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High-*Q* micromechanical resonators in a two-dimensional phononic crystal slab

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By creating line defects in the structure of a phononic crystal (PC) made by etching a hexagonal array of holes in a 15 μm thick slab of silicon, high-*Q* PC resonators are fabricated using a complimentary-metal-oxide-semiconductor-compatible process. The complete phononic band gap of the PC structure supports resonant modes with quality factors of more than 6000 at frequencies as high as 126 MHz. The confinement of acoustic energy is achieved by using only a few PC layers confining the cavity region. The calculated frequencies of resonance of the structure using finite element method are in a very good agreement with the experimental data. The performance of these PC resonator structures makes them excellent candidates for wireless communication and sensing applications. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3078284]

Structures with periodic variations in their mechanical properties named phononic crystals (PCs)[1,2] have gained much attention in recent years due to their unique frequency characteristics which cannot be achieved using conventional bulk materials. A very important property of PCs is the existence of phononic band gaps (PBGs) that are frequency bands in which mechanical energy cannot propagate through the structure. PCs with PBGs can be used to filter, confine, or guide mechanical energy and hence are useful for a variety of applications including wireless communications and sensing. Of special interest for such applications are planar PCs with two-dimensional (2D) periodicity in space that can provide a low-loss platform with flexibility in the lattice type, size, and location of the periodic inclusions. Therefore, it was recently proposed to use 2D PC slabs (also called 2D PC plates) in which the acoustic properties of a solid slab with limited thickness are periodically modified in its two in-plane dimensions.[3–6] Exemplarily, such structures can form by etching an array of holes in an appropriate substrate [for example, Si on insulator (SOI)] and then undercutting the structure underneath the holes to form a membrane that is supported on the sides.[6] The acoustic waves in PC slabs are confined within the thickness of the slab as they cannot leak into the air (or vacuum) on top and bottom of the structure due to the large acoustic mismatch. Therefore, unlike surface acoustic wave-based PC structures[7,8] that can suffer considerable loss due to coupling of acoustic waves to the substrate,[9,10] PC slabs provide a very low loss platform for implementing PC functionalities. Due to this important advantage, there has been much recent interest in PC slab structures.[3–6,11–15] Besides observation of high attenuations in the transmission spectrum of specific acoustic modes in certain crystalline directions,[4] complete PBGs (CPBGs) (for all types of waves and for all propagation directions) were theoretically predicted for solid[3] and vacuum (or air)[5] inclusions in a solid slab. CPBGs were then evidenced experimentally both at low[11] (less than 1 MHz) and high[6] (more than 100 MHz) frequencies. Guiding of acoustic waves in PC line defects was also predicted theoretically for either free-standing or supported PC slabs.[12] The possibility of wave guiding in free-standing PC slabs was also evidenced by experiments very recently.[13,14]

Due to their ability to confine and guide acoustic waves with low loss, PC slabs have become excellent candidates for the implementation of chip-scale integrated wireless devices, especially for high frequency applications in which PC feature sizes are small, resulting in compact structures. The availability of complimentary metal oxide semiconductor (CMOS)-compatible fabrication facilities makes SOI substrates a natural choice for such PC slabs. However, to implement individual functionalities needed for integrated wireless applications, reliable frequency-selective structures must be implemented. Such structures are usually formed using resonators with high quality factors (or high *Q*s). Thus, the development of high-*Q* resonators with high resonance frequencies in PC slabs is an urgent need for the deployment of PC-based integrated wireless systems. However, up to now there have been only very limited theoretical studies[15] on the properties and quality of PC slab resonators.

In this letter we report the design, analysis, fabrication, and characterization of high frequency Si micromechanical resonators with high *Q*s using the CPBG of a PC slab structure. We show that mechanical energy can be efficiently confined using only a few periods of such PC slab structure. We believe that the results presented in this letter can lead to more efficient approaches for designing the micromechanical devices used in wireless communications and sensing systems.

The PC structure used in this letter is made by embedding a honeycomb array of cylindrical holes in a thin Si slab, as shown in the inset of Fig. 1(a). The inset of Fig. 1(a) shows a unit cell of the PC structure in which d is the thickness of the PC slab, a is the distance between the centers of the nearest holes in the structure, and r is the radius of the holes. In the designed structure, the geometrical parameters are chosen as $d=15$ μm, $a=15$ μm, and $r=6.5$ μm. The band structure of the thin PC slab (calculated using the plane wave expansion method described in detail in Ref. 5) is shown in Fig. 1(a). It is clear that this geometry of PC slab

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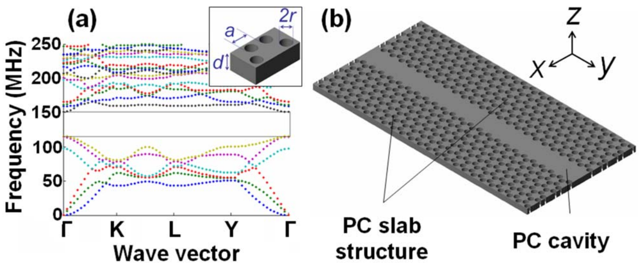

FIG. 1. (Color online) (a) The band structure of a hexagonal lattice PC of circular holes in Si slab with $r=6.4\ \mu\text{m}$, $a=15\ \mu\text{m}$, and $d=15\ \mu\text{m}$. A unit cell of the structure is shown in the inset. r, a, and d represent the holes radius, the distance between the two closest holes, and the slab thickness, respectively. (b) Schematic of the designed PC slab resonator in which a cavity is made in the PC structure by removing four rows (one period) of holes from the PC structure.

provides a large CPBG with frequency extent of $115\ \text{MHz} < f < 152\ \text{MHz}$ allowing for confining mechanical vibrations in a wide frequency range. The basic PC resonator presented in this letter is formed by removing a period (four rows) of PC holes from the PC structure, as demonstrated in Fig. 1(b), forming a PC cavity. This cavity is surrounded by three periods (12 rows) of holes on each side in the x direction, as shown in Fig. 1(b), and is considered very large compared to the wavelength in the y direction.

We analyzed the PC resonator structure using three-dimensional finite element method (FEM). Si is considered to be fully crystalline with its main symmetry axes in the x, y, and z directions. Since the structure is large and has translational symmetry in the y direction, periodic boundary conditions are used to limit the simulation to only one period in this direction. Three periods of PC holes are placed on each side of the PC cavity to provide enough confinement for the trapped modes in the CPBG. The structure is terminated by the stress-free boundary condition in the x and z directions. Our simulations show that the PC slab resonator supports two symmetric shear-horizontal, a dilatational, and two flexural plate modes. Due to the ease of excitation using interdigital transducers (IDTs) and good frequency distinction from other slab modes excited by IDTs (which facilitate the fabrication and characterization of the PC resonator) we only consider the two flexural modes in the remaining of this letter. The profiles of the three components of the displacement vector of these two modes along with their frequencies of resonance are shown in Figs. 2(a) and 2(b). The resonance frequency of the first mode is approximately in the middle of the CPBG at 126 MHz while the resonance frequency of the second mode is at 149.5 MHz, which is very close to the upper limit of the CPBG. Since the resonance frequency of the first mode has enough frequency separation from the edges of the CPBG, we expect a better confinement of this mode (and thus, a higher Q) compared to the second resonant mode.

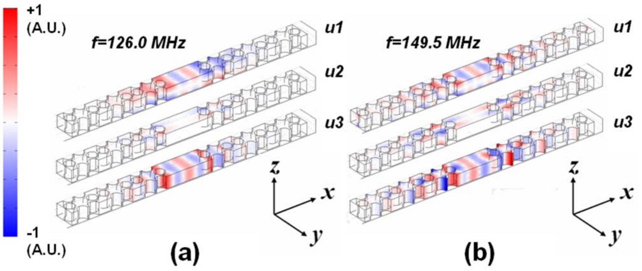

FIG. 2. (Color online) Mode profiles of the displacement vector components on the structure boundaries and the frequency of resonance of the (a) first and (b) the second studied mode in the PC cavity. u_1, u_2, and u_3 denote the displacement vector components in x, y, and z directions, respectively. The color bar indicates the amplitude of each field component in an arbitrary unit.

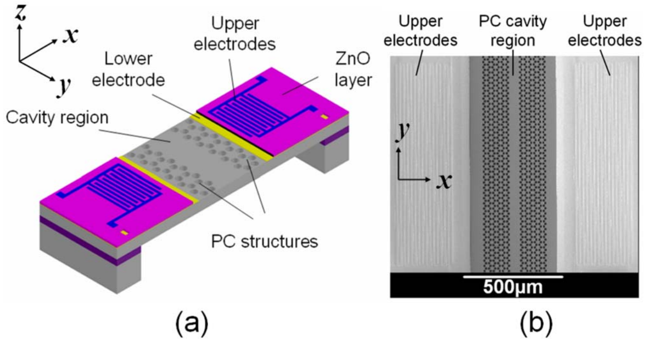

FIG. 3. (Color online) (a) Schematic of the PC slab resonator structure with excitation and receiving transducers on its two sides. In this schematic, the cavity region is surrounded by four rows of holes (one period of the PC) on each side. (b) Top SEM image of a fabricated PC slab resonator with the transducer electrodes on each side. The cavity region is surrounded by 12 rows (three periods) of holes on each side.

To experimentally characterize the designed PC slab resonator, we fabricated it on a SOI wafer with two transducers on its two sides, as illustrated in Fig. 3(a), to measure the transmission of the flexural plate waves through the PC resonator as a function of frequency. The details of the fabrication procedure of the device are discussed elsewhere[6] and will not be repeated here for brevity. A scanning electron microscope (SEM) image of the fabricated structure is shown in Fig. 3(b). The size of the device in the y direction is 1.2 mm, which is very large compared to the wavelength of the studied waves ($\sim 50\ \mu\text{m}$) satisfying the translational symmetry condition used in the simulation. The structure is connected to the SOI substrate at its two ends in the y direction.

Utilizing the appropriate piezoelectric properties of the ZnO, flexural acoustic waves are launched toward the PC resonator structure. The transmission through the PC structures is then measured using the second transducer on the other side of the PC structure. Similar to the resonant tunneling effect in semiconductors,[16] we expect peaks in the transmission of acoustic waves through this structure at the frequencies of resonance of the cavity. The measured transmission is then normalized to compensate for the frequency response of the transducers using a similar procedure as discussed in Ref. 6.

The normalized transmission profiles at frequencies around the resonance frequencies of these two modes are shown in Figs. 4(a) and 4(b). As expected, two peaks associated with the two flexural resonant modes of the cavity appear in the transmission spectrum of the flexural waves passing through the PC structure. A peak in the transmission profile is centered at 126.52 MHz, which is in a very good agreement with the predicted resonance frequency of 126.0 MHz of the first studied mode found using FEM. The Q of the transmission profile (and hence the first resonant mode) is 6300, resulting in a frequency by quality factor product

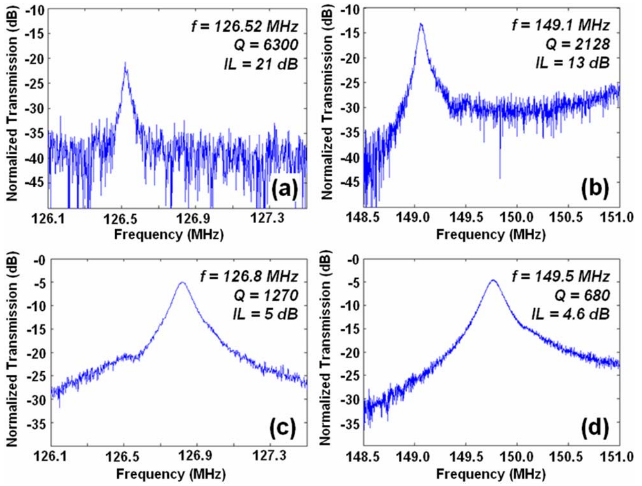

FIG. 4. (Color online) Normalized transmission through the PC cavity slab structure for (a) first, (b) second studied mode for the structure with three periods (12 rows) of PC holes on each side of the cavity, (c) first, and (d) second studied mode for the structure with only two periods (eight rows) of PC holes on each side of the cavity. The peak frequency (f), quality factor (Q), and insertion loss (IL) are given in each figure.

(FQP) of 0.8×10^{12} Hz, which is among the highest FQPs (a common figure of merit for micromechanical resonators) reported to date for Si micromechanical resonators operating at atmospheric pressure.[17]

The measured frequency of the second peak in the transmission is 149.1 MHz, which is again in excellent agreement with the theoretical value of 149.5 MHz found using FEM. The Q of the second resonant mode is measured to be 2128, which is nearly one third of that of the first mode. This is an expected result as the resonance frequency of the second mode is much closer to the edge of the CPBG compared to the first mode.

To evaluate the effect of the number of PC layers on the Q of the resonant modes of the PC resonator, we also fabricated the structure with only two periods (eight layers) of holes on each side of the cavity and measured the transmission throughout the CPBG with the same procedure discussed above. The corresponding normalized transmission profiles of the two studied modes are shown in Figs. 4(c) and 4(d). As it can be seen in Fig. 4, the Qs of first and second modes are dropped to 1270 and 680 (as compared to 6300 and 2128 for the previous structure). As expected, reducing the number of PC layers results in higher coupling of the PC cavity modes to propagating modes of the Si slab and consequently much lower Qs and lower insertion loss (IL).

The FQP of the PC resonator reported here, although one of the highest FQPs reported for Si resonators in atmospheric pressure, is still an order of magnitude less than the material limited FQP and the highest reported FQP in micromechanical resonators.[17] However, based on the results presented we believe much higher Qs can be obtained by increasing the number of PC layers around the cavity in both x and y directions. Further, air damping plays an important role in the cavity loss in this frequency range[17] and operation at lower pressure will also lead to considerably higher Q values. Due to the potentially support loss-free structure of these PC slab resonators, we expect the material loss to be the main limit on the achievable Q. The extension of these PC resonators to higher frequencies (multiple gigahertz) is also possible by scaling the PC structure. Such high-Q, high-frequency resonators are greatly desired for wireless communication and sensing applications. Also, simultaneous achievement of photonic and phononic band gap in the same PC structure can lead to interesting optomechanical interactions such as enhanced stimulated Brillouin scattering[18] and radiation pressure excitation of the resonators.[19]

In summary, we reported here PC slab resonators with high resonance frequencies (~150 MHz) with very high Qs (up to 6300) using a CMOS-compatible fabrication process in Si. The resulted frequency by quality factor product is among the highest values reported to date for Si-based PC resonators operating at atmospheric pressure. We studied the effect of different number of PC layers on the Q of the PC structure. The results presented here suggest that PC slab resonators have the potential to achieve the highest performance among all possible acoustic cavities to be used in wireless communication and sensing systems.

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