Improving Quality Factor of Drum Resonators via Gas Confinement

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Abstract:

The frequency of micro- and nano- scale devices is sensitive to stress, force, and mass, which makes the devices useful for applications in chemical and biological sensing. The ability to resolve small changes in frequency is dependent on the quality factor, *Q*, a measure of how much energy is lost relative to the stored energy of the resonator. Mechanical resonators vibrating in air lose energy to the surrounding gas, which negatively impacts *Q* and diminishes the sensitivity of these devices.

Drum resonators were fabricated with a self-aligned glass cap to prevent the formation of sound waves and minimize energy loss. At atmosphere, high frequency devices show larger improvements in *Q* than low frequency devices.

Introduction:

Micro- and nano- mechanical resonators have the potential for many chemical and biological sensor applications because of their ability to resolve small changes in frequency. In order to be useful, the resonators need to perform well when exposed to air. One measure of performance is the quality factor, since a higher quality (Q) factor equates to better sensitivity [1].

Several types of energy loss diminish the Q of mechanical resonators in air: squeeze film damping, sound radiation, and energy transfer in a free molecular flow regime. Squeeze film damping describes the behavior of air between a stationary and moving plate. In the resonators studied, damping occurs in the incompressible regime, where air is trapped between two plates and acts as a spring, and the squeeze number, σ, is greater than 10. In the incompressible regime, dissipation falls as $\sigma^{0.4}$, offering a pathway to improve Q [2, 3].

Sound radiation is another source of energy loss. As the resonators are driven, their movements propagate sound waves, which remove energy from the system. Sound is governed by the equation $c = \lambda f$ where c is the speed of sound, λ is the wavelength and f is frequency. Sound waves can be blocked from forming, however, when $\lambda << c/f$.

However, these energy loss models are less accurate when the dimensions of nanomechanical devices are comparable to the mean free path of the gas particles. Damping in this "free molecular flow regime" (fmf) arises because of energy transfer from the resonator to the gas molecules, which occurs more frequently than particle-particle interactions. Fmf is characterized by Q having inverse pressure dependence [4].

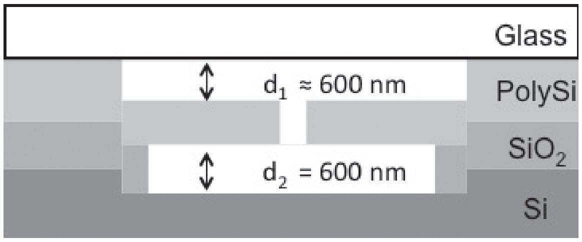
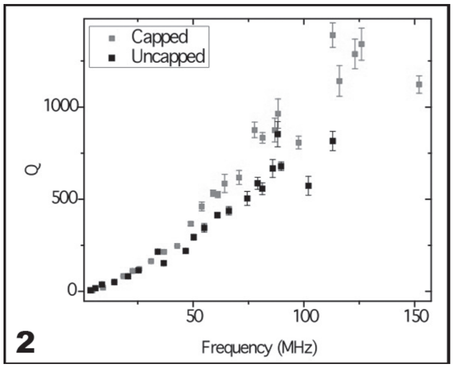
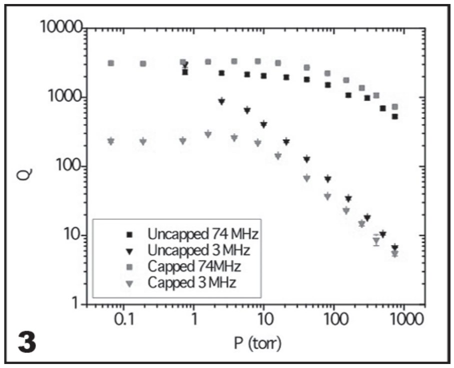


Figure 1: Side view of drum resonator.

Methods:

A self-aligned glass cap procedure was used to fabricate capped drum devices. Channels were etched in silicon using photolithography techniques. Complementary metal oxide semiconductor (CMOS) processes were used to put down silicon oxide and n+ polysilicon. Some of the underlying oxide layer was removed using 49% HF, creating drum resonators within the channels. Poly(methyl methacrylate) (PMMA) was spun on diced borosilicate glass. The glass was clamped on top of the resonator chip with a C clamp and baked at 200°C. A side view of the device can be seen in Figure 1.





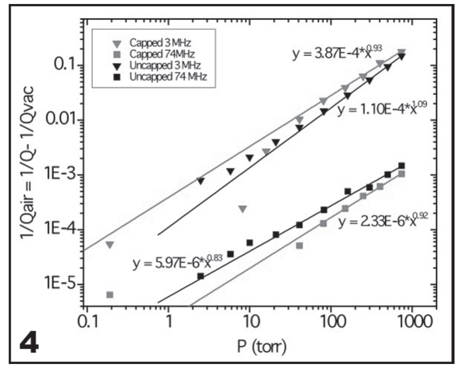


Figure 2: 48 µm drum resonators at 1 atm.

Figure 3: 48 µm drum resonators at varying pressures.

Figure 4: 48 µm drum resonators at varying pressures with intrinsic losses subtracted.

Motion was actuated and detected optically as described in detail by Ilic, et al. [5]. Q was calculated by dividing the resonant frequency by the full width half maximum of observed Lorenztian peaks.

Results and Discussion:

By interrogating multiple modes of a single device, we obtained the frequency dependence of the dissipation and results are displayed in Figure 2. At frequencies below 35 MHz, the Q of the uncapped drums is the same or higher than the capped drums. At frequencies above 35 MHz, capped devices performed better than uncapped devices.

A pressure dependence experiment was performed and results are displayed in Figure 3.

For all frequencies and at low pressure, Q is dominated by intrinsic energy losses due to imperfections in the resonator. As pressure increases, losses due to air impact Q more. We attribute these losses to energy transfer in the fmf regime. At high frequency, we hypothesize that squeeze film terms are diminishing, and therefore Q is better for both capped and uncapped devices. However, the capped devices have less squeeze film damping than uncapped devices because the gas is clamped.

The ratio of Q_{capped} : $Q_{uncapped}$ for drums driven at 3 MHz, ranges from 0.07 to 0.81. The same ratio for drums driven at 74 MHz ranges from 1.38 to 1.66. The capped devices see approximately a 50% improvement in quality factor.

Intrinsic resonator energy losses were subtracted from original data and the resulting pressure dependency of damping due to air is shown in Figure 4. Trend-lines show slopes close to the inverse pressure dependence expected from fmf theory; however, the dramatic improvement when comparing coefficients of the trend-lines for Q is unexpected.

Conclusions:

At higher frequencies, the cap has improved the quality factor by 50%, by decreasing energy loss from squeeze film damping and/or sound radiation. Further work must be done to understand which modes of energy loss are dominating and optimize dimensions and design accordingly.

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