FULLY DIFFERENTIAL INTERNAL ELECTROSTATIC TRANSDUCTION OF A LAMÉ-MODE RESONATOR

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ABSTRACT

This paper reports the parallel internal electrostatic transduction of a laterally driven Lamé-mode polysilicon resonator. This resonator is fabricated using a manufacturable double nanogap process that provides ultrathin high-aspect ratio lateral gaps. The transduction electrodes are optimally placed and oriented to maximize electromechanical transduction efficiency for the fundamental Lamé mode. A 128.15 MHz Lamé-mode resonator is driven and sensed differentially with a 20 V DC polarization voltage: the motional resistance is about 30 kΩ and the quality factor Q > 12000 in air.

INTRODUCTION

The promise to integrate fully wireless transceiver systems has focused research efforts on developing on-chip high quality factor micro-electro-mechanical systems (MEMS) resonators. Electrostatic air- or vacuum-gap transduction has been used to drive and sense micromechanical resonators at frequencies above 1 GHz, with quality factors exceeding 10,000 [1]. However, one of the challenges of conventional electrostatic transduction is their relatively low efficiency. Previous efforts to minimize this impedance have been focused on reducing the gap, increasing the transduction area by using geometries such as rings [2] or by coupling arrays of resonators [3]. Internal electrostatic transduction, where a dielectric material replaces the air gap, offers an alternative route to reducing the motional impedance and also offers greater reliability by eliminating air gaps [4][5]. By optimally placing the dielectric within the resonator one can achieve higher frequencies and quality factors [6].

Another challenge facing electrostatic transduction of MEMS resonators is the presence of capacitive feedthrough, which makes direct measurement of resonators especially difficult at RF frequencies and motivates different measurement techniques [7]. Differential sense and excitation of electrostatic resonators allow for cancellation of capacitive feedthrough and offers extended linearity and better power handling [8]. The Lamé-mode resonator is ideal for differential measurements since the stresses in the perpendicular principle orientations in the plate are 180 degrees out of phase during resonance. Quality factors exceeding 1,000,000 have also been reported in vacuum [9]. For the Lamé-mode resonator reported in this paper (Figure 2), the four arrays of internal electrodes are optimally placed in the quadrants of the resonator such that adjacent electrodes are subjected to opposite stresses. Two signals that are 180 degrees out of phase are applied to the drive electrodes (1) and (2) and the currents out of sense electrodes (3) and (4) are combined for the total motional current (Figure 2). The net current from the resonator body (gray area in Figure 2) can approach zero, if the Lamé mode is differentially excited, due to the matched drive electrodes. This operating mode reduces ohmic loss through the anchor, thereby increasing Q.

DESIGN AND SIMULATION

The Lamé-mode resonator is a square plate that is anchored at its four corners. The Lamé mode shape is isochoric, which minimizes energy loss due to thermoelastic dissipation (TED), resulting in high quality factors. Figure 1 shows the results for a Lamé-mode resonator simulated in COMSOL Multiphysics, showing that the adjacent edges vibrate 180° out of phase.

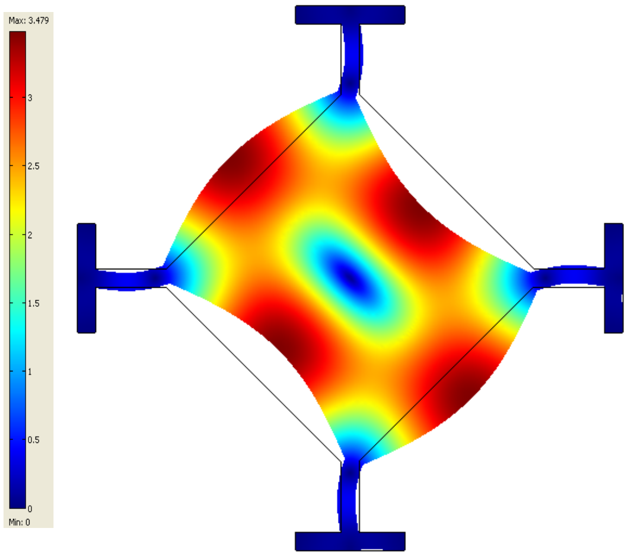

Figure1: COMSOL simulation of a Lamé-mode resonator.

Figure 2 is a schematic depiction of the Lamé-mode resonator, where the transduction electrodes are integrated within the vibrating plate. The four arrays of internal electrodes are optimally placed in the quadrants on the resonator such that adjacent electrodes experience opposite stresses. Electrodes (1) and (3) go under compressive stresses and electrodes (2) and (4) experience tensile stresses. The presence of multiple dielectric gaps increase transduction efficiency and coupling to the fundamental Lamé mode. The resonant frequency of the Lamé-mode resonator is given approximately by [10]:

$$f_o \cong \frac{1}{\sqrt{2} \cdot L_r} \sqrt{\frac{G}{\rho}}$$

where L_r is the length of the resonating plate, ρ and G are the mass density and shear modulus of polysilicon respectively. For the resonator shown in Figure 2, since the silicon nitride dielectric is acoustically well matched to silicon and very thin (few nanometers), we assume that the presence of the dielectric does not affect the resonance

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frequency or the mode shape significantly. The overall performance of the resonator, including motional impedance, also depends on the thickness of the silicon nitride "dielectric gap", and the size and spacing of the internal electrodes.

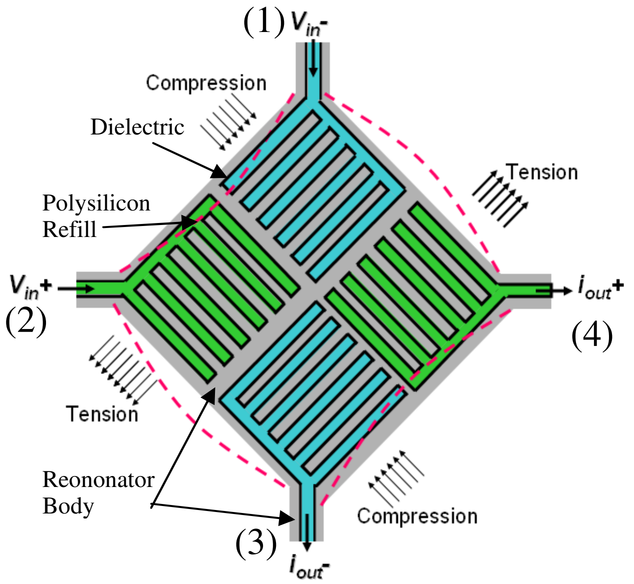

Figure 2: Overview of the Lamé-mode resonator with the integrated internal transduction electrodes (1-4). The DC bias voltage is applied to the resonator body. The electrodes are isolated from each other by dielectric routing (black).

FABRICATION

The resonators were fabricated using a manufacturable double nanogap process shown in detail in Figure 3. First a 1μm layer of thermal silicon oxide is grown on a conductive silicon substrate, followed by 200nm layer of LPVD silicon nitride. This stack provides the necessary isolation and also acts as a etch stop during the release. (1) A 500nm layer of phosphorus (n+) doped polysilicon is deposited and annealed. This layer, which acts as a routing layer for the resonators, is then patterned using an ASML stepper and etched in a RIE step. (2) A 1μm-thick sacrificial silicon oxide layer (LTO) is then deposited. (3) This oxide is then patterned and etched to define the anchors. (4) A 2.5um-thick n+ doped LPCVD structural polysilicon layer is deposited followed by a 0.25μm layer of oxide hard mask. (5) The 600nm-wide trenches are defined lithographically and etched into the hard mask and structural layer using a two-step RIE etch. (6) A 50nm layer of conformal stoichiometric silicon nitride defines the transducing dielectric. (7) The remainder of the trench is filled by a conformal layer of doped LPCVD polysilicon. This polysilicon layer defines the electrodes for this resonator. (8) A chemical mechanical polishing (CMP) step is used to planarize the surface and remove the polysilicon on top of the structural layer to isolate the electrodes from the resonator body. (9) The resonating plate and contact pads are defined and etched using an RIE step. (10) The resonator is then released in a buffered HF solution in a timed etch step. This is followed by a critical point drying (CPD) step to prevent stiction.

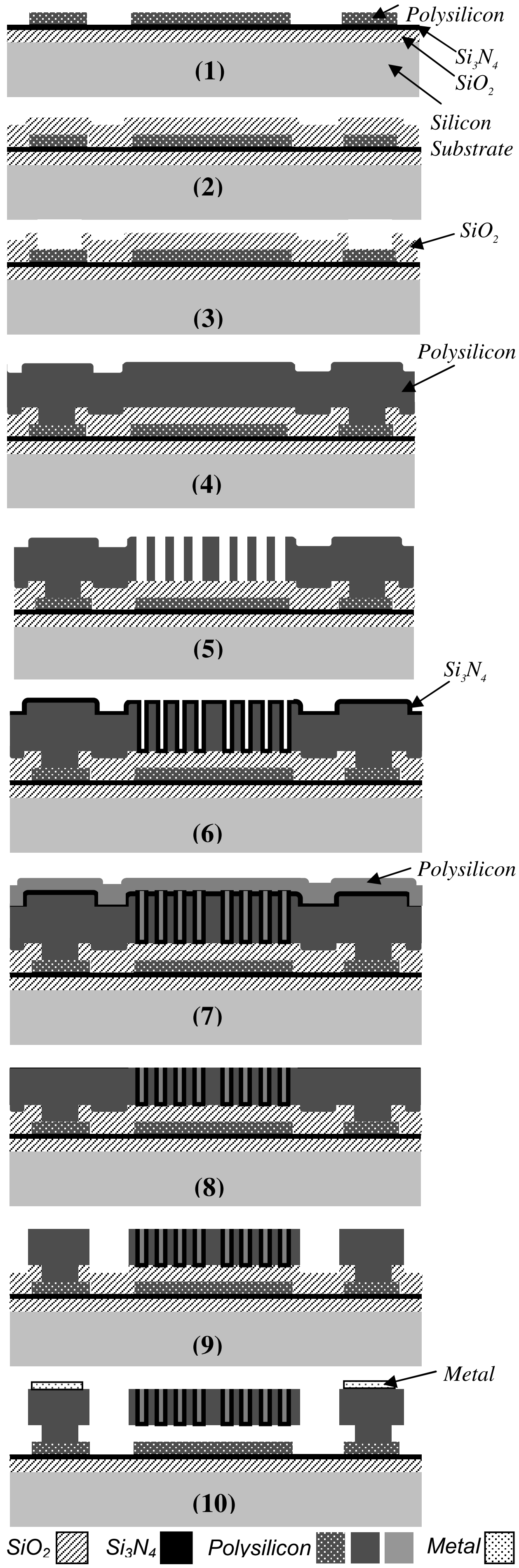

Figure 3: Double Nanogap Process flow for the Lamé-mode resonator.

One of the main features of this process is that nanoscale high-aspect ratio gaps can be fabricated using optical lithography. This is not possible using the conventional fabrication processes, where the gaps are defined by direct etching or a spacer process. Figure 4 shows SEMs of the Lamé-more resonator including the routing lines and contacts pads. The four corner pads are connected to the resonator body and are used for biasing the resonator. The other four electrodes are used for drive and sense. Isolation between pads is done by properly arranging the dielectric routing.

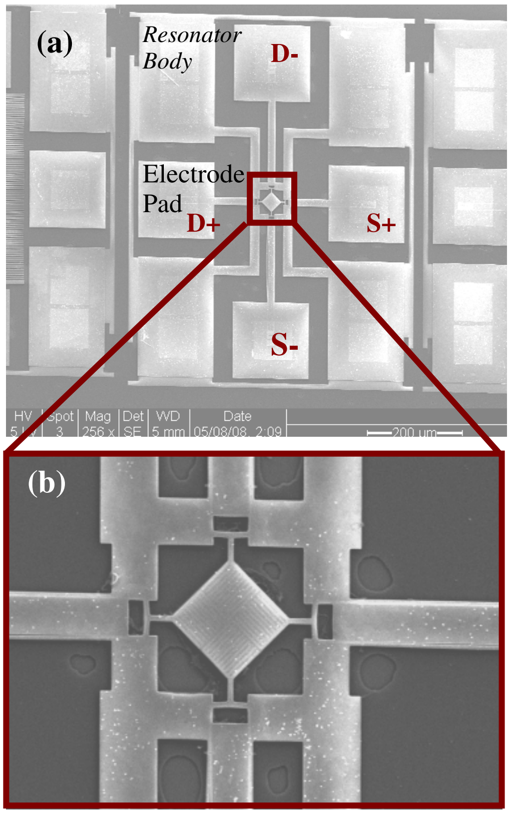

Figure 4: SEMs of the Lamé-mode resonator (a) overall view showing Drive (D+/D-) and Sense (S+/S-) electrodes. The four corner electrodes are connected to the resonator body (b) close up of the released resonating structure.

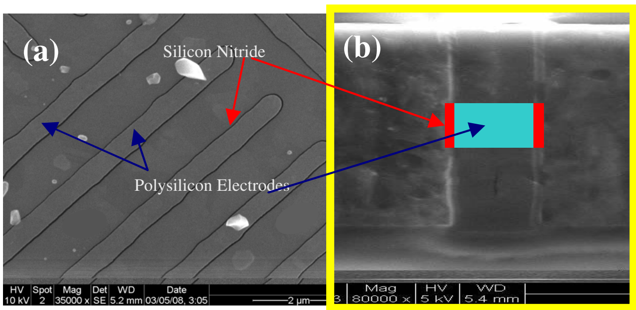

Figure 5: SEMs of the Lamé-mode resonator. (a) Close-up view of the polysilicon electrodes and silicon nitride gaps (b) cross-sectional view showing the trenches filled with silicon nitride/polysilicon.

EXPERIMENTAL RESULTS

Electrostatic resonators are often driven using a two port drive/sense configuration. This scheme limits the feedthrough capacitance to the substrate capacitance plus fringing field capacitance above the resonator. Even though this method has improved the ability to characterize many resonating structures, it deems insufficient to detect the resonance for some structures. As we move towards higher frequencies, the current due to feedthrough capacitance increases and eventually completely masks the motional current of the resonator. In order to cancel out feedthrough, different solutions have been proposed, such as the use of mixing techniques [7]. Differential measurements using a dummy resonator to null out feedthrough has been demonstrated as an effective method. This method is not desirable for on-chip applications because of the added area and complexity of having a dummy resonator next to the actual device [11].

In the single-ended drive and sense configuration, the polarization DC bias voltage is applied to the body of the resonator through the corner electrodes in Figure 4 (a). One of the electrodes in adjacent quadrants is used for drive and sense, respectively. The two other electrodes are grounded. In this measurement scheme, the ohmic resistances of the anchors are in series with the motional impedance and can significantly increase the damping in the resonator. Also, the effective capacitive feedthrough is much higher, which results in a much higher noise floor.

Single-Ended Drive and Differential Sense

Figure 7 shows the measurement setup for a single-ended drive and differential sense scheme. The input voltage is applied to electrode (1), and the signals from the two other adjacent electrodes (3) and (4) were added together using an off-chip power combiner [12]. The fourth electrode, (2) was grounded. The DC bias was applied to the resonator body through the anchors. By adding the sense signals that are 180° out of phase the capacitive feedthrough is reduced to ~ -80 dB, making it easier to detect a resonant peak. The resistive losses from the anchors greatly degrade the quality factor to ~ 2500.

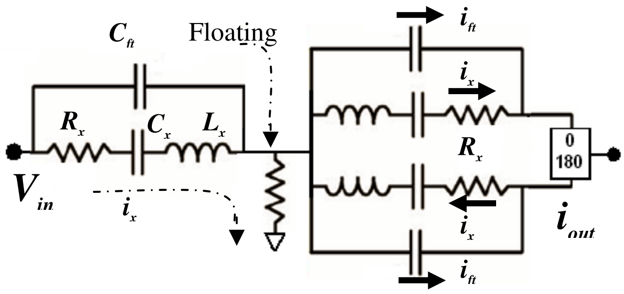

Figure7: Equivalent circuit model for Single-ended drive, differential sense configuration.

Differential Drive and Sense

A fully differential drive and sense scheme takes advantage of the matched internal electrodes to suppress feedthrough. Figure 8 shows the test setup for this configuration. The input signal from port 1 of a network analyzer (Agilent PNA E8361A) was divided into two signals that are 180° out of phase using a power splitter [12]. These two signals were applied to the two adjacent electrodes (1) and (2) in Figure 2. The signals from the two other electrodes (3) and (4) were again combined together using a second power combiner [12]. This signal was then input to the second port of the network analyzer. In this setup, the electrostatic charges are internal between the electrodes and there is no current that passes through the anchors. The "resonator body" node is therefore a virtual ground and capacitive feedthrough is significantly reduced. This measurement scheme also allows for much higher quality factor since the anchor losses are minimized. Using this fully differential drive and sense method, a quality factor of 12050 in air has been demonstrated at a resonant frequency of 128.15MHz. The measured frequency is close to the simulated value of 125.9MHz. The effective motional impedance for this Lamé-mode resonator is calculated to be 31KΩ, including an interconnect resistance of about 8kΩ. The motional impedance can be further reduced by decreasing the thickness of the silicon nitride dielectric, and by further optimization of the spacing and width of the electrodes.

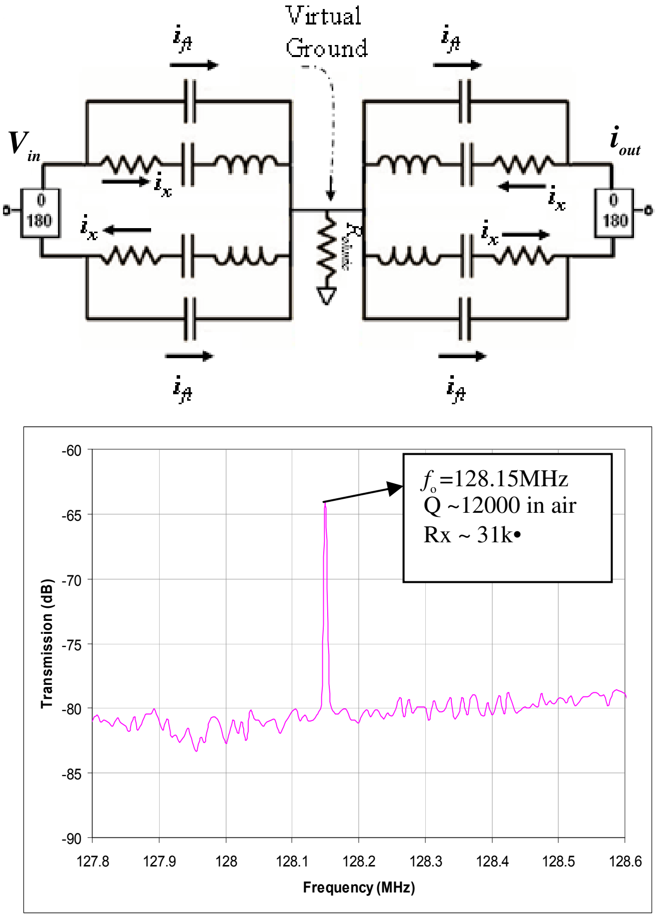

Figure 8: Fully differential configuration (a) Equivalent circuit model and (b) Measured frequency response with a Q of 12050 at 128.15MHz. P_{in} = 0dBm, V_{DC} =20V.

CONCLUSION

This paper, reports a polysilicon Lamé-mode resonator that is driven and sensed by internal capacitive electrodes at 128.15MHz. By optimally placing and orienting the electrodes, the fundamental Lamé mode is efficiently excited and a fully differential drive and sense interface can be implemented within the resonator structure. Using this interface, ohmic losses through the anchors are minimized and a quality factor exceeding 12000 is demonstrated in air.

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