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Q-factor enhancement of MEMS Resonators with Ditetragonal Prism shaped Phononic Crystal (DTP-PnC)

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1. Introduction

Controlling and manipulating the propagation of elastic waves through a material has been of great scientific and technological interest for decades [1]. In this regard, study of the ways to be used in trapping elastic waves leaking from the resonating structure of MEMS resonators through the supporting structures has got our attention as the quality factor(Q) could be boosted in doing so. For this cause, taking the property of phononic crystals in providing acoustic bandgaps which can prevent the elastic wave propagation [2][3] of frequencies in the bandgap range as an advantage, designing ultra-wide bandgap PnCs and deploying it in the supporting structures could prevent energy leakage through the supporting structures.

In this study, we propose a novel DTP-PnC structure with ultra-wide bandgap, low filling fraction as well as relatively small in size and deployed array of DTP-PnC in the supporting structure of a MEMS resonator to improve Q-factor and other important parameters like the motional resistance. All FEM simulations in this study are done using COMSOL Multiphysics.

2. Phononic crystal design and simulation

Wave propagation in anisotropic material based 2D PnCs can be analyzed by using the equation of motion of the displacement vector written as [4][5]:

$$\rho(\mathbf{r})\, \partial^2 u_i(\mathbf{r},t) / \partial t^2 = T_{ij,j}(r) \qquad (1)$$

$$T_{ij}(r) = C_{ijkl}(\mathbf{r}) u_{kl}(\mathbf{r},t) \qquad (2)$$

Where T_{ij} is the stress tensor, u_i is the displacement components u_x , u_y or u_z ,r is the position vector (r = x(x, y), z), t is time, ρ is position dependent mass density and C_{ijnm} is elastic stiffness tensor.

Taking material properties and geometric parameters as dominant factors in determining the bandgap of PnCs in to consideration, we have designed a novel PnC structure with dimensions specified in **Fig.1a** by using silicon (single-crystal anisotropic) material. Analysis is done on the square reciprocal lattice as shown in **Fig.1b**.Bloch-Floquent periodic boundary conditions along the repetition direction of the PnC structure is set (**Fig.1a**) such that, violet and green surfaces represents an infinite

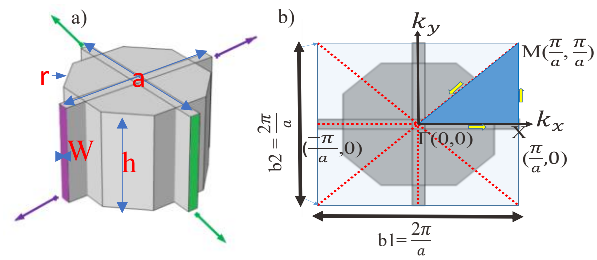

Fig.1 Illustration of a) Floquet boundary conditions applied to a PnC unit cell with diementions a=16μm, r=3μm, h=10 μm and w=3μm, b) Primitive unit cell with its first IBZ

number of repetitions in the x-direction and y-direction respectively. The discrete form of the eigenvalue equations in the unit cell [3] given by Eq. (3) is solved by sweeping wave vectors $\mathbf{k}(k_x,\ k_y)$ along the boundary of first irreducible brillouin zone(IBZ) to get the dispersion relation of the PnC.

$$(K-\omega^2 M)u = 0 \qquad (3)$$

Where K, M, ω and u are the global stiffness matrix, global mass matrix, angular frequency, and vector of nodal displacements respectively.

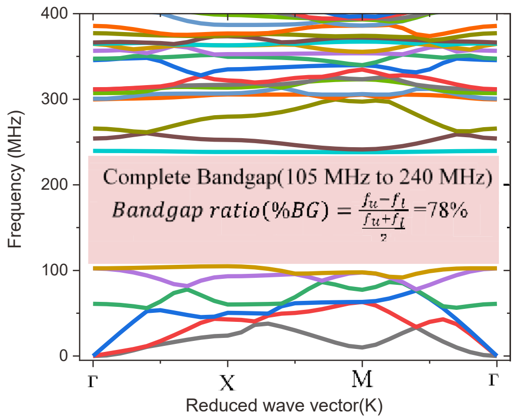

Fig.2 FEM simulated Band structure of DTP-PnC

3. Transmission Characteristics of the PnC

Transmission characteristics of the PnC is simulated and compared with that of a silicon bar used as a transmission medium by using the setup given **Fig.3 a** and **b**.Transmission spectrum S_{21}(dB) is given by [6]:

$$T = S_{21}(dB) = 10\log_{10}\left(\frac{P_0}{P_i}\right) \qquad (4)$$

Where P_0 is output power and P_i is input power. **Fig.3c** reveals inhibition of elastic wave propagation

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when the frequency is in the bandgap range of the DTP-PnC.

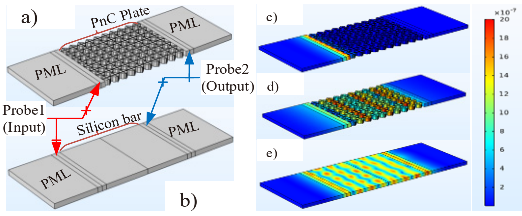


Fig.3 Transmission model with a) DTP-PnC, b)silicon bar;c)transmission map of DTP-PnC for frequencies in the range of the bandgap, d) transmission map of DTP-PnC for frequencies out of the range of the bandgap, and e) Transmission map of silicon bar as a transmission medium respectively.

4. Resonator design and analysis

The resonant frequency of the resonator is given by [5][6]:

$$f_r = \frac{n}{2W_r}\sqrt{\frac{E}{\rho}} = \frac{1}{2W_p}\sqrt{\frac{E}{\rho}} \quad \ldots\ldots (5)$$

Where W_r is width of resonant body, W_p is the Pitch width, n is harmonic mode of vibration

W_p=25µm ;$Duty\ factor, \frac{W_{IDT\ metal}}{W_p} = 0.88$

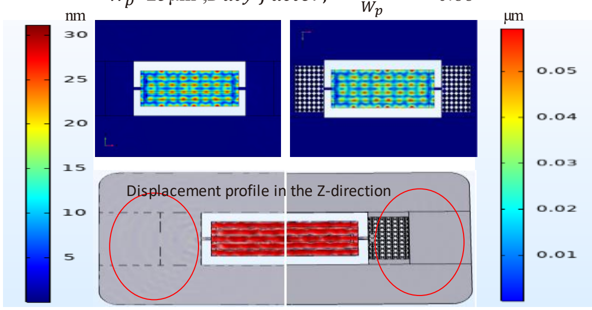


Fig.4 Vibration mode shape of 5th order MEMS resonator at the resonance frequency (f_r) without PnC(left) and with PnC (right).The displacement profile in the Z-direction shows the effect of DTP-PnC in reflecting the elastic waves as it could be noticed from the space marked by red circles.

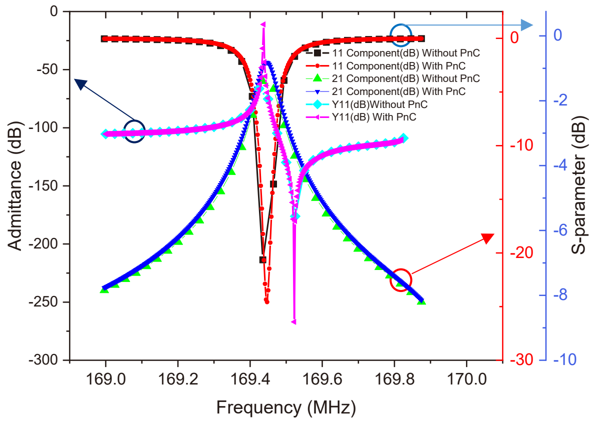
frequency, E is the Young's modulus and ρ is the density of substrate material used(silicon).The resonant body comprises of 0.5µm thick AlN sandwiched by 1µm thick Al interdigitated (IDT) electrodes and the bottom substrate of 10µm thick silicon(Si).

The electromechanical coupling coefficient and Figure of Merit are calculated from the FEM simulation results using the following equations. [5][6]:

$$K_{eff}^{\ 2} = \frac{\pi^2}{8}\left(\frac{f_p^{\ 2} - f_s^{\ 2}}{f_p^{\ 2}}\right) \ldots(6);\quad FoM = K_{eff}^{\ 2} * Q_u \ ..(7)$$

5. Results and discussion

Fig.5 Illustrates the values obtained from the FEM simulation of the 5th order MEMS resonator with and without DTP-PnC. Compared to the conventional resonator, the results obtained from the resonator with PnC revealed capacity of the DTP-PnC in reflecting acoustic energy as a result of which quality factor (Q) and other performance parameters of the resonator significantly improved.



Without PnC	With PnC
f_r =169.45MHz; R_m= 357Ω	f_r= 169.44MHz;R_m= 53Ω
$K_{eff}^{\ 2}$ = 0.14%; IL = 1.5dB	$K_{eff}^{\ 2}$= 0.12%; IL= 0.67dB
Q_{anch} = 85,076	Q_{anch}= 3,219,706
Q_l= 2,258; Q_u= 14,23	Q_l= 3,227; Q_u= 43,469
FoM =1993	FoM = 5216

Fig.5 Admittance ($Y_{11}dB$) and S-parameter (dB) FEM simulated results of the MEMS resonator with and without PnCs in the anchoring boundaries.

6. Conclusion

This paper demonstrated a novel ultra-wide acoustic bandgap PnC with a BG% of 78% having very high elastic wave isolation capability. With its application in the supporting structures of a MEMS resonator, the results reveal that the DTP-PnC can effectively increase the Q_U by about 3 folds from 14,237 to 43,469. In line with this, R_m reduces from 357 Ω to 53 Ω.

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