Laser Annealing for high-Q MEMS Resonators

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ABSTRACT

High frequency and high quality factor, *Q*, (defined as a half-width of the resonant peak) are the key factors that **enable** applications of microelectromechanical (MEMS) oscillators for supersensitive force detection or as elements for radio frequency signal processing. By shrinking the dimensions of MEMS resonators to the sub-micron range one increases the resonant frequency of the devices. Shrinking the devices, however, also increases the surface-to-volume ratio leading to a significant degradation of the quality factor (to below 5,000) due to the increased contribution of surface-related losses[11]. We demonstrate that local annealing performed by focused low-power laser beams can improve the quality factor of MEMS resonators by more than an order of magnitude, which we attribute to the alteration of the surface state. Quality factors over 100,000 were achieved after laser annealing3.1 MHz disc-type oscillators (radius R=10 micrometers, thickness h=0.25 micrometer) compared with a Q=6,000 for the as-fabricated device. The mushroom-type design of our resonator (a single-crystal silicon disc supported by a thin silicon dioxide pillar at the center) provides low heat loss. The combined power of a red HeNe laser (P_{red}=4mW) and a blue Ar+ ion laser (P_{blue}=5mW) focused on the periphery of the mushroom provides enough energy for surface modification. The post-treatment quality factor, exceeding 100,000 for MHz-range resonators, boosts the performance of MEMS to be comparable to that of lower frequency single-crystal quartz devices. The local nature of laser annealing, safe for surrounding electronics, is a crucial element for integration of MEMS resonators into a CMOS environment.
Keywords: MEMS, anneal, oscillator, laser, high-Q

1. INTRODUCTION

Micro- and nano-scale resonators show promise to have far reaching applications in RF circuits as filters and frequency standards, in microscopy as force detectors[2], and as mass sensors[1]. The selectivity of the filter or accuracy of the detector depends greatly on the quality factor (Q) of the oscillator[2]. As device dimensions shrink to increase the resonant frequencies of MEMS oscillators, it has been seen that quality factor decreases. It is thought that this is due in part, to increased contribution to loss from surface effects since, as dimensions shrink, the surface-to-volume ratio increases[3,6,11]. In this paper we discuss a useful method of improving the quality factor of microelectromechanical system (MEMS) resonators. Using low power (~mW) continuous wave (CW) laser light to anneal the structures, we find that we can increase the quality factor of our devices by more than an order-of-magnitude, obtaining a maximum Q of over 100,000. The usefulness of this technique over previous techniques, such as baking[3,6], or resistive heating[4], is that it affects only the MEMS structure, and requires no additional on-chip elements or wiring. Any surrounding structures or electronics, such as CMOS transistors, or other metallized structures would be unaffected by the local heating of the oscillator. We believe that the improvement in quality factor comes from the removal of surface contaminates, such as oxide, as has been seen in previous studies[3,5,6].

2. METHODOLOGY

The resonators used in this study were fabricated using methods similar to those described previously[7]. Nominally undoped, commercially available silicon-on-insulator (SOI) wafers, along with electron beam lithography were used to fabricate our structures. A pattern was defined in a polymethylmethacrylate (PMMA) mask. Evaporation and lift-off of

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chrome provided a mask for a CF_4-H_2 reactive ion etch that exposed the oxide layer in unmasked areas. The chrome was then removed using a wet chrome etch. The structures were released using a wet oxide etch that removed the oxide from beneath the silicon disk.

The resulting oscillators consisted of a 0.25 μm thick single crystal silicon disk attached to a silicon substrate by a 1 μm thick silicon-oxide pillar at the disk's center, the cross-section of which resembled a very flat mushroom (see figure 1). The pillar dimensions were controlled by timing the oxide wet etch. Similar structures have been used previously in non-linear vibration experiments[7,8]. The disks had a radius of 10-20 μm. Atomic force microscopy of oxide pillars whose disks were no longer attached showed the pillar to be conical in shape with a minimum radius of 0.32 μm and a maximum radius of 1.5 μm (figure 2). The mode studied was γ_{00}, which has no radial or circular nodes. The frequency of vibration of this mode was 3.1 MHz, for disk radius of 10 μm.

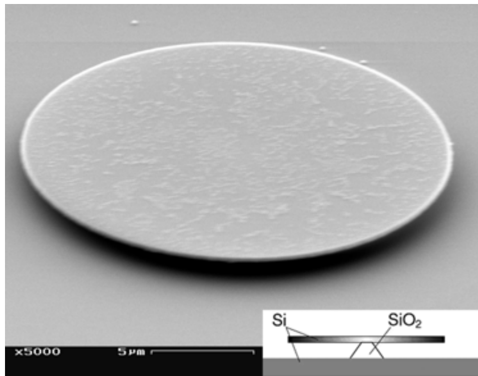

Figure 1: SEM and cross section schematic of the device. Disk radius is 10 μm.

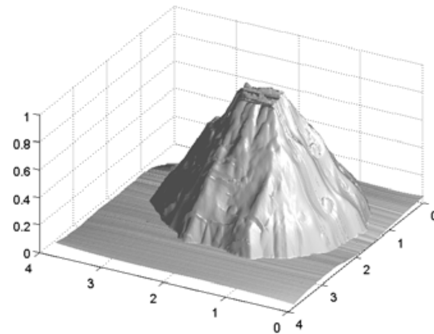

Figure 2: AFM image of the supporting oxide pillar. The scales are in microns.

The devices were measured in vacuum (10^{-7} Torr) using an interferometric setup developed by Carr *et. al.*, which we summarize here[9]. The devices were mounted on top of a flat piezo-electric transducer and placed in a vacuum chamber with the devices facing a transparent window. Very low power (~250 μW) HeNe (λ = 633 nm) laser light was focused on the periphery of a disk for the purpose of measurement. The reflective surfaces of the substrate and the device set up a Fabry-Perot type interferometer. Motion of the device perpendicular to the laser beam modulates the intensity of the reflected laser light by changing the device-substrate distance. An AC-coupled photodetector and a spectrum analyzer were used to detect this modulation. The spectrum analyzer also provides a sweeping RF voltage to the piezo actuator, allowing us to obtain frequency-amplitude response curves (figure 7).

In addition to a HeNe measurement laser, an Ar^+ (λ=450 nm) laser was used to provide extra power for the purpose of annealing. An adjustable polarizer in the beam path controlled the power of the HeNe laser, while the CW Ar^+ laser power was controlled using an electro-optical modulator. The range of laser power that could impinge on the device with this setup ranged from 0.03 to 12 mW. A schematic of the experimental setup is shown in figure 3.

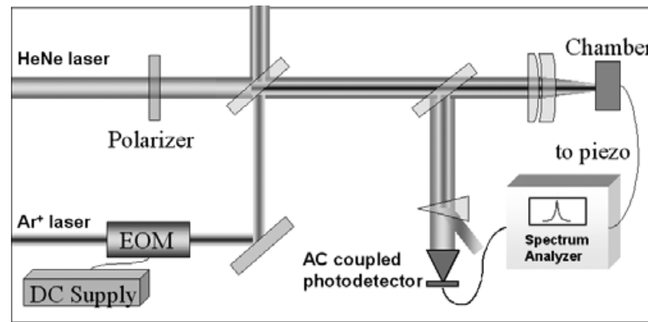

Figure 3: Sketch of experimental setup

Using the optical properties of stacked thin films[10], we estimate that the absorption of the laser light by the silicon disk to be about 25%. Both lasers were focused on the periphery, but on opposite sides of the oscillator, each having a spot diameter of about 2 μm. The temperatures obtained using this process were calculated using thermodynamics and finite element methods (FEM).

It can be shown that the temperature of the silicon disk just above the pillar is given by:

$$T = \frac{L}{k_{ox}\pi}\left(\frac{P_{las} - P_{rad}}{r_{\max} r_{\min}}\right) + T_0,$$
$$P_{rad} = \varepsilon\sigma T^4 (2\pi R^2).$$

where L is the height of the pillar, P_{las} is the absorbed laser power, k_{ox} is the thermal conductivity of silicon oxide (1.6 W/m/K), $r_{\max}$ and $r_{\min}$ are the maximum and minimum radius of the conical oxide pillar, T_0 is the temperature of the substrate (assumed to be 300 K), P_{rad} is the power radiated by the disk, σ is the Stefan-Boltzmann constant, and R is the radius of the disk. The emissivity, ε, was taken to be unity to assume the worst case with respect to radiation losses.

It was found that the maximum obtainable temperature above the oxide pillar is around 1300 K. Furthermore, FEM simulations show that the temperature of the disk will be 20-40% higher than this at the points where the lasers are focused (figure 5). We observed device damage after annealing at higher powers (see figure 4), which we attribute to sublimation.

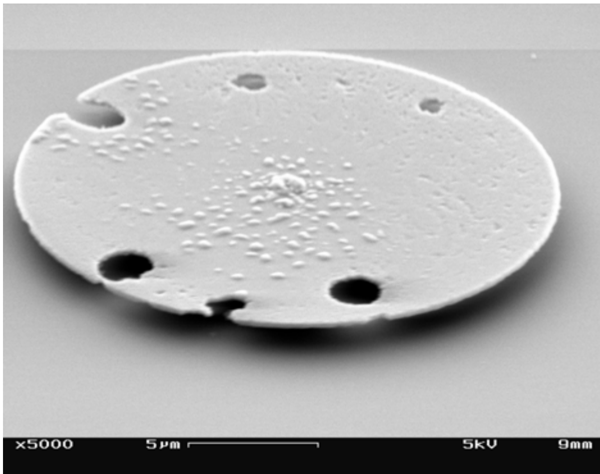

Figure 4: Damage to a device after multiple high intensity (~6 mW) laser exposures.

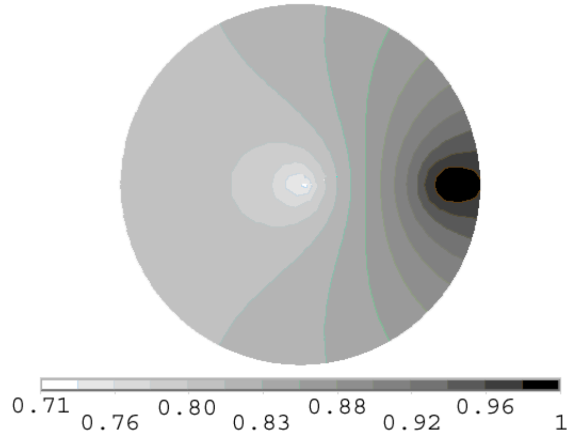

Figure 5: Depiction of the ANSYS FEM calculation of temperature distribution.

In our measurements, we would first increase the argon and HeNe laser powers to the desired levels. We would then expose the device to the beams for 30 seconds, block the Ar laser and reduce the HeNe laser power to 250 μW in order to measure the lorentzian response curve of the device. Care was taken to ensure that the RF voltage applied to the piezo element was low enough so that asymmetries in the response curve due to non-linearity were minimized. The measurement power of the HeNe laser was below the regime where limit-cycle oscillations are possible[8]. Vacuum was not broken during the process of annealing.

3. DATA AND RESULTS

Using the method described above, we measured an order-of-magnitude increase (from 7,000 to over 100,000) in quality factor for a 3.105 MHz resonator. As the quality factor increased, so too did the resonant frequency of the oscillator from 3.105 to 3.133 MHz (figures 6 & 7). We attribute these changes to the removal of surface contaminates, such as oxide. Surface related losses have been found to be a large factor in determining the quality factor of an oscillator as device dimensions shrink and the surface-to-volume ratio increases[3,6,11]. The exact nature of these contaminates is still under investigation, but experimental evidence is consistent with the assumption that the removal of oxide is responsible for enhanced quality factor, which has been seen in other annealing experiments[3,6]. Vacuum conditions and estimates of the device temperature during anneal and are such that the device would be in the so-called region of "active" oxidation, where the surface remains free of SiO_2, but is slowly etched by the reaction $2Si + O_2 \rightarrow 2SiO$[12,13]. Post-anneal decay of the quality factor and resonant frequency was observed with time scales ranging from hours to minutes depending on vacuum conditions. We believe this phenomenon is caused by "passive" oxidation (the formation of an oxide film) and the acquisition of other contaminates over time. Annealing at UHV pressures is planned for the future, in order to reduce and investigate this effect.

Device damage occurred at higher laser powers (~6 mW), resulting in a lower Q-factor and a much higher frequency increase (~10%). These frequency increases are likely due to the sublimation of the silicon at the point of laser focus. Follow up measurements of the quality factor of annealed, but undamaged structures after cycling the chamber pressure from atmosphere to vacuum, revealed that the Q had dropped to a level about twice that of the original low Q. This would indicate that some of the original surface contaminates were acquired during fabrication of the device.

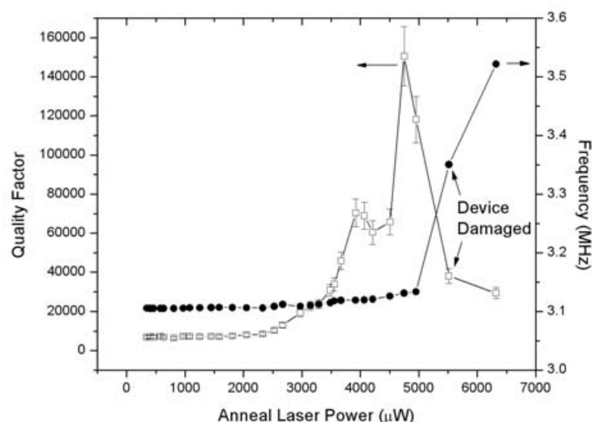

Figure 6: Quality factor and frequency as a function of anneal laser power.

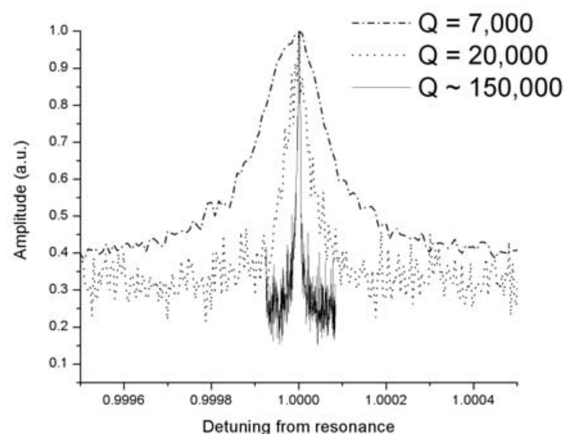

Figure 7: Resonant curves of the disk oscillator at different stages of annealing.

4. CONCLUSION

We fabricated disk shaped MEMS oscillators with resonant frequencies of 3.1 MHz and initial quality factors of 7,000. Order-of-magnitude improvement of the quality factor was achieved through local annealing using low power (~mW) focused laser light. We attribute this improvement to the removal of surface contaminants. Because this method would not damage any other structures or electronics on a chip containing the MEMS device, it would be a very useful tool for improving the sensitivity of applications, such as mass or force sensing, where the quality factor of the resonator must be maximized. In addition, this method requires no addition elements, such as electrical contacts or resistors, to be fabricated with the device. It requires only a short anneal time and relatively low laser powers.

5. ACKNOWLEDGEMENTS

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