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Novel Platform for Resonant Sensing in Liquid with Fully-Electrical Interface based on an In-Plane-Mode Piezoelectric-on-Silicon Resonator

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Abstract

In this paper, we experimentally demonstrate full electrical characterization (i.e. both electrical input and output) of a MEMS resonator that is fully immersed in water towards realizing a novel resonant sensing platform capable of operating in liquid. Operation in liquid for resonant sensing has always been a challenge for electrical characterization. Our approach combines the strong electromechanical coupling of piezoelectric transduction provided by Aluminium Nitride (AlN), lower viscous damping by exciting an in-plane vibration mode, and higher energy storage capacity provided by the silicon device layer that is much thicker than the AlN film. Our device shows a measured quality factor (Q) of 200 when fully-immersed in water, which is over 2 times that of previously reported resonators. We are able to extract the motional resistance of the device in water, which we have found to be 40.5kΩ.

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Keywords: MEMS resonator; Aluminum nitride; Length extentional mode; Thin film piezoelectric-on-silicon; feedthrough capacitance.

1. Introduction

The use of miniaturize resonant devices based on micro- & nano- electromechanical systems (MEMS & NEMS) technology in liquid media has all along been a significant challenge in terms of transduction as well as maintaining a high quality factor (Q). MEMS resonators have been extensively used to monitor liquid properties in numerous

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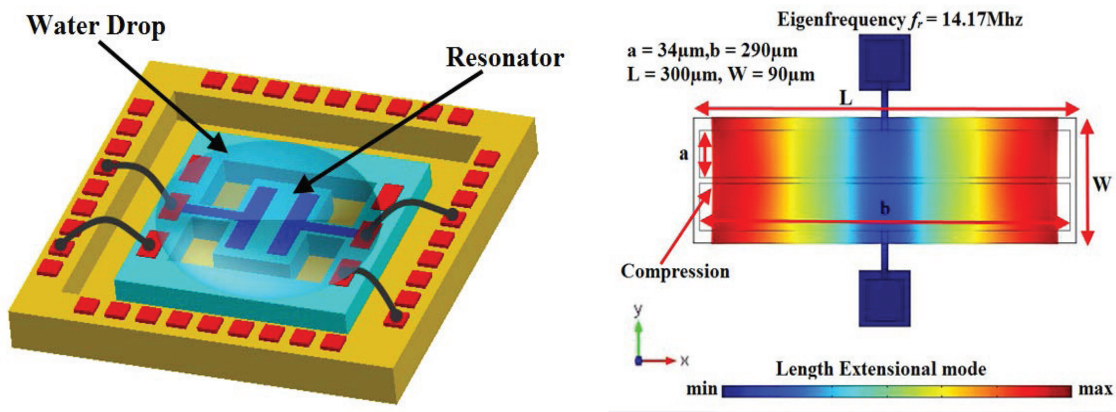
fields of application, such as cell biology, the automotive industry and food analysis. In all these applications, the resonator is typically fully immersed in liquid media. As a result, the vibration amplitude is consequently damped when the device is immersed in liquid media, leading to a considerable reduction in Q. For a conventional capacitive transduction setup, operating the resonator in polar liquids places a limit on the level of DC bias voltage that can be applied, thus requiring droplets to be skillfully confined within the resonator alone for electrical characterization to be even possible [1]. For resonant sensing, a high Q is desirable for better resolution of frequency shifts. Vibration modes can be generally classified into two groups: in-plane and out-of-plane modes, the former being less sensitive to viscous damping. The contour mode is an example of an in-plane mode. As such, different contour mode piezoelectric MEMS resonators have been reported to show promising results in air and vacuum. But in viscous media the value of Q is highly degraded, with Qs no higher than 90 at best [2-3], although the resonance is still detectable due to the strong electomechanical coupling of the piezoelectric. Resonators based on out-of-plane vibration modes suffer yet lower Q and require the displacements to be detected by a benchtop optical setup [4], unfeasible for point-of-care applications. In this work, by exciting the length-extensional (LE) mode (i.e. in-plane vibrations) of a thin-film piezoelectric-on-silicon (TPoS) resonator, we achieve higher Q over previous AlN-only resonators in liquid, with fully electrical interfaces that allow detection of the electromechanical resonance in liquid.

2. Design and Simulation

A schematic of the electrical characterization setup with the fabricated TPoS resonator packaged in a 44-pin ceramic chip carrier is shown in Fig. 1(a) using wire bonds as the interconnect. The chip carrier is mounted on a PCB through socket for electrical characterization with the device immersed under a droplet of water as shown in Fig.1 (a). The resonance frequency of the LE-mode is defined by the length L and material properties of the TPoS resonator, where E is the Young's modulus and ρ is the density:

$$f = \frac{1}{2L}\sqrt{\frac{E}{\rho}} \tag{1}$$

As shown in Fig. 1(b), the LE mode shape may be described by an elongation and compression in the length direction according to a modal analysis using finite elements. The structure is excited to resonance by applying an out-of-plane electric field through the input electrode (see Fig. 2(a)) to generate a lateral force through the reverse piezoelectric effect. The motional current is sensed at the output electrode (see Fig. 2(b) through the direct piezoelectric effect.

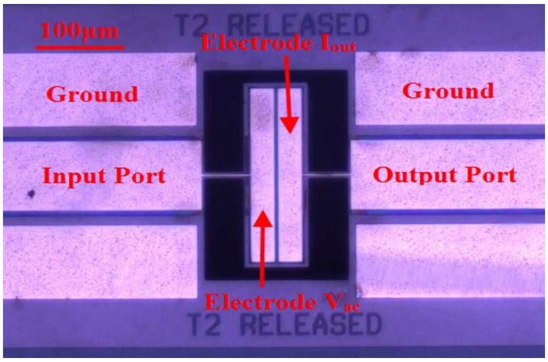


(a) (b)

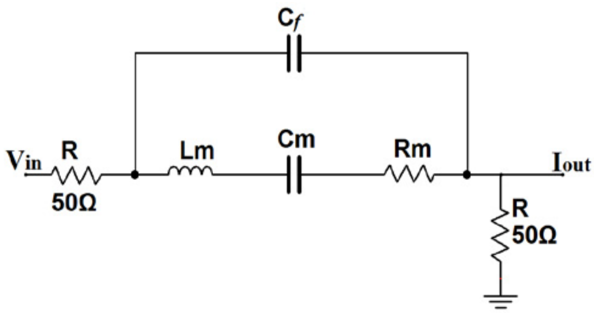
Fig. 1. (a) Perspective view schematic of the TPoS MEMS LE-mode resonator packaged in a ceramic chip carrier with water loaded on the top surface; (b) Primary vibration mode shape (LE mode) of the TPoS MEMS resonator simulated by finite element analysis.

3. Measurement and Discussion

A micrograph of the fabricated TPoS resonator using 4-mask foundry AlN-on-SOI MEMS process is given in Fig. 2(a). The fabrication process flow is described in Fig 3. The hetero-structure comprises a 10µm (100) silicon substrate, 500nm sputtered AlN thin film, and 1µm Cr/Al metal stack that defines the contact pads and top electrodes (see Fig. 3(e)). The silicon device layer is highly n-doped to create ohmic contacts and also allowing it be directly used as the bottom ground electrode of the AlN. The electrical equivalent circuit of the TPoS resonator is shown in Fig. 2(b). In this circuit L_m, C_m and R_m represent the electromechanical motional behaviour of the device while C_f is the feedthrough capacitance associated with the parasitics from the chip carrier and PCB board in the characterization setup.



(a)



(b)

Fig. 2. (a) SEM Optical micrograph of the TPoS MEMS LE-mode resonator; (b) Butterworth-Van-Dyke (BVD) electrical equivalent circuit model for TPoS resonator with 50Ω load resistors at the input and output ports.

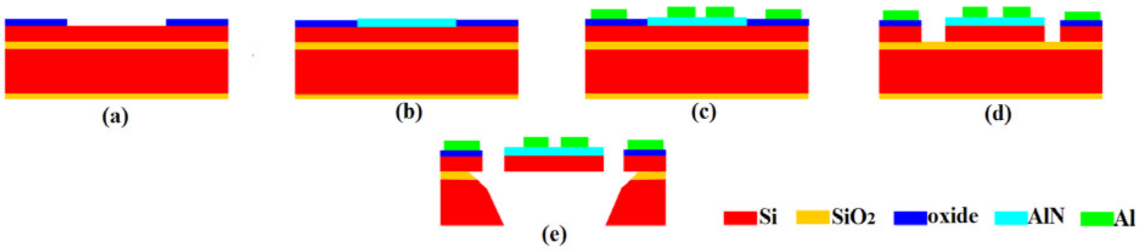
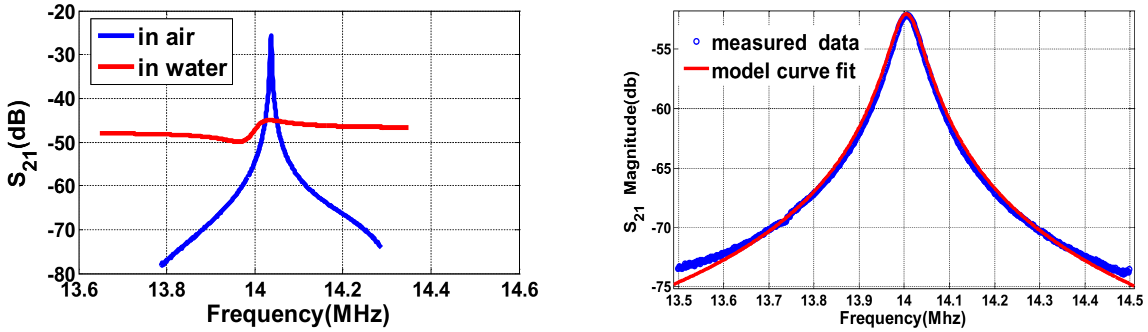


Fig. 3 Transverse view schematic view of the fabricated TPoS MEMS resonator showing the respective layers in the structure. The silicon device layer is 10µm thick: (a) 0.2µm thermally oxide is grown and patterned by reactive ion etch (RIE); (b) Piezoelectric AlN (0.5µm) is deposited by reactive sputtering and then patterned; (c) a metal stack consisting of 1µm Cr/Al is patterned to define the top electrodes and metal contacts for wire bonding; (d) Using RIE and deep reactive ion etching (DRIE) of oxide and silicon device layer respectively to create the structures; (e) Release of structure from the bottom side by DRIE of the silicon handle layer following by buffered HF etch of the buried oxide layer.

The device was first characterized in air by measuring the transmission S21 using a network analyzer with an RF power of 0dBm. We then loaded the device with a droplet of deionized water using a pipette, ensuring the device was fully-immersed in water before measuring the S21. All of the results are shown in Fig. 4(a). Due to the increase in feedthrough capacitance (C_f) and damping of Q, we extracted the lumped parameters by curve fitting as shown in Fig. 4(b). Table 1 summarizes the extracted lumped parameters based on the BVD model. It can be seen that Q dropped from 4920 in air to 200 when the resonator is completely covered under a droplet of water.



(a) (b)

Fig. 4. (a) Measured electrical transmission of TPoS MEMS LE-mode resonator in air and then in water; (b) Measured transmission of device when fully-immersed in water with model curve fit for lumped parameter extraction and feedthrough removed.

Table 1: Extracted lumped parameters of the LE-mode TPOS resonator air and water.

External conditions	**Quality factor (Q)**	**Motional capacitance (C_m)**	**Feedthrough capacitance (C_f)**	**Resonance frequency (f_r)**	**Motional resistance (R_m)**
In air	4920	1.2fF	40fF	14.04MHz	1.93kΩ
In water	200	1.4fF	490fF	14MHz	40.5kΩ

4. Conclusion

We have demonstrated full electrical characterization of a MEMS resonator in water. This was enabled by the strong electomechanical coupling provided by the piezoelectric AlN thin film sputtered on a 10µm silicon device layer. By exciting the in-plane LE-mode as well as exploiting the low intrinsic damping in silicon, the resonator exhibits a Q of 200 when fully immersed in water, which is double the value that have been previously reported for AlN-only resonators. These preliminary results lay the ground work for further innovations in creating a novel platform for resonant sensing in biological environments.

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