Research article

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Photonic crystal nanobeam cavities with lateral fins

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Abstract: We present the design, fabrication, and characterization of suspended arrays of small volume, high quality factor (Q) silicon nitride photonic crystal nanobeam (PCNB) cavities with lateral nanorod fin structures. By controlling the alignment position of the fins with respect to the air holes, the resonance wavelength and Q -factor of the PCNB cavities can be tuned to realize the desired performance. Measured tunable range of 2×10^4 and 10 nm is achieved for Q -factor and resonance wavelength, respectively, with the highest Q -factor measured at 2.5×10^4 . Incorporating such nanorod fins into the nanobeam cavity is demonstrated to provide improved mechanical support, thermal transport, and channels of lateral carrier injection for the suspended PCNB. The proposed PCNB cavities with lateral fins are advantageous for energy efficient, ultra-compact lasers, modulators, filters, and sensors.

Keywords: fin structure; nanobeam; photonic crystal.

1 Introduction

During the last several decades, the field of photonic crystal has seen drastic developments in both theory and application [1–5]. Scaling of optical cavities has been of great interest for future high performance, low energy consumption, and high-speed optical devices such as semiconductor lasers, light-emitting diodes (LEDs), optical sensors, and modulators. Nanobeam cavity, among other microcavities,

has drawn stronger attention for its superior characteristics of ultra-compact size, extreme low mode volume (V), and high quality (Q) factor [6–9]. These characteristics have made the nanobeam cavity a competitive candidate for nanolasers, on-chip modulators, optical switches, and filters [10]. In the past decade, nanobeam cavity on III–V platform has achieved a lasing threshold of $2.3 \mu\text{W}$ by optical pumping [11] and $5 \mu\text{A}$ by electrical pumping [12]; Integrated lasers on silicon nitride nanobeam cavity have also been demonstrated to be promising options for lasers on Si [13, 14]. Nanobeam modulators on Si and Si integrated platforms have reached a footprint of a few μm^2 [15] in the experiment and have the potentials to realize a high modulation speed larger than 100 GHz at the energy efficiency below f/bit theoretically [16, 17]. Nanobeam-based optical switches utilize thermo-optic [18], Electro-optic effect [19], and Kerr nonlinearity [20] have been of growing interest for their simplicity in fabrication. On-chip nanobeam sensors can obtain a figure of merit >2000 for label-free sensing, one order higher compared to other PC sensors [21].

However, the nature of ultra-high performance nanobeam resulted from deep etching [22] and suspending [23] also compromises the implementation of nanobeam structures. Current nanobeam cavities have non-negligible trade-offs in electrical/optical/mechanical/thermal efficiencies due to the required high index contrast cladding and suspended structure. Earlier, non-suspending tunable nanobeam cavities were reported with one-sided nanotentacles (connecting fins) that improve thermal conductivity and tunability [24]. Other configurations of the vertical supporting structure were also proposed that offers electric injection for nanobeam lasers [12].

In this work, we propose and investigate a suspended silicon nitride photonic crystal nanobeam (PCNB) cavity with lateral nanorod fin structures on both sides of the nanobeam cavity, where the alignment of the fin position is tunable to achieve a range of desired Q -factor and resonance wavelength. We also compare the optical performances of the very same PCNB with and without fins. The PCNB structures are shown schematically in Figure 1(a) and (c), for PCNBs without and with fin structures, respectively. Shown

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in Figure 1(b) and (d) are scanning electron micrographs (SEMs) for PCNBs without and with fins, respectively. Compared to the traditional suspended nanobeam cavity, the introduction of the lateral fins improves the mechanical strength, thermal conduction, and electrical carrier injection of the suspended PCNB cavity.

2 Photonic crystal nanobeam cavity design

The PCNB cavity is designed to utilize the maximum mirror strength in the one-dimensional (1D) PC, thus it is desirable to have a symmetric radius taper of six periods on each side about the center of the cavity according to the deterministic method [25]. As shown in Figure 2(a), two different parabolic radius tapers are fabricated, one with taper radius changing from 46.9 to 66.8 nm (taper01, red square), and

Figure 1: (a), (c) Schematic illustrations and (b), (d) scanning electron micrographs of the suspended nanobeam cavity without, and with fin structures, respectively. Scale bars in (b) and (d) are 1 μm .

another with taper radius changing from 52.8 to 69.2 nm (taper02, blue circle), to verify the mirror strength theory. Figure 2(b) shows all the key design parameters for PCNB with fins, including cavity thickness t , PC nontaper regular radius r , PC lattice constant a , fin width w , beamwidth W_b , and the fin alignment position D . We define $D = 0$ for fins aligned to the center point of two air holes, as shown by the solid fins; and $D = 0.5a$ for fins aligned to the center of each air hole, as shown by the transparent fin. The optimized values by the deterministic recipe in Ref. [25] for these parameters are $r = 71.8$ nm, $a = 272$ nm, $w = 30$ nm, $t = 150$ nm, and $W_b = 300$ nm for the target resonance wavelength at 660 nm.

Previous work by J. Zhang [24] has demonstrated that the presence of an optimized lateral tentacle structure on one side of the cavity has minimal effect on the optical performance of the cavity. To investigate impact brought by the presence of fins on both sides of our PCNB cavities, we explored two scenarios of nanobeam cavity in numerical simulation as shown in Figure 3: a suspended nanobeam (a) without and (b) with fins; and a nanobeam cavity on SiO_2 substrate (c) without and (d) with fins. Simulations are performed with the finite-difference time-domain (FDTD) method, using an open-source software package [26]. It shows that the presence of fins on our PCNBs also has minimal impact on the mode distribution in the cavity and brings less than 2% change in Q -factor when fins are thin ($\sim 0.1a$) and aligned to the electric field minima. This is verified by the experimental data shown later.

3 Fabrication and measurement

3.1 Fabrication

The fabrication process of the PCNB cavities includes Si_3N_4 film deposition on Si wafer and PCNB cavity pattern lithography. The 150 nm thick Si_3N_4 film is stoichiometrically grown with low-pressure chemical vapor deposition

Figure 2: (a) Fabricated radius taper of the nanobeam cavity (inset is the SEM image of the taper part), and (b) defining parameters of the nanobeam cavity, the dashed arrow and the transparent fin illustrate the fin position shift in the cavity array.

Figure 3: Comparison of simulated E_y component of the electrical field distribution and quality factor of suspended Si_3N_4 nanobeam cavity (a), without and (b), with lateral fins (fin width $0.1a$, second-order band edge of air mode), and of Si_3N_4 nanobeam cavity on SiO_2 substrate (c), without and (d), with lateral fins (fin width $0.2a$, first-order band edge of dielectric mode).

method at 770°C on a p-type silicon wafer in a Tystar Titan nitridation furnace. The patterning of the PCNB cavity consists of standard electron beam (e-beam) lithography (EBL), directional reactive ion etching (RIE) of Si_3N_4 layer, isotropic RIE of Si substrate, stripping, and plasma cleaning of the e-beam resist.

The EBL process starts from the spin coating (4000 rpm, thickness 371 nm) of e-beam resist (ZEP 520A), followed by pre-baking at 180°C for 3 min, and afterward e-beam exposure under accelerating voltage of 20 kV on the Nanometer Pattern Generation System (NPGS, by J. C. Naby Lithography Systems). The exposed pattern is then developed by Amyl Acetate under refrigeration temperature for 60 s followed by a post-baking at temperatures heating up from 60 to 100°C .

The PCNB pattern on the e-beam resist is then etched onto the Si_3N_4 layer by inductively coupled reactive ion etching (IPC-RIE) process, at gas flow rate ratio of SF_6 : CHF_3 : $\text{He} = (1: 2.5: 2.77)$, with a resulted aspect ratio of 5.3. A following isotropic IPC-RIE process with only SF_6 gas etches the Si substrate to create the suspension of the PCNB on Si_3N_4 . The residues of e-beam resist are then dissolved in N-Methyl-2-pyrrolidone (NMP) solution heated up to 75°C . The suspended thin fins are proved to be intact during this wet process, but the most used combination step of ultrasonication is completely prohibited. Instead, a final process of oxygen plasma ashing for 1 h completely cleans up all the remains of e-beam resist.

3.2 Measurement and analysis

For the nanobeam cavity design without lateral fins, two different tapers are fabricated and compared on the same 1D

PC structure, with the taper profiles shown in Figure 2(a). The resonance wavelength of the 1D PC is determined by the photonic band diagram, as shown in Figure 4(a) where the airband (solid lines) and dielectric band (dashed lines) are plotted for 1D PCs with different r/a ratios. For the target wavelength at 660 nm, $r/a = 0.27$ is picked. The fabricated cavity resonance is then measured by optically pumping the Si_3N_4 cavity with a 450 nm laser to activate the defect states in the Si_3N_4 . Shown in Figure 4(b) is the measurement result of cavities where a series of radius offset is scanned to achieve the target device dimension. For both tapers, the resonance wavelength shifts linearly, with Q -factor maximizes near the optimized radius. Taper02 has a closer match of radius profile to the optimized design and the optimized cavity resonance spectrum is shown in Figure 4(c). The highest Q -factor obtained is 2.3×10^4 with full width at half maximum (FWHM) of 28 pm. Shown in the inset is the full spectrum measured. Figure 4(d) shows the SEM image of taper02.

After confirming the cavity radius taper profile, arrays of nanobeam cavities with fins are fabricated with fin alignment varies from the center point of two air holes (defined as $D = 0$) to the center of each air hole (defined as $D = 0.5a$). At $D = 0$, the presence of fin rod has minimal influence on the distribution of the electromagnetic (E&M) field compared to nonfin nanobeam cavity, as shown in the measured spectrum in Figure 5(a), where the measured $Q = 2.46 \times 10^4$ and $\text{FWHM} = 26$ pm. The true Q -factor can be higher since the resolution on our testing setup is limited to resolve finer peaks. This is close to the result shown in Figure 4(c) and agrees well with the simulation result described in the previous section. As the fin position shifts to the center of each air hole, the E&M field starts to couple to the lateral rod. As a result, the confinement (Q -factor) in the cavity is reduced and the resonance shifts to lower frequency (higher wavelength). The measured result is shown in Figure 5(b), where the red (blue) dashed line is the Q -factor (resonance wavelength) of the nanobeam cavity with the same dimension but without fins. It agrees well with the simulation result shown in Figure 5(c). The lower Q -factor in the measured result is due to both fabrication defects and measurement setup limit.

To find out the influence of fabrication offsets in the air hole radius, fin width, and more importantly, the resonance tuning capability of the fin-tuning nanobeam cavity array, another series of PCNBs is fabricated where the radius and fin width offsets are scanned. Shown in Figure 6(a) and (b) are the measured resonance wavelength and Q -factor on PCNBs with air hole radius and fin width varies independently. For both $D = 0$ and $0.5a$ alignments, there is an optimized airhole radius and an optimized fin width. The variations of the radius or fin width around the optimized design ($r = 64.5$ nm and $w = 24.2$ nm) cause the Q -factor and

Figure 4: (a) Photonic band plot of one-dimensional photonic crystal structure for r/a ratio of 0.2, 0.27, and 0.29, the shaded region is the light cone of Si_3N_4 . (b) Measured resonance wavelength and quality factor of two different taper structures at different radius offsets. (c) Measured optical emission spectrum around the resonance peak and its Lorentzian fitting (inset is the full range spectrum) of one nanobeam cavity without fin that has the same radius as the cavity with fins. (d) Top view SEM of the taper region on the suspended nanobeam cavity without fins.

Figure 5: (a) Measured optical emission spectrum around the resonance peak and its Lorentzian fitting of the nanobeam cavity with fins aligned to the center of two air holes, (b) measurement result of tuning of resonance wavelength and Q -factor as fin alignment position changes, where position $D = 0$ is when fins are aligned to the center of two air holes and position $D = 0.5$ is when fins are aligned to air holes, (c) simulated result of tuning Q -factor and resonance wavelength by changing fin alignment position.

resonance wavelength to change gradually, which agrees with the numeric simulation results shown in Figure 6(c) and (d) in general. The minor discrepancies may be related to the fabrication variations. For both radius and fin width that are 10 nm away from the optimized design value, the Q -factor drops to about half of the optimized Q -factor. It is worth mentioning that the range of wavelength tuning by fin position broadens for larger air hole radiuses and for wider fins. But the broader tuning range comes with a reduced Q -factor in both cases.

4 Summary

We designed, fabricated, and measured arrays of nanobeam cavity with lateral fins where the fin alignment position is

tuned to control the resonance Q -factor and wavelength. The lateral fins can provide mechanical support, act as thermal conduction channels, and enable carrier injection to the suspended nanobeam cavity. These low mode-volumes, high Q -factor nanobeam cavities are ideal candidates for novel lasers, LEDs, optical modulators, filters, and sensors. The nanobeam cavity can also be applied on different materials and can be integrated with new photonic/electronic on-chip platforms for high speed, low-power consumption applications.

It is worth mentioning that the proposed structure can be designed to have extremely high Q -factors or moderate Q -factors depending on the application requirements. The impact of the lateral fins may be very small (2%) to the nanobeam cavity Q -factors. So extremely high Q -factors can be achieved. This could be

Figure 6: (a) Measured and (c) simulated resonance wavelengths and Q -factors with different radius offsets; (b) measured and (d) simulated resonance wavelengths and Q -factors with different fin width offsets.

useful for high-speed modulators or high sensitivity sensors. On the other hand, moderate Q -factors are desirable for nanobeam lasers if we consider trade-offs in modulation speed and energy cost.

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