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Published in:
Procedia Engineering

Published: 01/09/2015

Published version (DOI):
10.1016/j.proeng.2015.08.554

Publication details:
Tu, C., & Lee, J. E. -Y. (2015). Low temperature quality factor scaling of laterally-vibrating AlN piezoelectric-on-silicon resonators. In *Procedia Engineering* (Vol. 120, pp. 7-10). ELSEVIER. https://doi.org/10.1016/j.proeng.2015.08.554

Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 120 (2015) 7 – 10
Procedia Engineering
www.elsevier.com/locate/procedia

EUROSENSORS 2015

Low Temperature Quality Factor Scaling of Laterally-vibrating AlN Piezoelectric-on-silicon Resonators

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Abstract

We present empirical results showing that the quality factors (Q) of 48MHz Aluminium Nitride (AlN) thin-film piezoelectric-on-silicon (TPoS) resonators double as a result of cryogenic cooling them from room temperature to 78K. The increase in Q_u leads to a corresponding 5dB reduction in insertion loss (IL) and a motional resistance as low as 154Ω. This temperature scaling effect on Q is however absent at shorter acoustic wavelengths (λ) for the same resonators vibrating at higher order modes (143MHz). This absence was also found to be the case for other resonators with interdigitated electrode layouts to transduce 3rd and 5th order vibration modes of similar λ (107MHz). These results suggest that reducing the ratio of λ to the resonator thickness (h) strongly determines the dominance of anchor losses that do not scale with temperature.

Peer-review under responsibility of the organizing committee of EUROSENSORS 2015

Keywords: Piezoelectric-on-silicon resonators; cryogenic cooling; anchor loss.

1. Introduction

TPoS micromechanical resonators have become highly attractive for high-frequency oscillators, radio frequency (RF) filters and low power sensors owing to their excellent electromechanical coupling, high power handling, and compatibility with CMOS fabrication [1-3]. High Q is desirable for all these applications, which helps suppress the close-to-carrier phase noise in oscillators, reduce the insertion loss (IL) in filters and improve resolution in resonant sensors. However, the reported values of Q for TPoS resonators are usually much smaller than those achievable in

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Peer-review under responsibility of the organizing committee of EUROSENSORS 2015
doi:10.1016/j.proeng.2015.08.554

silicon capacitive resonators at the same frequency range. To improve Q, better understanding of the main sources of damping in TPoS resonators is needed. The Q of piezoelectric MEMS resonators is widely seen to be limited by anchor loss and electrode-related loss [4]. These two damping mechanisms are typically present together and are difficult to isolate for fundamental studies apart from specially fabricating capacitive-piezo resonators [5]. Recently, it has been suggested that electrode-related dissipation is temperature dependent in the case of 1GHz piezoelectric AlN-only resonators [6]. In contrast, anchor loss does not scale with temperature because it is determined by the physical dimensions of device and the wavelength of the mechanical vibration mode which are temperature-independent. Thus, the Q of TPoS resonators operating in vacuum can be expressed as:

$$\frac{1}{Q(T)} = \frac{1}{Q_{anchor}} + \frac{1}{Q_{electrode}(T)} \tag{1}$$

where T is temperature, Q_{anchor} and $Q_{electrode}$ represent anchor loss and electrode-related loss respectively. In this work, we show that Qs of 48MHz TPoS resonators doubles when cryogenically cooled from room temperature to 78K. By cryogenically cooling other contour mode resonators with reduced λ, we also show that the effect of cryogenic cooling on Q strongly depends on λ/h, which suggests that the underlying damping mechanisms differ depending on the ratio of λ/h.

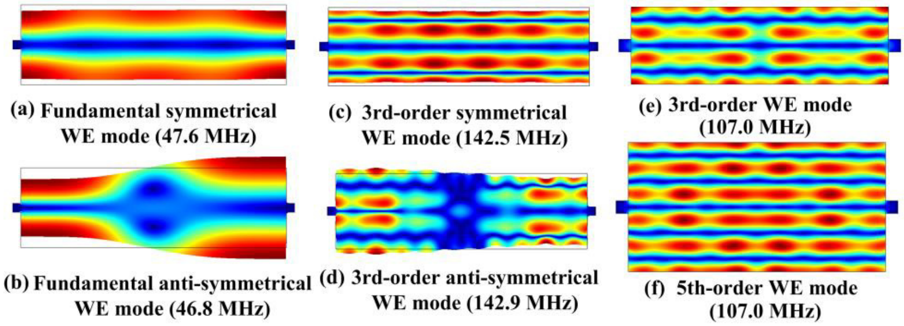

Fig. 1. FE simulations of different vibration modes and resonator designs under test in this work.

2. Design and Simulation

Six variations of width-extensional (WE)-mode resonators were considered in this work. This includes the symmetrical and anti-symmetrical fundamental WE-modes (λ=180µm), which are depicted in Fig 1(a) and 1(b). Fig 1(c) and 1(d) show the same pair of vibration modes but in the 3rd order overtone (λ=60µm). The resonator is a 300µm×90µm rectangular plate with a matching patch electrode layout shown in Fig 2 (a). Fig 1(e) and 1(f) show the 3rd and 5th order vibration modes. These two resonators have the same lengths (400µm) and associated λ (80µm) and use interdigitated electrodes as shown in Fig 2(b) and (c). All the devices were electrically characterized in mTorr vacuum using a network analyzer after performing short-open-through (SOT) calibration. The two-port electrical characterization setup applied to all the devices is illustrated in Fig. 2 (d). Their measured resonant frequencies match the finite element (FE) simulations to within 4%. Each design was measured across two die samples to verify the repeatability of results.

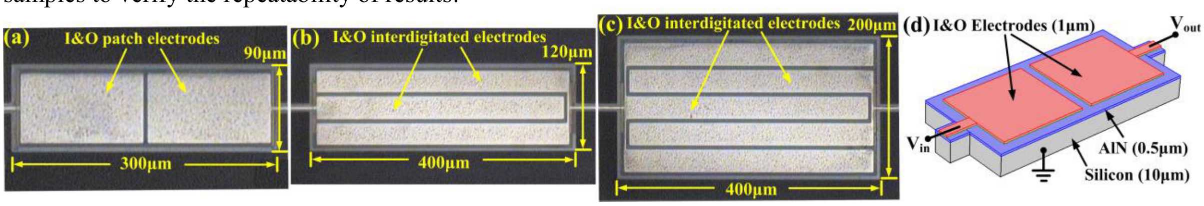

Fig. 2. Optical micrograph of (a) resonator operating in fundamental WE mode; (b) resonator operating in 3rd order vibration mode; (c) resonator operating in 5th order vibration mode; (d) two-port electrical characterization setup applied to all devices.

3. Measurement and Discussion

Fig 3 shows the electrical transmission magnitudes for the symmetrical and anti-symmetrical fundamental WE-mode of one device measured at 3 temperatures when cooled from room temperature to 78K. For brevity, we only present the unloaded quality factors in this paper (Q_u). We see that in cooling the resonator to 78K, Q_u doubles in the case of either modes each and IL reduces by 4dB and 5dB, resulting in a motional resistance of 119Ω and 154Ω. For devices on both dies and both modes, the variations of Q_u with temperature (T) are consistent and approximated with $Q_u \propto T^{-0.6}$. Metal electrodes have been attributed as a source of thermoelastic dissipation (TED) [6], which has a first order temperature dependence [7]. It is possible that the temperature dependence on Q is not strong as compared to if only TED was at work due to a notable presence of anchor loss that becomes more apparent at low temperature.

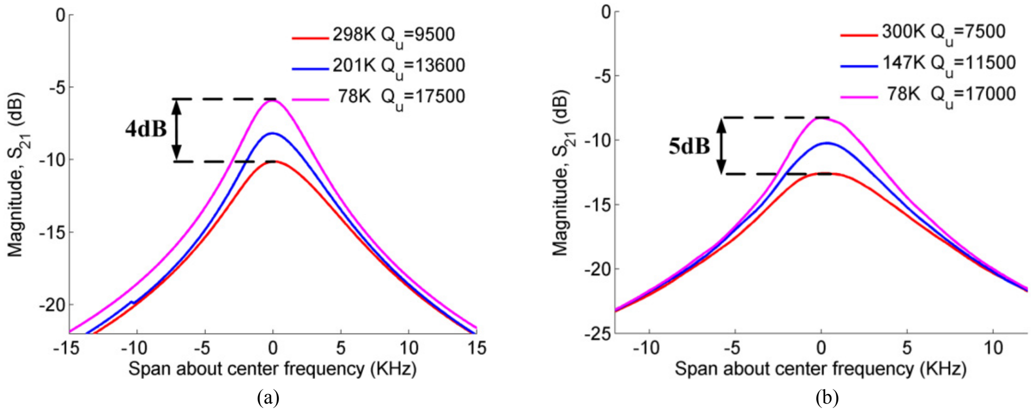

Fig. 3. Measured electrical transmission magnitude for (a) symmetrical and (b) anti-symmetrical width-extensional mode resonator (λ =180μm) at decreasing temperatures.

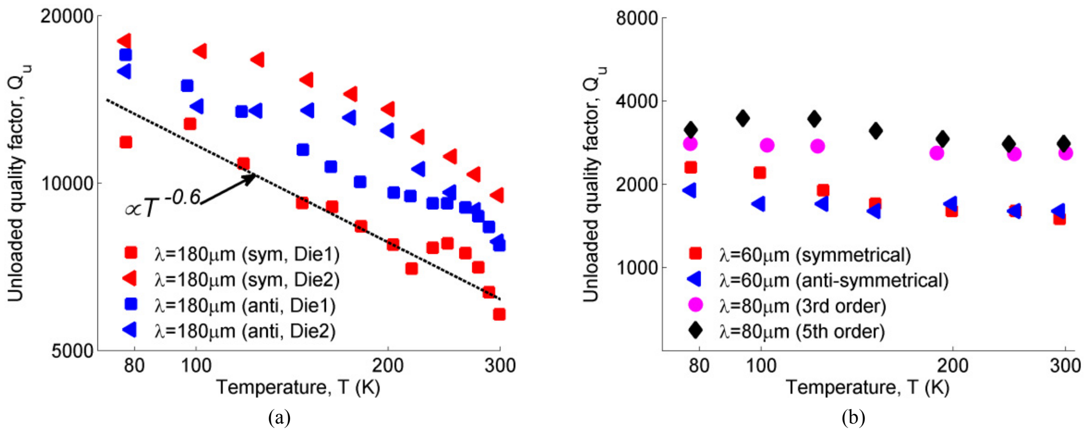

Fig. 4. (a) Measured Q_u for (a) a fundamental WE mode resonator (λ=180μm) when cryogenically cooled from 300K to 78K.; (b) measured Q_u for 3rd and 5th order vibration modes among 3 different resonators on Die 1 when cryogenically cooled from 300K to 78K (Similar trend of measured Q_u vs. temperature has been found for the same group of devices on Die 2).

We then cryogenically cooled another set of resonators with shorter acoustic wavelengths by exciting the 3rd and 5th order overtones. For all the resonators transduced in the higher-order modes (i.e. reduced λ/h), Q_u was found to be largely constant with temperature as seen in Fig 4 (b). This suggests that anchor loss becomes more dominant over electrode-related loss (assumed to be temperature dependent) when λ/h decreases.

Finally, we have also extracted the motional capacitance (C_m) which captures the electromechanical transduction efficiency of the fundamental modes over the specified temperature range. The extracted values of C_m correlate well with the FE simulation results and remain constant with temperature as shown in Fig 5.

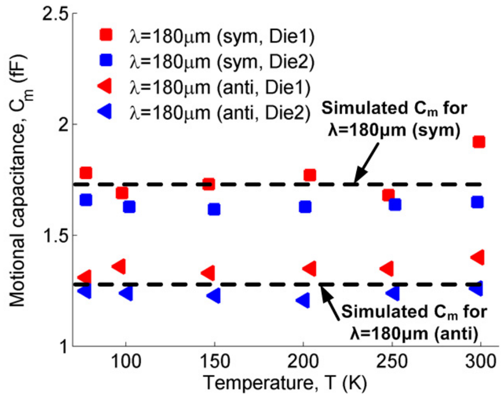

Fig. 5. Extracted motional capacitance (C_m) for a fundamental WE mode resonator (λ=180μm) when cryogenically cooled from 300K down to 78K; C_m obtained by FE simulation of the TPoS resonator denoted by the broken line.

4. Conclusion

This work shows that cryogenically cooling a 48MHz TPoS resonator from room temperature to 78K doubles Q with a temperature dependence characteristic that suggests the presence of thermoelastic damping. This temperature scaling effect on Q is absent for higher order modes with reduced λ. These measured results suggest that reducing λ/h increases anchor losses to dominate over temperature-dependent damping mechanisms that one might attribute to the metal electrodes.

Acknowledgements

The work described in this paper was supported by a grant from the Research Grants Council of Hong Kong (Project Number: CityU 116113).

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