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Single device on-chip feedthrough cancellation for enhanced electrical characterization of piezoelectric-on-silicon resonators in liquid

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ABSTRACT

Even though piezoelectric MEMS resonators are known to possess substantially stronger electromechanical transduction efficiencies than the more traditional capacitive MEMS resonators, parasitic feedthrough remains an impediment for electrical characterization of resonators in liquids. The increase in parasitic feedthrough is particularly pertinent in liquids with high dielectric constants like water. In this paper, a previously proposed pseudo-differential parasitic feedthrough cancellation technique involving only a single capacitive MEMS resonator operating in vacuum is here adapted for a Thin-film Piezoelectric-on-Silicon (TPoS) MEMS resonator that is fully immersed in deionized (DI) water. The proposed technique targets parasitics on the package level rather than parasitics intrinsic to the device. We have tested the proposed technique on three different resonator designs to investigate its scalability, and have found that the method is most beneficial when the resonators are smaller. The proposed technique is thus highly relevant to resonant mass sensing applications. We experimentally demonstrate a reduction in feedthrough by as much as a factor 90 using the proposed method, which results in a corresponding increase in the signal to background ratio from 3.45 dB to 25 dB despite a quality factor of 221 in water.

1. Introduction

Miniaturized resonant devices based on micro- and nano- electromechanical systems (MEMS and NEMS) have emerged as a promising technology in the field of biological and chemical sensing [1–3]. The ability to probe these devices electrically allows the possibility to interface a large array of resonant sensors with readout electronics realized on integrated circuits. As such, the advantages of MEMS and NEMS resonant sensors include low cost, portability, high sensitivity (which scales inversely with mass), and the capability to provide rapid sensing of biological and chemical species. In the context of biological and chemical sensing, there will be instances where the device will be required to operate in a viscous media such as liquids (in contrast to simply ambient conditions). Compared to operating the device in ambient conditions, electrically characterizing such a device in liquid [4] is known to be highly challenging given the signal strength is expected to drop significantly due to a reduction in quality factor as a result of viscous damping. This well-recognized challenge of electrically characterizing MEMS/NEMS resonant devices in liquid is further complicated by the presence of various sources of parasitic elements in the electrical characterization setup. The impact of these parasitic elements is most significant observed in the form of a parasitic capacitor that appears between the input and output ports as depicted in Fig. 1. From our previous work [5], we have classified the main sources of parasitic capacitance as follows:

(1) Capacitive coupling between the input and output ports intrinsic to the device (C_{dev}),
(2) Capacitive coupling from the electrical characterization setup when the die containing the device is packaged on a printed circuit broad (PCB) with wire bonds as interconnects (C_{ext}).

The basic schematic circuit shown in Fig. 1 illustrates the location of the abovementioned parasitic capacitive elements in relation to the resonator relevant to electrically characterizing the device in air as well as in a liquid as such water. Fig. 1 is modification of the commonly used Butterworth Van Dyke model where the electromechanical admittance of the resonator is represented by an LRC series resonant circuit. It is useful at this point to define a figure of merit based on Fig. 1 that compares the strength of the signal from the resonator (i.e. through the LRC path) to the unwanted background signal (referred to elsewhere in the literature as feedthrough) associated with the parasitic elements. We refer to this figure of merit as the Signal-to-Background Ratio (SBR) when $\omega_0 C_f \ll 1/R_{dev}$

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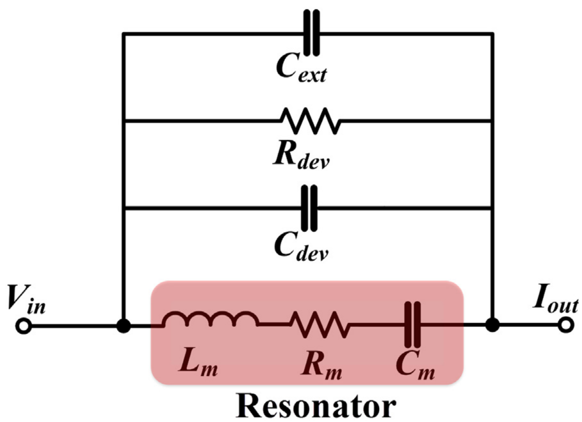

Fig. 1. Modified Butterworth van Dyke (MBVD) model depicting the relation between key parasitic elements (that contribute to feedthrough) in relation to the electromechanical resonance of the resonator (represented by the LRC series resonant branch) with a respect to a generic electrical characterisation setup for measurements in DI water.

$$SBR = \frac{C_m Q}{C_f} = \frac{C_m Q}{(C_{dev} + C_{ext})} \quad (1)$$

where ω_0 and Q respectively denote the angular resonant frequency and quality factor of the resonator, C_f is the total parasitic feedthrough capacitance, and C_m denotes the motional capacitance of the resonator; C_m is an equivalent circuit parameter (refer to Fig. 1) that describes the transduction efficiency of the resonator. R_{dev} represents a leakage resistance between the input and output ports that is intrinsic to the resonator and is generally not dependent on the characterization setup.

The SBR holds significant importance for the electrical characterization of MEMS and NEMS resonators in liquids particularly where the liquid has a high dielectric constant. As mentioned before, immersing the resonator in liquid results in a greatly reduced quality factor (Q) due to the increase in viscous damping. Given that C_m does not change in theory, we see that the numerator of the SBR expression in Eq. (1) would be reduced. In air, the background signal is set by C_{dev} and C_{ext} is insignificant in comparison. In water, C_{ext} is greatly increased due to the high dielectric constant of water while C_{dev} remains unchanged in theory. In our previous work reporting the electrical characterization of a piezoelectric resonator in water [5], we found that C_{ext} can be much greater C_{dev} due to the high dielectric constant of water which contacts the wire bond interconnects. Under such circumstance, the denominator term in the SBR expression given in Eq. (1) will decrease. Consequently, given the simultaneous reduction in the numerator and increase in the denominator of the SBR, we can expect a very significant drop in the SBR in water compared to characterizing the same device in air [5,6]. A weaker SBR corresponds to a weaker resonance peak relative to the background. In the limit where the background is much larger than the electromechanical resonance (i.e. low SBR) to the point where the resonance signal is buried in the background, it becomes impossible to recover the resonance signal. It is worth pointing out that the SBR cannot be improved by applying electronic amplification at the output port. This is because both the resonance peak and background are amplified by the same factor: the SBR remains unchanged. In other words, electronic amplification helps increase the magnitude of a resonator peak but not its relative strength over the background. As such, improvements in SBR have to be made on the characterization setup and/or device design.

As illustrated by Eq. (1), the SBR can be improved by:

(a) Increasing C_m and Q
(b) Decreasing the associated parasitic capacitance (i.e. feedthrough cancellation)

In boosting signal strength, the choice of transduction method determines C_m. The maturity of piezoelectric film deposition techniques has opened up new avenues to realizing resonant devices operable in liquids. Piezoelectric resonators [7] have emerged as a highly promising alternative to more traditional capacitive resonators [8,9] when it comes to targeting applications in liquids by offering significantly higher transduction efficiencies. To illustrate the magnitude of difference in electromechanical coupling between piezoelectric resonators over the more conventional capacitive resonators, we use one of the resonators described in this paper as an example: a 300 μm by 90 μm resonator that is 10 μm thick vibrating in the length-extensional mode (referred to as Device A in this paper). We can compare the coupling efficiency using the electromechanical coupling factor (η), defined here as the force per actuation voltage. Using piezoelectric actuation, η is 3.85 nN/V. With capacitive actuation, if we assume a 1 μm transducer gap and a moderate DC bias voltage of 10 V, η is 6.35 fN/V; six orders of magnitude lower. Even if we assumed more aggressive fabrication methods to reduce the gap to 0.1 μm, the difference is still four orders of magnitude. Besides, when operating the capacitive resonator in water, we can expect yet lower DC bias voltages to avoid electrolysis, which further reduces η.

On reducing background, much has been reported on feedthrough cancellation techniques applied to traditional capacitive resonators [10–18]. In all of these reports, the resonators were excited in either air or vacuum. Given the comparatively low coupling efficiency of traditional capacitive transductions, feedthrough cancelling is still necessary despite the low damping in air or even vacuum (where the quality factors are high) to improve the SBR. One approach to cancel feedthrough is to apply a fully-differential configuration, which is most commonly seen in the case of anti-symmetric modes such as the Lamé [15] and wine glass (otherwise referred to as elliptical) [16]. A more generic and commonly applied approach is to use a pseudo-differential configuration [17]. This involves fabricating two identical resonators alongside, one of which functions as a dummy device that is never excited into resonance but used as a compensating capacitor. This approach increases the total device area. Another more recent approach cancels feedthrough using a single resonator by targeting the parasitics at the package level [18]. But these above techniques are still insufficient when characterizing resonators in water due to poor transduction of the capacitive method. In the case of quartz crystal microbalances (QCMs), [19,20] have reduced the background signal using additional electronic circuitry for feedthrough compensation in different liquids (trichloroethylene, ethanol, water). More recently, the pseudo-differential method (mentioned above for capacitive resonators), by including an unreleased dummy resonator, has been applied to thin-film piezoelectric-on-silicon (TPoS) resonators to cancel feedthrough when characterizing in liquids [4,21]. Piezoelectric transduction provides for much high transduction efficiencies than traditional capacitive transduction. Apart from taking up extra area, it was found that the parasitics from the dummy device alone is insufficient to compensate feedthrough.

In this work, we report a practical on-chip single device feedthrough cancellation technique applied within the context of Thin-film Piezoelectric on Silicon (TPoS) resonators intended to be electrically characterized in water. In contrast to the previous work in [4], the reported technique targets parasitics at the packaging level in the setup (i.e. C_{ext}) rather than the device level (C_{dev}). The technique has been adopted from a previous work where the technique was applied to a capacitive-piezoresistive resonator that was characterized in vacuum, required due to poor transduction effi-