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A megahertz nanomechanical resonator with room temperature quality factor over a million

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We demonstrate the fabrication and operation of high aspect ratio tensile stressed silicon nitride string resonators. We explore the parameter space of small cross sections, on the order of 100 nm, and long lengths up to 325 μm, demonstrating that such high aspect ratio resonators can be made with standard wet release processing using a material with internal tensile stress. Room temperature quality factors exceed one million at frequencies above 1 MHz. The utility of such high quality factor flexural resonators to probe the interaction of high frequency nanoscale devices with rarefied gases is demonstrated. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2822406]

Nanomechanical resonators have been employed as tools to measure mass, charge, and displacement with exquisite sensitivity,[1–5] to demonstrate back-action cooling in mechanical systems,[6] as selective frequency reference and filtering elements for signal processing applications,[7] and to probe the dynamics of fluids and rarefied gases at small lengths scales and high frequencies.[8] More distant future applications might use such devices for computing, e.g., with mechanical logic elements,[9] or to take advantage of the complexity that arises with systems of coupled oscillators.[10] Achieving optimal performance for each of these applications, defined in terms of maximizing sensitivity to external stimuli, maximizing selectivity to a certain frequency, or even minimizing the footprint and power requirements of a given oscillator will ultimately require developments that minimize mass, as well as maximize spectral purity. The achievement of the later goal can be recast as maximizing resonator quality factor Q or the ratio of resonant frequency to the bandwidth over which the resonator responds to a driving force. For example, the minimum mass detectable with a resonant sensor is[11]

$$\Delta m_{\min} = 2m_{\mathrm{eff}}\sqrt{\frac{B}{\omega Q}}10^{-\mathrm{DR}/20}$$

where m_{eff} is the effective resonator mass, B is the measurement bandwidth, ω is the fundamental resonant frequency, and DR is a dynamic range term. For this application there is an advantage to achieving maximum quality factor as well as frequency, while minimizing device size.

Empirically, reduction of resonator size is typically associated with a reduction in Q.[12–14] Whereas macroscopic audiofrequency oscillators have been reported with Q as high as 10^8 at room temperature,[15] devices with cross sections on the order of 100 nm tend to exhibit Q well below 10^5.[12,13] High temperature annealing, thought to help mitigate surface losses associated with thinning resonators, has been used in some cases to elevate quality factors above 10^5 for devices with sub-micron thickness.[16,17] Room-temperature quality factors near a million have been demonstrated with silicon paddle oscillators with dimensions at the microscale, and frequencies below 1 MHz.[18,19] Also notable is the recent result of a 134 kHz membrane resonator with a thickness of 50 nm and a Q of 1.1×10^6 at room temperature.[20]

We have previously demonstrated that through the addition of tensile stress, doubly clamped string resonators of a given size display increases in both frequency and quality factor, while for devices made from a film with built-in tensile stress, longer and lower frequency resonators demonstrate the highest quality factors.[21,22] In this letter, we explore the parameter space of longer length, while maintaining high tension and nanoscale cross sections. We demonstrate that room temperature $Q>10^6$, characteristic of macroscopic oscillators, can be retained with flexural resonators, even while cross sectional dimensions are reduced to the nanoscale.

The devices were fabricated in a stoichiometric silicon nitride material possessing internal tensile stress ($\sim$1200 MPa), using standard photolithographic techniques, plasma etching, and wet release steps, as previously described.[21,22] We have suspended strings 350 nm wide, 110 nm thick, and up to 325 μm long. The devices as long as 275 μm were attained with nitrogen drying, demonstrating the resilience of these highly tensed strings against stiction effects; however, yield was significantly improved and longer strings were achieved with critical point drying. A freshly released device 275 μm in length, identical to the device shown in the optical image in Fig. 1(a) and whose response is shown in Fig. 1(b), has a quality factor (at room temperature) of 1.3×10^6 at 1.033 MHz, as measured with inertial drive provided by a piezoelectric buzzer, and optical interferometric detection.[21] This quality factor is significantly higher than that we have previously reported for shorter high tensile stress resonators [3.9×10^5 for a 75-μm-long device at 3.7 MHz (Ref. 22)], and illustrates that the increase in Q associated with increasing string length observed for our previous devices extends over a range of lengths and aspect

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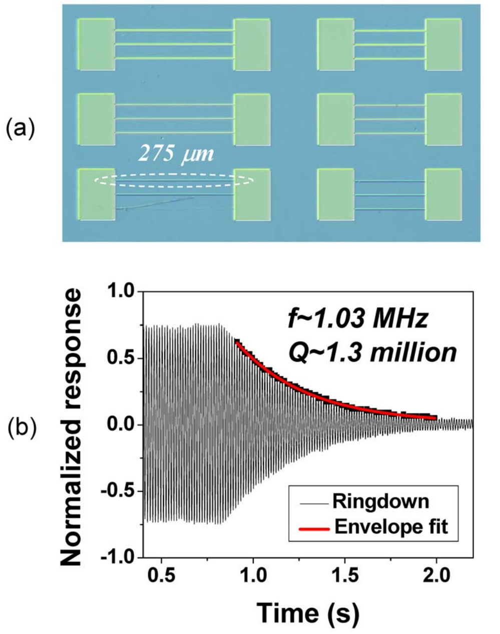

FIG. 1. (Color online) (Color online) An optical differential interference contrast image of nanostrings is shown in (a) (the bottom left string is clearly broken, not having survived the release process). The circled string, of the type whose response is measured by the ringdown measurement shown in (b), is 275 μm long, and 350×110 nm^2 in cross section.

ratios beyond what was previously explored. The Qs for these devices were measured by fitting the envelope of the ringdown of the optical response signal (mixed to near 1 kHz and amplified).

To put this result in context of other nanoscale resonators, we consider the product of surface-to-volume ratio (R) and Q for the highest Q we present. This is an important figure of merit for the surface sensitivity of resonator-based mass assays, normalizing Q to the smallness of the device as measured by surface-to-volume ratio, which is large for small device sizes.[19] A 350 nm wide, 110 nm thick device with a quality factor of 1.3×10^6, has a room temperature RQ product of 31 000 nm^{-1}, close to the value of 44 000 nm^{-1} for the high-Q membrane resonator [20] (the membrane was 1 mm square by 50 nm thick). We note that our result is with *both* cross-sectional dimensions reduced to the nanoscale, and frequency over 1 MHz. By contrast, radiofrequency carbon nanotube and graphene resonators,[4,23] have very high surface-to-volume ratio (several nm^{-1}), but have room temperature RQ values on the order of 1000 nm^{-1}.

The higher harmonics of our devices have products of frequency and quality factor (fQ) among the highest values reported for a flexural resonator. The 10.02 MHz mode of a 325-μm-long device was measured shortly after a hot-plate bake step which has previously been observed to lead to moderate improvements in quality factor for similar devices.[22] This mode has a Q value of 6.8×10^5, for an fQ product of 6.8×10^{12} Hz, of the same order as previously demonstrated with much larger lower frequency single-crystal bulk resonators[15] and within a factor of ~2–3 of that attained with higher frequency micromechanical systems.[24]

For device applications requiring both high frequency and high Q, such as mass sensing, or high frequency signal processing where a narrow bandwidth is desired, it is advantageous to maximize the product of the two quantities. Material dependent internal sources of damping such as that associated with thermal gradients set up by expansion and contraction during resonance (known as thermoelastic dissipation[25]), set an upper limit on the fQ value that is attainable for a particular mode of a given device.[26] Therefore high fQ implies that a device is operating closer to its limiting Q at a given frequency. We calculate the thermoelastic limiting fQ product following Lifshitz and Roukes,[25] using

$$Q_{\mathrm{TED}}=\frac{c_v}{E\alpha^2T}\left(\frac{6}{\xi^2}-\frac{6}{\xi^3}\frac{\sinh\xi+\sin\xi}{\cosh\xi+\cos\xi}\right)^{-1},\quad \xi=t\sqrt{\frac{\omega\rho c}{2\kappa}},$$

where c_v is specific heat per unit volume, E is Young's modulus, α is the coefficient of linear thermal expansion, t is resonator thickness, ρ is density, c is specific heat per unit mass, and κ is thermal conductivity. Setting $T=300$ K, $t=110$ nm, and using $\rho=2700$ kg/m^3, $E=211$ GPa, $\alpha=2.3\times10^{-6}$ K^{-1}, $c=710.6$ J/(kg K) and an upper limit for $\kappa=30$ W/(m K) for bulk ceramic silicon nitride,[21] we calculate that the fundamental mode of our doubly clamped silicon nitride beam resonators would have a thermoelastic limiting fQ value of $\sim10^{13}$ Hz. The devices we present, with Q over 1×10^6 and f over 1 MHz, are therefore within a factor of 10 of this internal limit.

To take advantage of such high quality factor flexural resonators, we consider their use to explore the interaction of high frequency nanoscale devices with gaseous environments. Such studies should provide input valuable for the

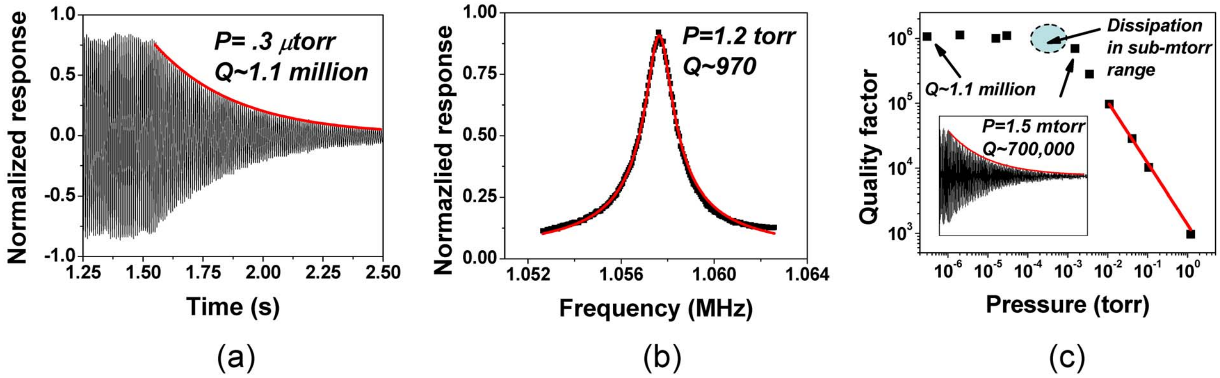

FIG. 2. (Color online) (Color online) Dissipation was measured as a function of air pressure for a 275-μm-long, 350×110 nm string resonator, between 0.3 μTorr (a) 1.2 Torr (b), with the Q dependence on pressure shown in (c). At 1.5 mTorr, quality factor had dropped to 64% of its initial value at high vacuum, from 1.1×10^6 to 700 000, indicating that this device is sensitive to gas damping in the submillitorr range. Resonant frequency was ~1.058 MHz over the pressure range explored. A fit of the data from 0.01 T to 1.2 Torr to $a^{*}P\hat{}b$ yields $b=-0.95$, consistent with expectations for a device in a free molecular flow damping regime.

design of next generation nanomechanical resonant sensors which would be purposely designed for operation in gaseous or liquid environments. In doing so, we gain insight into the interactions of vibrating structures operating in the nonhydrodynamic regime where $\omega\tau > 1$ and/or $\lambda > l$ where ω is the operating frequency, τ is the collision time between particles, λ is the mean free path, and l is the characteristic device size.[8] The Q^{-1} is a measure of the energy dissipated to the surrounding gas; thus, a high vacuum quality factor extends the dynamic range for the measurement of pressure. A 275-μm-long, 350×110 nm string resonator was operated at pressures ranging from high vacuum [0.3 μTorr, shown in Fig. 2(a)) to 1.2 Torr [shown in Fig. 2(b)] of room air. Over this pressure range, the quality factor decreased from 1.1×10^6 to ~ 1000, as shown in Fig. 2(c). At 1.5 mTorr, the quality factor had decreased by 64%. Thus, these high-Q resonators are sensitive to gas damping in the submillitorr range, comparable to the pressure at which the onset of gas dissipation sensitivity for lower frequency, larger cross-section resonators has been demonstrated.[27,28]

Previous work examining high frequency gas dynamics utilizing damping effects on nanomechanical oscillators was typically limited to pressures above 0.1 Torr, due to the relatively low Q ($\sim 10^3$) of most high frequency flexural oscillators with nanoscale cross sections. Thus, these nanostring resonators with $Q > 10^6$ extend the lower end of the pressure range over which studies of the interaction of nanoscale, high frequency structures with gaseous environments can be carried out. For pressures that are high enough for gas damping to be the dominant dissipation mechanism, while low enough that device size is small compared to the mean free path ($l < \lambda$), resonators are in a free molecular flow damping regime, for which it is expected that[27,29]

$$Q = \frac{\rho t \omega}{4}\sqrt{\frac{\pi}{2}}\sqrt{\frac{RT}{M}}\frac{1}{P} \propto \frac{1}{P}.$$

A power law fit of our quality factor data in Fig. 2(c) follows an inverse pressure dependence closely in the range from 0.01 Torr to 1.2 Torr. Due to the nanoscale cross section, this resonator would remain in a free molecular flow regime at higher pressures than devices with significantly larger cross sections,[30,31] increasing the range over which dissipation would depend linearly on pressure before entering into a viscous damping regime.

We have demonstrated mechanical resonators with nanoscale cross-sectional dimensions that retain Q in excess of a million at room temperature and at 1 MHz. These results demonstrate that previously observed improvements in the quality factor of highly tensed nanostrings resulting from increased device length continue for devices of significantly longer lengths. These devices possess products of quality factor with both surface-to-volume ratio as well as frequency approaching the highest values that have been separately reported for either of these quantities. The high quality factor nanostring resonators should be useful as they provide quality factors characteristic of bulk resonators, while providing a physical footprint, as well as sensitivity and power consumption levels characteristic of microscopic devices.

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