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Electrical characterization of piezoelectric-on-silicon contour mode resonators fully immersed in liquid

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ABSTRACT

Biological sensing in the mechanical domain offers novel opportunities to measure cellular processes. Operating mechanical resonators in liquid environment for the detection of mass presents a challenge at least for electrical characterization. In this paper, we demonstrate the full electrical characterization of a micromechanical resonator that is fully immersed in DI-water. The reported device uses piezoelectric transduction through an Aluminium Nitride (AlN) film sputtered on a low damping silicon substrate to provide strong electromechanical coupling. The effect of viscous damping in DI-water is lowered by exciting the resonator to vibrate in an in-plane contour mode. We believe that incorporating a 10 μm thicker silicon substrate layer stiffens the resonant system and thereby increases the energy storage capacity in relation to a resonator structured purely by a thin AlN film. The 14 MHz length extensional (LE) mode resonator presented in this paper shows a quality factor (Q) of 200 when fully immersed in DI-water, which is twice that of previously reported resonators structured purely in AlN. The associated motional resistance of the device in DI-water is 40 kΩ. We have also measured the values of Q for several other in-plane resonant modes with higher resonant frequencies (up to 141.69 MHz) when immersed in DI-water. Having found that the high dielectric constant of DI-water significant affects the characterization setup, we have also modeled the various sources of parasitics involved in the setup.

1. Introduction

The use of miniaturized resonant devices based on micro- and nano- electromechanical systems (MEMS and NEMS) technology in liquid media has all along presented significant challenges for maintaining high quality factor (Q) and allowing full electrical characterization (whereby both the input and output interfaces of the device are electrically accessed). Yet there are a number of applications in the automotive industry, cell biology, and food analysis where the devices are expected to be interfaced in liquid in order to monitor the properties of the liquid [1–3]. MEMS resonators provide a highly attractive technology platform to perform such sensing functions owing to their small form factor. Miniaturization of the device form factor in turn allows for smaller liquid volume requirements and realization of low power low cost portable analytical systems with improved sensor resolution that could include arrays of multiple resonant sensors [4]. However, immersing a MEMS resonator in liquid typically results in significant viscous damping of its vibration energy and a notable reduction in Q. This significant reduction in Q presents a challenge to electrical characterization when one considers the signal-to-background ratio (SBR) for measurements in liquid. A reduction in Q leads to a reduction in the electromechanical signal amplitude. There is also unwanted direct coupling between the input and output ports through parasitic elements, referred to in this paper as feedthrough, which constitutes the background signal. As we will show in this work, this background signal from feedthrough can increase by as much as tenfold in high dielectric constant liquids like DI-water. In short, a simultaneous reduction in Q due to damping in liquid and an increase in the background signal due to increased feedthrough results in a significant drop in the SBR. In the limit where the SBR reduces to a point where the resonant peak is substantially buried in the background signal, recovery of the resonance becomes highly challenging if not impossible. As such, although a drop in signal amplitude alone can be compensated by adding gain through electronic amplification, it should be noted that the associated fall in SBR cannot be mitigated by gaining up the signal electronically

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since both the resonant and background signals are simultaneously amplified.

Based on the experimental results from several acoustic resonators such as micro/nano cantilevers, film bulk acoustic resonators (FBAR) and lateral bulk acoustic resonators (LBAR), it has been shown that the value of Q in a viscous media is strongly associated with the mode of vibration [5]. Micro/nano cantilevers have been employed for sensing different kinds of biological, physical and chemical species in viscous environments [6–12]. The major advantages of resonant micro-cantilevers are their fast response time, small size, and high sensitivity. On this note, the sensitivity and limit of detection are directly related to the value of Q, which is one of the figures of merit to evaluate the performance of the resonator. Tao et al. [13] and Díez et al. [14] have previously reported results of micro-cantilevers in liquid media, in which the structure was excited in two modes of vibration: in-plane mode and out-of-plane mode. It was found that the Qs of out-of-plane modes were much more severely damped (with values in the order of 1) compared to in-plane modes (with values in the order of 10). Johnson et al. [15] also reviewed more than 50 studies of cantilever-based micro-resonators of various geometries excited in liquid media and reported that the Qs of out-of-plane modes did not exceed 35. The same study also showed that exploiting the in-plane bending mode in a micro-cantilever could minimize the effect of viscous damping on the resonator immersed in liquid media, achieving a Q of 67 [15]. While micro-cantilevers provide high sensitivity due to their small mass, this advantage is related to lower stiffness. Lower stiffness in turn translates to lower energy storage capacity and therefore lower Q for the same amount of damping.

Single crystal silicon based lateral bulk acoustic wave (BAW) resonators possess much higher energy storage capacities compared to flexural mode resonators like cantilevers. As an illustration, Tappura et al. [16] have previously demonstrated excitation of a lateral BAW wine-glass mode resonator using a capacitive transduction electromechanical interface. The reported device had Q of about 20,000 in air. This high value of Q was reduced to 1000–2000 when a liquid droplet was loaded on the lateral BAW resonator. It is worth noting that the resonator could not be fully immersed in liquid as with other another example of loading liquid droplets on the BAW plate resonator [17]. In both cases, the droplets have to be skilfully confined within the centre of resonator alone for full electrical characterization. The difficulty of realizing full electrical characterization with a capacitive device that is immersed in liquid stems from limitations in the electromechanical transduction interface. In capacitive transduction, the transduction efficiency scales with the square of the DC bias voltage applied across the capacitive transducer. As such, when the resonator is immersed in DI-water, the maximum allowable DC bias voltage is limited to a few volts beyond which electrolysis occurs; the DI-water in the gap then ceases to function as a dielectric for the capacitive transducer to work. Limiting the DC bias voltage thus limits the electromechanical transduction efficiency often rendering it too low for detection to be possible. Besides, the existence of DI-water in the capacitive gaps leads to significantly higher viscous squeezed film damping within the capacitive gaps as well as increased parasitic resistance through the gap due to existence of a liquid between the ports.

In contrast to capacitive MEMS BAW resonators, FBARs have capitalized on the strong electromechanical coupling provided by the piezoelectric transducer formed by sputtering a thin piezoelectric film. Qs up to 300 have been reported for FBARs operating in air [18,19]. However in liquids, based on the results of longitudinal mode (LM) FBARs, maintaining Qs of the same order still remains a challenge. In particular, this mode of vibration is marked by compressional waves that are heavily damped as a result of acoustic energy radiating normally into the liquid. As an alternative, shear mode (SM) FBARs have proven to be more suitable for operation in liquid as shear acoustic waves avoid the problem of acoustic energy leakage into liquid. Zhang et al. [19] reported a Q of 15 in liquid when exciting the LM FBAR, which is a drop by a factor of 20 compared to operating in air. The SM FBARs in comparison showed higher Qs up to 150 when operated in liquid [20–22]. The main drawback of these SM FBARs lies in having to fabricate micro-fluidic channels in their microstructure, which adds to the fabrication complexity and thereby manufacturing costs.

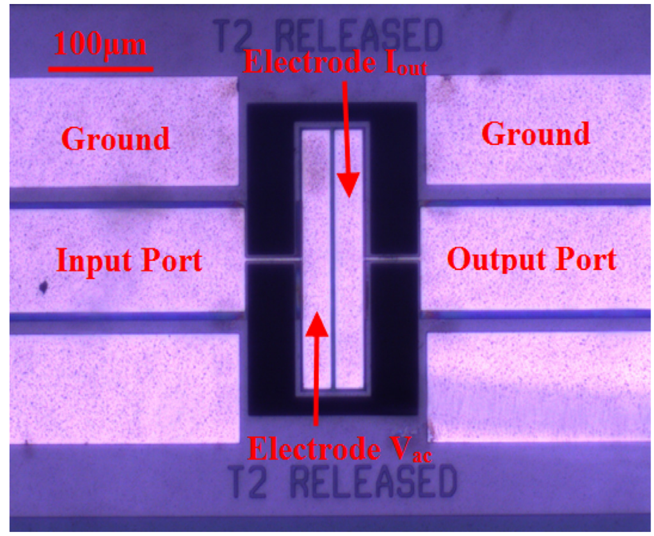

Fig. 1. Micrograph of Device A.

More recently, thin-film piezoelectric-on-silicon (TPoS) resonator technology has been proposed as a solution to combine the merits of strong electromechanical coupling from the piezoelectric film with the merits of low intrinsic mechanical loss from single crystal silicon. [23,24]. With respect to realizing resonators for operation in liquid, TPoS technology provides two inter-related advantages. Firstly, the strong electromechanical coupling provided by the piezoelectric transducer benefits electrical characterization of the resonator. Secondly, the addition of a silicon substrate that is much thicker than the piezoelectric film increases the stiffness of the resonator. Increasing the stiffness of the resonator increases its energy storage capacity and thus helps to buffer reduction in Q when damped in liquid.

In this paper, we demonstrate full electrical transduction of both length-extensional (LE) and width-extensional (WE) modes in TPoS resonators. Both the LE and WE modes are in-plane modes of vibration. We have measured Qs that are all around 200 among the different resonators and modes tested. This value of Q is higher than those previously reported for piezoelectric resonators structured by Aluminium Nitride only (with metal electrodes) when operated in DI-water [4,25]. The next section provides a description of the resonators considered in this work (four different resonator designs) and their working principle. The fabrication process is described in Section 3. Section 4 presents the measurement results of the resonators electrically characterized in air and then in DI-water. In Section 5, we analyse the various sources of parasitic feedthrough capacitances in the current characterization setup with the aim to identify the main contributors of feedthrough when the resonator is immersed under a DI-water droplet.

2. Resonator design and simulations

Four different resonator designs were considered in this work with respect to the effect of viscous damping on their respective Qs. These resonator designs are referred to in this paper simply as Device A, B, C and D. Device A, depicted in Fig. 1, comprises a