LOW IMPEDANCE VERY-HIGH-FREQUENCY (VHF) BAND THERMAL PIEZORESISTIVE SILICON BULK ACOUSTIC RESONATOR

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ABSTRACT
We present results for full-electrical characterization of a 64 MHz silicon bulk acoustic resonator with quality factor (Q) of 10⁴ and achieving an insertion loss of -35dB without depending on sub-micron capacitive gaps. The high transduction results from using thermal actuation in addition to piezoresistive sensing. In contrast to typical capacitive bulk acoustic resonators, both transduction and Q increase when reducing the device thickness. To this effect, our 10μm thick resonators had 23dB less insertion loss than ones that were 25μm thick, with the same lateral dimensions. We also present an equivalent circuit model which we show to be capable of providing a close fit to our experimental measurements.

INTRODUCTION
Thermally-actuated micromechanical resonators with piezoresistive readout (thermal-piezoresistive resonators - TPRs) are highly attractive as they scale much better with frequency compared to capacitive resonators in terms of electromechanical transduction [1]. These afford for low impedance without the dependence for nanometer narrow capacitors. It has been further shown that self-sustained oscillation is attainable in such resonators, eliminating the need for amplifying electronics [2]. Given these benefits of TPRs, this paper examines the effects of dimensional scaling (including both lateral feature size and thickness) on their performance. In particular, we here focus on Q and the transduction efficiency of thermal drive relative to capacitive drive. Our proposed equivalent circuit model and related parameters closely match the measured S21 transmission, including the frequency-dependent effects in the heavy feedthrough interference.

DEVICE DESCRIPTION AND MODELING
Fig. 1 provides a schematic of the VHF silicon bulk acoustic resonator that comprises a pair of parallel beams serving both as mechanical springs and thermal actuators. The parallel beams are clamped mid-way and terminated on each end by proof masses. We have simulated the desired vibration mode shape by finite-elements (FE) using COMSOL, shown in Fig. 1. The simulated modal frequency is 64.76MHz. Fig. 2 shows a micrograph of the resonator, fabricated using a standard SOI MEMS process. The biasing schematic to drive the beams by thermal actuation has been included in Fig. 3. AC (Iac) and DC (Idc) drive currents are applied across the resonator. This generates joule heating in the beams at the AC drive frequency that is determined by the product of Iac and Idc. As the beams vibrate according to the mode shape shown in Fig. 1, the resulting stress modulation of in the beams changes their resistance because silicon is piezoresistive. This allows piezoresistive readout. The result is a high coupling coefficient difficult to achieve in capacitive resonators without sub-micron gaps. The output current of the TPR is typically accompanied by a much stronger resistive feedthrough current, which can be described by our proposed equivalent electrical circuit shown in Fig 4.

The output current iout is a combination of the motional current (g_m(ω)v_m), g_m(ω) is the transconductance and v_m is the input AC drive voltage) and feedthrough current that is associated with a parasitic element of admittance Y_f(ω):

\[ g_m(\omega) = \frac{\Pi}{(1-(\omega / \omega_0)^2 + j(\omega / \omega_0)/Q)} \]

(\(\omega_0\) is the modal frequency, \(\Pi\) is the thermal-piezoresistive transduction factor that is given by:

\[ \Pi = \frac{16\alpha G R_{dc}}{\pi \omega_0 C} \]

(2)

\(G\) is the gauge factor, \(C\) is the thermal capacitance, and \(\alpha\) is the thermal coefficient of expansion.

DEVICE MEASUREMENT AND MODEL FIT
Figs. 5 and 6 respectively show the magnitude and phase plots of the measured S21 transmission with 60mA DC drive current. The level of feedthrough (modelled by the dashed line) is sufficiently high to mask the resonant peak. By subtracting this from the measured transmission, we obtain just the motional output, to which we fitted a model curve based on equation (1) as shown in Fig 7. In comparing the 10μm-thick to 25μm-thick device, we have found that \(Q\) and \(\Pi\) are each greater by a factor of 4 and 3.6 respectively. This leads to an overall enhancement by 25dB from thinning the device. Adding feedthrough back to the model, we obtained the good fit in Figs. 5 and 6. As a reference, thermal compared to capacitive drive (even at 50V bias) provided close to 50dB increase in force. This advantage equals out when the beams are longer (e.g. 300 μm). The reported device is aligned to the [110] axis. No resonance was detectable for devices aligned to [100].

REFERENCES

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Figure 1: FE simulation of the desired vibration mode shape of the TPR silicon resonator using COMSOL.

Figure 2: Optical micrograph of the fabricated silicon bulk acoustic TPR with device layer thickness of 10μm.

Figure 3: Circuit schematic of biasing configuration to provide thermal actuation and piezoresistive readout.

Figure 4: Equivalent electrical circuit seen from the two anchor points of the silicon bulk acoustic TPR.

Figure 5: Measured S21 transmission magnitude of a silicon TPR (10μm-thick) with $I_d$ of 60mA.

Figure 6: Measured S21 transmission phase of a silicon TPR (10μm-thick) with $I_d$ of 60mA.

Figure 7: Extracted S21 transmission magnitudes of resonators with device layer thicknesses of 10 and 25μm. Dashed lines are the model predictions obtained using equation (1).

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