AQUEOUS TRANSDUCTION OF POLY-SIGE DISK RESONATORS

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Abstract: This paper demonstrates an electrostatic transducer for lateral contour-mode resonators in which the transduction gaps are filled with a liquid dielectric (water) having much higher permittivity than air ($\kappa_{water} = 80.1$). Aqueous transduction is more efficient than air-gap transduction (lower motional impedance) and has a higher frequency tuning range compared than solid-dielectric transduction. We have demonstrated a 42 MHz poly-SiGe disk resonator with de-ionized (DI) water confined to the electrode gaps. The resonator has a measured quality factor (Q) of 3,800, motional impedance (R_X) of 3.9kΩ and 3% series frequency tuning range.

Keywords: aqueous transduction, dielectric, poly-SiGe, electrostatic tuning

TRANSDUCERS & EUROSENSORS '07
The 14th International Conference on Solid-State Sensors, Actuators and Microsystems, Lyon, France, June 10-14, 2007

1. INTRODUCTION

The increasingly crowded radio spectrum and the impending arrival of next generation 7-band cellular phones and the joint task force radio system (JTRS) has necessitated front-end filter arrays capable of eliminating both out-of-band and out-of-channel interferers. The filters will require extremely narrow bandwidth, good stop-band rejection and excellent shape factor. Dielectrically-transduced contour-mode MEMS resonators with $Q > 10,000$, low R_X and CAD-defined resonance frequencies from 40 MHz – 2GHz are excellent candidates for designing channel-select filter arrays [1-3]. But unlike thickness shear mode resonators, the frequency expressions for contour modes and flexural vibration modes do not directly couple. It is therefore difficult to perform orthogonal frequency tuning of contour-mode resonators [4].

Sournart *et al* demonstrated that by using a local oscillator (LO) signal that is faster than the response time of a polar fluid, it is possible to prevent electrode polarization and double-layer formation [5]. Electrostatic actuators and viscosity sensors operating in water have been demonstrated using this technique [6,7]. The high permittivity of DI water ($\kappa_{water} = 80.1$) enhances the efficiency of the actuators and sensors, thereby enabling operation at very low DC bias voltages. In this paper we demonstrate that the same approach enhances the performance of contour-mode poly-SiGe disk resonators by constraining DI water to the lateral transducer gaps.

2. POLY-SIGE DISK RESONATOR

To verify the feasibility of using DI water for aqueous transduction of MEMS resonators, we used a previously fabricated 50 nm air-gap poly-SiGe contour mode disk resonator (Fig. 1) [8]. The resonator has $Q = 5,300$ and $R_X = 517$ kΩ in air with a 5V polarization voltage (Fig. 2). However, after submerging the resonator under a water droplet, we could not measure a transmission response due to excessive mass-loading and Q losses resulting from viscous drag.

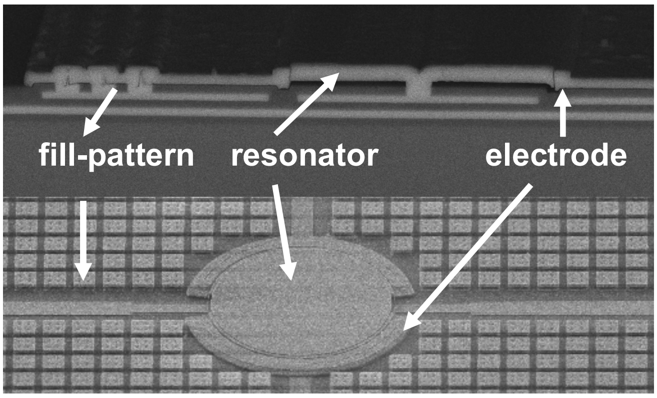

Fig. 1. SEM of poly-SiGe disk resonator showing the resonator, electrodes and chemical-mechanical polishing(CMP) fill pattern.

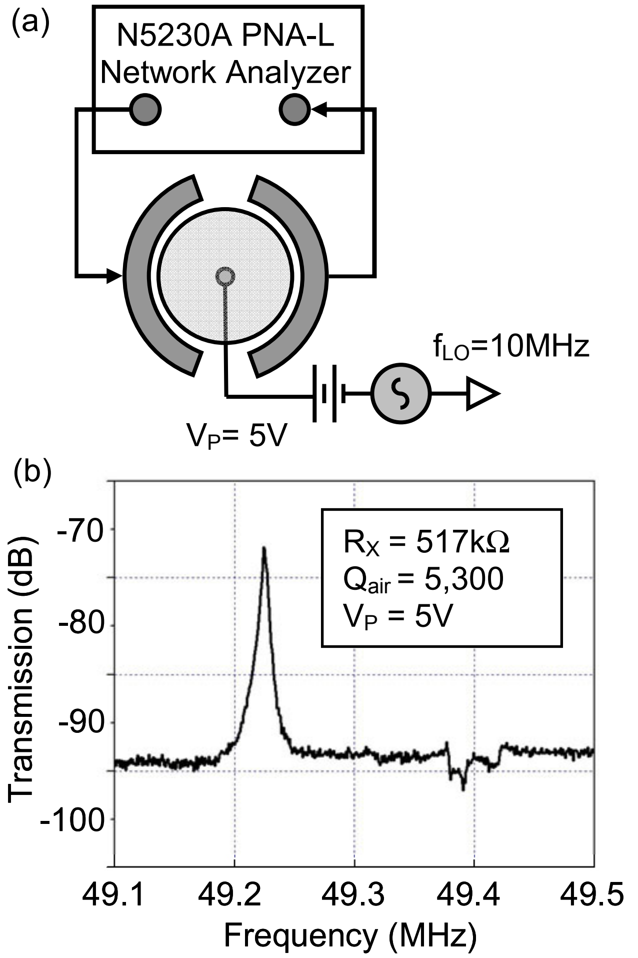

Fig. 2. (a) Transmission measurement setup. The superimposed LO signal prevents bi-layer formation [5] and enables aqueous transduction and (b) Transmission response in air. The LO signal is a harmonic-attenuated source to prevent non-linear excitation.

3. SAM COATING

The resonator was coated with a hydrophobic self-assembled monolayer (SAM) to eliminate mass-loading and viscosity effects of the water droplet on the resonator. The SAM layer is non-conformal, coating the top surface of the poly-SiGe disk resonator, while leaving the 50 nm transducer gaps hydrophilic. A drop of DI water was placed on the resonator and then the chip was slowly tipped to one side to let the water droplet roll-off the structure. The DI water 'wicked' the electrostatic transducer gaps and a transmission response with a Q of 430 at 36 MHz was measured due to the reduced mass-loading and viscous damping on top of the resonator (Fig. 3).

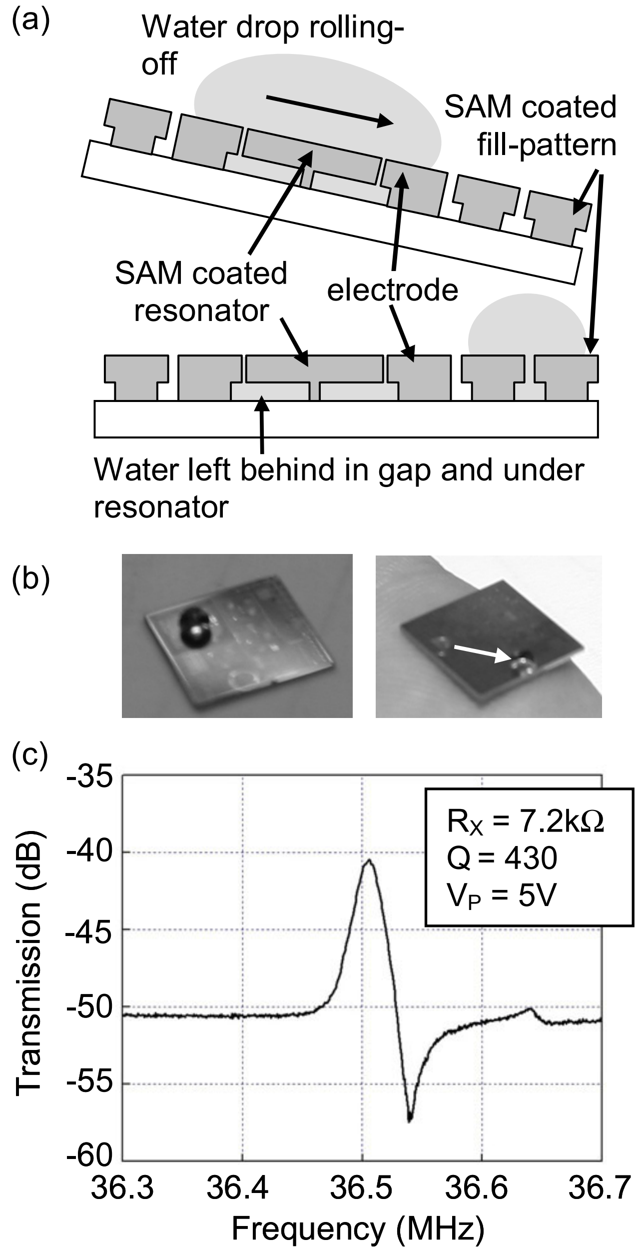

Fig. 3. (a) Schematic illustrating the experiment. The water wicks the 60 nm gap and is left under the structure, (b) Photograph of water droplet placed on resonator and then moved to the edge, and (c) Measured transmission response after water drop moved from the resonator: Q of 430 at 36 MHz.

We suspected the Q was low because water got under the resonator through the space between the resonator and the CMP fill-pattern. Even though the gap under the disk was < 2μm, water underneath would cause viscous damping and degrade the resonator quality factor. To reduce this effect, the water droplet was initially placed further away from the resonator on the SAM-coated fill pattern. The chip was slowly tipped, ensuring that the water droplet rolled over both the transducer gaps of the resonator. The short time that the water droplet overlapped the resonator was sufficient to wick the transduction gaps but greatly reduced the chance of water seeping under the resonator.

The hydrophobic SAM-coated CMP fill-pattern enabled the droplet to 'roll' rather than drag along the chip surface. This allowed repetitive measurements with reasonable control over droplet roll-over. All measurements have Q > 3,500 and $R_X = 4.2$ kΩ near 42 MHz (Fig. 4).

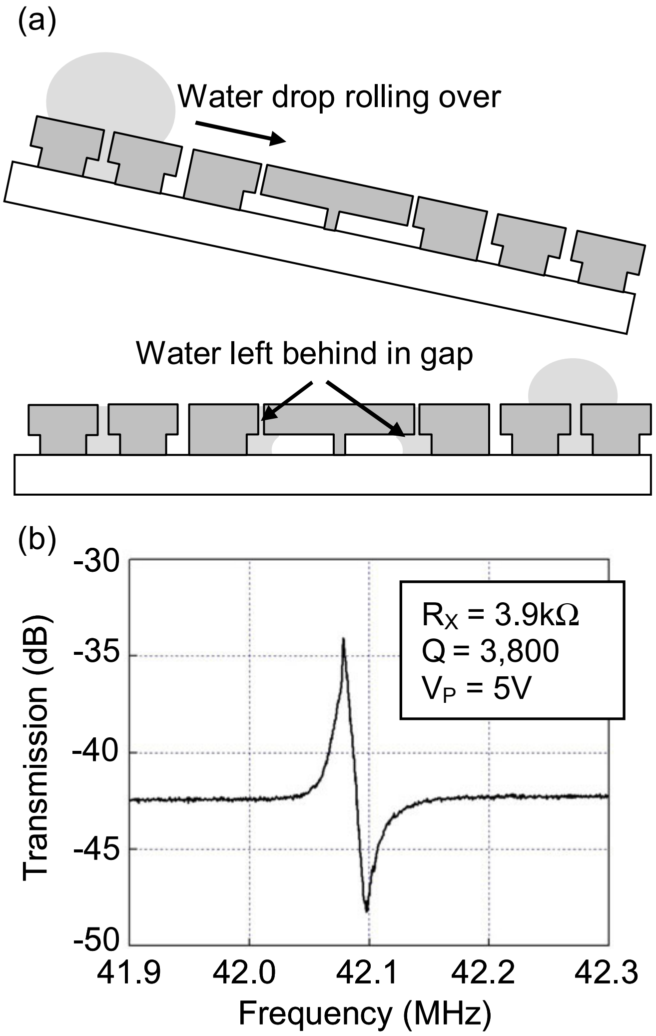

Fig. 4. (a) Schematic of water droplet rolled across the resonator, wicking the transducer gap, but minimizing the water left underneath the resonator (b) transmission response: Q of 3,800 at 42 MHz with Rx = 3.9 kΩ.

The 100× improvement in motional impedance from air-gap to DI water is comparable to previous solid-dielectric transduced resonators [1-3]. The experimental R_X improvement is smaller than the theoretical enhancement (~3000×) most likely because the water did not entire wick the transducers gaps.

4. SERIES FREQUENCY TUNING

Non-linearity in air-gap parallel-plate electrostatic transducers introduces a DC bias-dependent resonant frequency shift. This electrical spring stiffness is given by

$$k_e = \frac{V_P^2 \cdot C_0}{gap^2} \tag{1}$$

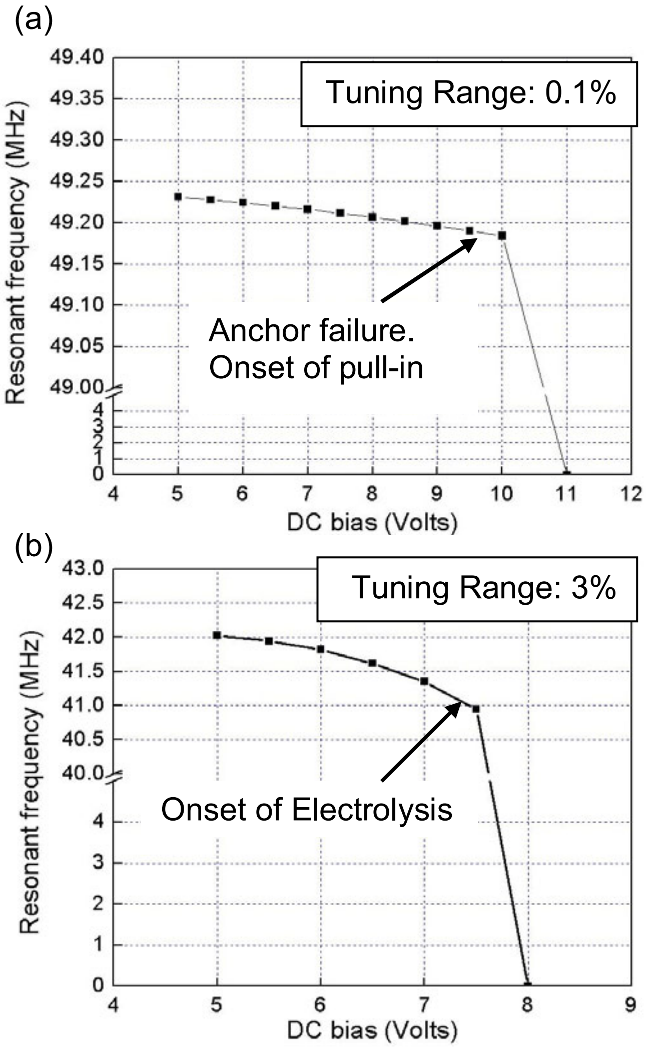

Fig. 5. (a) 0.1% resonant frequency tuning of the air-gap transduced disk resonator before anchor failure, (b) In DI water, the resonator is tuned up to 3%, before the onset of electrolysis.

and directly subtracts from the mechanical spring stiffness k_r. The electrical spring constant provides DC-bias controlled, post-fabrication tuning of electrostatically transduced resonators:

$$\frac{\Delta f}{f_{mech}} = -\frac{1}{2}\cdot\frac{V_P^2\cdot C_0}{k_r\cdot gap^2} = -\frac{1}{2}\cdot\frac{V_P^2\cdot\varepsilon_0\cdot\kappa_r\cdot Area}{k_r\cdot gap^3} \qquad (2)$$

The tuning range of low frequency (< 10 MHz) bending-mode beam resonators using electrostatic spring softening is on the order of 5-10%. This facilitates resonator designs which not only overcome fabrication tolerances and temperature drift, but also enables frequency-agile filter and oscillator design. However, because tunability relies on the ratio of k_e to k_r, the relatively large effective stiffness of air-gap contour mode resonators limits their tuning range < 0.05% [9]. Other tuning techniques such as tuning the series capacitance and heating the resonator, de-*Q* the resonator [10] and cost excessive power consumption [11] respectively. Replacing air in the sub-micron transducer gap with DI water enhanced the electrostatic spring by > 50× and extended the tuning range to 3% - the highest tuning-range reported to date for contour-mode resonators (Fig. 5).

5. CONCLUSION

Aqueous transduction is an excellent alternative to solid-dielectric transduction due to the high permittivity and low acoustic velocity of water. However the operating frequency is limited to <2GHz as water has a significant loss tangent above that frequency [12]. The 3% limit was mainly due to electrolysis of water and bubble formation, which suggests that using an alternate low loss-tangent liquid such as dielectric oil [13] will enable high resonant frequency operation and wide tuning range. In addition to RF applications, aqueous transduction can be used for thermal cooling and isolation, single-molecule mass detection in liquid media and frequency-domain dielectric spectroscopy.

ACKNOWLEDGEMENTS

The authors wish to thank RF Micro Devices, DARPA/MTO's ASP and NMASP programs and the Cornell Center for Materials Research, whose generous grants made this research possible. We would also like to thank Professor David Erickson for liquid droplet dispenser and the UC Berkeley Microfabrication facility for device fabrication.

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