indicated in the figure. From the simple calculation, the maximum slope is obtained at the wavelength $\lambda_{res}\pm\sqrt{3}w/6$, where w is the FWHM, and the maximum output change is given by $\Delta\lambda_{res}\cdot 3\sqrt{3}Q/4\lambda_{res}$. From sensitivity $S=\Delta\lambda_{res}/\Delta n$, it is derived that the detection limit of the refractive index change Δn is proportional to

Table I Performance comparison of different type of PhC resonator.

Ref.	$Q=\lambda_{res}$/FWHM	Sensitivity, $S=\Delta\lambda_{res}/\Delta n$ (nm/RIU)	Device type	Detection limit, $DL=\lambda_{res}/QS$ (RIU)
6	17890	500	Defect	1.0×10^{-4}
7	2966	131.7	Cavity	3.8×10^{-6}
8	50000	1500	Slot	7.8×10^{-6}
9	7500	370	Cavity	2.3×10^{-5}
10	25000	235	Cavity	1.25×10^{-5}
This work	$>10^5$	1500	Double cavity	$< 8.4 \times 10^{-7}$