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Differential-capacitive-input and differential-piezoresistive-output enhanced transduction of a silicon bulk-mode microelectromechanical resonator

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ABSTRACT

Parasitic capacitive feedthrough poses a challenge typical to electrical detection of resonance in micron (and even more so for nano) scale silicon-based mechanical resonant devices. The most efficient methods of capacitive transduction solely address the issue of feedthrough at most and with preference for certain vibration mode shapes. In this work, we present an electrical characterization configuration that allows both a substantial degree of feedthrough cancelation (by as much as 53 dB) and an increase in the electromechanical coupling by use of piezoresistive sensing. Due to the balanced setup, parasitic feedthrough associated with the transducers is canceled at both the input and output interfaces. The figure of merit, given by the ratio of the resonant peak value to the direct feedthrough is increased by 67 dB from applying the proposed transduction setup. Variations in the effect of feedthrough cancelation through this configuration are analyzed and studied experimentally. Although demonstrated for breathing mode square-plate resonators in this paper, the technique can be extended to any topology given an even number of electrodes usable for capacitive actuation.

1. Introduction

Scaling down the physical dimensions of silicon-based mechanical resonators affords a number of advantages such as increasing sensitivity in some sensor applications [1], scaling the operating frequency up to radio-frequency spectrums [2], lower power consumption, and an easier path toward integration with complementary metal oxide semiconductor (CMOS) technology. However, such physical scaling brings with it practical challenges in realizing efficient fully-electrical transduction interfaces in silicon-based micromechanical resonators. To date, capacitive interfaces still remain one of the more common means of transduction. In the case of lateral-mode resonators where the vibrational acoustic waves propagate in the plane of fabrication, capacitive electrodes are convenient to realize. No additional fabrication steps are needed as these can be fabricated in the step of defining the shape of the resonator. One advantage of exciting lateral-modes of vibrations is that their resonant frequencies are defined by the lateral dimensions of the resonant device, which can thus be lithographically defined. This in turn allows for realization of multiple frequency references on a single chip using the same number of process steps for fabricating a single device. For a microresonator that employs capacitive transduction to actuate and detect resonance, its electromechanical frequency response can be described by a lumped equivalent circuit model that comprises a series resonant LRC. At the same time, some of the drive signal at the input couples directly to the output through parasitic elements, the most dominant of which appears as a capacitor (C_{par}) that lies between the input and output port as depicted in Fig. 1 and described by [3]. In addition, parasitic shunt capacitances (C_{s1}, C_{s2}) have been incorporated into the circuit model to account for signal leakage to ground in the measurement setup.

In the case of using capacitive transducers, the most basic underlying source of parasitic electrical feedthrough typically stems from the capacitive transducers themselves. As such, the admittance through this feedthrough capacitor at the resonant frequency (ω_r) is given by:

$$Y_{par} = j\omega_r \left(\frac{\varepsilon_0 A}{d}\right) \tag{1}$$

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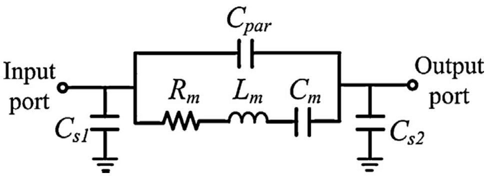

Fig. 1. Traditional Butterworth–van Dyke (BVD) equivalent circuit model. Parasitic shunt capacitors (C_{s1}, C_{s2}) have been incorporated into the circuit model to account for signal leakage to ground in the measurement setup.

A is the total overlapping area of the capacitive transducer, *d* is the transducer gap, and ε_0 is the permittivity in vacuum.

A common figure of merit (FOM) to assess the transduction efficiency of a resonator is defined by the ratio of the output resonance peak signal (when all the parasitic feedthrough is extracted out) over the parasitic feedthrough level. The output resonance peak signal without any feedthrough added is associated with the admittance of the resonator at resonance (Y_{mo}), which is given by:

$$Y_{mo} = j\omega_r \frac{(\varepsilon_0 A)^2 V_{dc}^2}{k \cdot d^4} Q \tag{2}$$

Q is the quality factor, V_{dc} is the DC bias voltage, and *k* is the spring constant which depends on the specific vibrational mode shape of interest. In the case of the square-extensional (SE) mode depicted in Fig. 2, and the test example used in this paper, *k* is known to be given by:

$$k = \pi^2 Eh \tag{3}$$

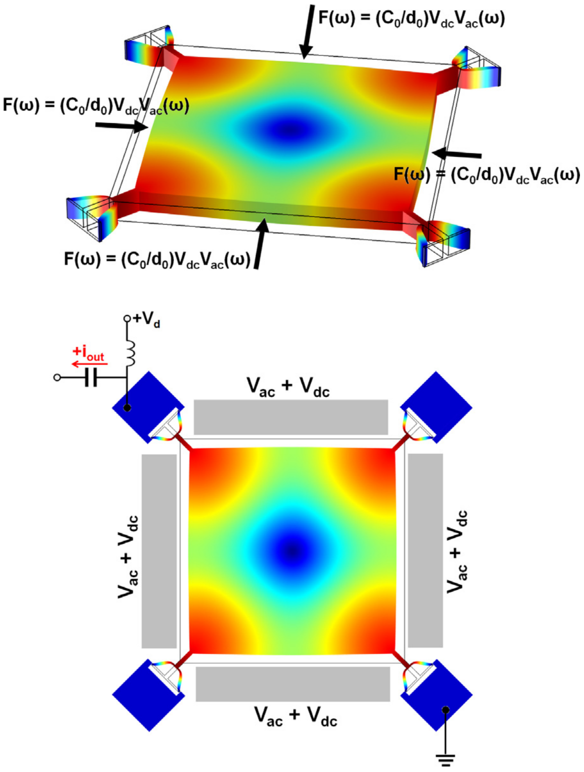

Fig. 2. Finite element (FE) simulation of the breathing mode for the square-plate resonator in COMSOL Multiphysics; (a) required symmetry of actuation forces; (b) single-ended capacitive drive and piezoresistive readout configuration.

E here is specifically the invariant biaxial modulus and *h* is the thickness of the resonator. Substituting Eq. (3) into Eq. (2), and also using Eq. (1), we obtain the FOM:

$$\mathrm{FOM} = \frac{\varepsilon_0 L_e Q V_{dc}^2}{\pi^2 E d^3} \tag{4}$$

where L_e denotes the total perimeter of the transducer overlapping area. For contour modes like the SE mode, the resonant frequency scales inversely with the length of the device. If we assume a constant frequency–quality factor (*f*·*Q*) product in the limit of Akhiezer damping, this FOM would scale with the second order of a contour mode resonator's lateral feature size according to Eq. (4). As such, capacitive transduction efficiency generally diminishes by scaling down the physical size of the resonator. In contrast, the FOM for piezoresistive sensing scales much more favorably with physical size, and thus also frequency as compared to capacitive sensing [4]. As a caveat, apart from selective doping to define the piezoresistors around specific locations on the resonator [5], piezoresistive sensing generally requires the stress distribution associated with a vibration mode to be symmetrical overall. As such, transduction setups that have been applied specifically to capacitive transduction, and also preferentially for certain modes like the Lamé square or wine glass disk resonator [6], cannot be extended to piezoresistive-related modes. On this note, we have recently reported a method that was aimed at canceling feedthrough at the package level while also allowing use of piezoresistive sensing to increase transduction [7,8]. This approach, though slightly more space-efficient than the use of the more commonly used pseudo-differential method based on dummy resonators [9,10], addresses the issue of parasitic feedthrough only partially as it does not deal with parasitics at the device-level as in [6]. Targeting parasitics at the device level with respect to employing piezoresistive sensing, Li et al. have reported a novel differential piezoresistive readout configuration [11,12]. Applying this kind of configuration, they have achieved a feedthrough reduction of around 25 dB. It is noted that a single-ended capacitive input was used, which may have limited the extent of feedthrough cancelation. In this work, we describe an improvement on the differential piezoresistive readout to also now include a differential capacitive input. This allows us to reduce feedthrough by as much as 53 dB. This work focuses on characterization with regards to improving the transduction FOM, but we have previously derived a semi-analytical model for the transconductance of the device reported herein [13]. Details on the derivation can be found therein. We here simply refer to the verified model for the transconductance to obtain an FOM which takes into account the estimated feedthrough from the proposed biasing configuration. From [13], the motional transductance (G_m) is given by:

$$G_m = \frac{\pi_l Q I_D \varepsilon_0 L \lambda}{\pi^2 E d^2} \tag{5}$$

I_D is the DC bias current applied through the piezoresistors integrated into the square-plate resonator, and λ is a linear proportionality constant relating the longitudinal stress in the piezoresistors (given by the tethers) and edge displacement of the square-plate at resonance. Although derivation of a fully-analytical form for λ is highly complex (hence the use of FE computation in [13]), its dependence on physical scaling is sufficient in the analysis of G_m (Eq. (5)) in relation to Y_{mo} (Eq. (2)). It is reasonable to assume that the size of the piezoresistors-tether scales accordingly with length of the square-plate. As such, λ would scale inversely with *L* and also the thickness *h*. Hence to a first approximation, G_m is very much independent of *L* and scales inversely with *h*. Y_{mo} on the other hand scales with L^2 and *h* respectively. As such, piezoresistive readout is in principle more robust to miniaturization compared to capacitive readout, at least in the case of the square-plate resonator described herein. In addition, we also study the variation in the