HIGH-Q MECHANICAL TUNING OF MEMS RESONATORS USING A METAL DEPOSITION - ANNEALING TECHNIQUE

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ABSTRACT

A method for coarse and fine mechanical frequency tuning of MEMS resonators is presented in this paper. Controlled material deposition onto microresonator top surfaces enables resonance frequency shifts toward higher or lower frequency, depending on the resonator structural materials. An analytical derivation is presented and experimental testing on single-crystal silicon resonator beams coated with gold demonstrates the viability of the method. Resonance frequency shifts over 11% with a tuning resolution of 90 Hz /nm of deposited metal are recorded. The performances of the tuned resonators are investigated and modeled. Metal deposition on SCS resonators revealed large Q-decreases, from 25,000 to 5,000. A post-tuning annealing step, at temperature <300C, is utilized to restore the initial high-Q of the resonators.

Keyword: mechanical tuning, metal deposition, high-Q resonators, annealing

INTRODUCTION

As the size of microelectromechanical devices shrinks, geometric process variations inherent to microfabrication technologies can limit device precision. Specifically, microresonator coupling for complex filter architectures is only achievable if the resonance frequency of each coupled resonator is individually tuned [1]. Multiple microresonator tuning and trimming methods have been proposed over the past decade. They are divided into two main categories: active tuning and passive tuning. Active resonator tuning methods, such as electrostatic [2,3] or electrothermal [4,5] tuning, base their operations on electrical or mechanical spring softening of the resonator flexure. Passive tuning techniques usually involve permanent changes of the resonator dimensions [6,7] or mechanical properties [8], though trimming or thermal annealing. Unlike most reported passive tuning techniques, the method presented here allows frequency shift toward higher or lower frequency. Mechanical tuning is performed by deposition of materials on the top surfaces of microresonators.

MECHANICAL TUNING CONCEPT

Depositions of thin layers of materials over a resonating beam change the mechanical property of the overall structures and subsequently affect the resonance frequency of the resonator. The resonance frequency of a clamped-clamped beam in the first resonance mode is given by [9]:

$$f_0 = \frac{4.730^2}{2\pi L^2}\sqrt{\frac{EI}{\rho.w.t}}$$

where L, w and t are the length, width and thickness of the beam, respectively. E is the Young's modulus of the structural material and I is the area moment of inertia around the principal axis. The deposition of materials over a resonating beam not only affects its mass but also its stiffness. After materials depositions, the microbeam must be considered as a composite structure. Considering that the deposited materials cover the entire top surface of the beam, the overall stiffness, K_c, and resonance frequency, f_c, of a composite beam are:

$$K_c = \sum_i E_i I_i$$

and

$$f_c = \frac{4.730^2}{2\pi L^2}\sqrt{\frac{\sum_i E_i I_i}{w\sum_i \rho_i . t_i}}$$

where E_i, I_i, ρ_i, t_i are respectively the Young's modulus, moment of inertia, density, and thickness of each layer (substrate included).

The following analysis is restricted to the case where one metallic layer, *m*, is deposited onto a resonant beam substrate, *s*. The resonant beam is in motion in its width direction. The moments of inertia of both elements are:

$$I_s = \frac{t_s w^3}{12} \text{ and } I_m = \frac{t_m w^3}{12}$$

The resonance of frequency, f_b, of bi-layer beam is then:

$$f_b = f_0\sqrt{\frac{1+\frac{E_m}{E_s}\frac{t_m}{t_s}}{1+\frac{\rho_m}{\rho_s}\frac{t_m}{t_s}}}$$

with

$$f_0 = 1.03\frac{w}{L^2}\sqrt{\frac{E_s}{\rho_s}}$$

where f_0 is the resonance frequency of the microbeam prior to deposition. We define A, B and T as:

$$A = \frac{E_m}{E_s},\ B = \frac{\rho_m}{\rho_s} \text{ and } T = \frac{t_m}{t_s}$$

thus

$$f_b = f_0\sqrt{\frac{1+AT}{1+BT}}$$

Increases as well as decreases in resonant frequency can in principle be achieved through the deposition of additional material. This can be seen clearly through the limiting case of BT<<1. In this case, f_b can be simplified to:

$$f_b \cong f_0\sqrt{1+(A-B)T}$$

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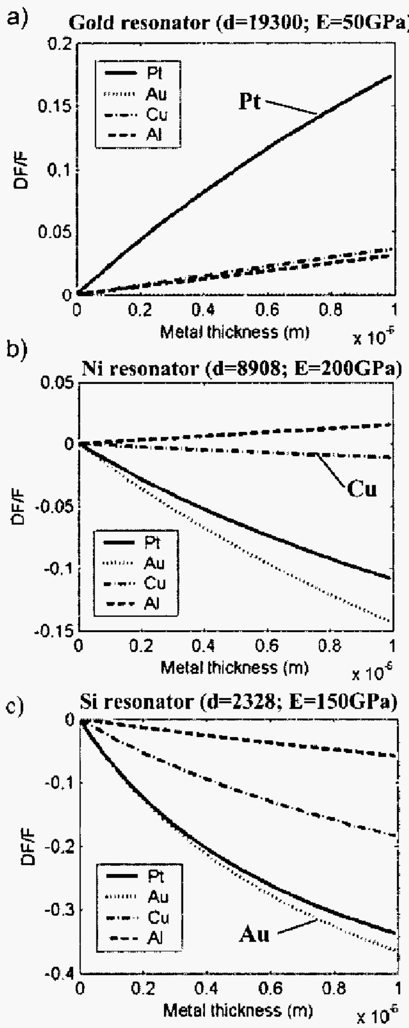

Figure 1- The different tuning cases: (a) tuning to higher frequencies; (b) resonance frequency unchanged; (c) tuning to lower frequencies.

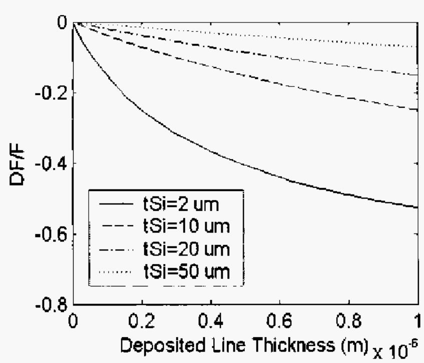

Figure 2- Tuning capabilities vs. deposited gold thickness for different silicon resonator height.

Where clearly the resonant frequency increases or decreases depending on the relative magnitudes of A and B. Hence:

i. **If A>B** e.g., the ratio of the Young's moduli is higher than the ratio of the densities, **the resonance frequency is tuned upward**.
ii. **If A=B** e.g., the ratio of the Young's moduli is equal to the ratio of the densities, **the resonance frequency is unchanged**.
iii. **If A<B** e.g., the ratio of the Young's moduli is lower than the ratio of the densities, **the resonance frequency is tuned downward.**

Figure 1 shows three graphs presenting the different aforementioned cases. In all three graphs, the tuning capabilities are plotted as a function of the thickness of the deposited layers. The effects of platinum, gold, copper or aluminum deposited on substrates such as silicon, gold and nickel are investigated. In all cases the substrate thickness is set to 5 μm.

Case 1 is presented on graph a), Figure 1. Different materials are deposited on a gold resonator beam. Gold is one of the denser materials used in microfabrication technologies. For most materials deposited on a gold resonator, the ratio of the densities is likely to be low: B<1. Furthermore an evaporated gold film exhibits a low Young's modulus, on the order of 50 GPa [10]. The ratio of the Young's moduli is therefore likely to be high: A>1. Since A>B, upward frequency shifts are expected. For instance, deposition of 0.6 μm of platinum on a 5 μm thick gold resonator should result into a 13% frequency shift upward.

Case 2 is presented on graph b), Figure 1. Different materials are deposited on a nickel resonator beam. Copper and nickel having very similar mechanical properties, A and B have similar values, and no frequency shift is expected. Fir example, deposition of a 1 μm thick copper layer onto a 5 μm thick nickel microbeam barely generates any resonance frequency shift (less than 1%). This case can find applications in several areas of MEMS, such as deposition of passivation layers on resonators without affecting their resonance frequencies.

Case 3 is presented on graph c), Figure 1. Different materials are deposited on a silicon resonator beam. The density of (100) SCS (ρ_{Si}=2328) being fairly low, and its Young's modulus being relatively high (E_{Si}=150 GPa), A is likely to be less than B. Hence, SCS is a good candidate for mechanical tuning downward. For example, a downward frequency shift of over 25% is achievable by depositing a 0.5 μm thick layer of gold on a silicon beam. In this case, mass increase is the driving tuning phenomenon: the lighter the silicon resonator, the higher the tuning. For instance, Figure 2 shows that a 2 μm thick silicon resonator can be tuned by more than 30% after deposition of a 200 nm thick gold layer. The mechanical frequency tuning method presented here is expected to be highly efficient for tuning of ultra-light UHF resonators.

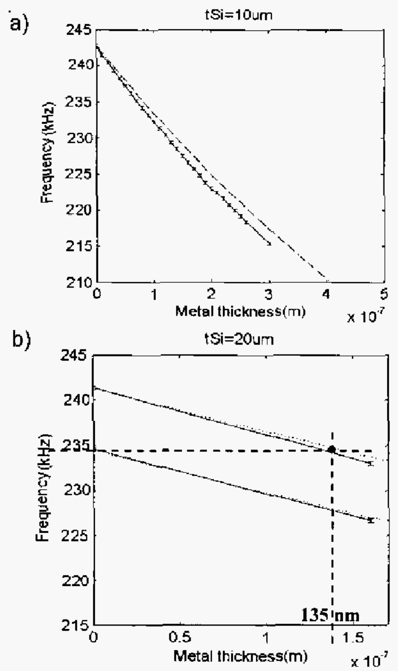

Figure 3- Experimental frequency shift vs. analytical predictions for 2 different silicon resonator thicknesses: (a) 10 μm; (b) 20 μm.

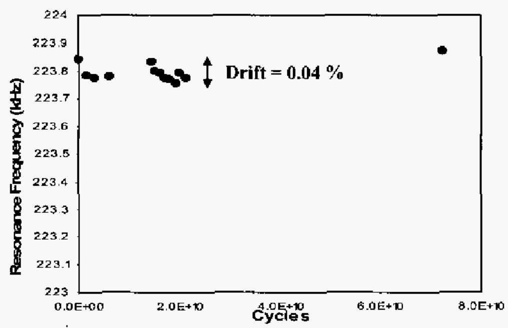

Figure 4- Tuned resonator long-term testing.

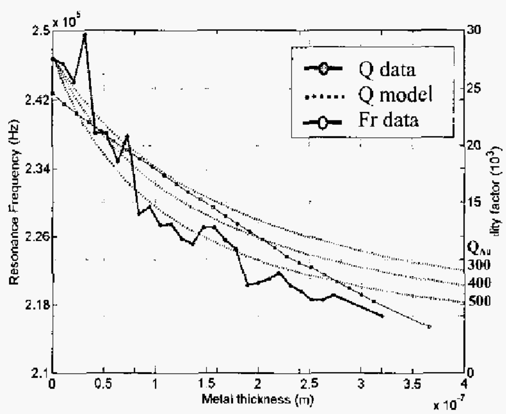

Figure 5- Resonator Q vs. deposited gold thickness

SCS MICRORESONATOR TUNING

Low-frequency axially-loaded electrostatic resonators are fabricated on (100) SOI substrates. They are packaged and placed into a filament evaporator, where their resonance frequencies are monitored in-real time, as gold is deposited on their top surfaces. Figure 3 shows good agreements between the expected tuned frequency values (dotted lines) and the recorded resonance frequencies (continuous line), for two different resonator thicknesses. In both cases the recorded frequency shifts are slightly higher than the calculated shifts. This behavior may be due to residual stress in the evaporated gold film. Deposition of a 300 nm gold layer on a 10 μm thick silicon beam results into a 11% frequency shift, with an average tuning resolution of 90 Hz / nm of deposited gold (Fig 3.a). The graph, figure 3.b), also demonstrates frequency matching capabilities. Two resonators fabricated on the same 1 cm^2 die exhibit different initial resonance frequencies. Selective deposition of a 135 nm gold layer on the resonator presenting the highest resonance frequency would result into resonance frequency matching of the two resonators.

TUNED RESONATOR PERFORMANCE

Long-term testing of tuned resonators (Fig 4.) reveals good stability over time, as the recorded resonance frequency drift, in the order of 0.04%, remains within the range if the instruments resolution

The quality factor, Q, of a 10 μm thick SCS resonator is monitored, in-situ, as gold is deposited on its top surface. Figure 4 shows that the measured quality factor (red bold line) of the tuned resonator clearly decreases as the metal thickness increases. The Q-factor of a damped system depends on various parameters such as: viscous air damping, acoustic radiation in the support or internal losses. Since electrical parameters and vacuum levels (P<1mT) are unchanged while tuning occurs, and considering that a thin layer of gold does not drastically affect the overall resonator dimension, the Q variation is likely due to the appearance of internal losses in the composite structure. Although this is a complex problem, a simplified view may be taken by considering the composite beam as two independent resonating elements. Losses in the silicon beam are assumed not to be affected by the gold layer. On the other hand, internal losses in the metal layer are expected to increase with the thickness of the film. Neglecting Au/Si interfacial losses, superposition is applied to extract the Q-factor of the composite structure. If the contribution of the respective Q on the overall structure depends on the thickness of each element, the following equation is extracted:

$$\frac{t_{Si}+t_{Au}}{Q}=\frac{t_{Si}}{Q_{Si}}+\frac{t_{Au}}{Q_{Au}}$$

Q_{Si} of the bare silicon beam is experimentally measured to be 28,000. The behavior of doubly-clamped electrostatic resonators made from evaporated gold have been previously studied [13], and Q_{Au} in the order of 300 to 600, in vacuum, has been reported. Since the respective Au and Si thicknesses as a function of deposition are known, the Q of the composite can be predicted. The dotted red lines, figure 5, shows good agreement of this simple model with the recorded data.

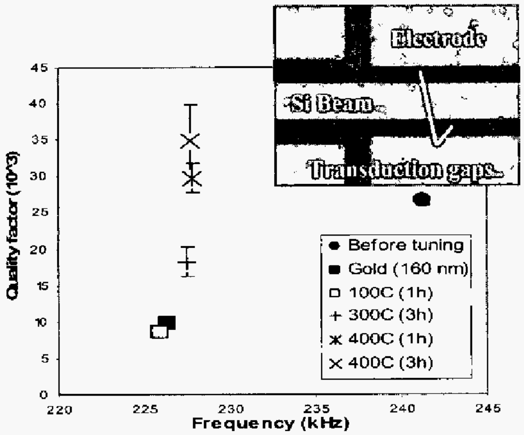

Figure 6- Q-factor and resonance frequency for different annealing temperatures and times.

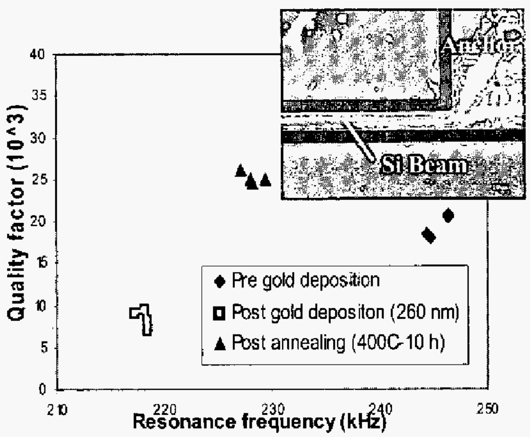

Figure 7- Post-annealing frequency shift resulting from spinodal decomposition of the Au-Si beam during annealing.

The quality factor degradation associated with the presented mechanical tuning method must be addressed in order for this tuning scheme to be adopted. Performances of nickel electroplated resonators have been previously investigated [12] and annealing of nickel microbeams have resulted in significant Q enhancements. Following this approach, the Au/Si resonators are annealed in N_2 at temperatures up to 400°C, to preserve CMOS process compatibility. The graph, Fig 5 shows that Q increases with the annealing temperature and time. SEM picture showing a top view of the coated resonating beam, displays typical surface morphology of an annealed Si-Au composite beam. Nevertheless, when annealing temperatures reach 360°C (eutectic temperature of the Au-Si alloy) and beyond, two different phenomena have been observed. In most cases the coated beam is not subjected to any major variations. But, in some other rare cases, the morphology of the composite beam surface is critically affected as the Au-Si alloy undergoes spinodal decomposition [13], resulting into an unwanted frequency shift (Fig 7). As the temperature reaches 350°C, the Au-Si alloy composition reaches the eutectic composition and the film becomes highly thermodynamically unstable. If impurities or defects are present at the surface of the beam, the system returns into equilibrium by a proceeding to a phase change, from solid to liquid. When the temperature decreases the film re-solidifies and islands of Au-Si are left on the silicon beam (SEM Fig 7). Annealing temperatures kept below 350°C allow high-Q restoration and avoid spinodal decomposition of the deposits.

CONCLUSION

A MEMS resonator mechanical tuning method, based on controlled deposition of materials on the resonating elements is presented. Tuning experimentations are in good agreement with analytical predictions. 11% tuning with a resolution of 90 Hz/nm has been demonstrated on LF SCS resonators. Tuning in both directions of the frequency spectrum are potentially achievable and remain to be experimentally verified. Moreover, the performances of the tuned resonators, in terms of long-tern drift and quality factor have been investigated and modeled. A post-tuning anneling step, at temperature <300C, is utilized for restoring resonators initial high-Qs. Integration of this tuning method with micro-shadow masks fabrication technologies previously developed [14,15], can lead to individual in-situ MEMS resonator mechanical tuning at the wafer scale.

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