A SELF-CONTROLLED FREQUENCY TRIMMING TECHNIQUE FOR MICROMECHANICAL RESONATORS

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ABSTRACT

This work demonstrates the proof of concept for a self-controlled electronic frequency trimming technique for micromechanical single crystalline silicon resonators. Trimming is carried out via localized self-induced thermal oxidation occurring during extreme thermal actuation of the resonant structures. The cooling effect at resonance, discussed for the first time in this work, allows the localized oxidation to stop automatically as soon as the resonator frequency reaches the targeted actuation frequency applied to the structure. The viability of this concept is demonstrated by application of both off-resonance and at-resonance actuation signals to fabricated resonators showing that as opposed to the off-resonance signals, the at-resonance signals with the same intensity do not lead to frequency trimming.

INTRODUCTION

As the potential emerging technology for next generation integrated resonant sensors and frequency references as well as electronic filters, micro-electro-mechanical resonators have attracted a lot of attention over the past decade. [1,2]. The resonance frequency of silicon micromechanical resonators is dependent on the physical dimensions of the resonating structure. Even very small (few nanometers) fabrication induced dimensional imprecision can lead to intolerable frequency inaccuracies for micromechanical resonators. Therefore, process variations across the substrate (e.g Non-uniformities in photolithography, etching and film thickness) leading to variations and mismatch in the mechanical resonant frequencies are a major challenge for batch fabrication of micromechanical resonators [1,3]. Achieving ppm level frequency accuracy and uniformity in batches of micromachined resonators is a daunting task necessitating post-fabrication trimming [4].

Frequency trimming techniques for MEMS silicon based micromechanical resonators, range from pulsed-laser-deposition/trimming, electrostatic trimming and other process alterations. Post-fabrication frequency trimming via pulsed-laser-deposition [4,5] is unlikely to be able to provide ppm level frequency accuracy due to the difficulties in controlling the geometry and the amount of the mass deposited by the laser. Furthermore, the quality factor of the resonator is often degraded with additional materials on the resonator. An alternative method to laser enhanced material deposition for frequency trimming is based on material removal [4] which also suffers from frequency accuracy issues.

Digital trimming technique has been reported by using a high resolution fractional-N synthesizer in a phase lock loop architecture for locking a voltage-controlled oscillator to a silicon microresonator-based reference oscillator [4]. On the downside, such a digital trimming technique may not be contiguous, is power hungry, and considerably increases the overall phase noise of the oscillator and the integrated circuit die area.

Other post fabrication processes such as gold diffusion into the bulk of the resonator have also been demonstrated for frequency trimming purposes. In this method by running a current through the structure, a gold coating is diffused into the resonator

silicon structure. Upon cooling, the gold diffusion slightly increases the stiffness of the resonating structure, which results in an upward shift in resonance frequency [6].

I-shaped thermally actuated micromechanical resonators are among the most suitable resonant structures offering unmatched design and transduction flexibility [7]. However, relatively narrow thermal actuators (often submicron) required to minimize power consumption of such devices, make achieving frequency accuracy even more challenging. It has previously been shown that localized thermal oxidation via joule heating can be used as a simple method for post-fabrication frequency trimming of such resonators. Using this technique, permanent frequency shifts up to ~3.7% were demonstrated for a 53 MHz resonator [8]. The approach was based on a relatively large bias current passing through the resonator structures. Joule heating caused by ohmic losses locally raises the temperature of the structure in the actuator beams (which supply the structural stiffness in the resonant mode of interest) to several hundred degrees Celsius (700-1200°C). The elevated temperature causes thermal oxidation to occur on the surfaces when placed in an oxygen rich atmosphere. The change in dimensions and Young's modulus as well as internal stress, caused by oxidation, result in a permanent change in the resonant frequency of the device.

This work shows preliminary measurement results for a more advanced version of the same localized oxidation based trimming approach with the potential ability to automatically limit itself.

RESONATOR DESCRIPTION

The resonators utilized in this work are referred to as I-shaped resonators [7]. Such devices are very suitable for thermal actuation as they can easily be actuated by passing a fluctuating electrical current through the actuator beams in the middle of the structure. Their operating principle has thoroughly been explained in [7]. The resonators vibrate in the in-plane extensional resonant mode. In this mode the masses on the two ends of the beams vibrate back and forth in opposite directions. At resonance, the resistance of the pillars is modulated by the resulting alternating mechanical stress due to the piezoresistive effect. This results in a detectable alternating motional current component in the device.

Fabrication of the resonators was carried out using the standard single mask SOI-MEMS process which starts by growing a thin (~200nm) layer of thermal silicon dioxide on the substrate. The silicon dioxide layer is patterned to define the resonator structures. The silicon structures are then carved into the SOI device layer by deep reactive ion etching (DRIE) of silicon all the way down to the buffer oxide layer. Finally, the structures are undercut by dipping in 49% hydrofluoric acid (HF) to etch the underlying buried oxide layer (BOX) layer. At the same time the remaining oxide mask on top of the structures is also etched away. The result will be suspended single crystalline silicon resonant structures with integrated thermal actuator/piezoresistive sensors. Figure 1 shows the SEM view of a 4µm thick 18MHz I-shaped

resonator which was fabricated on an N-type low resistivity SOI substrate with a BOX thickness of 5μm.

Figure 1: SEM view of an 18MHz, 4μm thick thermal-piezoresistive I-shaped resonator. The resonator is fabricated on a low resistivity (~0.01Ω.cm) N-type SOI substrate using a single mask process.

SELF-CONTAINED TRIMMING PRINCIPLE

As opposed to the previous work in which we applied a DC current [8], in this method localized oxidation is induced by applying an AC voltage ($V_{ac}\cos(2\pi f_a t)$) (Figure 2a) across the structure. The generated power has a square relationship with the applied voltage and gives birth to two frequency components at DC and twice the actuation frequency ($2f_a$):

$$P = \frac{v_{ac}^2 \cos^2(2\pi f_a t)}{R_A} = \frac{v_{ac}^2}{2R_A} + \frac{v_{ac}^2 \cos(4\pi f_a t)}{2R_A} \quad (1)$$

where R_A is the electrical resistance of the resonator and f_a is the actuation frequency. The resulting power translates to elevated temperature of the thermal actuators. It can be shown that the AC temperature term is proportional but also has a 90° lag in comparison to the AC power [9]. The resulting fluctuating temperature causes a thermal stress and therefore an alternating mechanical force inside the thermal actuators. If this applied force has the same frequency as the resonance frequency of the resonator, it actuates the device. In order for this to happen, the frequency of the actuation voltage should be half of the mechanical frequency. The resulting mechanical vibration of the resonator has a 90° lag with respect to the mechanical force [9]. The mechanical vibration leads to resistance fluctuations of the resonator due to the piezoresistive effect. The AC value is proportional and in phase with the mechanical vibration. Therefore this AC term which adds to the electrical resistance of the device has a 180° lag with respect to the applied actuation current due to thermal and mechanical delays. For N-type silicon the piezoresistive coefficient is negative which itself adds a 180° lag. Thus, the resistance fluctuation is in phase with the applied voltage (blue plot in Figure 2b) and this leads to the overall resistance of: $R_A + r_{ac} \cos(2\pi f_0 t)$. As a result the ohmic power in the structure will be:

$$P = \frac{v_{ac}^2 \cos^2(\pi f_0 t)}{R_A + r_{ac} \cos(2\pi f_0 t)} = \frac{v_{ac}^2 (1 + \cos(2\pi f_0 t))}{2(R_A + r_{ac} \cos(2\pi f_0 t))} \quad (2)$$

The r_{ac} value itself is equal to:

$$r_{ac} = \frac{R_A |\pi_l| E x_m}{L} \quad (3)$$

where π_l is the longitudinal piezoresistive coefficient, E is the young's modules, L is the length of the thermal actuator and x_m is the vibration amplitude. The DC component of Eq.2 can be found to be equal to:

$$P_{DC} \cong \frac{v_{ac}^2}{2(R_A + r_{ac})} \quad (4)$$

By comparing the DC power consumptions in the two different states of off-resonance (DC part of Eq. 1) and at-resonance (Eq. 4), it is obvious that at-resonance state the power consumption goes down (Figure 2c). Therefore, during resonance the static temperature decreases (Figure 2d). This difference in temperature between the two cases of at-resonance and off-resonance can be utilized for self controlled trimming of the structures.

Figure 2: Waveform representation of a) Input AC voltage, b) Resistance of the resonator, c) Ohmic loss and d) Temperature in both conditions of off-resonance (red) and at-resonance (blue). It is assumed that $r_{ac}=0.15R_A$. Therefore, the DC power consumption drops 14% during resonance with respect to its off-resonance mode. As a result assuming the initial static temperature of 1100°C, temperature decreases to 950°C.

Figure 3 schematically depicts the proposed self-controlled electronic frequency trimming technique for micromechanical single crystalline silicon resonators. Half the desired frequency is applied with sufficient amplitude to allow the actuators to reach the temperatures required for oxidation. As the oxidation process starts, the internal stress of the thermal actuators changes. This causes the resonance frequency of the resonator to gradually change and become closer to the desired resonance frequency. The process goes on until the resonance frequency of the resonator exactly matches the desired resonance frequency. At this point, the resonator starts vibrating and therefore the overall resonator static temperature drops significantly which could stop the local

oxidation. In order to investigate the feasibility of this technique, assuming large vibration amplitudes and large piezoresistive coefficients, r_{ac} can become comparable with R_{DC} . For instance, with a conservative piezoresistive coefficient of $(-10 \times 10^{-11} \text{Pa}^{-1})$, and vibration amplitude of 100x smaller than the actuator length, $r_{ac} = -0.15R_A$. In this case the value of P_{DC} at resonance becomes 14% less than its value out of resonance. This translates to a 14% reduction of the actuator static temperature difference from the surroundings. For instance, a resonator heated up to 1100°C by the

applied currents out of its resonance frequency, can cool down to about 950°C if the actuation frequency becomes equal to its mechanical resonant frequency. Therefore, the overall resonator static temperature could drop significantly if the applied actuation AC signal has the right frequency required for excitation of the resonant mode. Sharp dependence of thermal oxidation rate on temperature can turn small temperatures changes into major changes in the oxidation rate and completely stopping it.

Silicon dioxide forming on the hot surfaces

Silicon dioxide formation and freq. shift stop

Figure 3: Schematic demo of the frequency trimming technique. When an actuation voltage with half the target resonance frequency is being applied across the actuator beams, the elevated temperature allows oxidation to take place on their surface. As a result, the structural stiffness gradually changes and the resonant frequency moves towards the target. When the mechanical resonant frequency reaches the target frequency, the resonator starts vibrating and therefore cools down. As a result, oxidation stops and the frequency will not shift further.

MEASUREMENT SETUP AND RESULTS

Figure 4 shows the schematic diagram of the test setup used for performing the localized thermal oxidation process. The

Figure 4: Schematic diagram of the setup used in this experiment. Moisture rich oxygen was driven into the chamber while a sinusoidal ac current was run through the device.

resonators were placed in a chamber while connected to the test setup. Moisture rich oxygen was delivered into the chamber through an inlet tube to provide a suitable atmosphere for wet oxidation of silicon. The localized oxidation and therefore frequency trimming starts by application of a large amplitude AC voltage applied through the structure using a function generator. After this localized oxidation run, the devices were disconnected from the AC voltage source and were tested at room temperature using a network analyzer.

Figure 5 shows the change in the measured resonance frequency after different oxidation steps, for the 18MHz resonator of Figure 1. Different plots show data taken after localized oxidation runs via actuation by AC voltage with both off-resonance and at-resonance frequencies. It has been shown through 4 consecutive oxidation periods with alternating off/at resonance signals applied to the device that the cooling effect is occurring. Off-resonance oxidation which has been applied in steps 1 and 3 has led to changes in the resonator frequency, whereas in steps 2 and 4 it is shown that when the excitation causes mechanical resonance, it results in almost no oxidation (no frequency trimming).

Another set of interesting data that was collected was with regard to the resonator temperature drift. Figure 6 shows the temperature drift characteristics of the same resonator measured before and after each of the oxidation steps.

Figure 5: Measured resonance frequency of the 18MHz resonator of figure 1, at different bias currents. Different plots show the data taken after different localized oxidation runs at room temperature when the oxygen source was removed. As can be seen from the graph, the actuation at half the resonance frequency has had no effect on the shift in resonant frequency (steps 2 and 4), whereas each time the resonator was actuated at an off-resonance frequency, the resonance frequency has

Figure 6: Temperature drift characteristics for the 18MHz resonator of figure 1 measured before and after each of the oxidation steps. The TCF becomes more positive (less negative) after each step due to the formation and thickening of SiO_2 on the surface of the actuators.

Silicon resonators typically exhibit temperature coefficient of frequency (TCF) in the -20 to -40ppm/°C range [10]. Figure 6 shows that while the initial TCF for this resonator was measured to be -35 ppm/°C, its value has gradually increased (become less negative) after oxidation steps with off resonance frequency. Due to no oxidation occurring when mechanical resonance is caused, no change in TCF is expected. Increase in TCF is due to the formation and thickening of the SiO_2 film (which has a positive temperature coefficient of Young's modulus) on the surface of the resonator.

CONCLUSIONS

Self-controlled post-fabrication electronic frequency trimming of individual single crystalline silicon thermal-piezoresistive resonators was demonstrated. Trimming was carried out via localized self-induced thermal oxidation while taking advantage of the cooling effect of resonators at resonance. This technique can potentially be used for automatic trimming of a whole batch of resonators after fabrication.

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