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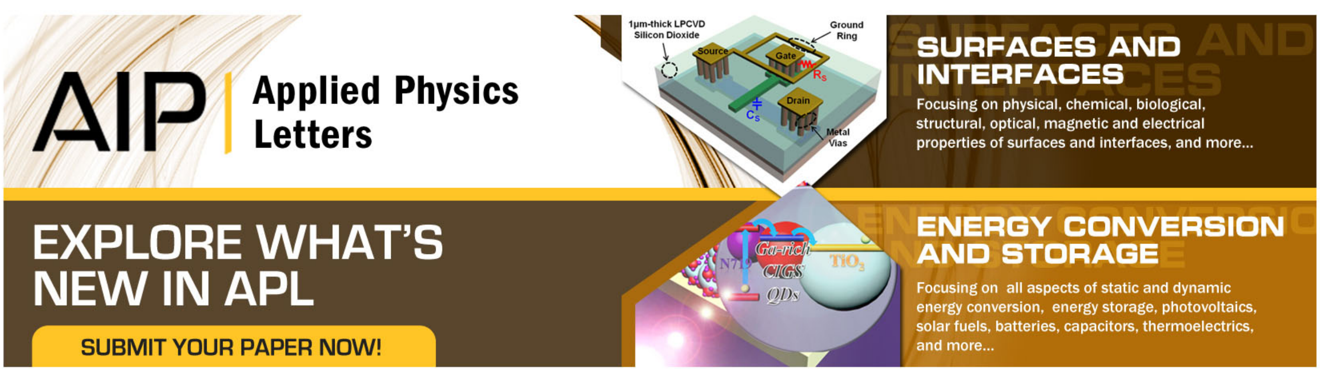

Evidence of large high frequency complete phononic band gaps in silicon phononic crystal plates

Saeed Mohammadi,[1] Ali Asghar Eftekhar,[1] Abdelkrim Khelif,[2] William D. Hunt,[1] and Ali Adibi[1,a)]
[1]*School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, Georgia 30332, USA*
[2]*Institut FEMTO-ST, CNRS UMR 6174, Université de Franche-Comté, 32 Avenue de l'Observatoire, 25044 Besançon Cedex, France*

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We show the evidence of the existence of large complete phononic band gaps (CPBGs) in two-dimensional phononic crystals (PCs) formed by embedding cylindrical air holes in a solid plate (slab). The PC structure is made by etching a hexagonal array of air holes through a freestanding plate of silicon. A fabrication process compatible with metal-oxide-semiconductor technology is used on silicon-on-insulator substrate to realize the PC devices. Measuring the transmission of elastic waves through eight layers of the hexagonal lattice PC in the ΓK direction, more than 30 dB attenuation is observed at a high frequency; i.e., 134 MHz, with a band gap to midgap ratio of 23%. We show that this frequency region matches very well with the expected CPBG found through theoretical calculations. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2939097]

Phononic crystals[1,2] (PCs) are special types of inhomogeneous materials with periodic variations in their elastic properties. The frequency characteristics of the PCs can be very different from those of the constituent materials and can be engineered to achieve functionalities not obtainable using conventional bulk materials. One of the most interesting phenomena that can be obtained in the PC structures is the existence of phononic band gaps (PBGs), which are frequency ranges in which the propagation of elastic waves is prohibited. PBGs can be used to realize fundamental functionalities such as mirroring, guiding, entrapment, and filtering for acoustic/elastic waves by creating defects in the PC structure. The possibility of implementation of these functionalities in the PC structures can lead to integrated acoustic devices with superior performance over the conventional electromechanical devices used in wireless communication and sensing systems.

While most of the earlier demonstrations of PBGs have been in the PCs with bulk[3,4] or surface acoustic wave[5] (SAW) modes, there has been a growing recent interest in PC plates (slabs) with two-dimensional (2D) periodicity, and a finite thickness (of the order of wavelength) in the third dimension.[6–12] These structures are important as the elastic energy will be manipulated by the PC structure in the plane of periodicity while being confined within the finite thickness of the plate in the third dimension. The air (or vacuum) on top and bottom of the PC plate (or membrane) decouples the elastic modes of the PC structure from those of the bulk (supporting) structure. Thus, the loss of the elastic waves in the PC plates is considerably lower than that of the SAW-based 2D PC structures.

In addition to theoretical reports for the possibility of having complete PBGs (CPBGs) in PC plates,[7] experimental evidence for partial PBGs (i.e., for certain type of modes),[6,8] and CPBGs (for all types of modes),[11] have been reported recently. While partial PBGs have some special applications, CPBGs are of primary interest as they allow the complete engineering of the propagation of elastic waves in the PC structure. Recently, a CPBG was experimentally verified for spherical steel beads placed in a plate made of epoxy; a waveguide was also created by introducing a line defect to the PC structure.[11] However, the CPBGs reported for such epoxy based structures are in the 228–344 KHz frequency range, and their extension to the high frequency range (hundreds of megahertz to gigahertz) is not trivial. Such high frequency PC structures are of considerable interest for compact wireless and sensing devices. Among several material systems proposed for the fabrication of PC plates, silicon (Si) is of great interest due to its wide usage in electronic and photonic devices (for eventual integration of electronic, photonic, and phononic functionalities), low cost, the availability of complimentary-metal-oxide-semiconductor (CMOS) fabrication tools that allow accurate and economical fabrication of Si structures with very small (even tens of nanometers) feature sizes, and proper mechanical properties that are required for high frequency applications. We recently demonstrated theoretical evidence for the existence of a sizable CPBG in the PC of air cylinders in a Si membrane with both square and hexagonal (or honeycomb) lattice geometries.[12] We particularly showed that hexagonal PC plates with practical holes sizes can be designed to have large CPBGs.

In this letter, we show the evidence for the existence of large CPBGs in a PC of air holes embedded in a solid plate. The structure is made by etching a hexagonal lattice of cylindrical holes through a freestanding plate of single-crystalline Si. We show that such devices are realizable by the use of a CMOS-compatible fabrication process and they can operate in high frequency applications.

A unit cell of the studied PC structure is shown in Fig. 1(a). The distance between the centers of the nearest holes and the hole radius are $a=15$ μm and $r=6.4$ μm, respectively, as shown in Fig. 1(a). The thickness of the Si layer is $d=15$ μm. These values have been selected after extensive theoretical optimization to achieve a PC with a large CPBG and practical geometrical features (that can be accurately

a)Electronic mail: adibi@ece.gatech.edu.

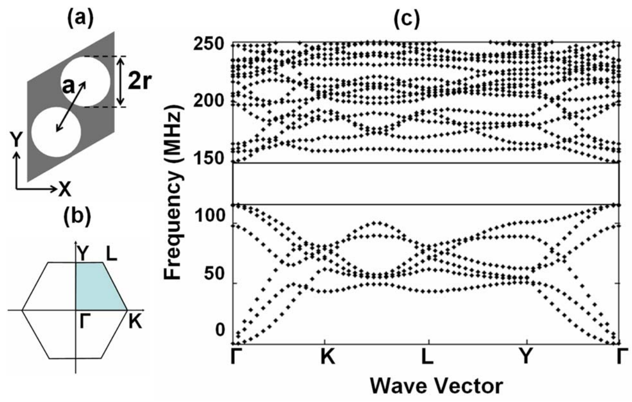

FIG. 1. (Color online) (a) A unit cell and (b) the irreducible part of the Brillouin zone for hexagonal lattice in Si considering both the anisotropy of Si and the symmetry of the lattice. (c) Band structure of the hexagonal PC plate with a (closest lattice spacing)=15 μm, d (the thickness of the plate) =15 μm, and r=6.4 μm calculated with the PWE technique.

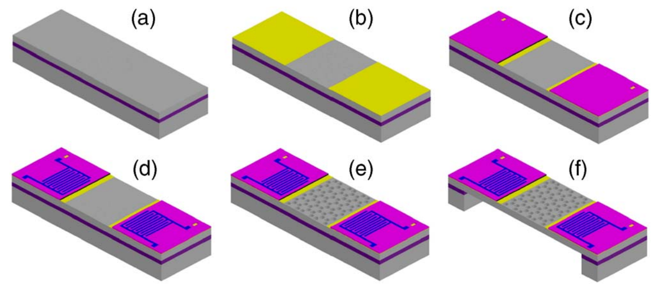

FIG. 2. (Color online) Fabrication steps for Si PC plate structures: (a) the original SOI substrate, (b) lower electrode is deposited and patterned, (c) ZnO layer is sputtered and patterned, (d) top metal electrode is deposited and patterned, (e) PC holes are etched through the device layer, and (f) lower Si substrate and the insulator layers are etched away using plasma etching to form the final structure.

fabricated).[12] The irreducible Brillouin zone of the PC lattice is shown in Fig. 1(b). This zone is chosen considering both anisotropy of the crystalline silicon and the symmetry of the hexagonal lattice. To calculate the PC band structure, we used the plane wave expansion (PWE) technique with 441 plane wave components for each field component and solved the governing wave equation for propagation in all major directions. The finite thickness (i.e., the three dimensional (3D) nature) of the structure was explicitly considered in our full 3D analysis. The details of the simulation have been presented in Ref. 12, and will not be repeated here for brevity. Figure 1(c) shows the band structure of the PC shown in Fig. 1(a). The existence of a CPBG in the frequency range of 117 MHz$<f<$151 MHz is clear from the figure. This corresponds to a gap to midgap frequency ratio of about 25%, which is large enough for all practical applications envisioned for PCs.

To investigate the band gap properties of the Si PC plate, we developed a 14-step fabrication process which includes metal deposition (for electrical transducers to excite the acoustic modes of the structure), zinc oxide (ZnO) sputtering (for adding the piezoelectric effect to the structure for electrically exciting the elastic waves), lithography (for various patterning purposes), and deep plasma etching (for forming the PC holes, and for removal of the substrate and the oxide layer underneath the Si plate). Five masks were used for patterning the PC membrane and also the transducer electrodes that are used for the excitation and detection of the acoustic waves. These fabrication steps are shown in Figs. 2(a)–2(f). The process starts with silicon-on-insulator (SOI) substrate, as shown in Fig. 2(a), with the Si device layer thickness being 15 μm. A thin layer of gold ($\sim$100 nm) is evaporated and patterned on the Si layer (to form the lower electrode of the transducers) in a lift-off process [Fig. 2(b)]. Gold is chosen as it provides an appropriate platform for deposition of a piezoelectric zinc oxide (ZnO) layer. A thin ($\sim$1 μm) layer of piezoelectric ZnO is deposited and patterned using radio frequency (rf) sputtering and wet etching [Fig. 2(c)]. A second layer of metal (i.e., aluminum) is then patterned to form the second set of electrodes for the transducers [Fig. 2(d)]. The fabrication continues by patterning and etching the PC holes through the Si layer using optical lithography followed by deep plasma etching [Fig. 2(e)]. Finally, the lowest substrate, i.e., Si, and the insulator (i.e., the oxide) layers are etched away after backside lithography and etching of the SOI wafer to form the PC membrane and the appropriate transducers on its two sides [Fig. 2(f)]. All the mentioned fabrication steps are performed at low temperatures and can be implemented as post-CMOS processes. Scanning electron microscope images of the top and cross sectional views of a typical device are shown in Figs. 3(a) and 3(b), respectively.

To characterize the band gap properties of the fabricated PCs, we monitored the transmission in the ΓK direction through a structure with at least eight PC periods to allow the band gap to appear as a large dip in the transmission spectrum. We used a network analyzer to excite the structure by applying a high frequency electrical signal between the first and the second layer of metal producing an electric field across the ZnO layer. The ZnO layer was sputtered by setting appropriate parameters to give highly oriented crystalline nanograins to show proper piezoelectric properties for efficient excitation and detection of elastic energy in the structure. To cover the large frequency range of interest (at least from 50 to 250 MHz to assure the appropriate characterization of the CPBG), we designed a large set of electrodes with appropriate geometries. A large number of devices (18) with the same PC structure but with different electrode geometries was fabricated to cover the entire frequency range of interest by different plate modes. For each set of electrodes, we also

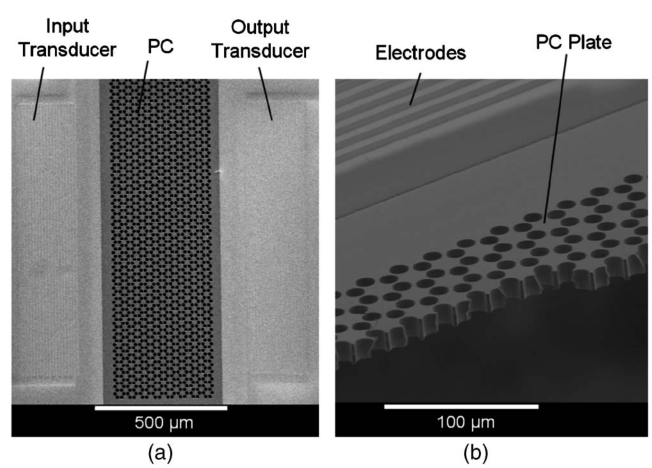

FIG. 3. (a). Top view of one of the fabricated devices with the hexagonal lattice PC structure in the middle and the transducer electrodes on each side and (b) cross sectional view of the same structure.

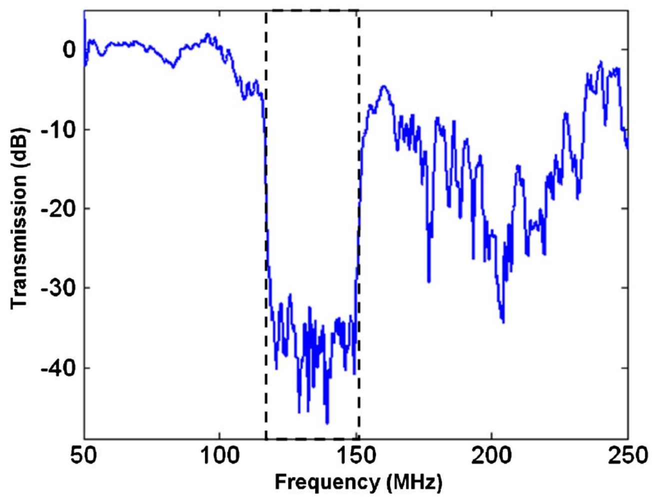

FIG. 4. (Color online) Normalized average transmission through the PC structure shown in Fig. 3 as a function of frequency. The length of the PC structure between the two electrode structures is eight layers [i.e., $12a$, with a defined in Fig. 1(a)]. The geometrical properties of the structure were summarized in the caption of Fig. 1.

fabricated a flat plate (without any holes) with the same total propagation length as the PC structure to form the reference. As a result, the first three plate modes all covering the entire frequency range of interest were excited and their corresponding transmission spectrum through the PC and the flat plate were measured separately. The transmission coefficients through the PC structures were then summed up and divided by the corresponding sum of the coefficients measured through the flat plate structure to get the normalized average transmission coefficient of all the excited modes. The normalized average transmission response is shown in Fig. 4. The wide window of low transmission (with higher than 30 dB reduction in transmission) in the frequency range of 119 MHz $< f <$ 150 MHz (i.e., a 23% band gap to midgap frequency ratio) observed in Fig. 4, corresponds to the CPBG of the structure. This is in excellent agreement with the theoretical predictions shown in Fig. 1(c).

The transmission spectrum measured along the ΓX direction, as presented here (Fig. 4), provides the experimental evidence for the possibility of achieving a large CPBG in PC structure formed by etching air holes in a solid plate. By using crystalline Si as the solid material, we showed that using a CMOS-compatible fabrication process, PCs with large CPBGs can be achieved at high frequencies with appropriate geometries. This is a major advantage of this PC structure in contrast to previously reported results for CPBGs. With the possibility of extending the CPBG to higher frequencies (using smaller feature sizes) and the possibility of integrating these structures with photonic and electronic functionalities using a CMOS-compatible process, we expect PC membranes in Si to open another dimension in design and implementation of acoustic devices for wireless and sensing applications.

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[1]M. M. Sigalas and E. N. Economou, J. Sound Vib. **158**, 377 (1992).
[2]M. S. Kushwaha, P. Halevi, L. Dobrzynski, and B. Djafari-Rouhani, Phys. Rev. Lett. **71**, 2022 (1993).
[3]J. V. Sanchez-Perez, D. Caballero, R. Martinez-Sala, C. Rubio, J. Sanchez-Dehesa, F. Meseguer, J. Llinares, and F. Galvez, Phys. Rev. Lett. **80**, 5325 (1998).
[4]F. R. Montero de Espinoza, E. Jimenez, and M. Torres, Phys. Rev. Lett. **80**, 1208 (1998).
[5]F. Meseguer, M. Holgado, D. Caballero, N. Benaches, J. Sanchez-Dehesa, C. Lopez, and J. Llinares, Phys. Rev. B **59**, 12169 (1999).
[6]X. Zhang, T. Jackson, E. Lafond, P. Deymier, and J. Vasseur, Appl. Phys. Lett. **88**, 041911 (2006).
[7]A. Khelif, B. Aoubiza, S. Mohammadi, A. Adibi, and V. Laude, Phys. Rev. E **74**, 046610 (2006).
[8]B. Bonello, C. Charles, and F. Ganot, Appl. Phys. Lett. **90**, 021909 (2007).
[9]J. O. Vasseur, A. C. Hladky-Hennion, B. Djafari-Rouhani, F. Duval, B. Dubus, Y. Pennec, and P. A. Deymier, J. Appl. Phys. **101**, 114904 (2007).
[10]J. H. Sun and T. T. Wu, Phys. Rev. B **76**, 104304 (2007).
[11]F. L. Hsiao, A. Khelif, H. Moubchir, A. Choujaa, C. C. Chen, and V. Laude, Phys. Rev. E **76**, 056601 (2007).
[12]S. Mohammadi, A. A. Eftekhar, A. Khelif, H. Moubchir, R. Westafer, W. D. Hunt, and A. Adibi, Electron. Lett. **43**, 898 (2007).