**Integration of a high-Q photonic crystal nanocavity in current silicon photonics devices**

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We report the fabrication of a high-Q photonic crystal nanocavity \((Q = 2.2 \times 10^5)\) with photolithography. Photolithography has been used with the CMOS process and can be employed to mass-produce devices. Therefore, we can employ the existing process to fabricate photonic crystal nanocavities. Moreover, the process has high productivity. Another feature of our device is that it has SiO₂ cladding, which is also realized with the CMOS process. We show two advantageous features of the photonic crystal nanocavity. The first is that it has 4.2 times the ability to diffuse heat compared with air-bridge devices because of the silica over-cladding. The second is that it can be used for all-optical switching. The switching speed of ~0.12 ns is almost as fast as that of a previously reported photonic crystal nanocavity fabricated with EB lithography.

**Key words:** Silicon photonics, photonic crystal, CMOS process, width-modulated line defect photonic crystal nanocavity, thermo-optical effect, carrier-plasma effect and all-optical switching.

1. **Introduction**

Silicon photonics is a candidate for the next generation of signal processing. This is because silicon, which has a high refractive index \((n = 3.47)\), can both confine and propagate light with low loss in the communication band (1550 nm). Many devices have already been realized with the aim of achieving signal processing optically rather than electrically. Switches\(^1\),\(^2\), detectors\(^3\),\(^4\) and lasers\(^5\),\(^6\) have been realized. These are driven by interactions between light and matter, and from that perspective confining light in a small region is important. Specifically, photonic crystal (PhC) nanocavities have been utilized due to their high \(Q\) factor and small mode volume. However, they were all fabricated with electron-beam (EB) lithography, which takes time. Moreover, they cannot be mass-produced, and their cost is high, making them impractical for usual producers. They have another disadvantage, namely an air-bridge structure. To enhance light confinement, air is chosen as the material surrounding the silicon. The structure is therefore often unstable, weak against dust and less compatible with other CMOS devices.

This report summarizes the work we undertook in the academic year 2014 to provide a solution for the two above-mentioned problems. We have confidence in the result and it will lead to the future integration of PhC nanocavities and CMOS devices.

2. **Design of nanocavity**

To fabricate a PhC nanocavity with photolithography properly, the design should be carefully considered. This is because the resolution with photolithography is poorer than with EB lithography and the nanocavity structure may not form as it should. We have used a PhC nanocavity design called a width-modulated line defect cavity\(^7\). This design is categorized as a mode-gap confinement cavity, and there is another type of design categorized as a bandgap cavity. The characteristic of the former is that it confines light in a small region using the difference between the propagation frequencies of each region along a PhC waveguide. The characteristic of the latter is that it confines light creating a relatively large structural defect in the PhC periodical structure. In addition to a width-modulated line defect cavity, we fabricated an L3 cavity\(^8\), which is a bandgap cavity. Therefore, here we compare these two types of PhC nanocavity designs in Fig. 1.

**Fig. 1.** SEM images of (a) a width-modulated line defect cavity and (b) an L3 cavity. The distance in each figure shows the maximum amount of shift in each cavity structure.

3. **Calculation and fabrication**

As discussed in the previous section, we chose a width-modulated line defect cavity for our photolithographically fabricated nanocavity. To analyze its mode profile and band structure, we performed a 3D finite-difference time domain (FDTD) and fully vectorial 3D calculation. The results are shown in Fig. 2. The
results of the 3D FDTD estimated slab thickness, hole shift and refractive indexes of Si and SiO$_2$ were 204 nm, 2, 4, 6 nm, 3.47 and 1.44, respectively. The calculated $Q$ value is 7.2$\times$10$^6$, which is very high despite this structure having SiO$_2$ cladding. The mode volume, $V$, is 1.7 ($\lambda/n$). And from the band diagram (Fig. 2(b)), we can see that mode-gap confinement is realized and that the wavevector is far from the light line$^9$, which proves that the loss in the vertical direction of the Si slab is suppressed.

We employed the services of the Institute of Microelectronics (IME), Singapore, which uses a CMOS compatible photolithographic process. In this process, an ArF (excimer laser of 248 nm) is used for the exposure. They decided the slab thickness of 210 nm, so the actual design we used corresponds to the schematic shown in Fig. 3.

Utilizing the design and process described above, we fabricated a width-modulated line defect cavity with SiO$_2$ cladding and measured certain characteristics. In this section, we discuss the transmittance, $Q$-factor and thermal diffusion ability.

The transmittance of the fabricated device is shown in Fig. 4. The measuring light is coupled to a Si nanowire via a spot size converter (SSC), which takes advantage of the use of the photolithographic CMOS process. Because of this the coupling loss is only 0.8 dB. The inset shows the expansion of the cavity mode peak whose center wavelength is around 1619.20 nm. This is in the photonic bandgap of the W0.98 region, which can be explained by the steep band edge seen around 1615 nm. Lorentzian fitting is applied to the peak, which exhibits a $Q$ factor of 2.2$\times$10$^5$. This value is the highest for a photolithographic PhC nanocavity.

Next, another measurement was conducted in which the input light wavelength was scanned four times with various input powers. When the intra cavity power increases and the thermo-optical (TO) effect appears relatively strong, optical bistability is observed (see Fig. 5). In this measurement, we used a SiO$_2$-clad cavity with a $Q$ of 2.1$\times$10$^5$, and the threshold power was 19 $\mu$W. This value is four times that of the air-bridge structure with almost the same $Q$ (2.3$\times$10$^5$). This result shows that SiO$_2$ cladding has an advantage in terms of heat diffusion. This is very useful when it is applied to signal processing architecture, because heat (in the cavity region) usually causes a pattern effect due to its slow diffusion time.

Finally we performed all-optical switching with the device we described in previous sections. The switching speed is defined in several ways, and here it is defined as the time at which the light power becomes half the maximum contrast to the time at which it recovers. The $Q$ factor corresponds to the ability to confine light, and thus light will be trapped for a long time in a high-$Q$ nanocavity. This is undesirable because a faster driving speed is necessary for switching. Therefore, a device with a $Q$ of 3.6$\times$10$^4$ (one order lower than the device with the highest $Q$) was selected in this demonstration.

The result provided in Fig. 6(a) was obtained with the setup shown in Fig. 6(b). Here, the switching technique was the control-signal method$^2$. This is the first demonstration of all-optical switching with photolithographic PhC nanocavities. The switching speed is 0.12 ns and this value is the same as that of a previous report in which a PhC nanocavity fabricated with EB lithography was used$^2$. 

Fig. 2. (a) Mode profile of $H_z$ component calculated by 3D FDTD simulation. (b) Band diagram of the structure. The red and red dashed lines show the bands of a PhCWG whose widths are W0.98 (mirror), W1.00 (cavity), respectively.

Fig. 3: Schematic of a PhC nanocavity fabricated with a photolithographic CMOS process.

Fig. 4. Transmittance of a PhC nanocavity with a $Q$ of 2.2$\times$10$^5$. The inset shows the expansion of the peak region and the black line is a calculated Lorentzian fitting.

Fig. 5. Resonant wavelength shift toward red side due to TO effect. The threshold when optical bistability is observed is 19 $\mu$W (intra cavity power).
6. Conclusion

We realized a PhC nanocavity fabricated with a photolithographic process that has a high $Q$ and SiO$_2$ cladding. This is the first time that all-optical switching with photolithographic PhCs has been demonstrated, and the switching speed is the same as that of previous EB lithographic PhCs. This work will lead to the integration of PhC nanocavities and CMOS devices.

References