INVESTIGATION OF ENERGY LOSS MECHANISMS IN MICROMECHANICAL RESONATORS

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ABSTRACT

Micromechanical resonators with resonant frequencies from 500kHz to 10MHz were built and examined for several energy loss mechanisms. Thermoelastic damping, clamping loss and air damping were considered. The devices were shown to be limited by thermoelastic damping, providing experimental verification of this phenomenon at the microscale. Resonators with scaled dimensions also matched well with scaling theory of damping at a given pressure. An energy loss mechanism other than thermoelastic dissipation, most likely clamping loss, was shown to be dominant for resonators whose ratio of length to width was less than 10:1. The devices were fabricated using a single-wafer encapsulation process.

INTRODUCTION

Micromechanical (μmechanical) resonators show great promise in the field of electronics for communications applications. They have high quality factors, Q, and since they are often made from silicon, they can potentially be integrated with their control circuitry. For this reason alone, it is important to understand in what ways they store and lose energy, the two processes that define Q. Also, experimental trend has shown that when resonators are scaled to smaller sizes to increase resonant frequency, Q decreases dramatically [1]. This trend makes the understanding of energy loss mechanisms necessary if high frequency, high Q resonators are to be made.

There are several energy loss mechanisms commonly associated with μmechanical resonators. They include air damping, clamping loss through the substrate, thermoelastic dissipation (TED), surface loss mechanisms and intrinsic material losses. This work focuses on the first three loss mechanisms: air damping, clamping loss, and TED. Intrinsic material losses in polysilicon were not significant for the Q values seen in this work. Surface losses, which usually are most influential in devices that have dimensions in the nanometer range, were not dominant for the resonators whose dimensions were on the μscale.

Thermoelastic dissipation, TED, is a phenomenon that occurs in the following way: a beam is flexed, inducing tension on one side and compression on the other. The side in tension has a slight decrease in temperature related to its coefficient of thermal expansion, while the side in compression has an increase in temperature for the same reason. This small temperature gradient will cause heat to flow, reestablishing thermal equilibrium. Heat flow through a thermal resistance will result in power dissipation, which is a Q limiting energy loss mechanism. This loss is the most prominent when the period of the resonator is of the same order as the thermal time constant across the beam. One may also view TED from a thermodynamic standpoint; the initial flexing of the beam causes the temperature profile of the beam to become more ordered. If the beam reestablishes equilibrium this order is lost, resulting in an irrecoverable increase in entropy, which is an energy loss.

TED is an energy loss mechanism worthy of attention for two reasons: (1) it is a fundamental scientific phenomenon that is difficult to design around and (2) its frequency of highest energy loss scales inversely to the square of the thickness of the resonator (in the direction of motion). The second reason implies that the commonly used technique of scaling resonator size down to increase resonant frequency will not allow one to avoid TED. In fact, the limitation of TED will scale in the same direction, proving to be a nuisance into the high frequency range. Also, the granular structure of polysilicon may also act as another outlet for TED, causing Q limitation to exist in the GHz range regardless of resonator dimensions [2].

In order for resonators to be suitable for use in real applications, the environmental factors (i.e. pressure, ambient gas constituents, temperature, particles) must be controlled. For this reason, a single wafer encapsulation scheme was used to provide a protective environment [3]. The seal was shown to be robust, withstanding probing, dicing, handling, and wire bonding with no special handling techniques. The encapsulated devices were used to perform measurements of air damping, and the encapsulation seal was released so that further tests could be made under vacuum where air damping was no longer the limiting factor.

FABRICATION

The fabrication process is an extension of work by Partridge et. al [3], who developed a single wafer encapsulation for piezoresistive accelerometers. The encapsulation involves the deposition of a thick polysilicon cap over the MEMS device for protection and vacuum seal. The encapsulation can withstand standard back end processes, such as wafer dicing, handling, and wire bonding with no loss in yield.

The first several steps in the process are typical for a MEMS device: grow a sacrificial oxide, deposit a silicon layer from which the devices will be etched, and etch the desired structure with a plasma etch (figure 1). At this point, rather than release the devices, they are covered by a Low Pressure Chemical Vapor Deposition (LPCVD) oxide. The oxide seals over the trenches etched in device layer. It also serves as a spacer layer between the devices and the silicon encapsulation layer, which will be grown next. Openings are etched into the oxide to allow contact to the device.

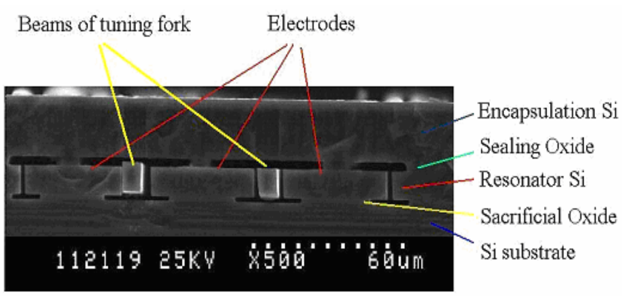

Figure 1. Cross section of a doubly clamped tuning fork resonator

Next, a thick polysilicon layer is deposited over the wafer in a CVD reactor. This layer will serve as the encapsulation layer, or "cap" layer, providing robust mechanical protection. Trenches are etched all the way through the cap layer for two reasons: (1) there needs to be a pathway for the sacrificial oxide to be etched away and (2) electrical isolation paths need to be created. The electrical isolation paths are necessary, because the contacts are routed from the buried device *through* the cap layer to the surface. The buried nature of the device structure is shown in figure 2, which consists of a picture taken with an optical microscope, and the same resonator as seen in the Infrared spectrum where the light passes through the silicon.

At this point, the devices are released via an etch with Hydrofluoric Acid (HF) in the vapor phase. Using HF in the vapor phase prevents stiction and eliminates the need for a critical point dry step. The released devices are sealed by covering the trenches with LPCVD oxide. Since the oxide is deposited in a vacuum ambient, there exists a low pressure inside the cavity. The oxide is etched to allow electrical contact to be made to the cap layer. Aluminum is deposited and etched, and the parts are ready for probing or dicing.

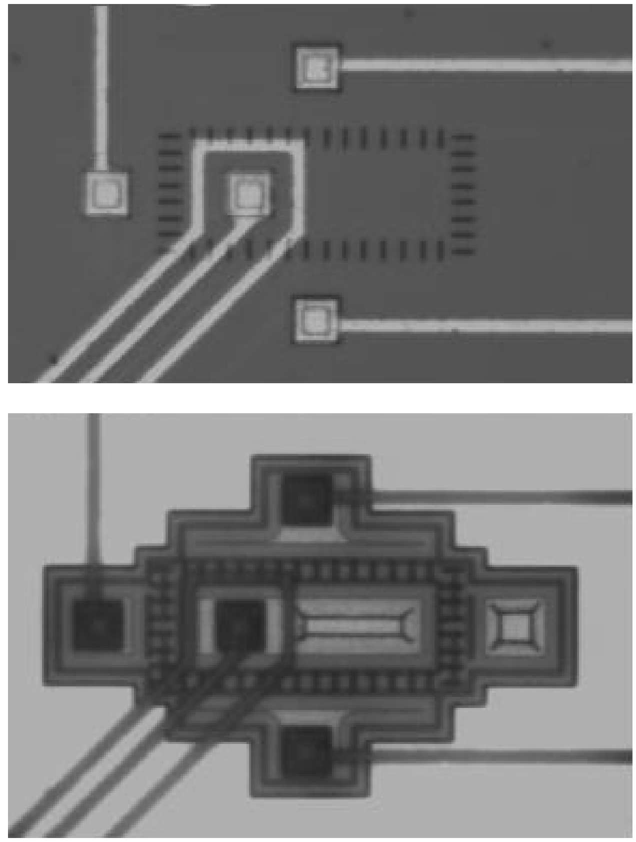

Figure 2. View of encapsulated doubly clamped tuning fork in the visible spectrum (top) and illuminated from beneath in the Infrared spectrum (bottom).

RESULTS

Several designs of a doubly clamped tuning fork were tested. The devices were all 8µm wide (where width is measured in the direction of resonance for these in-plane resonators) with varying length. This provided resonators with a spread of resonant frequencies, with all resonators having the same width. Keeping the width constant was important for TED comparisons.

The encapsulated devices were initially tested to determine resonant frequency and Q. Since all the devices were encapsulated in the same run, they all had the same pressure inside the cavity. For encapsulated devices, it was determined that all the devices were limited in Q by pressure (figure 3). The one exception was the very short device. It was not limited by air damping. It had a length:width ratio less than 10:1, making it more likely to be limited by clamping loss. A difference in quality factor for the different resonators is caused by their differing lengths. Longer resonators had more surface area in the direction of motion, which lead to a greater probability of collisions with gas molecules and greater energy loss. It should be noted that the resonators in this case are interacting with the gas in a molecular regime and not in the squeeze film regime [4].

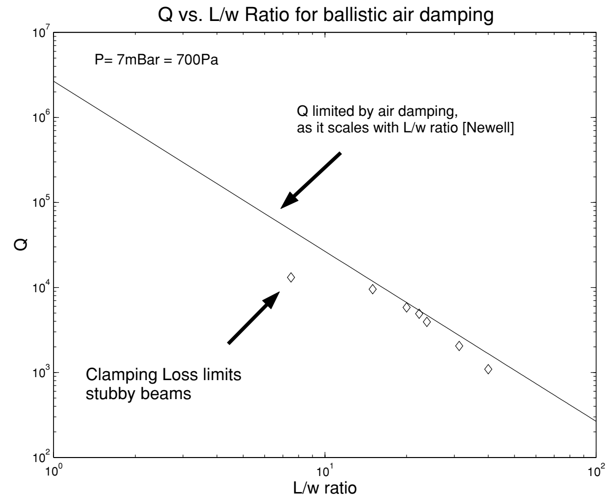

Figure 3. For constant pressure in the air damping limited regime, Q scales predictably with geometry, except when L/w ratio is less than 10, when clamping losses dominate.

The pressure inside the cavity was determined to be 7mBar (700Pa). This value was found by first determining the Q of encapsulated devices from a gain-phase plot (figure 4). The encapsulation seal was then intentionally removed by exposure to HF vapor. The part was placed in a vacuum chamber and the pressure was varied. The pressure where the Q matched the Q of the resonator when it was encapsulated was determined to be the cavity pressure. This technique yielded similar results, 6-8 mBar (600-800 Pa), for several devices of different resonant frequency.

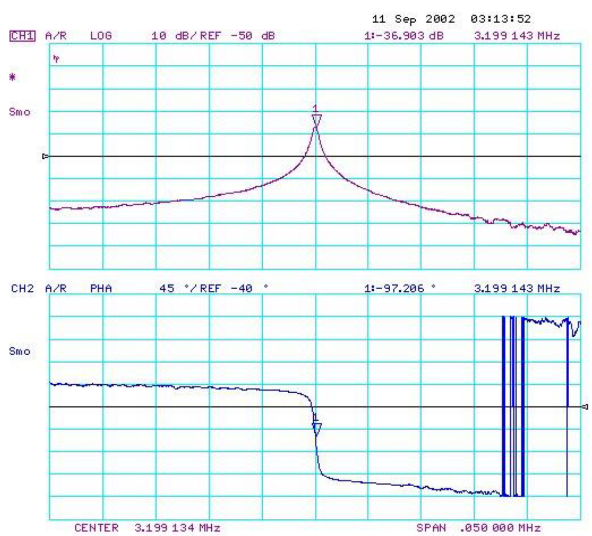

Figure 4. Gain/phase plot of encapsulated 3 MHz resonator with Q ≈ 10,000

A typical plot of Q versus pressure is shown (figure 5). There are two limiting regimes demonstrated, air damping and TED. For the higher pressure region, the limiting damping mechanism is air damping in the molecular regime. As can be seen, Q is inversely related to Q in this regime. At pressures below ~0.01mBar (1 Pa), pressure is no longer the limiting loss mechanism. For this resonator the Q levels off at ~10,000 which is the point where it is limited by TED.

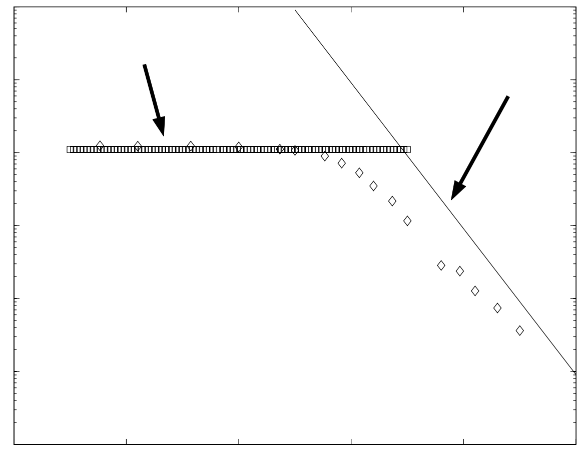

Figure 5. Quality factor vs. pressure for ~800kHz resonator (thick line shows theoretical Q limit from TED, thin diagonal line shows theoretical Q limit from air damping)

The maximum Q when limited by TED is given by [5],

$$Q_{TED}^{Max} = \frac{1}{\Gamma(T)\Omega(f)} \tag{1}$$

where Γ is a material and temperature dependent value and Ω approximates the change in Q^{Max} with frequency.

$$\Gamma(T) = \frac{\alpha^2 T E}{4\rho C_p} \tag{2}$$

$$\Omega(f) = \frac{F_0 F}{F_0^2 + F^2} \tag{3}$$

$$F_0 = \frac{\pi K}{2\rho C_p t^2} \tag{4}$$

where

α = thermal coefficient of expansion
T = beam temperature
E = Modulus of Elasticity
ρ = material density

C_p = heat capacity at constant pressure
K = thermal conductivity
t = thickness of resonator in direction of motion
F_0 = characteristic damping frequency

These equations provide a curve that shows the maximum Q attainable under the given conditions (where t = width for our in-plane resonators). This is the reason that all the resonators were designed with the same width, so that they would all be limited by the same curve. Several resonators with resonant frequencies ranging from 50kHz to 10MHz were built and tested under vacuum at room temperature. All of the resonators had Q values very close to the theoretical TED limit (figure 6), except the highest frequency part which was likely limited by clamping losses.

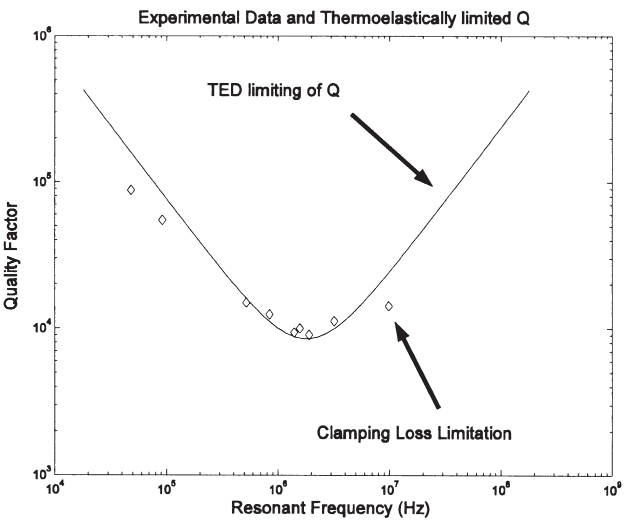

Figure 6. Q plotted against theoretical TED limit. High frequency part (10MHz) is limited by clamping loss.

CONCLUSIONS AND FUTURE WORK

An investigation of energy loss mechanisms was performed, focusing on losses through air damping, clamping loss, and especially thermoelastic dissipation. Doubly clamped tuning forks were built within a single wafer encapsulation that provided excellent protection against back end handling and environment. Good agreement with air damping theory was found. The Q of encapsulated parts was matched with the Q of the same parts after the encapsulation had been removed to determine the cavity pressure of ~7mBar (700Pa). Clamping loss was seen to limit the parts when the length:width ratio was less than approximately 10:1. TED was experimentally verified for devices on the μscale, and it was seen to be a barrier to the design of practical, useable resonators.

Future work will involve further study of clamping losses for several low loss architectures. Methods will be developed and tested to avoid limitation by TED. Also, experiments will be made in an attempt to quantify any difference in energy losses between single crystal and polycrystalline materials.

ACKNOWLEDGEMENTS

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