Framing holes phononic crystal structure for Q-factor enhancement of thin-film-piezoelectric-on-silicon MEMS resonator

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This paper presents an approach to reduce anchor loss in high frequency micro-electromechanical system (MEMS) resonator by using phononic crystal. The novel designed phononic crystal with supporting tethers is to see the formation of very wide and complete band gaps in desired frequency range from 65-252MHz and 305-388MHz, and improvement of quality factor from 13671 (without framing holes stub) to 51281 (with framing holes stub) by introducing a small putlog holes with unique frame stub with tethers width T_W =8 μm, and length T_L =0.5λ. We show that size of stub and holes can help to improve the formation of wide band-gaps, and Quality factor. This proposed PnC MEMS resonator can effectively decrease the anchor loss. The aim of this paper is to present a novel framing holes Phononic crystal configuration for applications in silicon-based MEMS resonators.

1. Introduction

Because of merits of less power consumption, easy fabrications and the better performance with high accuracy Phononic crystals MEMS resonator has become hot topic in the family of flexible electronics. The principle of phononic crystals MEMS devices is based on the energy conversion between the mechanical and electrical domains. The concept of phononic crystal followed by a few years the analogous concept of photonic crystals for the propagation of electromagnetic waves. Phononic crystals (PnCs)(i.e an artificial material composed by a periodic repetition of incorporation in a matrix and designed for acoustic or elastic wave propagation) have paid attention by researchers over the past few years [1-3]. Phononic crystals (PnCs) have a lot of applications in the field of electronics and technologies. The field of phononics is progressing very quickly. Nowadays there are many advances in the field of phononic crystals. The PnCs have significance role in the advancement of micro/nano fields. Scientist and engineers are paying deep attention in Phononic crystals (PnCs) MEMS resonator [4,5].

There are many MEMS component which are used in electronic application systems, Telematics, Medical Electronics, etc. But MEMS resonator play an important role in such kind of application systems and improve the performance of devices by quality factor. The researcher applied different ways to approach high quality Q such as to optimization of acoustic wave displacement, and reduction of anchor loss, etc. [6-8]. The PnCs can operate as coupling elements between resonators [9]. PnCs can prohibit the propagation of acoustic (elastic waves) inside their structures through existence of band gaps. Band gap is a frequency range in which there are no resonant guided modes or wave propagation within the structure. Supporting tether configurations to MEMS Resonators can also improve the quality factor [10]. The structures of tether improve the quality factor of MEMS resonators, and PnCs also support elimination of anchor loss in the resonators. PnC can give complete band gap where the propagation is stopped by generating the mechanical wave inside the phononic crystal. So the performance of MEMS resonator depends upon band gaps and quality factor. When the band gap is wider and quality factor is higher, the performance of resonator will be better.

In this paper we proposed phononic crystal holes MEMS resonator which is precisely designed to reduce anchor loss. This proposed PnC structure gives very wide and complete band gaps with good quality factor. In this study we have obtained the quality factor harmonic response of MEMS resonators without supporting PnC tether is 13671, and with supporting PnC tether is 51281 which shows its improvement and further can be improved. Our study about the quality factor and band gap are analysis in COMSOL Multiphysics. This work show that, tether width and tether length, PnC holes, and particularly the size of inner framing stub can play an important role in the formation of bandgap and variation of quality factor.

From Table 1 we see that the tether length 0.5λ with width 4μm gives the quality factor of 41061. When the

tether width increases to 6µm the quality reduces, and then quality increased when tether width and length tuned to be 8µm and 0.5λ respectively. This is because the quality factor must be consistent with the tether width and length, and this parametric tuned combination suppress the acoustic leakage loss. In this way the displacement is suppressed and energy loss is reduced in this tether combination.

Table 1. Simulation parameters of tethers.

Tether Width(TW) (µm)	Tether Length(TL) (µm)	Quality (Q)
4	0.25λ	29320
	0.5λ	41061
	0.75λ	41057
	λ	41064
6	0.25λ	3087
	0.5λ	29730
	0.75λ	41604
	λ	9459
8	0.25λ	20532
	0.5λ	51281
	0.75λ	18639
	λ	41003

2. Device analyzed

Silicon material commonly used in electronics, photonics, MEMS. For MEMS resonator field, silicon is used to fabricate silicon-on-insulator (SOI) MEMS resonators, thin-film piezoelectric-on-silicon MEMS resonators and PnC-based MEMS resonators [11-15]. PnC MEMS resonator play a key role an important role in the improvement of resonant frequency stability, quality factor of MEMS devices. PnCs also support the elimination of anchor loss in the resonators, because phononic system exhibit band gap phenomenon [16] In fact the propagation of elastic/acoustic waves can be controlled by the phononic crystals through bandgaps. We are familiar that band-gap can be formed by the tethers-based strip structure [17]. The phononic crystal strip with supporting tethers is designed to see the formation of band gap by introducing square holes, and improvement of quality factor and harmonic response. We show that holes can help to reduce the static mass of PnC strip tether without affecting on band gaps. Our proposed PnC holes tether resonator model illustrated in Fig.1 having length, width, and thickness of silicon (single-crystal, anisotropic) substrate is 60, 20, and 10µm respectively. The thickness of piezoelectric (Aluminum Nitride) is 0.5µm, and electrodes' thickness is about 1µm.
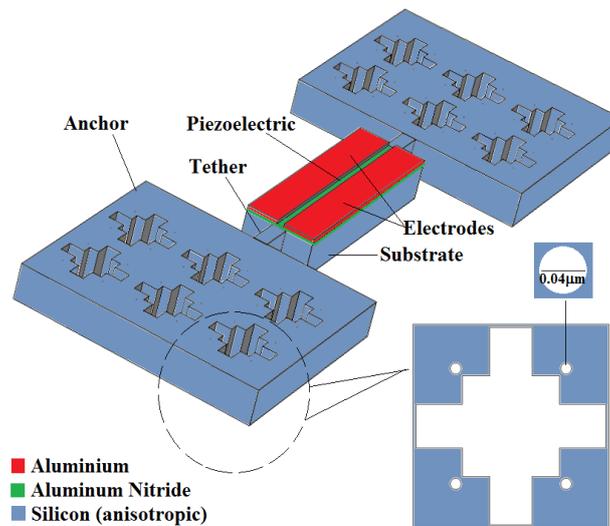

Fig. 1. Schematic of PnC MEMS Resonator (color online)

We have obtained Q factor for different configurations. From Tab.1 we see that the high quality obtained when tether width, and tether length is taken as 8µm and 0.5λ respectively.

We have found out the eigen mode shape phononic crystal resonator from the frequencies 203.64MHz to 210.54MHz. The eigen mode shape of phononic crystal resonator with eigen frequency 205.39 MHz is illustrated in Fig. 2.
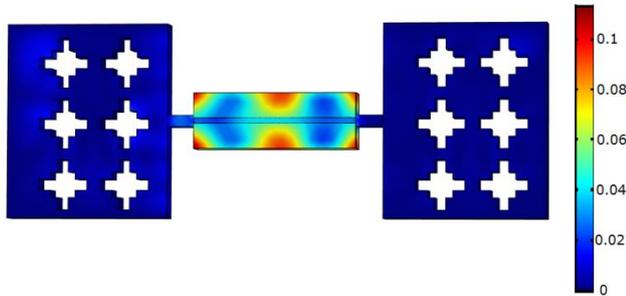

Fig. 2. PnC MEMS Resonator with Eigen mode shape (color online)

3. Bandgap and anchor loss

The unit cell is the basic block to produce the periodicity of structure. In this work the phononic crystal holes are introduced with the array of six unit cell on each side as shown in Fig. 2. The geometrical dimension of single unit cell is18.6μm×18.6μm with a pattern of small hole of diameter 0.04μm and stub (two rectangular shapes 18μm×4μm, and square shape is 9.2μm×9.2μm) as shown in Fig.3. This Phononic crystal structure is clamped to the body of resonator and design to investigate the band gap variations and quality factor. In Fig.3 the dispersion curves are investigated through FE method (FE simulation on one unit cell to obtained eigen frequency in Phononic crystal). In Fig.3 we investigate the formation of complete band gap map. The significant band gaps appear in the desired resonance frequency range from 65 to 252MHz, and 305 to 383MHz. It is worth mention that the band gap can be found and optimized by the putlog holes dimension. Larger the framing stub, and thinner the hole, wider the band gap and higher the quality factor.

The resonance frequency can be generalized by the following relation [18,19]

$$f = \left(\frac{1}{\lambda}\right)\sqrt{(E_{eff}/\rho_{eff})}$$

where $\lambda=2W$, ρ_{ff}, and E_{ff} are longitudinal wavelength (width of resonator mode), effective density of material, and Young's Modulus respectively.

And the quality Q of resonator is expressed as

$$Q = 2\pi \times (E_s)/(E_l)$$

where E_s is the energy stored in resonator, and E_l is the energy loss (the dissipation of energy in each cycle of vibration)

So the design of this phononic crystal dissipate less energy, gives higher Q, and wide band gap is obtained.
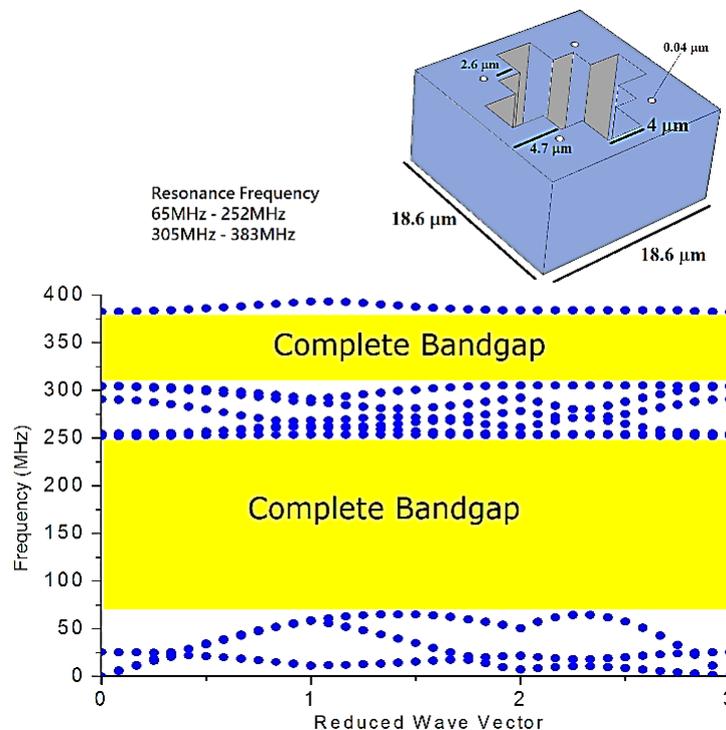

Fig. 3. Band structure with dispersion curves in PnC with inner stub length 18μm and hole size 0.04μm (color online)

In Fig. 4 we investigate that when the length of inner rectangular stub reduce to 16μm×4μm, and size of hole increase to 0.16μm the band gap becomes narrow in the desired frequency range 122 to 251MHz.

In Figs. 3 and 4, we investigate that the size of frame and holes can affect the band gap. In these two Figs. the dotted lines indicates the dispersion curves of elastic waves, and yellow area represent complete band gap.
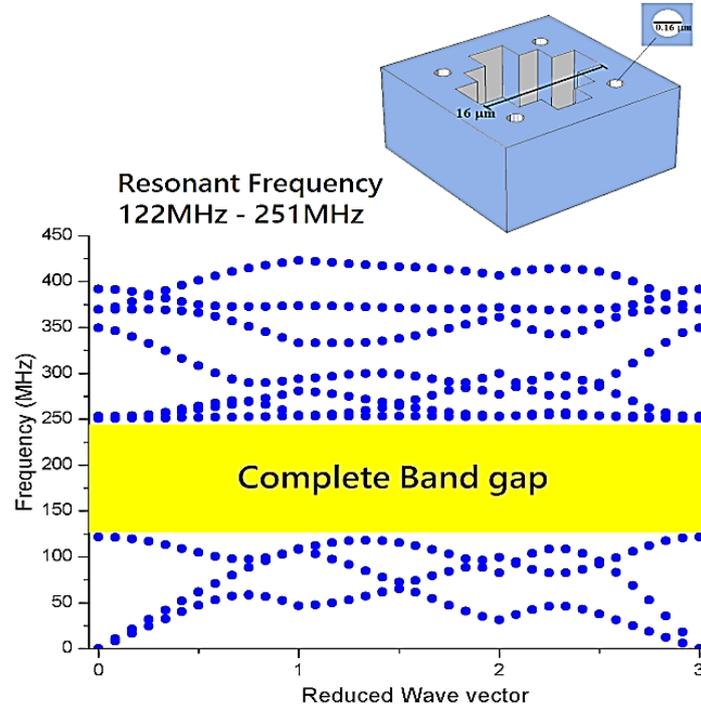

Fig. 4. Band structure with dispersion curves in PnC with inner rectangular stub length 16μm and hole size 0.16μm (color online)
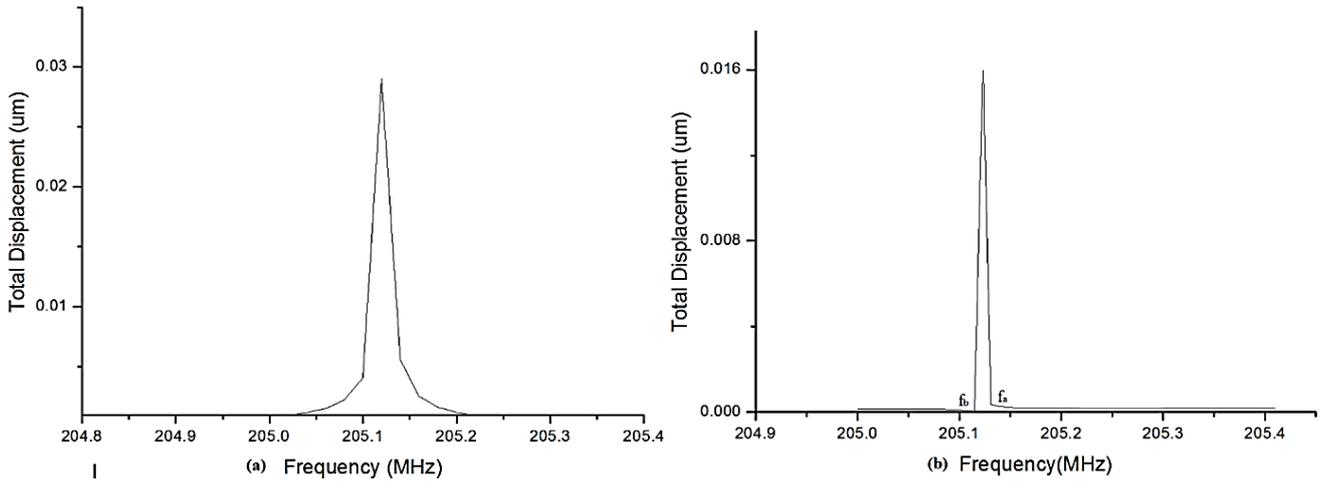

Fig. 5. Harmonic response: (a) MEMS resonators without supporting PnC tethers (b) MEMS resonators with supporting framing holes PnC tethers

Fig. 5 represents the harmonic response of resonator without supporting tether, and with supporting framing hole PnC tether. These curves represent their frequencies. The resonant frequency is represent by the peak of curve. The sharpness of the peak implies the resonator performance. The frequency of the designed resonator is well controlled and the resonator dissipate negligible amount of energy. The well controlled frequency means the clean frequency which helps to reduce the ripples. The sharpness of curve means the frequency difference between two side edges of the curve $\Delta f = f_a - f_b$ is small. Smaller the Δf higher the quality. Fig.5 (b) shows that the quality factor Q of MEMS resonator with supporting framing holes PnC tether is better than the MEMS resonator without supporting framing holes PnC tether.

4. Conclusion

In this work we have design a high frequency Micro-electromechanical (MEMS) resonator by using novel designed phononic crystal to reduce anchor loss. Very wide and complete band gaps from 65 to 252MHz, and 305 to 383MHz is obtained and the quality factor improved to 51281 by introducing framing stub and small holes in unit cell with tethers width TW =8m, and length TL =0.5λ. We also conclude that the wider band gap can be found by the adjusting framing stub and putlog holes dimension. Larger the frame and smaller the hole, wider the band gap. We show that the variation in quality factor depends upon the size of tether width and length. This proposed framing holes Phononic crystal design to improve quality of high frequency micro-electromechanical resonator, and can effectively decrease the anchor loss.

Acknowledgements

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