Actuation and internal friction of torsional nanomechanical silicon resonators

A. Olkhovets,[a] S. Evoy,[b] D. W. Carr,[c] J. M. Parpia, and H. G. Craighead
Cornell Center for Materials Research, Cornell University, Ithaca, New York 14853

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We report on the actuation and mechanical properties of silicon resonators with nanometer-scale supporting rods operating in the 3–20 MHz range. The symmetrically designed paddles can be excited both in their flexural and torsional modes of motion. Fabrication imperfections as small as 10–20 nm provide enough asymmetry to allow such torsional excitation. We also report on internal friction studies in these systems. Thin Al overlayers contribute to the room temperature internal losses, as quality factor drops from 3300 to 380 for 160 Å thick film. A temperature dependence of internal friction has a broad peak in the $T=160-190$ K range, and attributed to the Debye relaxation and thermally activated friction mechanisms. Analysis shows that the peak shifts to higher temperatures with increasing resonator frequency.
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I. INTRODUCTION

Nanoelectromechanical systems (NEMS) are of interest from both scientific and technological standpoints. Small resonant structures provide opportunities for new studies of mechanical properties of mesoscopic materials. NEMS can be used for sensitive studies of internal friction in evaporated overlayers,[1,2] or as force sensors and accelerometers. These applications require high quality factors (Q) to achieve high sensitivity. High-frequency mechanical resonators with high Q are of interest for the development of low-power compact rf filters, oscillators, and mixers.[3] One of the obstacles for practical applications is the intrinsic losses which lower the mechanical quality factor of these devices. Thorough understanding of loss mechanisms is important for fabricating high-Q resonators. We have recently reported on the fabrication and electrostatic operation of nanomechanical beams as thin as 30 nm and frequencies as high as 380 MHz.[4] We have also reported on the dynamical modeling and characterization of paddle oscillators operating in the 1–10 MHz range.[5] Here, we report on the actuation and the internal friction studies of paddle and wire oscillators. Temperature dependence of the internal friction has a peak in the $T=160-190$ K range, which we associate with surface and near-surface phenomena previously reported in larger kilohertz range devices.[6,7]

II. ACTIVATION OF TORSIONAL MODE

The fabrication, electrostatic actuation, and optical detection of these devices have been previously described.[4,5] The released devices are produced from silicon-on-insulator wafers consisting of a 200 nm single-crystal (100) Si layer over 400 nm of buried Si oxide using electron beam lithography, reactive ion etching, and wet chemical etching. Devices are operated in a vacuum of 10^{-3} Torr (Fig. 1). The motion is induced by applying a dc plus ac voltage between the paddle and the substrate. The resonant curves are acquired by sweeping the frequency of the driving voltage and observing the mechanical response, measured by an optical interferometric technique.[8]

The resonators exhibit two simple-mode resonances, namely translational and torsional.[5] While it is clear how the translation motion is excited, it is not evident for the torsional mode due to the symmetrical design of the oscillator. The linear equation of angular motion must be used to explain this apparent inconsistency:

$$I\ddot{\theta}+\kappa\theta+\frac{1}{\omega_0 Q}\dot{\theta}=\tau(t), \tag{1}$$

where I is the moment of inertia of the paddle, and κ is the combined torsional restoring constant of both Si wires. We calculate the external torque τ by solving the Coulomb equation for the electrostatic force and integrating over the area of the paddle, assuming that there is small off-center displacement δ [see Fig. 2(top)]:

$$\tau(t)=\varepsilon_0 w(V_{\mathrm{dc}}+V_{\mathrm{ac}})^2\frac{d}{2h^2}\left(\delta+\frac{d^2}{6h}\theta+\text{higher order terms}\right). \tag{2}$$

The term in front of θ will only modify the effective κ, and cannot drive the oscillator. However, the term in front of δ, can cause a net nonzero torque around the axis that will be piecewise linear with both dc and ac voltage at small drive amplitudes. It can be the cause of the motion. To test this assumption, we have designed, fabricated, and assayed arrays of paddles with controlled asymmetry δ.

The plot of the amplitude for varied asymmetry is shown in Fig. 2(bottom). The amplitude grows almost linearly with δ, supporting our assumption. From the intercept with the origin, we conclude that an uncontrolled asymmetry of only

[a]Electronic mail: ago2@cornell.edu
[b]Present address: Bradley Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061.
[c]Present address: Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974.

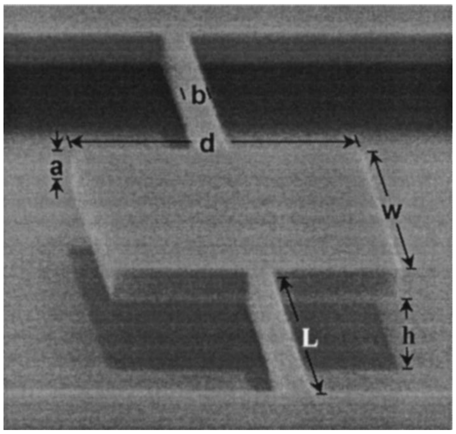

FIG. 1. Scanning electron microscope image of typical nanomechanical torsional resonators. The paddle is single-crystal silicon. Device dimensions used in this study were $w=2\ \mu$m, $d=3\ \mu$m, $L=2\ \mu$m, $a=200$ nm, $b=170$ nm, and $h=400$ nm.

10–20 nm would suffice to produce an observable torsional motion in the symmetrically designed paddles. This kind of uncontrolled asymmetry can easily result from fabrication imperfections. Furthermore, paddles with deliberately fabricated small off-center displacement can be made if larger amplitude of torsional motion is required. One can improve the sensitivity of the force detection with torsional resonators using this approach.

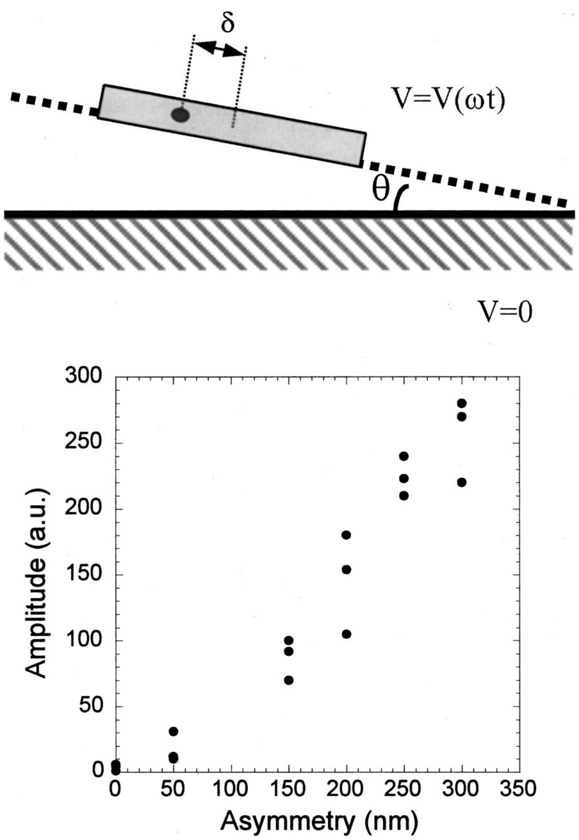

FIG. 2. (Top) View of a paddle (Fig. 1) along the supporting wires. There is a small displacement δ from the center of the paddle to the support point. (Bottom) Amplitude of oscillations at resonance as a function of asymmetry.

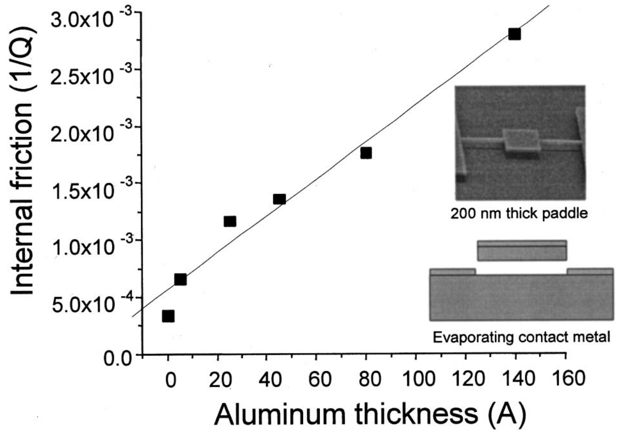

FIG. 3. Inverse of the quality factor of the resonator as a function of the thickness of evaporated aluminum.

III. LOSSES FROM METAL FILMS

We now turn to studies of internal losses in these resonators. Many microelectro-mechanical systems employ a thin metal overlayer to ensure adequate conductivity of the structures. Although metals have much higher internal friction than Si,[9] the impact of the thin layers on the overall internal friction is usually disregarded in large 100 μm scale devices. However, this may not be the case as typical dimensions are reduced down to the nanometer scale. We investigated the effect of thin Al layer on the quality factor of the torsional oscillator. A thin layer was evaporated in a vacuum better than 2×10^{-6} Torr and the resulting Q was measured. For the structure described by Eq. (1), the amplitude squared as a function of the driving frequency has a Lorentzian shape. The Q was determined by dividing the frequency of the resonance over the width of the fitted Lorentz curve. The experiment was repeated several times, each time adding another thin layer of metal. The internal friction versus the total Al thickness is plotted in Fig. 3. The metal is a source of additional internal friction, which grows almost linearly with the thickness of the metal layer. The mass of the evaporated layer, calculated from the thickness measured by the deposition monitor, was 50%–60% of the mass calculated from the frequency shift of the resonator. This is consistent with an almost completely oxidized Al_2O_3 layer. Even angstrom-scale thick layers have a dramatic degrading effect on Q.

Metal layers should not be used if possible. Doping[3] or a double oscillator with only the outside frame metallized[10] can be used instead. We were able to drive undoped 2–20 Ω cm paddles by bonding contact wires a few microns from the devices, thus avoiding the metallization completely, and not introducing additional damage to the single-crystal Si by doping.

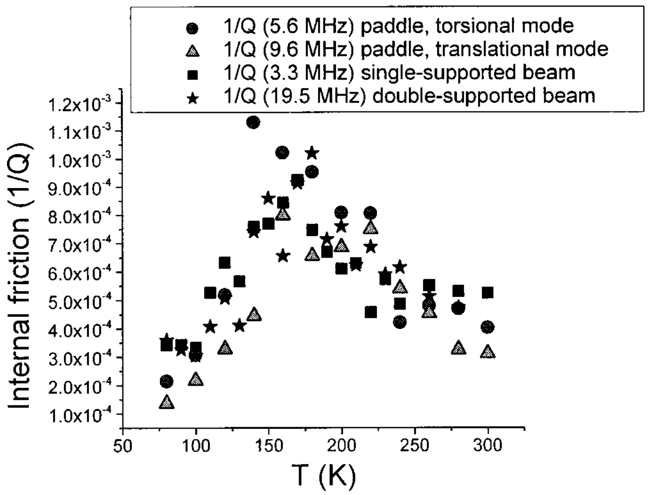

FIG. 4. Inverse of the quality factor of the resonators as a function of temperature. The single- and double-clamped Si beams had 10 μm$\times$2 μm $\times$0.2 μm dimensions, and had a 3 nm Cr (for adhesion) plus a 17 nm of Au thermally evaporated overlayer.

IV. TEMPERATURE DEPENDENT LOSSES

We also investigated the temperature dependence of Q for translational and torsional mode of the paddle oscillators, and translational mode of a single- and double-supported beam (Fig. 4). The paddle was not metallized, and the beams had an overlayer of 3 nm Cr (for adhesion) plus 17 nm of Au. The devices were operated in a better than 3×10^{-7} Torr vacuum in a cryostat. The cold finger with a heating coil allowed temperature control over the 4–300 K range. All four plots have a wide peak in the 150–180 K range. We previously reported the observation of this peak in the paddle resonators.[11] Here, we observe the same feature in a variety of geometries, independently of the presence or absence of metal overlayers, and in a range of frequencies. The effect is, therefore, not an artifact of the metal overlayer or of the device geometry, and is likely intrinsic to the as-processed silicon structure.

A thermally activated internal loss mechanism is governed by the Debye relaxation equations:

$$Q^{-1}\propto\frac{\omega\tau}{1+(\omega\tau)^2},\quad \tau=\tau_0\exp\left(\frac{E}{k_BT}\right), \tag{3}$$

where E and τ_0 are the defect activation energy and time, k_B is Boltzmann's constant, T is temperature, ω is the frequency of oscillation. The fits to the experimental data points produce activation energy in the $E=0.1-0.2$ eV range. The location and behavior of these peaks is similar to the one observed at $T=135$ K in larger kilohertz range microcantilevers. That peak has been attributed to surface or near-surface related phenomena, such as damage or presence of oxide.[6] The defects can result from the fabrication-induced damage of the surface, which is consistent with measured Young's modulus being a factor of two to three times softer than in bulk.[5] Equation (3) predicts a loss peak shift to higher temperatures with increasing resonator frequency. This is consistent with the observed shift from $T=110-140$ K at kHz frequencies,[6,12,13] to our $T=160-190$ K at 3–20 MHz. It becomes a significant contribution to the total internal friction even at room temperature for devices with resonant frequencies of 0.5 GHz and higher. It is important to study and minimize this loss mechanism for successful fabrication of future high-Q near-GHz frequency mechanical resonators.

V. SUMMARY

In conclusion, we theoretically and experimentally analyzed the actuation of torsional resonators, and showed that geometrical errors as small as 10–20 nm resulting from process imperfections provide sufficient asymmetry to drive the devices. Further, we found that thin Al film has a dramatic degrading effect on Q, and therefore metallization should be avoided. We observed a strong broad peak in the Q^{-1} dependence on T, and attribute it to Debye relaxation behavior. This loss mechanism can become a significant contribution to the total losses at room temperature for 0.5 GHz and higher frequency devices. Future studies of devices with cleaner, better passivated surfaces, and controlled damage will allow the development of high quality nanomechanical resonators for technological and fundamental science applications.

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