THERMAL ACTUATION, A SUITABLE MECHANISM FOR HIGH FREQUENCY ELECTROMECHANICAL RESONATORS

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ABSTRACT

This work presents high-frequency thermally actuated micromechanical resonators and demonstrates potential suitability of thermal actuation for high frequency applications. Thermally actuated single crystal silicon resonators with frequencies up 61 MHz have been successfully fabricated and characterized. It is shown both theoretically and experimentally that as opposed to the general perception, thermal actuation is a more efficient actuation mechanism for higher frequency rather than lower frequency applications. Thermal actuation can become a viable and competitive approach as the electromechanical device dimensions reach the lower micron and nanometer range.

INTRODUCTION AND MOTIVATION

As the potential emerging technology for next generation integrated frequency references and resonant sensors, MEMS resonators have received a lot of attention over the past decade [1-5]. A wide variety of high frequency micro/nanoscale electromechanical resonators have been demonstrated over the past few years. Most of such resonators use piezoelectric [1,2] or electrostatic (capacitive) [3-5] electromechanical transduction each having its advantages and disadvantages. Piezoelectric resonators are mainly limited by their material integration requirements and relatively low quality factors, while the major bottle-neck for capacitive resonators is the weak electromechanical coupling leading to the need for deep submicron transduction gaps and associated fabrication challenges.

Thermal actuation on the other hand is a well known mechanism that can be implemented at microscale without any fabrication challenges or the need for sophisticated material integration. In addition, thermal actuators have great properties such as large actuation force, low operating voltage and simplicity of design and integration. On the downside their power consumption and high body temperature limits their application in some cases. Furthermore, thermal actuators are usually considered and referred to as slow actuators only suitable for DC or very low-frequency applications. This is mainly due to the time delay for the temperature of a heating element to reach the desired level and generate the expected force. Consequently, although thermally actuated micromechanical resonant devices with frequencies in the hundreds of kHz have been utilized for chemical [6] or physical [7] sensory applications, there has been very little study on utilization of thermal actuation in high frequency resonant devices. In this work we demonstrate the possibility of thermal actuation of resonators with much higher frequencies in the tens of MHz range and show theoretically and experimentally that the thermal actuators become more efficient as the resonator dimensions are scaled down to reach higher resonant frequencies.

DEVICE CONCEPT AND OPERATION

Figure 1 shows the schematic top view of the resonator structures used in this work referred to as I^2-Bulk Acoustic wave Resonators (I^2-BARs) [4]. Thermal actuation occurs by passing a current between the two pads on the two sides of the structure resulting in an ohmic power loss in the structure.

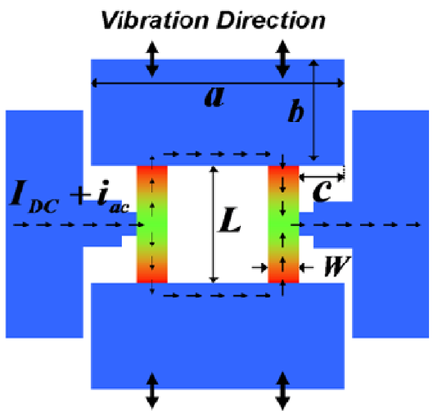

Fig. 1. Top view schematic diagram of a thermally actuated I^2-BAR showing the current flow and the qualitative distribution of AC temperature fluctuation amplitude (red being the maximum and blue minimum).

By passing a combination of a DC and an AC current, the power loss will have a component at the same frequency as the applied AC current: $P_{ac} = 2R_eI_{dc}i_{ac}$, where R_e is the electrical resistance between the two pads and I_{dc} and i_{ac} are the applied DC and AC currents respectively. The fluctuating power loss results in a fluctuating temperature gradient and therefore fluctuating thermal expansion of the structure. Due to their higher electrical resistance, most of the heat gradient is generated in the narrow pillars in the middle of the structure. The AC extensional force resulting from the fluctuating temperature in the pillars can actuate the resonator in its in-plane extensional resonance mode.

As the resonator vibrates, the alternating tensile and compressive stress in the pillars results in fluctuations in their electrical resistance (due to the piezo-resistive effect). This results in fluctuations in the DC current passing through the resonator that represents the vibration amplitude (output signal) of the resonator.

At resonance frequency the vibration amplitude of the resonator is Q times larger than the deformation amplitude resulting from a DC force with the same amplitude. It can be shown that the overall transfer function from the input AC voltage to the output current at the resonance frequency of the structure is:

$$g_m = \frac{i_{ac_{out}}}{v_{ac_{in}}} \propto \frac{2\pi_l EQ\alpha I_{dc}^2 R_{th}}{R_{th} C_{th} \omega_m + 1} \quad (1)$$

where π_l and E are the longitudinal piezoresistive coefficient and Young's modulus of the structural material respectively, R_{th} and C_{th} are the thermal equivalent resistance and capacitance respectively, and ω_m is the mechanical angular resonant frequency of the resonator. The denominator in Eq. 1, represents with the effect of thermal delay of the thermal actuators in the system (in this case the pillars). Typically, with the dimensions in the microscale and larger, the thermal time constant ($\tau_{th} = R_{th}C_{th}$) is much larger than the mechanical time constant of the structure and at resonance temperature fluctuations will be lagging ~90 degrees with respect to the input AC current. Therefore, Eq. 1 can be simplified as:

$$g_m = \frac{i_{ac_{out}}}{v_{ac_{in}}} \propto \frac{2\pi_l EQ\alpha I_{dc}^2}{C_{th} \omega_m} \quad (2).$$

If a mechanical structure is scaled down by a factor X, its mechanical resonant frequency (ω_m) increases by a factor of X. On the other hand, C_{th}, which is proportional to the mass and therefore volume of the thermal actuators, shrinks by a factor of X^3. Consequently, according to Eq. 2, if I_{dc} is kept constant, the resonator current gain increases by a factor of X^2. Furthermore, if I^2_{dc} is reduced by a factor of X, reducing the static power consumption of the resonator also by X times (assuming a constant electrical resistance), g_m will still be improved by a factor of X. In conclusion, both power consumption and current gain of a thermal-piezoresistive resonator can be improved simultaneously by shrinking the resonator dimensions and therefore increasing its mechanical resonant frequency.

RESONATOR FABRICATION

A single mask process [7] was used to fabricate the resonators on two different low resistivity SOI substrates: 1) an N-type SOI substrate with device layer thickness of 10μm and buffer oxide (BOX) thickness of 3μm, and 2) a P-type SOI substrate with device layer thickness of 15μm and BOX thickness of 5μm. The fabrication process starts by thermally growing a thin (~200nm) layer of silicon dioxide on the device layer that will serve as a hard mask for silicon etching. The silicon dioxide layer is patterned to define the resonator structures. The structures are then carved into the SOI device layer all the way down to the BOX by plasma etching. Finally, the structures are released by etching the underlying BOX layer in hydrofluoric acid (HF). At the same time the remaining oxide mask on top of the structures is also etched away.

Two different I^2-BAR structures, one having much narrower extensional beams (pillars) and larger masses (lower frequency) and the other set having much thicker extentional beams and smaller masses (higher frequency) were chosen. In order to study the scaling effect on efficiency of thermal actuators, scaled versions of each of the two structures (while maintaining the structural aspect ratios) were included in the layout.

Figure 2 shows the SEM view of a few of the fabricated resonators.

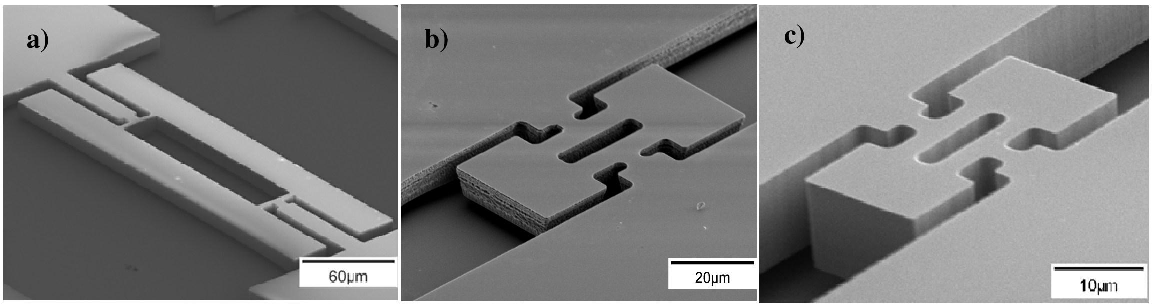

Fig. 2. SEM views of a) a fabricated 15μm thick 7.9MHz I^2-BAR etched by DRIE (ICP + Bosch process) b) a 31MHz 10μm thick resonator etched using a custom cyclic RIE recipe, and c) a 61MHz 15μm thick I^2-BAR etched by DRIE. (ICP + Bosch process).

MEASUREMENT RESULTS

The fabricated resonators were tested in a one-port configuration with the narrow pillars acting simultaneously as both thermal actuators and piezo-resistive sensors.

Figure 3 shows the measured resonant peaks for the resonator of Fig. 2c with different DC bias currents under both vacuum and atmospheric pressure. Resonant frequency of ~61MHz with quality factors ranging from 12,000-14,000 were measured for this resonator under vacuum. Under armonspheric pressure, the quality factor dropped to 6,000-8,000. As expected, as the DC bias current increases the output signal level increases while due to the higher static temperature and softening of the structural material, the resonant frequency decreases.

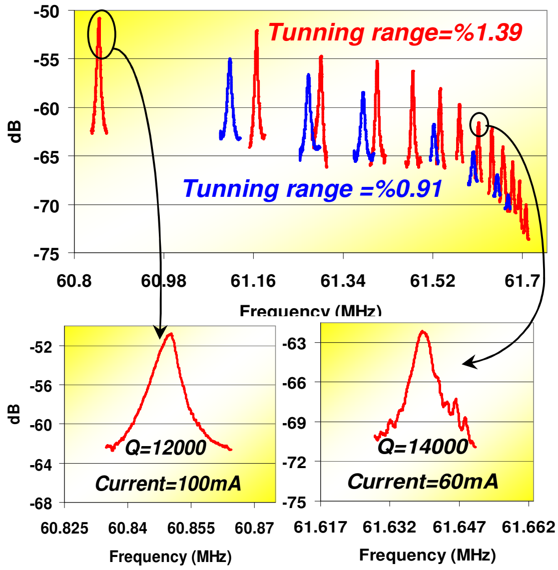

Fig. 3. Measured frequency responses for the thermally actuated 61MHz resonator of Fig. 2c with different bias currents. Red and blue plots refer to vacuum and Air testing conditions respectively. Current range = 45-100mA in vacuum and 55-100mA in air.

Figure 4 shows COMSOL modal analysis results on the same structure confirming that the measurements in Fig. 3, correspond to the fundamental in-plane extensional mode of the structure.

To have a measure of the thermal-piezoresistive transduction efficiency for comparison between different resonators, the effect of bias current and mechanical quality factor need to be factored out from the current gain. Therefore, a coefficient (*K*) has been defined as:

$$K = \frac{g_m}{QI_{dc}^2} = \frac{2\pi_l E\alpha}{C_{th}\omega_m} \qquad (3).$$

K coefficients extracted from the measurement results for different resonators under different DC biases are shown in Fig. 5. The data corresponding to similar resonators with different scales are presented on the same axes.

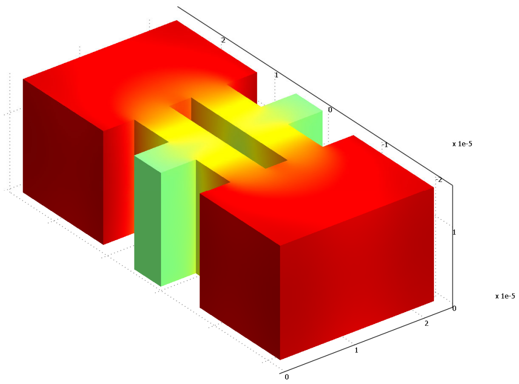

Fig. 4. COMSOL modal analysis, showing the in-plane resonance mode shape for an I^2-BAR with *a=22µm, b=15µm, c=4.4µm, L=18µm, W=5µm* showing a frequency of 60.77MHz for the fundamental in-plane extensional mode. Darker colors show locations with larger vibration amplitude.

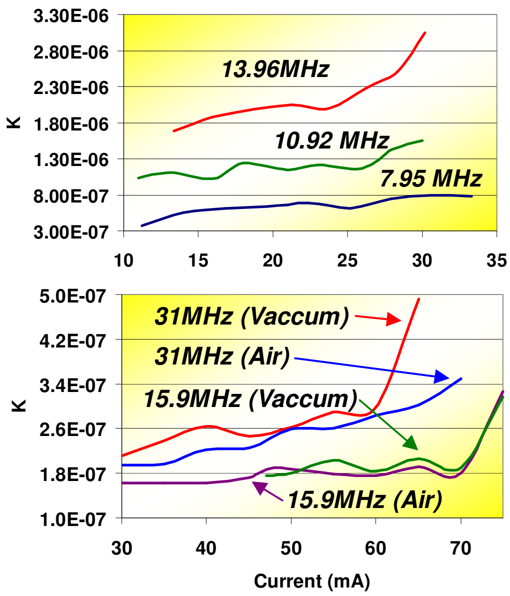

Fig. 5. Extracted thermal transduction efficiency (*K*) values for different resonators versus resonator bias current. In both sets of resonators, the smaller (higher frequency) devices have higher transduction efficiency.

As discussed previously and expected from Eq. 2, as the dimensions of the resonators are scaled down, the *K* coefficients become larger. This is in agreement with the discussion about the suitability of the thermal transduction for higher frequencies. The 61MHz resonator of Fig. 3 is not included in the lower plot of Fig. 5 along with the 15.9MHz and 31MHz devices as it is fabricated on a thicker SOI substrate with a different doping type and through a different silicon DRIE process causing much less undercut. Therefore, its aspect ratios are different from the other two resonators and it cannot be considered a scaled down version of the other two. The wider and taller pillars in the 61MHz resonator result in a lower *K*.

Table 1 presents measured data for different resonators under different bias current and pressure conditions.

Table. 1. Summary of the measurement results obtained from I^2-BARs with different dimensions showing increasing K as the same resonator is scaled down. The 15.9MHz and 31MHz resonators are fabricated on a 10µm thick device layer etched using a custom cyclic RIE recipe, the rest of the devices are fabricated on a 15µm thick device layer etched by silicon DRIE.

Scale Factor	Resonator Dimensions (µm)					Q	Freq. (MHz)	Current (mA)	g_m (µA/V)	K (×10-7 W^{-1})	Cond.
	a	*b*	*c*	*L*	*W*						
1X	274	30	67	31	4	59000	7.95	11.2	2.7	3.65	Vac.
						37000	7.75	40.5	53	8.67	Vac.
0.7X	193	21	47	22	2.7	24000	10.87	26	20.4	12.57	Vac.
						16000	10.63	30.5	22.2	14.93	Vac.
0.5X	144	16	35	16	2	12000	13.94	21.3	11.2	20.63	Vac.
						7000	13.63	30.9	24.4	36.49	Vac.
1X	80	53	16	64	17.4	28500	15.89	55	15.4	1.78	Vac.
						29000	15.65	80	55.5	3	Vac.
						10800	15.91	50	4.2	1.80	Atm.
						10900	15.73	90	30.3	3.43	Atm.
0.5X	39	25	8.5	32	8.5	43000	31.19	10	0.56	1.29	Vac.
						38500	30.72	65	83.3	5.12	Vac.
						13900	31.19	20	0.91	1.64	Atm.
						12000	30.90	70	20.4	3.47	Atm.
NA*	22	15	4.4	18	5	14000	61.64	60	7.7	1.53	Vac.
						12000	60.85	100	29.4	2.45	Vac.
						7500	61.65	60	4.54	1.68	Atm.
						7700	61.11	100	17.8	2.32	Atm.

* Unlike the other two resonators in this group, this device has been fabricated on a thicker substrate and etched in an ICP system. Therefore it has wider and taller pillars resulting in lower *K*.

CONCLUSIONS AND FUTURE WORK

It was demonstrated theoretically and experimentally that thermal actuation is not only a suitable approach for actuation of high frequency micro and nanoscale high frequency electromechanical resonators, but also it becomes a more viable approach as the resonator dimensions are shrunk down to reach higher operating frequencies. One of the major advantages of thermal-piezoresistive resonators over electrostatic resonators is their low output resistance, which is equal to the electrical resistance of the sensing piezo-resistors making it much easier to match such device to other components in electronic circuits.

Future work includes extensive modeling and design optimization to achieve stronger electro-thermo-mechanical coupling (higher current gain) and demonstration of nanoscale resonators with orders of magnitude higher frequencies and lower power consumption.

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