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SILICON CARBIDE PHONONIC CRYSTAL CAVITIES FOR MICROMECHANICAL RESONATORS

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ABSTRACT

This paper demonstrates silicon carbide phononic crystal cavities for RF and microwave micromechanical resonators. We demonstrate design, fabrication, and characterization of Silicon Carbide/air phononic crystals used as Bragg acoustic mirrors to confine energy in a lateral SiC cavity. Aluminum nitride transducers drive and sense SiC overtone cavities in the 2-3GHz range with *fxQ* products exceeding 3×10^{13} in air. This approach enables decoupling of the piezoelectric AlN material from the SiC cavity, resulting in high *Q* resonators at microwave frequencies. The SiC cavities are fabricated in a CMOS-compatible process, enabling integration with wirelesss communication systems.

INTRODUCTION

Phononic Crystals (PnC) or acoustic bandgap materials are realized by periodic arrangement of scattering inclusions embedded in a homogenous matrix material with lattice spacing comparable to the acoustic wavelength. Phononic crystals have recently gained much attention due to their ability to precisely control and manipulate propagation of acoustic waves for applications in wireless communication, acoustic imaging, sensing, acoustic isolation, and thermal energy management [1-3]. By strategically placing defects in the phononic crystal through removal or distortion of inclusions, cavities and waveguides have been demonstrated at RF and microwave frequencies [4-9]. Microfabricated high-*Q* phononic crystal cavity resonators provide a lower power small-footprint, CMOS-compatible alternative to Surface Acoustic Wave (SAW), Film Bulk Acoustic Resonator (FBAR), and other discrete components in wireless communication systems.

Polycrystalline cubic silicon carbide (SiC) has gained a lot of attention as a desirable structural material for micromechanical resonators due to its high acoustic velocity and low intrinsic material damping. Silicon carbide, due to its mechanical strength and chemical inertness, is a desirable material for a wide range of applications from high temperature microelectronics to micromechanical oscillators and harsh environment sensors [10-11]. This paper describes the design, optimization, fabrication, and characterization of lateral phononic crystal cavity resonators. The SiC phononic crystal cavities are micromachined using standard CMOS-compatible processes. This device combines the benefit of piezoelectric transduction, while storing the acoustic energy in a low loss material. High reflectivity acoustic mirrors separate the silicon carbide Fabry-Perot cavity from the aluminum nitride (AlN) piezoelectric transducers. This approach enables the decoupling of the piezoelectric material from the ultimate cavity quality factor, which determines the $f.Q$ and $k_t^2.Q$ products which are the figures of merit for oscillator and filter applications. The AlN transducers are integrated with the SiC phononic crystal cavity to drive and sense the 10^{th} and 50^{th} overtones at 2.24 and 2.3GHz respectively. We demonstrate silicon carbide cavities with quality factors exceeding 3,500. These results demonstrate the potential of phononic crystals for realizing micromechanical devices with high quality factors at microwave frequencies.

PHONONIC CRYSTAL CAVITY

Micromechanical resonators with ultrahigh quality factor (*Q*), small form factor, and reduced power consumption are desired for communication and sensing applications. One of the major challenges in integration of microresonators in communication systems is achieving high transduction efficiency and high quality factors in the same device. Electrostatically transduced micromechanical resonators have been demonstrated in the microwave regime with high quality factors making them attractive for on-chip signal processing and timing applications [12]. However, electrostatic resonators suffer from relatively low transduction efficiencies and high motional impedances. Piezoelectric microresonators have been demonstrated with high electromechanical coupling coefficients, making them ideal for on-chip micromechanical filter banks [13]. However, piezoelectric materials at GHz frequencies generally suffer from lower quality factors. The phononic crystal cavity resonator enables the decoupling of the piezoelectric transducers from the resonator quality factor. This approach allows for optimal piezoelectric materials to be used for transduction and low loss materials for the high-*Q* cavity.

Silicon Carbide has the lowest known phonon-phonon damping, which is the dominant loss mechanism at microwave frequencies [14-15]. A schematic of the phononic crystal cavity is shown in Fig.1. This device includes a silicon carbide Fabry-Perot cavity suspended above the substrate with SiC/air phononic crystals as high reflectivity acoustic mirrors on each side of the cavity. As the number of phononic crystal layers is increased, the quality factor of the cavity is also expected to increase [16]. The AlN transducers with interdigitated Al top electrodes are designed to excite the acoustic resonances in the cavity. The pitch of the top electrode determines the frequency of the transducer and the number of fingers determines the insertion loss and bandwidth of the transducers.

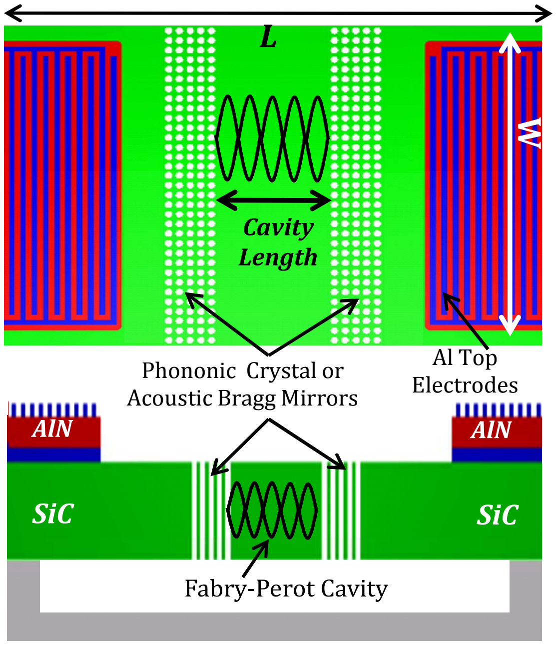

Figure 1: Schematic of an overtone phononic crystal cavity with 5 layer phononic crystals on each side of the cavity. The acoustic mirrors separate the cavity from the AlN piezoelectric transducers.

Phononic Crystal Acoustic Mirrors

Phononic crystals are the acoustic wave equivalent of photonic crystals, where a periodic array of scattering inclusions located in a homogenous material, causes certain frequencies to be completely reflected by the crystal. Phononic crystals also have the unique ability to achieve full control of acoustic waves using only 2D slab structures [17-18]. This is because unlike photonic crystals, vacuum (or air) acts like a perfectly reflecting boundary forcing the mechanical wave to be confined in a 2D plate without leaking in the third dimension. This property of PnC slabs results in lower losses compared to surface acoustic wave phononic structures [19], allowing for large bandgaps in lithographically-defined planar structures.

The physical origins of acoustic bandgaps can be understood using classical wave theory to describe the Bragg and Mie resonance based scattering of acoustic waves propagating within the crystal. Microscale phononic crystals formed by inclusion of low velocity air holes in a high velocity matrix can be realized solely from overlapping Bragg resonant scatterings [3]. A schematic representation of a 2D array of inclusions with acoustic impedance Z_i and acoustic velocity V_i arranged in a square lattice within a matrix with acoustic impedance Z_m, and acoustic velocity V_m is shown in Fig.2:

$$V_{i,m} = \sqrt{E/\rho}$$
$$Z_{i,m} = \rho . V_{i,m} = \sqrt{E\rho}$$

where, E and ρ are the Young's Modulus and mass density of the inclusion or matrix materials. The Bragg directions of acoustic propagation, ΓX and ΓM, are shown in Fig.2. The pitch of inclusions or lattice constant, a, and radius of inclusions, r, define the volume filling fraction of the inclusions in the matrix, r/a. Fig.2 also shows the Bragg resonance condition necessary to open a bandgap utilizing a air/solid phononic crystal:

$$f(Bragg)_{\Gamma X} = \frac{V_{avg}}{2a}$$
$$f(Bragg)_{\Gamma M} = \frac{V_{avg}}{2a\sqrt{2}}$$
$$V_{avg} = \pi\left(\frac{r}{a}\right)^2 V_i + \left(1 - \pi\left(\frac{r}{a}\right)^2\right) V_M$$

where V_{avg} is the approximate average acoustic velocity of the composite structure. Large acoustic impedance mismatch between the matrix and inclusions is necessary for achieving Bragg resonances that overlap to form wide and deep phononic bandgaps. The filling fraction, r/a, must be large enough to restrict transmission through the matrix material around the scattering inclusions. However, if the filling fraction becomes too high, hopping between the scattering inclusions leads to acoustic transmission [3].

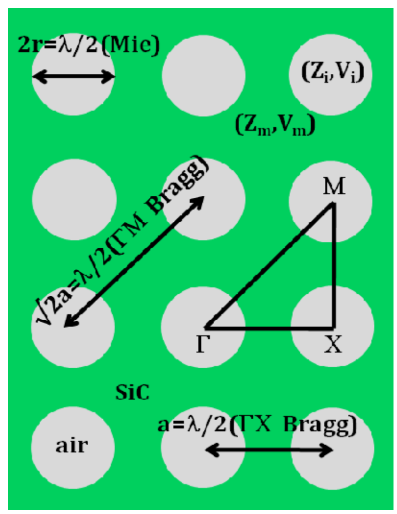

Figure 2:. Schematic of a 2D square lattice phononic crystal showing ΓX and ΓM Bragg directions of acoustic propagation. The radius of inclusions, r, and the lattice constant, a, define the volume filling fraction, r/a.

Opening a phononic bandgap requires proper selection of materials with mass density and modulus that yields the desired mismatch between the acoustic impedance and acoustic velocity of the inclusion and matrix materials. To understand the behavior of the phononic bandgap, Plane Wave Expansion (PWE) [20] simulations were performed for SiC/air phononic crystals with normalized inclusion radii r/a ranging from 0.35 to 0.5 and normalized slab thicknesses t/a from 0.25 to 5. All possible propagating modes of the structure were considered in these simulations including in-plane transverse, out-of-plane transverse, and longitudinal modes. The simulations were run for the Γ-X, X-M and Γ-M directions of the square lattice. A typical dispersion diagram of elastic waves in a cubic SiC/air phononic crystal with a lattice constant of 1.8μm shows complete bandgap about 2.3GHz (Fig. 3).

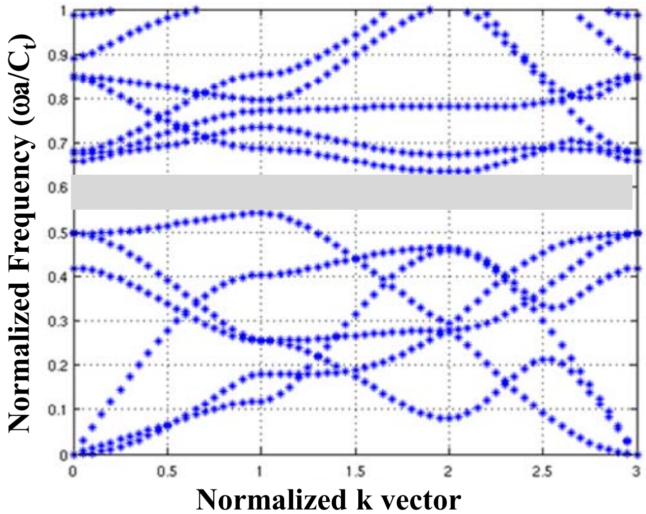

Figure 3: Acoustic band diagram of a 2D simple cubic SiC/air phononic crystal obtained from PWE simulations with r/a=0.45 and t/a=0.5, and lattice constant, a=1.8μm.

Phononic crystals formed by air inclusions in a solid matrix require larger filling fractions to open a complete bandgap [21]. For phononic crystals in the GHz frequency range, the crystal thickness and lattice constant are on the same order of magnitude. As the thickness increases, the bandgap narrows and becomes much less reflective. For a 3GHz SiC/air phononic crystal with a lattice constant of 1.8μm and filling fraction of 0.35, the bandgap width and depth are optimized for thicknesses of 0.75 to 1μm [6]. Figure 3 shows simulated Finite-Difference Time-Domain (FDTD) [22] normalized transmission versus frequency and volume filling fraction, *r/a,* for a 7 period, simple cubic lattice of vacuum inclusions embedded in SiC plate. As the filling fraction is increased, the bandgap increases in width and depth while moving to lower frequencies. Filling fractions of greater than 0.35 result in a high gap-to-midgap ratio of > 25% and a high reflectivity phononic crystal.

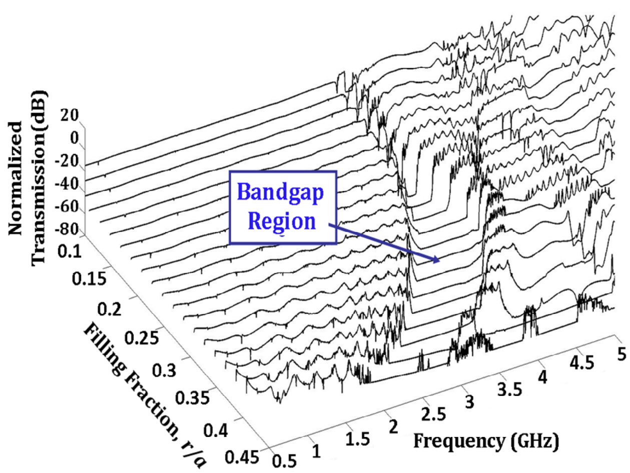

Figure 4: Simulated FDTD normalized transmission vs. frequency for a 7 layer cubic lattice of vacuum inclusions embedded in an infinitely thick SiC plate vs. inclusion filling fraction, r/a. The lattice constant, a, is 1.8μm.

EXPERIMENTAL RESULTS

The silicon carbide phononic crystal cavities were fabricated in a six mask CMOS-compatible surface micromachining process summarized in [6]. This resonator consists of a suspended silicon carbide plate and an aluminum nitride (AlN) transducer with Ti/TiN/Al bottom electrode, and Al top electrode (Fig.1). The highly-textured cubic SiC film is deposited in a low pressure chemical vapor deposition system and optimized to have low stress and low surface roughness for high quality factor. Figure 5(a) shows a scanning electron micrograph (SEM) of a silicon carbide 10^{th} overtone cavity with a length of 19.8μm, corresponding to the 10^{th} overtone. The cavity is separated from the drive and sense aluminum nitride (AlN) transducers by 5 layers of cubic SiC/Air phononic crystal as acoustic mirrors. Figure 5(b) shows a close-up SEM of the phononic crystals with a lattice constant of 1.8μm and a filling fraction of 0.44. The profile of the SiC etch is an important parameter that affects the response of the phononic crystal mirrors. Figure 5(c) shows a close up view of one of the air holes etched in silicon carbide with a nearly vertical sidewall (sidewall angle <5°).

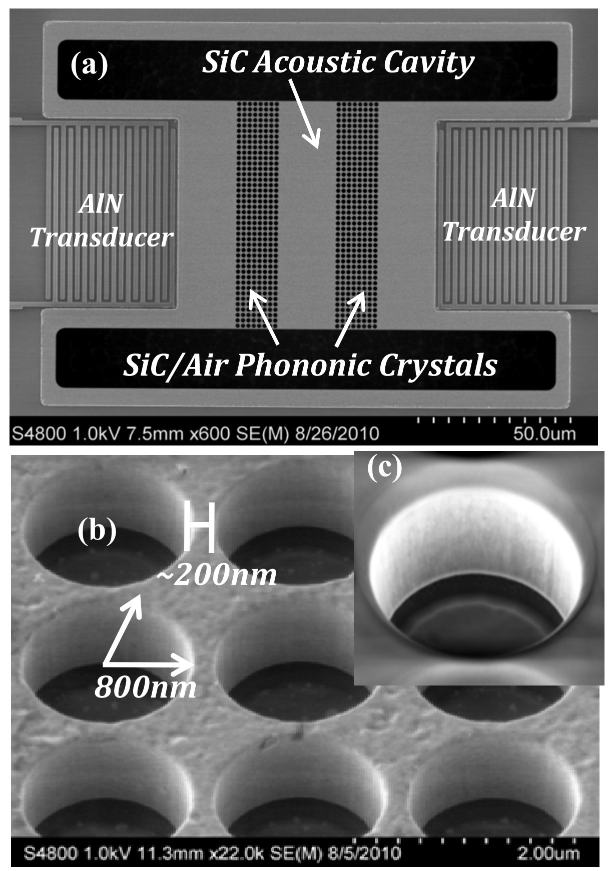

Figure 5: (a) SEM of a fabricated silicon carbide 10^{th} overtone cavity with drive and sense AlN transducers separated from the cavity by 5 layers of phononic crystals on each side (b) close-up SEM of the SiC/air phononic crystal with a pitch of 1.83μm and filling fraction of 0.44 (c) SEM of one of the holes with vertical sides walls.

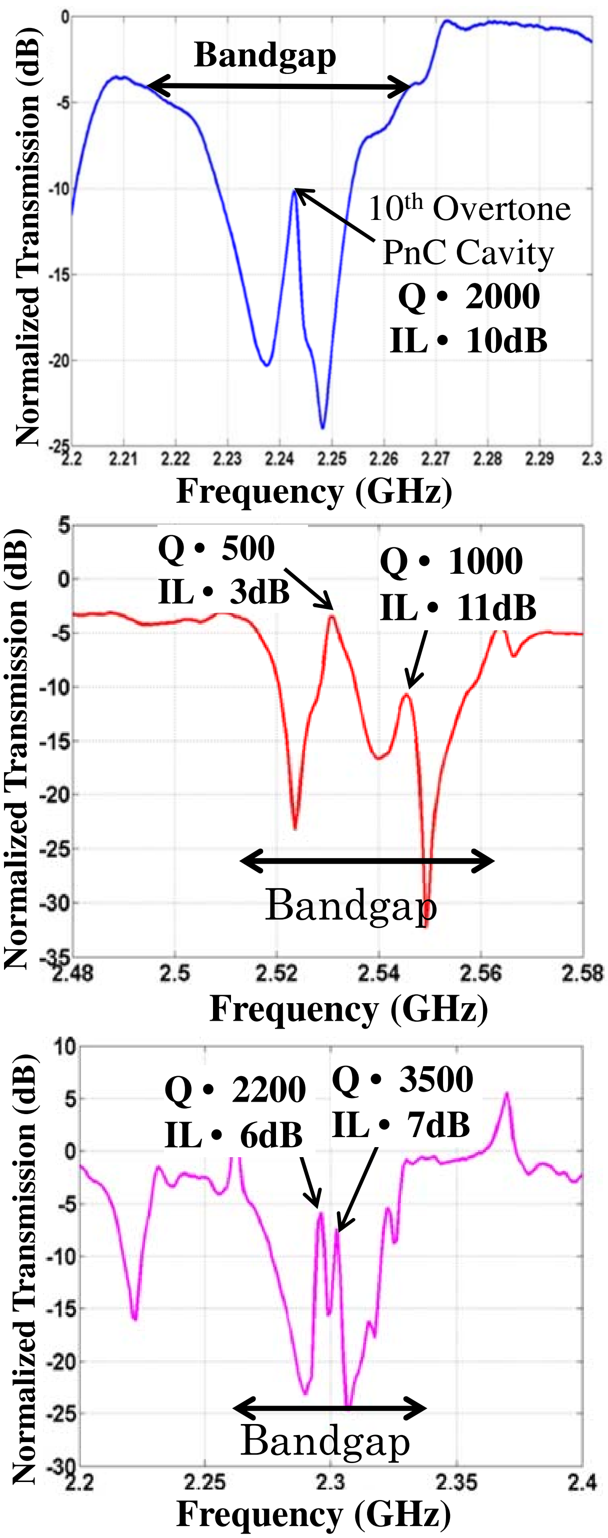

Figure 6: Normalized transmission response of (a) 10th overtone cavity with 5 PnC layers and Q of ~2000 at 2.24GHz (b) 50th overtone cavity with 3 PnC layers and Q's of 500 and 1000 at 2.53 and 2.55GHz respectively (c) 50th overtone cavity with 5 PnC layers and Q's of 2200 and 3500 at 2.295 and 2.305GHz respectively.

The silicon carbide phononic crystal cavity resonators were tested in air on a Cascade probe station using direct two-port transmission measurements. Aluminum nitride piezoelectric transducers were used to excite and detect the overtone acoustic cavities with frequencies ranging from 2 to 3GHz. Figure 6(a) shows the normalized transmission response of a 10^{th} overtone cavity (cavity length=19.8µm) with 5 phononic crystal layers at 2.24GHz with a quality factor of 2000. Figure 6(b) shows the normalized transmission response for a 50^{th} overtone cavity (cavity length=99µm) with 3 phononic crystal layers resulting in two resonant peaks with quality factors of 500 and 1000. As the number of phononic crystal layers is increased to 5 layers, the quality factors are improved to ~2200 and 3500 respectively. The normalized transmission response is calculated by subtracting the matrix transmission response, where no phononic crystal is present, from the transmission response of the phononic crystal cavity. The results in Fig. 6 demonstrate the potential of phononic crystal cavities for high frequency and $f.Q$ product micromechanical resonators. By increasing the number of phononic crystal layers the quality factor of the cavity can be further increased. The design of phononic crystals should be further optimized to maximize coupling to the resonant cavity resulting in lower insertion loss and higher quality factors.

CONCLUSIONS

Micro and nanoscale acoustic bandgap materials have a wide range of applications such as communication, sensing, acoustic imaging and focusing [23-24], and thermoelectric energy harvesting. Phononic crystal Bragg mirrors allow for decoupling of the piezoelectric transducers from the quality factor of the cavity. Silicon carbide/air phononic crystals were designed and simulated in PWE and FDTD to create wide and deep acoustic bandgaps. Quality factors exceeding 3,500 in the frequency range of 2-3GHz have been measured, resulting in high $f.Q$ products at microwave frequencies. These results demonstrate the potential of phononic crystals for realizing high performance micromechanical devices that can be used in acoustic filters and advanced signal processing elements. The use of CMOS compatible processes enables monolithic integration of such resonators with electronic circuits to achieve fully integrated, low power communication systems.

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