Pressure dependent resonant frequency of micromechanical drumhead resonators

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We examine the relationship between squeeze film effects and resonance frequency in drum-type resonators. We find that the resonance frequency increases linearly with pressure as a result of the additional restoring force contribution from compression of gas within the drum cavity. We demonstrate trapping of the gas by squeeze film effects and geometry. The pressure sensitivity is shown to scale inversely with cavity height and sound radiation is found to be the predominant loss mechanism near and above atmospheric pressure. Drum resonators exhibit linearity and sensitivity suitable to barometry from below 10 Torr up to several atmospheres. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3141731]

Micro- and nanoscale resonant technology shows enormous promise in sensor applications due to their high frequency, low mass, and large surface-to-volume ratio. Detection of extremely small masses has been demonstrated with nanomechanical resonators in vacuum[1,2] and liquid environments.[3] Force sensors (accelerometers) and scan probe techniques based on resonant microelectromechanical systems (MEMS) have been developed. In this letter we describe a linear resonant pressure sensor based on squeeze film effects. In our circular membrane drum resonators, we harness squeeze film effects by using the compressibility of the air film below the drumhead membrane to create a pressure-proportionate addition to the mechanical spring constant. The result is a resonator that displays sensitive and linear frequency response from a few torrent to multiple atmospheres of pressure.

Drum resonators, depicted in Fig. 1(b), inset, are fabricated entirely by CMOS foundry processes on a silicon-on-insulator wafer. We lithographically define etch orifices in a polysilicon device layer that comprises the drumhead when the underlying oxide layer is removed by wet etch in HF to create the drum cavity. We use a 330 nm thick *n*-doped polysilicon device layer grown by low pressure chemical vapor deposition in conditions resulting in an inherent tensile film stress of ~400 MPa; the tensile stress ensures that the membranes are flat, as verified by the absence of Newton rings.[4] Devices in this work move in the out-of-plane direction and are driven and detected optically,[5] but have demonstrated compatibility with piezobuzzer drive and both electrical drive and detection.

We investigate the pressure sensitivity of the resonant frequency to the variation in the cavity height by considering three identical drum geometries (28 μm diameter, 4 μm etch orifice). The drums exhibit vacuum frequencies of 9.38 ± 0.15 MHz and vacuum quality factors, $Q \approx 1.4 \times 10^4$, and differ only in their respective cavity heights of 95, 235, and 660 nm. The mechanical spring, k, constant of the membranes is found by $k=\omega^2 m_{\mathrm{res}}$ to be ~1500 N/m, where $\omega = 2\pi f$ and f is the resonance frequency of the fundamental mode.[6]

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It has long been observed[7–9] that microresonators operating in gas while in close proximity to a substrate experience damping due to compression, or squeezing, of the gas film. This arrangement, ubiquitous in MEMS applications, is

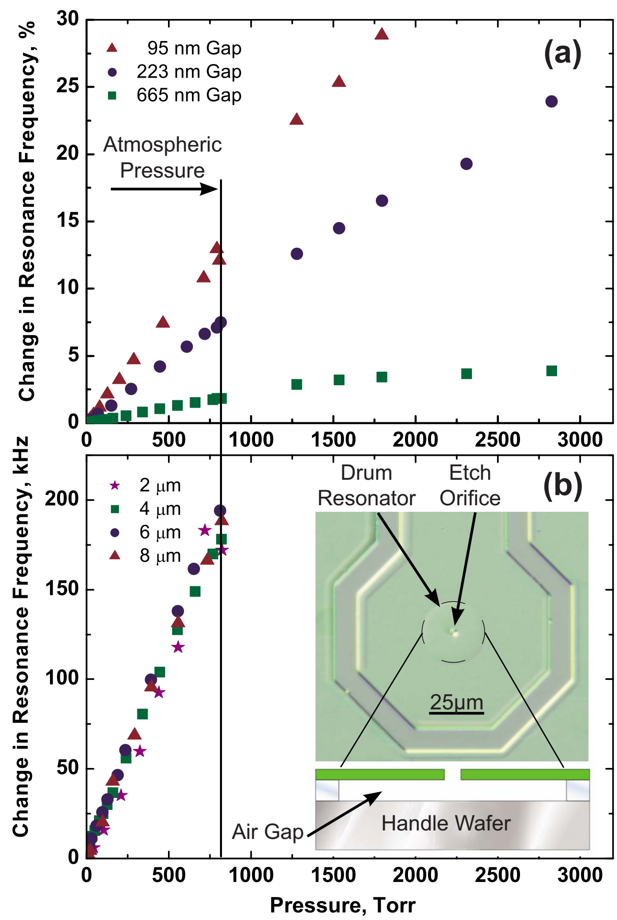

FIG. 1. (Color online) (a) Drum resonators' frequency increases linearly with pressure from ~1 Torr to ~4 atm. The pressure sensitivity varies inversely with cavity height for a drum with a 4 μm etch orifice diameter. Gas in the 665 nm cavity device is unclamped above 1 atm. (b) Negligible change in pressure sensitivity is seen for orifice diameters between 2 and 8 μm. Inset: drum resonator imaged from above and depicted in profile. The cul-de-sac surrounding the drum resonator electrically isolates the resonator from the rest of the wafer and is necessary for electrical readout of resonance.

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especially relevant to the platelike geometries and narrow air gaps associated with capacitive sensing and electrical drive, and squeeze film effects play a significant role in the design of microtorsional mirrors[10] and accelerometers.[11] The effects of squeeze film damping are still under investigation,[12–14] most often in the context of mechanical energy loss mechanisms. Squeeze film damping exhibits two distinct regimes, referred to by Bao and Yang[12] as the viscous and elastic damping regimes. In the first, dominant at lower frequencies and large gaps, the resonant motion of the device forces gas to flow from or toward the compressed volume. In the elastic, or high frequency regime, gas beneath the vibrating structure cannot flow a significant distance within the period of an oscillation and is compressed between the device and the substrate. A gas film trapped by elastic damping does not cause dissipation in the resonator due to viscous flow. However, the increased pressure beneath the device membrane contributes an additional restoring force, increasing the effective spring constant and the resonant frequency.

The viscous damping force and the elastic restoring force have equal magnitude at the cutoff frequency, ω_c, described by Griffin *et al.*[7] to be

$$\omega_c = \frac{\pi^2 d^2 P_a}{12\mu a^2}, \tag{1}$$

where d is the distance between the substrate and the vibrating surface, P_a is the ambient pressure, μ is the viscosity of air, and a is the typical dimension of the microstructure: the width or length in the case of rectangular geometries or radius in circular geometries. Previous research by Andrews *et al.*[15,16] explored the regime above the cutoff frequency. Their devices displayed a quadratic frequency dependence on pressure above 10 Torr. Below that pressure, the gas spring constant, k_g, was small compared to the mechanical spring constant and resulted in linear frequency shifts with pressure. In this letter, we demonstrate operation at frequencies $\omega \gg \omega_c$ and gas spring constant that is small compared to the mechanical spring constant (by a factor of 3 at atmospheric pressure). In these conditions, drum resonators reside in a regime where the resonant frequency is linear with pressure variation over the range of mTorr to several atmospheres. This development facilitates the operation of resonant pressure sensors at and above atmospheric pressures.

Figure 1(a) shows the variation in frequency with pressure for three cavity heights. Operation at higher pressure results in a linear increase in resonant frequency from the low Torr range to several atmospheres and a fractional frequency shift with pressure, $(\Delta f/f)/\Delta P_a$, that is inversely proportional to the cavity height.

Previous work by Andrews *et al.*[16] demonstrated that the squeeze film is compressed isothermally, signifying the equation of state for the gas $pV=\text{const}$. Blech[9] obtains a dimensionless squeeze number, σ, given by the expression

$$\sigma = \frac{12\mu a^2 \omega}{P_a d^2}. \tag{2}$$

Low squeeze numbers indicate that the gas will readily flow from the compressed area during an oscillatory period; high values indicate that the gas is trapped, clamped by its viscosity. Our resonators have σ of 3000, 550, and 60 at atmospheric pressure for the 95, 223, and 665 nm gap devices, respectively. In the limit of such large σ, the isothermal spring constant of the gas, k_g, formulated by Blech,[9] reduces to

$$k_g = \frac{P_a A}{d}, \tag{3}$$

where A is the plate area. For small changes in spring constant and small amplitude Δd, we make the approximations

$$\Delta f = \frac{1}{2} f\left(\frac{\Delta k}{k}\right), \quad \Delta k = \frac{dF}{dx}, \tag{4}$$

from which

$$\Delta f = \frac{f}{2}\left(\frac{AP}{kd}\right). \tag{5}$$

We find that our measured squeeze film contribution (Fig. 1) matches theoretical estimation for k_g at atmosphere to within 20%, the disparity most likely arising because the displacement of the drum, Δd, is not uniform across the entire surface, and thus the actual change in volume, $\Delta V = A\Delta d$, is an overestimate. The frequency dependence on temperature in drum resonators is small compared to pressure-induced frequency shifts; $\Delta f/\Delta T$ is found to be −44 Hz/C over the range of 20–250 C. No frequency dependence is found for different amplitudes of motion.

Significant earlier effort focused on the effect of edges and holes on squeeze film damping. Edge effects at the periphery may be neglected for drum-type resonators since those borders are closed. However, at the central orifice we find both the maximum amplitude of oscillation in the fundamental mode in which our sensors operate and the sole egress from the cavity. Although the pressure variation is expected to drop exponentially at the borders of a squeeze film, simulations by Veijola *et al.*[17] limit these border effects to roughly 1.3 times the cavity height, or less than 1 μm in all of our devices. We observe invariance of the dissipation (Q^{-1}) and absolute frequency shift to orifice dimension, Figs. 1(b) and 2(a). Thus the effect of the etch orifice is tantamount to a negligible loss of compression area. As long as the orifice is significantly larger than the cavity height, its dimension is irrelevant, and a drum resonator may be tailored to a desired pressure sensitivity and operating range entirely by varying the etch time (area) and oxide thickness of the device.

Above 1 Torr, gas damping overwhelms the intrinsic, material (or geometry)-dependent losses observed at lower pressures.[12,14,18] Gas within the drum cavity is elastically clamped, leaving acoustic radiation from the upper surface as the primary energy dissipation mechanism. Figure 2(a) shows the departure of the dissipation from the low pressure, low loss regime to a regime where Q^{-1} increases linearly with pressure. Calculations of energy loss from sound radiation[19] predict the dissipation to scale as

$$Q^{-1} = \frac{\rho_{\text{gas}} c_{\text{gas}}}{\rho_{\text{res}} t f}, \tag{6}$$

where t is the device layer thickness, c is the speed of sound in the gas, and ρ represents the density of the gas or the drum. We find that Eq. (6) predicts a quality factor $Q=19$ at $P_a=1$ atmosphere compared to a $Q \approx 30$ observed for the fundamental mode, f_{01}. The discrepancy most likely arises due to the nonuniform motion of the drum across its diam-

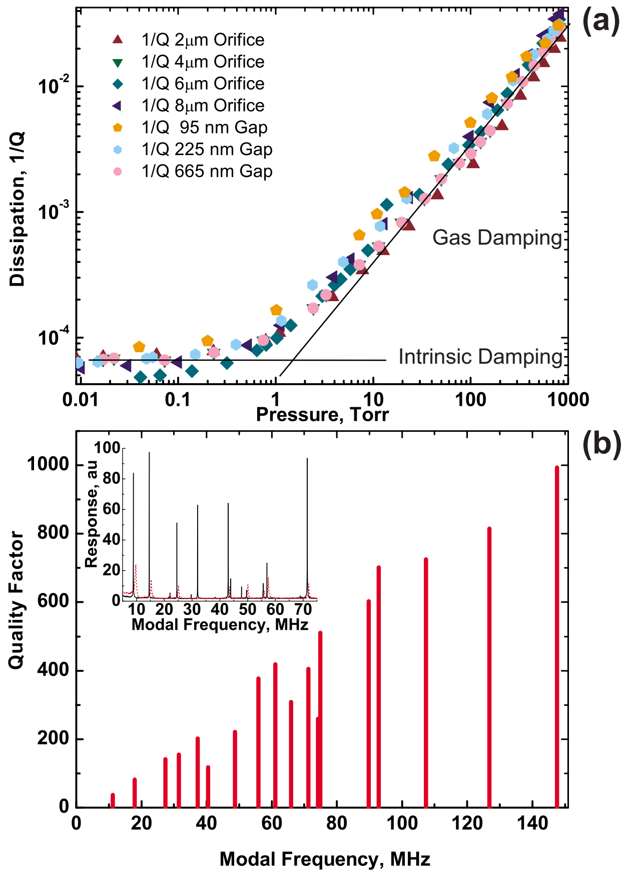

FIG. 2. (Color online) (a) Dissipation (Q^{-1}) in drum resonators in air is independent of cavity height or orifice size. (b) The Q of out-of-plane modes of a drum resonator at 1 atm pressure varies linearly with frequency. Inset: positive frequency shift in the spectrum of a drum resonator with a 223 nm cavity as the pressure is changed from 35 mTorr (solid lines) to 1 atm pressure (dashed lines).

eter. We examine the dissipation and frequency shift of harmonics of the resonator extending from the fundamental mode to modes with frequencies greater than 140 MHz and find Eq. (6) to be consistent with the observed linear increase in Q with mode frequency, shown for a drum in Fig. 2(b).

Drum resonators show sufficient frequency shift to function as pressure sensors in the Torr regime with linear response and high sensitivity (over 2 kHz/Torr in 95 nm gap devices) across this range. Moreover, the geometry of the devices has been optimized for efficient electrical drive and detection,[20] and this experiment has been demonstrated by these means. Compatibility with electrical detection methods, such as capacitive detection[20] or the embedding of a piezoresistive strip,[21] facilitates future integration with conventional electronics. Squeeze film pressure transducers are self-equilibrating and gas species-independent. The uncomplicated fabrication of drum-type resonators likewise lends itself to realizable pressure transducers and potentially to integration into CMOS foundry processes.[22,23]

In summary we utilize the squeeze film effect to demonstrate a pressure-induced linear increase in the resonance frequency of a drum resonator. The gas in the squeeze film trapped under the membrane is clamped by viscous effects and does not flow out of the central etch orifice, effectively creating a self-equilibrating closed volume. The dissipation (Q^{-1}) is found to be independent of orifice size and squeeze film thickness. We show that acoustic losses dominate energy dissipation and that operation at higher frequency results in smaller loss, extending the potential usability of these structures.

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