High-Q photonic crystal nanocavities on 300 mm SOI substrate fabricated by 193 nm immersion lithography

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On-chip one-dimensional Photonic crystal nanocavities, with a design based on the mode-gap modulation approach, were fabricated in a 300mm silicon-on-insulator wafer using a CMOS-compatible process with 193nm immersion lithography. Characterization of the transmission spectrum shows that a high quality factor of 6.8×10^4 is achieved in these cavities. The dependence of the resonant mode wavelength and quality factor on the width of the cavity and the size of the holes was investigated by sweeping the width, and by scaling the radius of the holes, respectively. These on-chip nanocavities with high-Q, fabricated through a high-resolution and high-volume CMOS compatible platform provide promising opportunities for integrated photonic applications.

Introduction

One-dimensional (1D) photonic-crystal (PhC) nanocavities have easier fabrication and compact structures compared to higher dimensional PhC cavities, and they have recently attracted strong attention in potential applications of integrated photonics and innovative optical devices [1-3]. More importantly, high-Q and extremely low-V have been demonstrated in these 1D PhC nanocavities both numerically and in experiments [4-6]. In spite of their structural simplicity, the fabrication of 1D PhC nanocavities still remains a challenge because of their nanoscale features and rigorous requirements with respect to fabrication imperfections. Most successful demonstrations thus far relied on high resolution electron beam lithography but because of its slow throughput this approach is likely to be limited to research

In this paper, we have successfully realized on-chip 1D PhC nanocavities, fabricated in a 300mm silicon-on-insulator (SOI) wafer using a complementary metal-oxide-semiconductor (CMOS) compatible process with 193nm immersion lithography. We experimentally demonstrate a high-Q in these on-chip 1D nanocavities. Furthermore, the influence of geometrical parameters of the cavity on the resonant mode is presented.

Design of 1D SOI Cavity

The design of the 1D nanocavity is based on the mode-gap modulation approach (or Bloch-wave engineering) [4,6], in which the mode gap of the 1D PhC waveguide is gradually modified by tapering structural parameters such as the lattice constant, the hole size (e.g., for a circular hole cavity) or the width of waveguide. Through this mode gap modulation, the cavity modes arise from the lower dielectric band edge. Moreover the radiation losses caused by the mismatch between the Bloch mode of the PhC and the dielectric waveguide mode are effectively suppressed due to the gradual tapering, resulting in cavity modes with high Q.

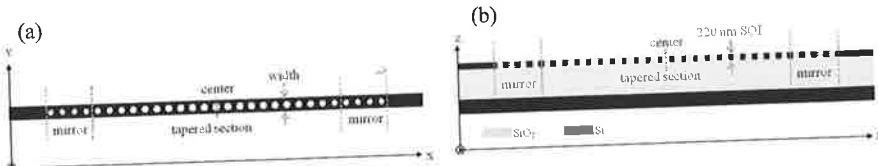

Fig. 1. Schematics of 1D circular hole PhC nanocavity embedded in SOI substrate, consisting of mirror and tapered section. The whole structure is symmetric with respect to the cavity center. (a) Top view and (b) xz-plane cross section of the cavity.

Fig. 1(a) and (b) show the whole view of the 1D SOI cavity, which is composed of a PhC lattice of circular holes etched in a 220nm-thick silicon layer lying on top of a 1μm buried silicon oxide layer. The lattice constant of the PhC, defined as the center-to-center distance between two holes, is fixed at a=400nm, and the total number of holes is 29 in the design. The radius of the holes is parabolically tapered by reducing the radius from 0.3a for the center hole to 0.22a for the edge holes, leaving four holes as PhC mirror with constant radius of 0.22a at each side of the cavity. We varied the width of the cavity from 460nm to 580nm and also scale the radius of the holes with factors from 0.8 to 1.1, in order to study the dependence of the resonant mode wavelength and Q on the width of cavity and the size of the holes. Three-dimensional finite-difference time-domain (FDTD) simulations were performed, using a freely available software package [7], to analyze the cavity numerically. We found that these 1D cavities can support the fundamental mode localized at the wavelength of around 1400-1600nm and that a Q as high as 2.5×10^5 and V of $0.6(\lambda/n)$ can be readily realized with appropriate geometrical parameters of the cavity. We present the electric field profile of E_y component and intensity $|\boldsymbol{E}|^2$ in Fig. 2(a) and (b), respectively. It can be clearly seen that the fundamental cavity mode is a transverse electric (TE)-like mode where E_y is dominant.

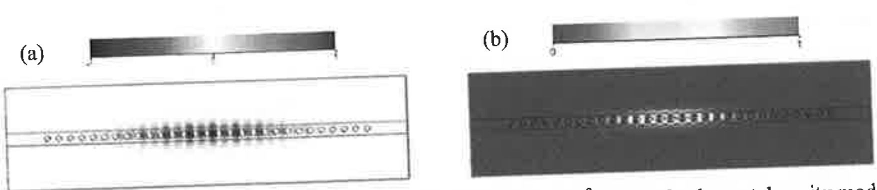

Fig. 2. (a) Normalized electric field (E_y), and (b) field intensity ($|\boldsymbol{E}|^2$) of the fundamental cavity mode.

Measurement Results

The complete fabrication process was carried out in a 300mm SOI wafer employing a CMOS pilot line with 193 nm deep ultraviolet immersion lithography. To allow straightforward characterization, the 1D PhC nanocavities are connected at both sides with around 500μm-long silicon waveguides and grating couplers optimized for TE polarization. We measured the transmission spectra of the cavities with a resolution of 1pm by using a tunable laser covering a wavelength range from 1470 to 1570nm. The experimental Q values of these nanocavities were extracted by fitting the transmission spectra with a Lorentzian line shape, namely, $Q=\lambda_c/\Gamma$, where λ_c and Γ are the associated wavelength and linewidth of the cavity mode, respectively. The input power was minimized to eliminate nonlinear effects (mostly due to temperature increase).

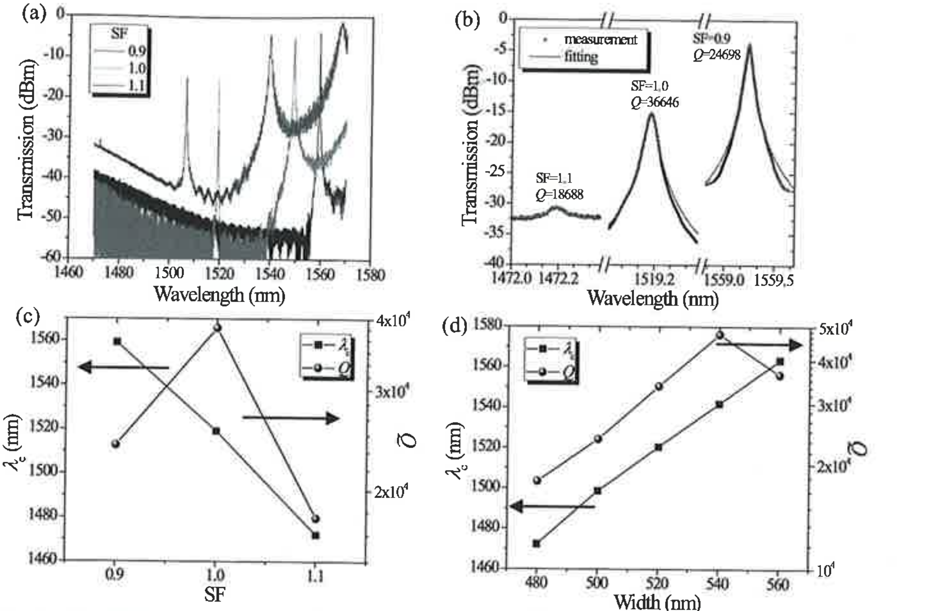

Fig. 3. (a) Transmission spectra and (b) the fitting results for the fundamental modes of the cavities with different SF. Peak position (λ_c) and Q factor of the fundamental modes of the cavities as a function of (c) SF of radius of holes, and (d) the width of cavities. Note that the width of the cavities in (a), (b), and (c) is 480nm; and the SF is 1.1 in (d).

Since the measured wavelength range is limited to only 100nm by our tunable laser, we selected the cavities that their fundamental mode lies in this scanning wavelength range. Firstly, we plot the transmission spectra and the associated fits for the fundamental modes of cavities with the same width of 480nm but various scaling factors (SF) for the radius of the holes in Fig. 3(a) and (b), respectively. Note that from the transmission spectra, it is obvious that at least three orders of modes can be supported by these 1D PhC cavities. Here we only focus on the fundamental modes. Fig. 3(c) shows dependence of the mode position λ_c and Q on the SF from the results of (a) and (b). It is clearly seen that the resonance peaks of the cavities shift to shorter wavelength when increasing the radius of the PhC holes. This is explained by the fact that the band gap of the 1D PhC shifts towards higher frequency (shorter wavelength). As shown in Fig. 3(c), in our measured region of SF, an approximately linear dependence of the resonance wavelength on the SF can be observed, exhibiting around 2nm peak wavelength-shift per nanometer of radius change. From Fig. 3(b) and (c), one can also see that the maximal Q is obtained at the SF of 1.0, which can be understood in terms of band gap of the 1D PhC. When scaling the radius of the holes, the band gap of the 1D PhC as well as the resonance position will change and thus at a proper radius size (i.e., SF) the resonance mode might be located at the midgap frequency where the mode is expected to be confined maximally by the PhC gap, giving rise to the maximal Q. From Fig. 3(a), it can be seen that, compared to those with the SF of 0.9 and 1.1, the mode at SF of 1.0 indeed lies within the minimum transmission window that best corresponds to the middle of the gap.

We also investigated the effect of the width of the cavities on the resonance wavelength λ_c and Q factor of the cavity modes, as presented in Fig. 3(d). Obviously, with increasing the cavity width, the resonance peaks are nearly linearly red-shifted at a rate of around 1nm-redshift per nanometer of increasing width, since the band gap is pushed to lower frequency. Similarly like the scaling radius of holes, certain width results in a maximal *Q*. From Fig. 3(c) and (d), it is obvious that the resonance wavelength of the cavity mode is very sensitive to and can by widely tuned by varying the radius of holes and the width of the cavity, while still sustaining a large *Q* (above 1.5×10^4), which in turn demonstrates the accuracy and robustness of the fabrication process using advanced CMOS technologies. With an appropriate scaling for the radius of holes and the width of the cavities, a *Q* of as high as 6.8×10^4 has been achieved in our cavities. We further would like to emphasize that these on-chip SOI cavities are embedded in a silicon oxide matrix and that an expected higher *Q* can be realized by removing the surrounding oxide of the cavities.

Conclusions

We fabricated on-chip 1D PhC nanocavities on a 300mm SOI wafer using a CMOS-compatible process. Through measuring the transmission spectra high *Q* factors were experimentally demonstrated, and the dependence of the cavity mode on the structural parameters of the cavities has been studied, which further demonstrated the accuracy and reliability of this CMOS process for fabricating on-chip PhC nanocavities with high resolution and high volume. These on-chip nanocavities open up new opportunities for integrated photonic applications.

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