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On-chip Feedthrough Cancellation Technique for Enhanced Electrical Characterization of a Piezoelectric MEMS Resonator in Water

Abid Ali[a]*, Joshua E.-Y. Lee[a, b]

[a]*Department of Electronic Engineering, City Univerisity of Hong Kong, Kowloon, Hong Kong*
[b]*State Key Labortary of Milimeter Waves, City University of Hong Kong, Kowloon, Hong Kong*

Abstract

In this work, we report a unique on-chip approach of cancelling feedthrough applied to a Thin-film Piezoelectric-on-Silicon (TPoS) MEMS resonator fully immersed in deionized (DI) water to enhance the signal-to-background ratio (SBR) in the context of full electrical characterization. We experimentally validate the proposed technique by demonstrating an SBR as high as 25dB despite a reasonably low quality factor (Q) of 162 and high dielectric constant of water from a reference SBR of 3.45dB. The proposed technique employs a pair of differential inputs where one input actuates the device while the other input cancels feedthrough and targets package-level parasitic elements associated with measuring in water. The resulting net feedthrough capacitance is reduced from 185fF to just 2.04fF in DI water. These results are based on a simple practical setup where the fabricated device is interfaced with a customized printed circuit board (PCB) by wire-bonds.

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Keywords: *AlN-on-silicon; MEMS resonator; Feedthrough cancellation; Quality factor; Differential inputs.*

1. Introduction

Micro/nano-electromechanical (MEMS/NEMS) resonant devices have the potential to open up a new era for sensing in the areas of food and industrial process monitoring as well as biosensing. In all such processes the resonator is faced with the challenge of having to operate in liquid where the device is unavoidably heavily damped. The large drop in Q leads to a huge reduction in the signal output, which is made more significant due to the increase in background interference when working in liquids with high dielectric constants like water, thus further

* Corresponding author. Tel.: +852-63164796; fax: +852-34420562.
E-mail address: abidali2-c@my.cityu.edu.hk

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attenuating the SBR. This presents a huge practical challenge for electrical characterization of resonators in liquids that cannot be skirted around by elegantly confining the liquid droplet to the resonator to avoid full immersion [1]. We here adopt a feedthrough cancellation technique that has been previously applied to a capacitive resonator in vacuum disadvantaged by poor transduction [2]. More specifically, we combine it with the strong electromechanical coupling available in TPoS technology, based on which we previously reported measurable signals in water despite considerably high feedthrough capacitance (482fF) [3]. The end result is a demonstration of on-chip feedthrough cancellation when exciting length-extensional (LE) mode TPoS resonator in DI water which greatly enhances the signal to background ratio compared to what has been reported previously in [3]. These results can provide a new era for many applications where the TPoS MEMS resonators electrically characterized under liquids that weaken the desired signal due to high parasitic feedthrough.

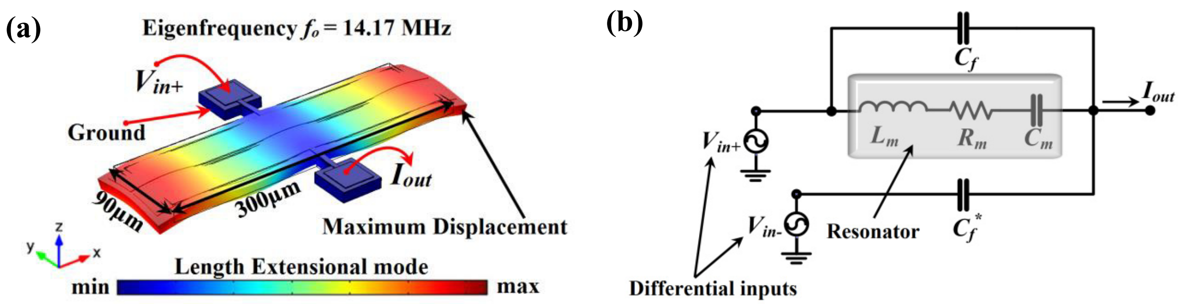


Fig. 1. (a) Profile of the LE vibration mode actuated by V_{in+} (simulated by finite element analysis); inset shows cross-sectional view with the different film layers (Al, AlN, and Si); (b) Lumped electrical model for a MEMS resonator to illustrate the basis of cancelling feedthrough by differential inputs (V_{in+} and V_{in-}).

2. Device Concept and Simulation

2.1. Device under test

The device under test is a LE mode resonator that is based on 300µm by 90µm rectangular plate as depicted in Fig 1(a). The plate comprises 3 layers: 10µm thick highly doped single-crystal-silicon (SCS) substrate, 0.5µm thick sputtered Aluminium Nitride (AlN) piezoelectric film, and 1µm thick Aluminium (Al) for the top electrodes (see Fig 2(b)). With the SCS layer is grounded, an input AC drive voltage is applied to one of the top electrodes to actuate the LE mode by the reverse piezoelectric effect. The LE mode shape can simply be described by the elongation and compression of the rectangular plate in the length direction (x-axis). A motional current is then sensed through the other top electrode by the direct piezoelectric effect. Given that the SCS substrate layer is much thicker than the other layers we can approximate the resonant frequency of the device with just the material properties of SCS for a known plate length (L):

$$f_o = \frac{1}{2L}\sqrt{\frac{E_{si}}{\rho_{si}}} \tag{1}$$

where E_{si} and ρ_{si} are respectively the Young's modulus (169 GPa) and density (2330 kg/m^3) of the SCS substrate layer. Finite element (FE) analysis has been carried out in COMSOL to determine the resonant frequency of the LE mode, which we have found to agree with equation (1) to within 0.2%.

2.2. On-chip feedthrough cancellation

Fig. 1(b) illustrates the basis of the proposed on-chip feedthrough cancellation technique based on the standard Butterworth-Van-Dyke (BVD) equivalent circuit model. The feedthrough comes from the direct coupling between the input and output ports which can be modeled by a parasitic feedthrough capacitor (C_f) that lies parallel to the resonator that is electrically represented by a series LRC circuit. A pair of differential AC inputs is used. V_{in+} drives the resonator to excite the LE vibration mode illustrated by Fig. 1(b). It can be seen that V_{in+} also couples through the feedthrough capacitor (C_f) to the output port. V_{in-}, having the same amplitude but out-of-phase with V_{in+}, is applied to a negating feedthrough capacitor (C_f*). When C_f and C_f* are well-matched, their feedthrough currents cancel out completely in principle.

Fig. 2(a) shows the layout of the contact pads on the fabricated device, which was fabricated using a foundry AlN-on-SOI MEMS process. As Fig. 2(a) shows, additional bond pads that are insulated from the SCS substrate by a 200nm thick thermal oxide have been fabricated close to the pad for the input AC drive (V_{in+}). Only one of these additional pads is used to feed the antiphase V_{in-} input signal (see Fig. 2(a)) which has no actuation function. The fabricated die was then mounted on a customized PCB using Al wire bonds as interconnects. Fig. 2(b) provides a schematic of the characterization setup illustrating the implementation of the proposed on-chip feedthrough cancellation technique.

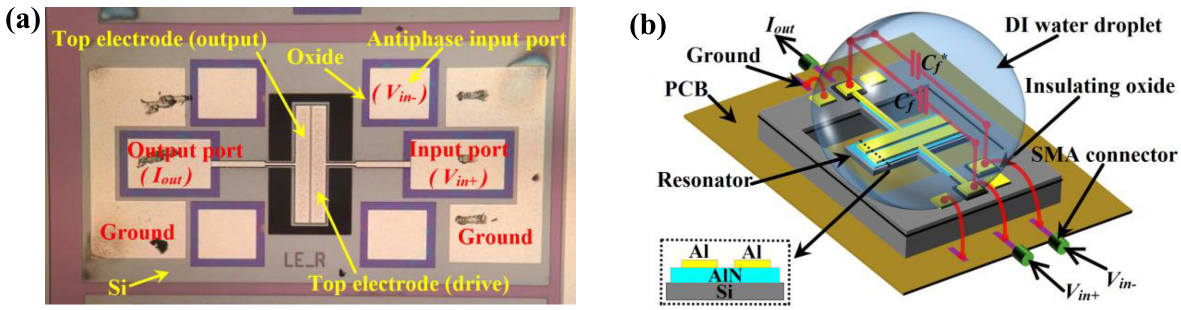
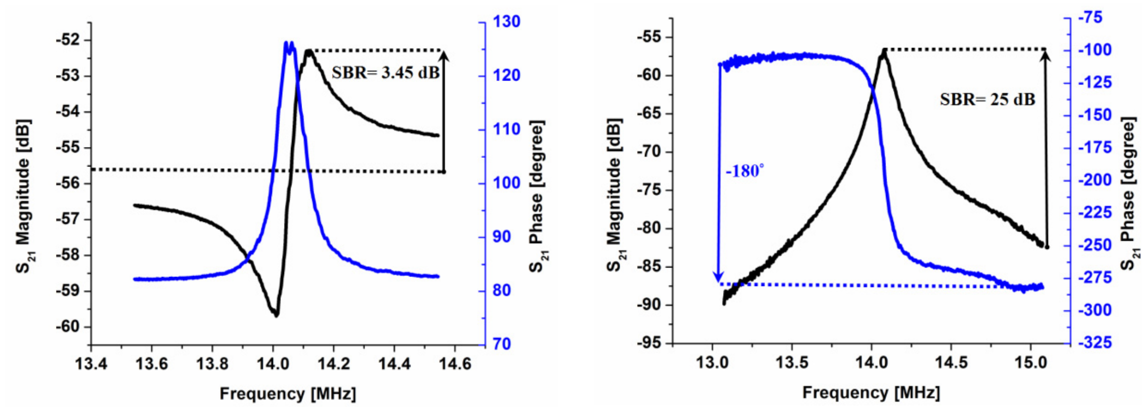


Fig. 2. (a) Optical micrograph of the fabricated resonator showing actuation pad (V_{in+}) and isolated input pad (V_{in-}) as well as the output port; (b) Perspective view schematic of the TPoS MEMS resonator wire-bonded to the PCB with DI water droplet on the top surface. Inset showing a cross-sectional view with the different layers.

3. Experimental Verification

We first measured the electrical transmission S_{21} by applying only V_{in+} (i.e. without feedthrough cancellation applied) with an RF power of 0dBm using a network analyzer. The resonator was fully immersed under a droplet of DI water dispensed through a calibrated pipette. As shown in Fig. 3(a), the large parasitic feedthrough due to the high dielectric constant of DI water results in a detectable but weak signal with an SBR of 3.45dB. We then measured the same device but with V_{in-} applied to cancel the feedthrough. As shown in Fig. 3(b), feedthrough has been effectively cancelled out to the point whereby the anti-resonance is almost removed even with a Q of 162, illustrating the good match between C_f and C_f^*. The associated SBR is substantially raised to 25dB. Table 1 summarizes the extracted lumped parameters based on the BVD model and reveals that the net C_f has been reduced from 185fF to 2.04fF.



(a) (b)

Fig. 3. (a) S_{21} magnitude and phase of TPoS MEMS resonator measured in DI water without antiphase input applied (i.e. no feedthrough cancellation); (b) S_{21} magnitude and phase of the device measured in DI water with antiphase input applied to provide on–chip feedthrough cancellation.

Table 1: Extracted lumped parameters based on the BVD model of the TPOS MEMS resonator electromechanically transduced in DI water with and without feedthrough cancellation applied through the antiphase input (V_{in-}).

External conditions	**Quality factor (Q)**	**Motional capacitance (C_f)**	**Feedthrough capacitance (C_m)**	**Resonance frequency (f_o)**	**Motional resistance (R_m)**
Without V_{in-}	145	185fF	1.09fF	14.05MHz	71.70kΩ
With V_{in-}	162	2.04fF	1.03fF	14.07MHz	67.61kΩ

4. Conclusion

In this work, we have demonstrated an on-chip feedthrough cancellation technique applied to a TPoS MEMS resonator in the context of electrical characterization in water where parasitic feedthrough is much higher than in air. Our approach targets parasitic elements at the level of the package or setup rather than at the device level. This has been achieved by fabricating extra bond pads (insulated from the grounded substrate by thermal oxide) for feeding the antiphase input signal V_{in-} to cancel parasitic feedthrough by implementing a pseudo-differential setup. We have experimentally demonstrated a significant increase in SBR from 3.45dB to 25dB despite a Q of 162 as a result of greatly reducing the net feedthrough capacitance C_f from 185fF to 2.04fF.

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