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Temperature-dependent internal friction in silicon nanoelectromechanical systems

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We report the temperature-dependent mechanical properties of nanofabricated silicon resonators operating in the megahertz range. Reduction of temperature leads to an increase of the resonant frequencies of up to 6.5%. Quality factors as high as 1000 and 2500 are observed at room temperature in metallized and nonmetallized devices, respectively. Although device metallization increases the overall level of dissipation, internal friction peaks are observed in all devices in the $T=160-180$ K range. © *2000 American Institute of Physics.* [S0003-6951(00)01541-2]

The mechanical properties of micro- and nanomechanical systems are of interest from both fundamental and technological standpoints. The understanding and control of composition, nanostructure, and interface properties are important for the development of nanostructured materials. Furthermore, high-frequency mechanical resonators presenting high quality factors are of interest for the development of sensitive force detecting devices,[1,2] and highly efficient rf electromechanical filters and oscillators.[3] Mesoscopic dimensions and high-frequency operation also open up fascinating possibilities for sensitive studies of extrinsic processes such as surface and near-surface effects, and of other fundamental phenomena such as coupling with lattice vibrations and interaction with electromagnetic fields. Unfortunately, the quality factor of resonant micromechanical devices decreases steadily with device dimension. Such high internal losses are the combination of both extrinsic and intrinsic issues that must be well understood for the optimization of resonator quality, and for experimental access to fundamental mesoscopic mechanical phenomena.

Defect motion is governed by an activation energy that will induce Debye relaxation peaks in the temperature dependence of internal friction. Analysis of such peaks offers useful information on the defect thermodynamics and its impact on mechanical properties. This approach has been used for several decades in hertz range bulk resonators.[4] More recently, macroscopic kilohertz range torsional silicon oscillators have been used to probe the mechanical properties of thin overlayers.[5,6] Nanomachining opens new avenues for the assay of structures whose dimension compare to typical nanostructural length scales. We have recently reported the fabrication and electrostatic operation of nanomechanical beams as thin as 30 nm and frequencies as high as 380 MHz.[7] We have also reported the dynamical modeling and characterization of paddle oscillators operating in the 1–10 MHz range.[8] Here we report the temperature dependent behavior of these paddle oscillators. We observe Debye internal friction peaks in the $T=160-190$ K range, which we associate with surface and near-surface phenomena previously reported in larger kilohertz range devices.[9,10]

The fabrication, electrostatic actuation, and optical detection of these devices have been described previously.[7,8,11] The released structures are produced using electron beam lithography on silicon-on-insulator (SOI) wafers consisting of a 400-nm-thick oxide buried underneath 200 nm of single-crystal (100) silicon. Devices are operated in a cryostat pumped down to the 10^{-5} Torr range. A cold finger allows temperature access and control over the $T=4-300$ K range. The resonant response of a structure is acquired by sweeping the drive frequency. The quality Q is closely approximated from the width of the resonance peaks using the relation

$$Q=1.54\frac{f_0}{\Delta f_{\mathrm{FWHM}}}, \tag{1}$$

where f_0 is the center of the resonance response, and Δf_{FWHM} is its full width half maximum. Although each set of data presented here was obtained on a single device, quantitative results were not seen to substantially deviate from device to device.

Figure 1 shows a micrograph of a nanofabricated paddle oscillator. All results reported here were obtained on paddles of length and width of $d=5.5\,\mu$m and $w=2\,\mu$m, respectively. The supporting beams are $L=2.5\,\mu$m long and $b=175$ nm wide. The whole structure has a thickness of $a=200$ nm, and rests at a height of $h=400$ nm above the surface, as fixed by the thicknesses of the SOI layers. Earlier devices discussed here included thin layers of Cr (3 nm) and Au (17 nm) evaporated on the entire structure to ensure adequate electrostatic actuation. We have recently concluded that such overlayers were unnecessary. We now successfully actuate our structures without any metal overlayers by plac-

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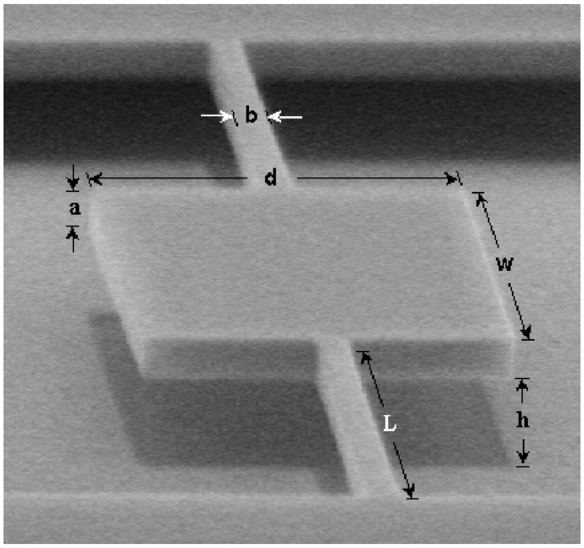

FIG. 1. Scanning electron micrograph of a nanofabricated single-stage paddle oscillator.

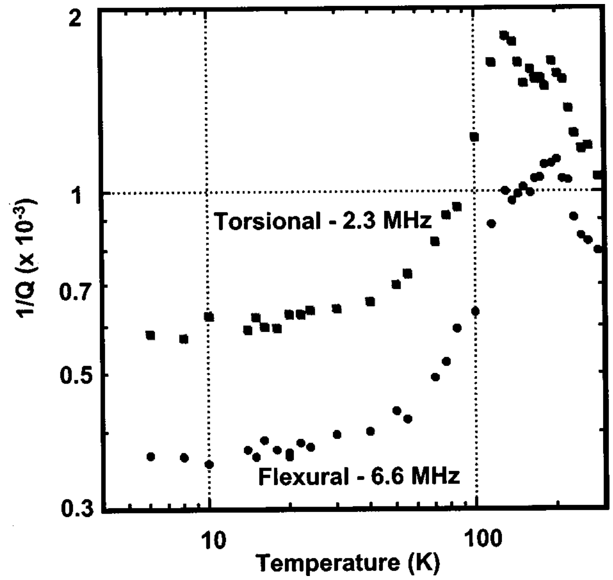

FIG. 3. Temperature dependence of the internal losses for the two modes of motion of a metallized nanofabricated silicon oscillator.

ing a bonding wire directly on the top silicon layer within a few microns of the device, and similarly bonding the grounding wire on the bottom surface also in close proximity of the device.

We have identified two modes of oscillation attributed to the flexural and torsional motion of the supporting beams, respectively.[8] These modes are sufficiently decoupled to allow their independent excitation by the application of the appropriate actuation frequency. Figure 2 shows the temperature dependence of the two resonant frequencies of a metallized device. The frequency steadily increases as the temperature decreases to $T=80$ K, at which point an inflection of the slope is observed. Overall increases in resonant frequency of 6.5%, and 1.5% are observed at the lowest temperature for the flexural and torsional modes, respectively. Ekinci *et al.* have recently observed a similar behavior in wide range of devices and materials. They elaborated on a combination of possible explanations including temperature dependence of the speed of sound and residual stress in the devices.[12] Additional control experiments on nonmetallized devices would allow a better understanding of the phenomena that dominate this shift over the various temperature ranges.

Figures 3 and 4 show the temperature dependence of the internal friction for the two modes of motion of a metallized and nonmetallized device, respectively. Within the precision of our measurement, all four sets of data show a peak structure centered at $T=160-180$ K. The existence of this peak in both metallized and nometallized devices suggests that the metal overlayer is not responsible for this loss. However, the reduction of the sloped dissipation background in the nonmetallized device suggests that metal film monotonically contributes to the total internal friction in that temperature range. This contribution could possibly peak at much higher temperatures, as expected from bulk polycrystalline metals.[4]

A similar peak has been observed at $T=135$ K in larger kilohertz range microcantilevers, and has been attributed to surface or near-surface related phenomena such as damage or presence of oxide.[9] Furthermore, studies of hydrogenated 2–8 kHz silicon membranes have revealed a hydrogen sorption-related Debye peak at $T=125-135$ K with an acti-

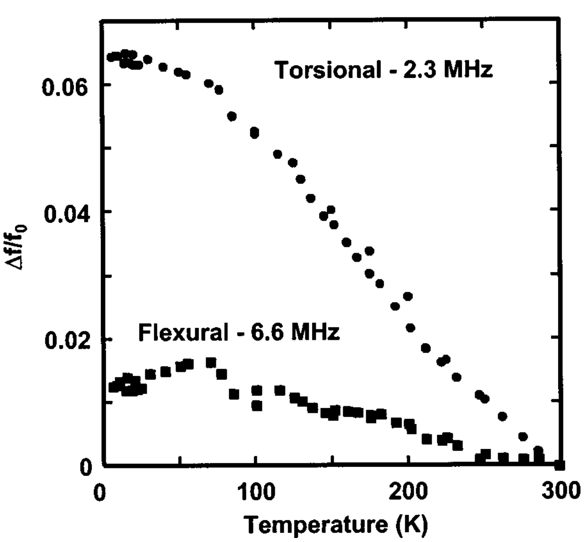

FIG. 2. Temperature dependence of the resonant frequency of the two modes of motion of a metallized nanofabricated silicon oscillator.

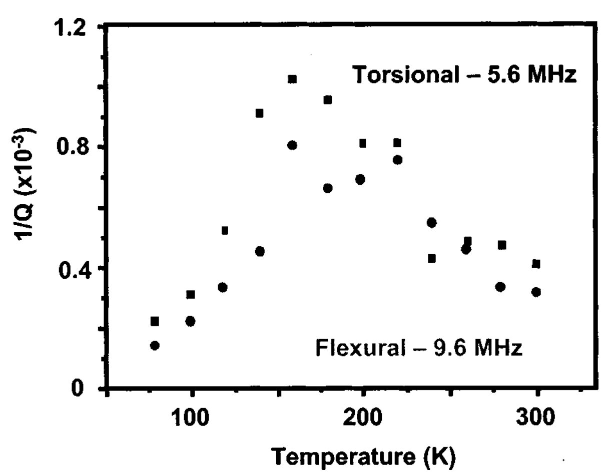

FIG. 4. Temperature dependence of the internal losses for the two modes of motion of a single stage nonmetallized nanofabricated silicon oscillator.

vation energy of $E_a = 0.226\,\mathrm{eV}$.[10] The peaks observed in our megahertz-range devices could potentially be related to similar phenomena, as a shift from $T = 120-140\,\mathrm{K}$ at 2–10 kHz to $T = 160-180\,\mathrm{K}$ at 5–7 MHz would be consistent with a Debye relaxation behavior dictated by an activation energy of $E_a = 0.25-0.5\,\mathrm{eV}$. Furthermore, we previously observed a strong surface-to-volume dependence of the room temperature internal losses in 100–400 MHz nanowires prepared with the same process as the devices described here.[7] This surface-to-volume ratio dependence would be consistent with the dominance of surface or near-surface internal losses that could originate from an HF-related hydrogen sorption, process-induced damage, or native oxide. Finally, the characterization of both modes of motion of these single-stage paddles consistently suggested a material 50% softer than expected from bulk silicon.[8] Well outside our margin of error on device dimensions, this discrepancy would also agree with a substantial departure from bulk silicon properties within the beam volume. Control *in situ* annealing experiments will provide important insights for the exact identification of this near-surface internal friction process, and its relationship with the phenomena previously reported in kilohertz range devices.

We have reported the temperature-dependent mechanical behavior of paddle oscillators with nanometer-scale supporting beams. A temperature dependent frequency shift has been observed. Low-temperature studies of internal friction at 5–7 MHz have also revealed a double peak centered in the $T = 160-180\,\mathrm{K}$ range that would be consistent with the activation energies expected from near-surface phenomena previously reported in larger devices. A surface or near-surface modification of the silicon properties is also consistent with previously reported analysis of our devices. Further investigation will allow a thorough understanding of the various extrinsic, intrinsic, and fundamental processes leading to internal losses at such scales. It will enhance the quality of such rf structures, allow the development of high-quality resonators for technological applications, and provide access to fundamental studies of surface effects and mesoscopic internal friction.

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