W.-C. Li, Y. Lin, B. Kim, Z. Ren, and C. T.-C. Nguyen, "Quality factor enhancement in micromechanical resonators at cryogenic temperatures," the 15th Int. Conf. on Solid-State Sensors, Actuators, & Microsystems (Transducers'09), Denver, Colorado, June 21-25, 2009, pp. 1445-1448.

QUALITY FACTOR ENHANCEMENT IN MICROMECHANICAL RESONATORS AT CRYOGENIC TEMPERATURES

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ABSTRACT

Quality factors as high as 362,768 have been measured for 61-MHz polysilicon wine-glass disk micromechanical resonators operated at cryogenic temperatures down to 5K. The measured results not only represent a ~2.5× increase in *Q* over the room temperature value, equivalent to a nearly 10-dB improvement in phase noise; but also provide some limited insight into the intrinsic material damping and other loss mechanisms that dominate over certain temperature ranges. In particular, a measured *Q* versus temperature curve verifies a peaking point for phonon-phonon interaction losses at a temperature around 150K. In addition, measurement versus theory for resonators with different support designs suggests that anchor losses probably still dominate the *Q*'s of the resonators over the entire measured temperature range, implying that improved anchor isolating designs are needed if the true intrinsic material *Q*'s of polysilicon are to be measured at cryogenic temperatures.

KEYWORDS

Resonator, cryogenic cooling, quality factor, loss, oscillator, filter, RF MEMS, wireless communications.

INTRODUCTION

On-chip vibrating micromechanical resonators have yielded *Q*'s over 160,000 at resonance frequencies in the VHF range [1] and larger than 15,000 at UHF [2], making them very attractive as on-chip frequency selecting elements for oscillators and filters in wireless communications. To date, oscillators that combine the above high-*Q* MEMS resonators with CMOS sustaining transistor circuits have been demonstrated with phase noise marks commensurate with GSM cellular phone specifications for reference oscillators [1]. Although already impressive, there are still other applications, such as radar systems, that require even better phase noise performance, hence, even higher *Q*'s [3].

One strategy that has been effective for raising the *Q*'s of mechanical (and electrical) resonators is to operate them cold, i.e., at cryogenic temperatures. Indeed, quartz resonators have been measured with *Q*'s exceeding 300 million at temperatures down to 5K [4]. At first, the thought of cooling to such temperatures seems quite impractical when considering the size and power consumption of the needed cooler. If one considers, however, that a micro-scale resonator is passive, presents a very small total surface area, and via proper support structures can be very well thermally isolated from its surroundings, as in [5], then the heat lift needed to achieve cryogenic temperatures will be quite small, perhaps achievable by a micro-scale cooler with reasonable power consumption. Indeed, there are research programs already underway seeking to miniaturize cryogenic coolers [6][7].

Pursuant to gauging the degree to which the *Q*'s of micromechanical resonators also rise significantly at cryogenic temperatures, this paper presents measured frequency spectra for 61-MHz polysilicon wine-glass disk resonators, showing *Q*'s >350,000 at temperatures down to 5K, which represents a 2.5× increase over the room temperature value and is equivalent to a nearly 10-dB improvement in the phase noise of an oscillator referenced to this resonator [1]. Before presenting the data, some discussion of the temperature dependence of *Q*-limiting energy loss mechanisms is in order.

Q-LIMITING ENERGY LOSS MECHANISMS

The energy loss mechanisms responsible for limiting the *Q*'s of micromechanical resonators have been widely discussed and modeled [8] and include gas damping [9], thermoelastic dissipation (TED) [10], phonon-phonon interactions [11], phonon-electron interactions [12], and anchor loss [13], each of which is summarized pictorially in Fig. 1. The energy loss contributed by each of these mechanisms can be modeled as an individual Q_i that combines with the other Q_i's to set the total *Q* of a given micromechanical resonator according to the expression

$$\frac{1}{Q}=\sum_{i}\frac{1}{Q_i} \qquad (1)$$

where *i* is meant to indicate any one loss mechanism.

Among the listed loss mechanisms, gas damping is

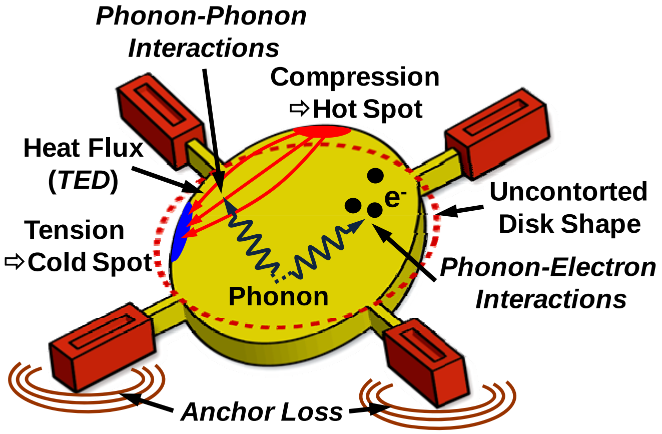

Fig. 1: Schematic pictorially summarizing important loss mechanisms that constrain the Q of a wine-glass disk resonator.

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Table 1: Expressions Estimating the Q Limits Imposed By Various Loss Mechanisms in Micromechanical Resonators

Phonon-Phonon Interactions[4]	$Q_{ph-ph} = \frac{\rho v^2}{C T \gamma^2} \frac{\omega \tau^*_{ph}}{1+\left(\omega \tau^*_{ph}\right)^2}, \ \tau^*_{ph} = \frac{3\kappa}{C V_D^2}$	(2)
Thermoelastic Dissipation (TED)[14]	$Q_{TED} = \frac{1}{\psi} \frac{C^2}{\kappa T \alpha^2 \rho \omega}$	(3)
Phonon-Electron Interactions[4]	$Q_{ph-e} = \frac{15}{8} \frac{\rho v^2 e^2}{\varepsilon_F m_e \sigma \omega}$	(4)

ρ: density
v: sound velocity
C: heat capacity
κ: thermal conductivity
V_D: Debye sound velocity
ψ: mode shape-determined const.
α: thermal expansion coeff.
σ: electric conductivity
m_e: electron mass
ε_F: Fermi energy
e: electron charge

most easily rendered inconsequential by merely operating under vacuum—something that will be necessary anyway when operating at cryogenic temperatures. All other listed mechanisms, however, are more difficult to eliminate, so must be considered. Table 1 provides analytical expressions from the open literature for some of the more well-researched ones.

Among the mechanisms in the table, phonon-phonon interaction and thermoelastic dissipation are generally more dominant than phonon-electron interaction and have reciprocal dependences on temperature that encourages the use of cryogenic operation to raise Q. So far, however, these loss mechanisms have never been measured for micromechanical resonators at VHF and higher frequencies. Rather, for micromechanical resonators designed to avoid TED, anchor losses have always dominated; or at least they have set an upper bound on Q that is lower than that predicted by the expressions in Table 1. For this reason, it is quite possible (and even likely) that measurements of Q versus temperature for any existing VHF and higher micromechanical resonator will reveal more the dependency of anchor loss on temperature, rather than the dependencies of the mechanisms in Table 1. To maximize the chances of actually observing phonon-phonon interactions or thermoelastic dissipation, a resonator design that minimizes losses to the substrate via anchors is needed.

WINE-GLASS DISK TEST DEVICES

In addition to anchor losses, transducer losses must also be minimized. For this reason, a resonator using capacitive transducers is perhaps most appropriate here, since such transducers intrude very little with resonator operation, so commonly allow the highest Q's among transducer types. This work utilizes the capacitively transduced wine-glass disk resonator depicted in Fig. 2(a) and (b), comprising a 32μm-radius, 3μm-thick disk surrounded by four closely spaced electrodes and supported by anchored beams attached at quasi-nodal locations, where radial displacements are negligible compared to other parts of the disk structure when the disk vibrates in its wine-glass mode shape shown in Fig. 2(c). As shown, the device is excited to resonance via a combination of a dc-bias voltage V_P applied to its conductive resonant structure and an ac signal voltage v_i applied to two symmetrically placed input electrodes, both of which combine to induce a drive force at the frequency of v_i. Once vibrating, an output current i_o is generated by the ensuing V_P-biased time varying capacitance between the disk and its output electrodes.

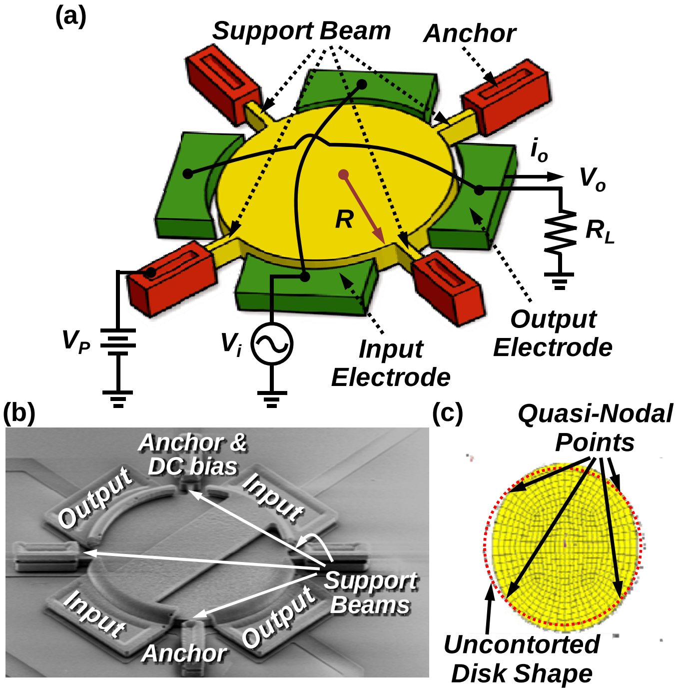

Fig. 2: (a) Schematic of a wine-glass disk μmechanical resonator in a preferred two-port bias, excitation, and sense configuration. (b)SEM photo of a wine-glass disk resonator test device. (c) Wine-glass mode shape simulated via finite element analysis showing the locations of quasi-nodal points.

Attachment of supports at nodal locations helps to block the energy conduit from disk to support, thereby minimizing anchor losses to the substrate. Such losses are further reduced by making the supports as thin as permissible by lithography and sizing them to correspond to quarter-wavelength dimensions [15]. With careful support design, wine-glass disks generally exhibit the highest VHF Q's at room temperature among other available geometries, including free-free beams and contour mode disks, so are arguably the best vehicles with which to study temperature

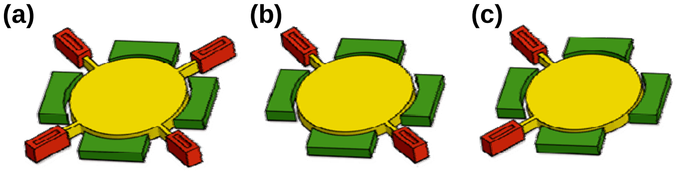

Fig. 3: Schematic of wine-glass disk μmechanical resonators using various support configurations to vary anchor losses in this work: (a) four 1-μm supports; (b) two 1.5-μm supports oriented 180°; and (c) two 1.5-μm 90°-oriented support beams.

dependent loss mechanisms.

The Q of this resonator design can be further increased by reducing the number of supports, which then further reduces anchor losses. As shown in [16], wine-glass disks exhibit their highest Q's over 150,000 when using two 1μm-wide supports; and much lower Q's ~9,000 when supported by four 3μm-wide supports. Thus, by merely varying the number and orientation of supports, such as in Fig. 3, the Q's of wine-glass disks can be tailored to within specific ranges. In fact, the variation in Q among wine-glass disks with varying numbers of supports can be used to gauge the degree to which anchor losses still influence the Q at any given temperature.

CRYOGENIC MEASUREMENTS

Fig. 4 presents a photo of the setup used to measure the frequency characteristics of micromechanical wine-glass disks under cryogenic temperatures. Here, a Suss MicroTec® PMC150 cryogenic probe station is used that allows probing of chuck-mounted wafers under high vacuum while they are cooled via liquid helium (to the chuck). A turbo pump is used to provide vacuums down to 6 μTorr, which practically eliminates air damping while providing thermal isolation against convection. A feedback control heating unit allows precise control of the device temperature during measurement. Ideally, devices can be cooled to ~4.2K using this probe station, dependent upon several conditions, e.g., the lowest achievable pressure.

Fig. 6 and 6 present frequency characteristics measured using this set-up for two-support 32μm-radius wine-glass disks with V_P=3V at 300K (i.e., room temperature) and at 5K, where Q's of 144,074 and 362,768, respectively, are observed. The increase in Q of ~2.5× not only verifies the utility of cooling to increase micromechanical resonator Q, but would also result in a nearly 10-dB improvement in the phase noise performance of an oscillator referenced to the tested device.

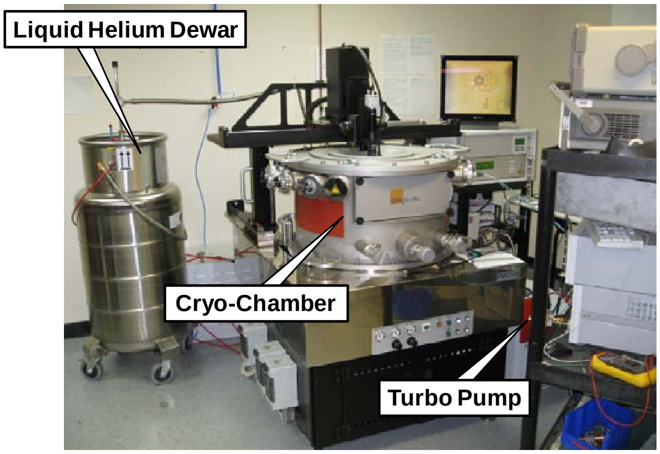

Fig. 4: Photo of the Suss MicroTec PMC150 probe station used to measure μmechanical resonators at cryogenic temperatures.

Fig. 7 presents a measured plot of Q versus temperature for 32μm-radius wine-glass disks with varying numbers and orientations of support beams. Here, the measured curves clearly show higher Q's for devices employing fewer supports, and this even at cryogenic temperatures. Thus, although Q's do rise with decreasing temperature, it is likely that anchor losses still dominate among loss mechanisms, and thus, still mask losses due to phonon-phonon interaction or other mechanisms.

Interestingly, the device employing an asymmetric two-support suspension performs better than that using a symmetric one, at least from a Q perspective. In addition, the Q of the symmetric two-support suspended device does not exceed that of the four-support device until the temperature drops below 20K. More study into this phenomenon is needed to identify the exact mechanism, but it is possible that over certain temperatures the symmetric two-support suspension imposes a more non-uniform stress field onto the disk than either the four-support or asymmetric two-support suspensions, thereby generating more loss over most of the low temperature range.

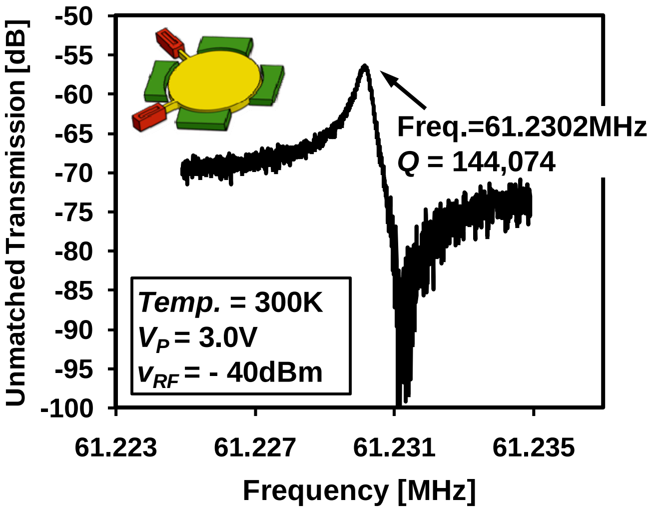

Fig. 6: Measured frequency response for a 32μm-radius wine-glass disk with two asymmetric supports at 300K with V_P=3V.

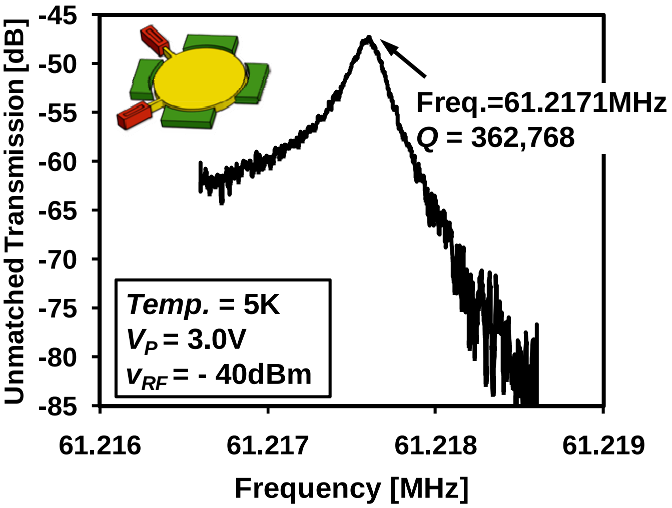

Fig. 5: Measured frequency response for a 32μm-radius wine-glass disk with two asymmetric supports at 5K with V_P=3V.

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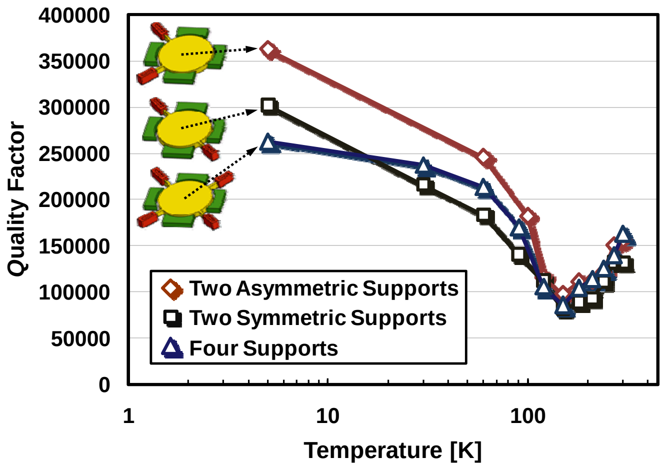

Fig. 7*: Measured Q vs. temperature for 32μm-radius wine-glass disks with varying numbers and orientations of support beams.*

Measurement vs. Theory

Although impressive, the measured Q of 362,768 at 5K is nowhere near the 300 million exhibited by quartz at a similar temperature. The question then arises: Why isn’t the Q of the micromechanical resonator also in the millions? As already mentioned, it is likely that anchor losses are still dominant in this work, and the measured curves of Fig. 7 still do not convey the ultimate Q limited by phonon-phonon or other interactions.

To convey the degree to which anchor losses (or some other loss) dominates, Fig. 8 plots the theoretically predicted Q limits imposed by TED, phonon-phonon interactions, and phonon-electron interactions, alongside the measured data of Fig. 7. Here, theoretical values are obtained via (2), (3), and (4), using parameter values obtained from existing literatures [14][17][18]. From the plot, phonon-phonon interactions impose the highest energy dissipation among these loss mechanisms, so set the lower bound on Q. Clearly, however, this lower bound is still much higher than the measured data, further bolstering a suspicion that another loss mechanism, most likely anchor loss, still dominates the measured Q’s.

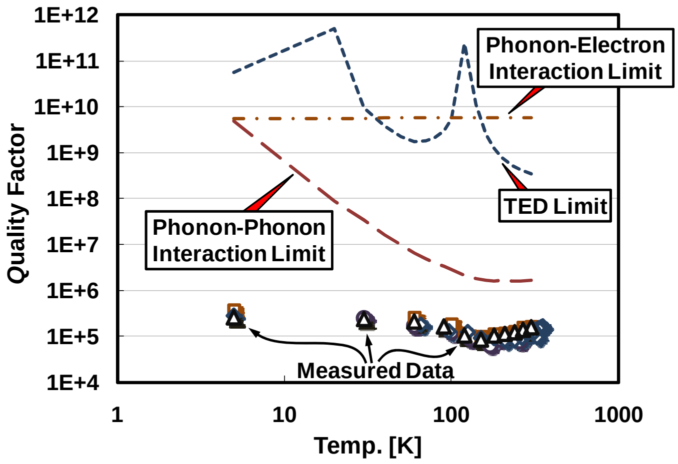

Figure 8: Plot of measured Q versus temperature alongside theoretical Q limits imposed by various loss mechanisms.

Whatever the dominant loss mechanism is, the Q seems to show a relatively weak dependence on temperature for temperatures below 100K. Above 100K, on the other hand, a dip in the Q versus temperature curve is observed. Looking closely at Fig. 8, this dip seems to coincide with the predicted dip imposed by phonon-phonon interactions, suggesting that although other loss mechanisms mask much of the desired information on phonon-phonon interactions, the data of Fig. 8 might still confirm at least the portion and parameters of the theory that set the temperature where phonon-phonon-based losses peak.

CONCLUSIONS

The measured Q of 362,768 for a 61-MHz wine-glass disk resonator at 5K verifies that cooling to cryogenic temperatures can indeed improve the Q’s of micromechanical resonators. This Q represents a ~2.5× enhancement over that measured at room temperature, which in turn corresponds to an improvement of almost 10dB in the phase noise of any oscillator using this resonator. However, even for the well-isolated design of the wine-glass disk used here, anchor losses still probably dominate the Q at cryogenic temperatures and limit our ability to see intrinsic micromechanical resonator energy loss mechanisms. Obviously, further reductions in anchor losses are needed, and work towards this goal is underway.

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