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Operation of nanomechanical resonant structures in air

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We report on the resonant operation of high-quality-factor silicon nanomechanical structures in air and at room temperature. We describe techniques used to actuate and detect nanomechanical structures in atmosphere, resulting in the enhancement of the effective quality factor to above 1000 and demonstrate the potential for successful sensor operation of resonant nanomechanical structures under ambient conditions. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1511287]

Many potential applications of nanomechanical or nanoelectromechenical devices (NEMS) have been limited by their sensitivity to viscous friction.[1] Their operation thus requires expensive vacuum packaging solutions. Successful operation of resonant NEMS in liquids or dense gases has not been realized to date. Our results may lift these restrictions and open up some of those possibilities for reconsideration. In addition, NEMS have been hindered by multiple sources of dissipation, from thermoelastic losses[2] to bulk- and surface-defect effects[3] that have placed limits even on their operation in vacuum. Resonant operation of these devices makes them ideal candidates for the detection of small masses (via a shift of the resonant frequency)[4] or weak forces[5] as the devices themselves have very small mass and thus a high resonant frequency. In order to achieve the highest possible sensitivity, the frequency response of these devices should be as narrow as possible. The mechanical quality factor Q is the measure used to define the performance of a resonant NEMS device. We define the mechanical quality factor (and the effective Q) as the ratio of the resonant frequency to the half-width of the device's power spectral response. In this work we describe the use of a laser-light driving scheme recently reported in vacuum[6] that adds energy to the resonating structure and helps to overcome viscous damping losses. The result should enable us to improve the sensitivity of mass-shift detection methods under ambient conditions.

To date, most nanomechanical resonant structures have been studied in vacuum. Viscous damping, which is the dominant loss mechanism at atmospheric pressures,[1] prevents actuation of the structures using drive techniques commonly employed when viscous damping is absent. The resonant motion of NEMS or MEMS (mechanical structures one to two orders of magnitude larger than NEMS) has been detected in air and the reported Q factor values are 100–300.[7] MEMS cantilevers with submicron thickness[8] exhibit similar Q factors in air. Undriven micromechanical cantilevers whose thermal motion in air can be detected,[4] exhibit inferred Q factors closer to 10. Compared to MEMS, NEMS operate at significantly higher frequencies (up to hundreds of MHz[9]) and are harder to actuate and detect. We are unaware of previously reported air operation of NEMS.

Recently we demonstrated[6] a technique that uses thermal effects from the device-modulated absorption of cw laser light to induce parametric amplification and self-oscillation in single-crystal silicon NEMS with resonant frequencies up to 40 MHz. The motion is induced via a variation of the thermal compressive stress that causes the structure to move to a position of higher light intensity and absorption. The heat is dissipated on a time scale similar to the period of oscillation, causing the structure to access the thermal pump energy efficiently. The details of that energy transfer can be found in previous publications.[6,10] The structures used in our present case study (shown in the inset of Fig. 1) are square silicon paddles with supporting arms of various lengths. Their fabrication and the optical detection of their motion have been described elsewhere.[11] In vacuum, light-induced parametric amplification on these devices increases the amplitude of the response by three orders of magnitude. The resonant frequency response also narrows due to the nonlinearity of the drive,[6] resulting in an increase of the effective quality factor from 6 000 to 20 000 for a structure similar to the one seen in Fig. 1 inset.[6] For comparison, similar values of the quality factors in silicon structures in vacuum are obtained only at low temperatures,[12] where thermoelastic dissi-

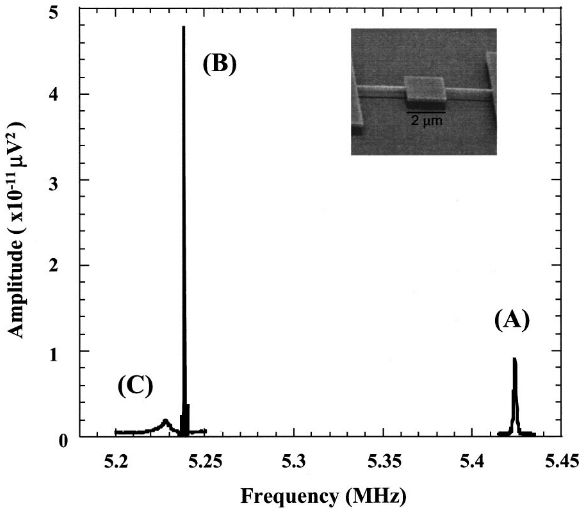

FIG. 1. Resonant response of the oscillating structure, similar to the one shown in the inset (paddle is 2×2 μm, suspension arms are 4.5 μm long, 200 nm wide, and 205 nm thick): (A) response in vacuum while driven with a piezo only; (B) response in vacuum under parametric amplification (with or without the piezo drive); (C) response in air while driven with a piezo and under parametric amplification.

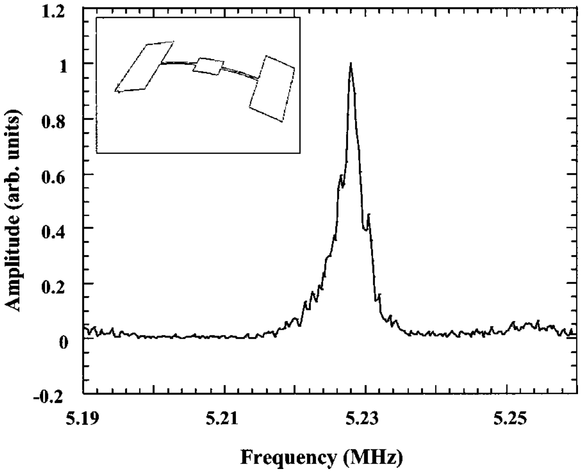

FIG. 2. Resonant response of a translational mode (inset) of a paddle (similar to the one shown in Fig. 1) oscillating in air and driven with a piezo drive and an optical parametric drive. The effective quality factor is about 1100. The same as peak (C) in Fig. 1.

pation is minimal, or through careful treatments of both the bulk and the surface.[3] These approaches are not practical for room temperature operation while exposed to the atmosphere. Figure 1 shows the response of the system in vacuum driven in the linear regime using a piezo element and without parametric amplification (A) with a Q of 3800. The response of the same structure in vacuum and under parametric amplification (B) shows an increase in amplitude, and the effective Q is 17 000. The same structure, under optical amplification and driven with a piezo drive in air (C), exhibits a high signal to noise ratio (as can be seen in Fig. 2) and an effective Q of 1100. Without the piezo drive, with sufficient cw laser pump levels, self-oscillation was detected with a further narrowing of the resonant response by another order of magnitude beyond (C) (the same effect as in vacuum). This response was short-lived, on the order of a few seconds, as the pump (laser power) amplitude was high enough to melt the structure. The change in the resonant frequency in vacuum between the piezo-driven and the optically-driven cases is due to the softening of the spring constant (due to thermally-induced compressive stress[6]). The mode of motion under consideration is the translational mode, depicted in the inset of Fig. 2. The further decrease in the resonant frequency when the structure is exposed to air most likely arises from the air damping or mass loading. A driven damped system will respond at a frequency ω_r, which is lower than its natural frequency ω_0, by

$$\omega_r^2=\omega_0^2-2\beta^2,$$

where

$$\beta\equiv\omega_0/2Q$$

and $-2m\beta(dx/dt)$ is the damping force term; m is the mass of the oscillator, and x is its position. From the measured change in frequency we would obtain an expected quality factor of about 2 (much lower even than that exhibited in the thermal motion of MEMS structures that are not driven[4]). It is therefore unlikely that the entire frequency shift can be attributed to viscous damping. However, the system is not operating as a simply driven, damped oscillator. Under parametric amplification the width of the resonant response is narrowed[6] resulting in the effective Q factor of 1000. Thus it is difficult to separate the effects of parametric amplification (that narrows the resonance) and the effects of damping (that broadens the resonance).

A small addition to the mass, Δm, will cause a change in the resonant frequency, Δf_r, according to

$$\frac{\Delta f_r}{f_r}=-\frac{1}{2}\frac{\Delta m}{m}.$$

If we assume that the change in frequency is entirely due to the air mass loading we would infer that the volume of air required to induce a change in frequency Δf_r, is about 15 times that of the device. Since the viscous penetration depth, $\delta=\sqrt{(2\eta/\rho\omega)}$ (where η, ρ are the dynamic viscosity and density of air respectively, and ω is the angular frequency), is about 2.4 μm and is much greater than the device (205 nm) and the gap (400 nm) thickness, it is likely that mass loading is a contributing and possibly dominant cause for the shift in the frequency. The mass equivalent of two bi-layers of water molecules would induce the same shift in the frequency, but that is a less likely cause for mass loading under the experimental conditions. A thermal shift due to the changes in the device's thermal profile in vacuum (B) and in air (C) should be considered because the free convection of air could provide an additional path for the heat loss in the device. Using the results derived from the momentum and energy equations for incompressible flow,[13] the rate of heat loss due to free convection was calculated for the silicon structure described here. Per unit temperature difference between the structure and the ambient, the convection loss is 5×10^{-10} W/K. Conduction through the silicon contributes 2×10^{-6} W/K, and dominates by almost four orders of magnitude. Thus a resulting increase in the frequency shift due to the added convection-heat path (cooling) would not be detectable in this case.

One of the sought-after applications of a NEMS device is for the detection of chemicals or biological entities. Many of those applications can require or favor NEMS operations in air and possibly in liquid. The ability to attain high sensitivity for mass detection in an easily integrated small sized package is attractive. The detection of a single bacterial cell on a cantilever with resonant frequency of about 1 MHz and quality factor of ~50 in air has been recently demonstrated.[4] The use of a structure such as one we have described here with a resonant frequency of 5 MHz and a quality factor of ~1000 increases the mass detection sensitivity by tenfold, thus enabling the detection of even smaller mass (~50 viruses) and the eventual operation of an optimized bacterial detector in liquid. The optical parametric pump technique used in our work is but one of a number of possible modulation mechanisms. Previously we reported[14] on a parametrically driven device of similar geometry, using electrostatic force. The electrostatic drive/pump is more easily integrated and would obviate concern about thermal damage to the species being detected. Other applications of NEMS in air could include, but are not limited to, integrated electrical processing systems, such as reference oscillator circuits. NEMS described herein with frequencies in tens of MHz and low bandwidth can compete with current components in their performance, while also sidestepping the hermetic packaging solutions.

In conclusion, we demonstrate operation of megahertz nanomechanical resonant structures in air and with effective quality factors above 1000. These results were obtained with the use of a parametric drive that enhances both the amplitude and the bandwidth response for their use as ultrasensitive mass detectors. A small frequency shift $\Delta f_r / f_r$ is consistent with the presence of damping and mass loading from the air, and an exact accounting of the origin of this frequency shift is the subject of an ongoing investigation.

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