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Published in:
Procedia Engineering

Published: 01/09/2015

Document Version:
Final Published version, also known as Publisher’s PDF, Publisher’s Final version or Version of Record

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Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1016/j.proeng.2015.08.689

Publication details:
Zhu, H., & Lee, J. E-Y. (2015). Design of phononic crystal tethers for frequency-selective quality factor enhancement in AlN piezoelectric-on-silicon resonators. In Procedia Engineering (Vol. 120, pp. 516-519). ELSEVIER. https://doi.org/10.1016/j.proeng.2015.08.689

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EUROSENSORS 2015

Design of phononic crystal tethers for frequency-selective quality factor enhancement in AlN piezoelectric-on-silicon resonators

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Abstract

In this work, we experimentally demonstrate frequency-selective improvement of unloaded quality factor ($Q_u$) using one-dimensional (1D) phononic crystal (PnC) ring tethers in Aluminium Nitride (AlN) thin-film piezoelectric-on-silicon (TPoS) micromechanical resonators. We show that the 1D-PnC tethers help boost $Q_u$ by 3 times specifically at the desired resonant modes that lie in the PnC stopband but not for resonant modes lying outside the PnC stopband. These results show that the 1D-PnCs serve as frequency-selective acoustic reflectors.

Keywords: Micro-electro-mechanical Systems (MEMS); Resonator; Quality factor; Anchor loss; Phononic crystal.

1. Introduction

Recently, thin-film piezoelectric-on-silicon (TPoS) micromechanical resonators (also commonly referred to MEMS resonators) [1] have become a promising alternative to quartz resonators for timing and frequency control applications. By exciting different vibration modes in a TPoS MEMS resonator, a single-resonator dual-frequency oscillator was debuted in IEDM 2007 [2]. Anchor loss is known to be one of the major loss mechanisms in TPoS resonators, which limits their $Q$ and hence phase noise performance in oscillator applications. Acoustic bandgap (ABG) PnCs have been shown to be useful for suppressing anchor loss and thus boosting $Q$ in various piezoelectric MEMS resonators including TPoS [3], AlN [4] and GaN [5]. In this paper, we present the latest results which show

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that the PnC is almost “transparent” (ineffective) to modes outside the ABG, which could be useful for controlling different modes independently for single-device multi-frequency oscillators.

2. Device design and fabrication

The TPoS resonators in this study are designed to resonate in the width-extensional (WE) modes to leverage high $Q$ and good electromechanical coupling using c-axis oriented AlN thin-film. The resonator body is aligned with the $<110>$ crystal orientation of the single-crystal silicon device layer for higher phase velocity ($v_p$). The resonant frequency ($f_0$) of the WE mode can be roughly estimated by $f_0 = v_p/\lambda$, where $\lambda$ is the acoustic wavelength and $v_p$ indicates the phase velocity of the in-plane longitudinal wave along the $<110>$ direction in this case. The devices have the same length (300$\mu$m) but differ in their widths (90$\mu$m and 150$\mu$m). By patterning the top electrodes for optimal electromechanical coupling, the 90$\mu$m and 150$\mu$m wide devices are intended to operate at the 3$^{rd}$ and 5$^{th}$ order WE modes respectively. As the desired $\lambda$ are kept the same (60$\mu$m), both the 3$^{rd}$ and 5$^{th}$-order WE modes have a similar resonant frequency ($f_0 \approx 142$MHz). It is noted that the 90$\mu$m and 150$\mu$m width devices have different resonant frequencies (at 47.5MHz and 28.4MHz, respectively) for their fundamental WE mode, in which case the width of resonator body equals $\lambda/2$. The finite-element (FE) simulated 3$^{rd}$ order and fundamental mode shapes and corresponding resonant frequencies for the 90$\mu$m TPoS resonator are illustrated in Fig.1a and 1b, respectively.

It is known that TPoS resonators are subject to various loss mechanisms, including anchor loss ($Q_{anc}$), interface loss ($Q_{inter}$), Akhiezer loss ($Q_{AKE}$), thermoelastic damping ($Q_{TED}$), viscous damping in air ($Q_{air}$), and other losses ($Q_{other}$). The measured $Q$ ($Q_{meas}$) is a summation of all these effects, as expressed below:

$$\frac{1}{Q_{tot}} = \frac{1}{Q_{anc}} + \frac{1}{Q_{inter}} + \frac{1}{Q_{AKE}} + \frac{1}{Q_{TED}} + \frac{1}{Q_{air}} + \frac{1}{Q_{other}}$$ (1)

Fig. 1. FE-simulated mode shape (only 1 side of resonator shown) and $Q_{meas}$ of the desired 3$^{rd}$-order mode (a) and fundamental mode (b) in the same TPoS resonator supported through 4-cell PnC tethers. (c) Simulated band structure of the 1D PnC tether and the unit cell used in the PnC structure.
To achieve a higher $Q_{\mathrm{res}}$ we adopted 1D-PnC structures in the tether design to reduce anchor loss thus enhancing $Q_{\mathrm{anc}}$. Our 1D-PnC tethers were designed to form an ABG around 150MHz. The simulated ABG structure using FE analysis by applying Floquet periodicity on the unit cell is shown in Fig. 1c. The FE simulation indicates that the 1D-PnC strip creates two complete ABGs (red shaded bars) below 200MHz: first in the span of 73–80MHz, then in the range of 135–148MHz. It is noted that the resonant frequencies of the intended higher-order modes lie in the second ABG. Hence when the PnC strip is used as tethers, outgoing acoustic wave from the resonator will be blocked from leaking to the substrate thus reducing anchor loss. Meanwhile, the resonant frequencies of the fundamental mode lie outside the ABG and no significant improvement on $Q$ is expected. In principle, increasing the number of PnC unit cells in the tether should increase $Q_{\mathrm{anc}}$, while having no effect for the fundamental modes.

The fabrication process used for these devices has been previously described in [6]. Fig. 2 shows the fabricated devices with conventional beam tethers (referred to as “plain”) and PnC tethers. For a fair comparison, the beam tether width (10µm) is kept the same as the width of the PnC tethers’ connecting part (noted as $w$ in Fig. 1c). The transverse view schematic of a device with PnC tethers illustrates that an insulating oxide layer is sandwiched between the silicon device layer and top metal layer at the tethers in place of AlN, which is previously used in other designs [1, 2, 3]. It is intended to avoid unwanted piezoelectric actuation at the tethers and may help to further improve the performance of PnC tethers for anchor loss reduction.

3. Device characterization and experimental results

Since air damping is not critical for these laterally vibrating TPoS resonators [6], all devices were electrically characterized in air using a two-port characterization setup with GSG probes and a vector network analyzer after a SOLT (short, open, load and through) calibration using a standard calibration substrate (CS-5). Typical measured electrical transmissions of the resonators are shown in Fig. 3a and 3b.

The PnC-tethered devices consistently show improved performance over devices without PnCs (referred to as plain) at the desired higher-order modes which lie in the ABG. As illustrated in Fig. 3a, the 3rd order mode resonator with 4-cell-PnC tethers show a nearly 3-fold increase of $Q_u$. In contrast, the PnCs make no notable difference to $Q_u$ or $R_m$ at the fundamental mode. This observation is consistent with FE simulations, as discussed in Section 2. Fig. 3c and 3d collate $Q_u$ and $R_m$ obtained from a number of devices with tethers comprising different numbers of PnC unit cells. Specifically, at the desired 3rd order mode, the PnCs provide improvements in $Q_u$ and reductions in $R_m$ when more than one PnC cell is used. Adding more unit cells does not appear to improve $Q_u$ beyond $\sim$7000. This upper bound on the achievable $Q_u$ by reducing anchor loss suggests other dissipation mechanisms (e.g. interface loss) are at work in limiting $Q$ below the respective theoretical material limits.

![Fig. 2. Scanning electron micrographs (SEMs) of the fabricated 3rd-order TPoS resonators (a) with beam tether and (b) 2-Cell or (c) 4-Cell PnC tethers; (d) 5th-order TPoS resonator with 3-Cell PnC tethers; (e) transverse view schematic taken along the red dashed line in (b).](image-url)
4. Conclusion

We have designed, fabricated and characterized the TPoS resonators with 1D-PnC tethers to enhance $Q$ at the desired frequency band of higher-order WE modes. Our results show that $Q$ of the fundamental WE mode modes outside ABG are almost unaffected by the PnC structures. These measurement results agree with the FE simulations and indicate that the effect of PnC tethers on anchor loss is frequency band specific.

Acknowledgements

This work was supported by a grant from the Research Grants Council of Hong Kong (under project number CityU 116113).

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