HOLLOW FLEXURAL RESONATORS WITH NANOSCALE THICKNESS

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ABSTRACT

Hollow resonators with nanoscale thickness have similar resonance frequencies but much lower spring constants and quality factors than solid resonators of the same dimensions, offering unique advantages in sensor applications. We report hollow beam cantilevers fabricated by performing atomic layer deposition of Al₂O₃ on solid silicon molds and then etching the internal mold. Compared to their solid counterparts, these hollow cantilevers demonstrate reduction of spring constant by up to 100x, quality factor by 10x, and resonance frequency by 1.5x. The reduced spring constant offers enhanced sensitivity in biological or chemical sensing applications while the reduced quality factor increases the bandwidth by approximately 5x.

INTRODUCTION

Resonators with nanoscale thickness (<100 nm) can offer high effective surface area and, therefore, high sensitivity in biological or chemical sensing applications. However, solid resonators with nanoscale thickness typically exhibit low flexural resonance frequency because the frequency is proportional to the thickness of the solid resonator: $f_0 \sim ct/l^2$, where c is the speed of sound of the resonator material, t is the thickness, and l is a characteristic lateral dimension (e.g., the length of a cantilevered beam). Reducing the lateral dimensions can be used to push the frequency back up but the

resulting cantilevers have high spring constants and small total areas, which is disadvantageous in some sensing applications [1].

These tradeoffs can be avoided by using hollow beam geometries, in which the resonance frequency is approximately independent of the wall thickness and instead scales with the height of the hollow beam. Although hollow beam cantilevers have been previously used for chemical [2] and biological [3] applications, the thickness of the walls was typically comparable to the height of the resonators, making their resonant properties similar to those of their solid counterparts. Here, we report hollow cantilever resonators with nanoscale thickness and micron-scale heights, resulting in greatly reduced mass, spring constants, and quality factors but nearly unchanged resonance frequency relative to solid counterparts of the same dimensions.

FABRICATION

We fabricated cantilevered hollow resonators by depositing various thicknesses (20-110 nm) of aluminum oxide (Al₂O₃) on silicon molds using atomic layer deposition (ALD). We used a variety of commercial AFM cantilevers as convenient silicon molds but also fabricated custom silicon molds for larger resonators. After deposition, an etch hole was opened on the top or the sides of the cantilevers using pulsed laser micromachining. Finally, isotropic etching with XeF₂ removed the internal silicon mold, leaving only hollow shell cantilevers. Figures 1a and 1c show original solid cantilever molds while Figures 1b and 1d show hollow cantilevers after fabrication.

RESULT AND DISCUSSION

We determined the resonance frequency, quality factor, and spring constant from both the thermal noise spectra and driven resonance curves (Figure 2). The measurement was first done for solid cantilever molds and then repeated for the final hollow cantilevers. Figure 3 shows the ratio of the resonance frequency (f), quality factor (Q), and the spring constant (k) of solid cantilever to

Figure 1: Scanning-electron micrographs of (a) solid and (b) hollow tapping mode cantilevers, as well as (c) solid and (d) hollow contact mode cantilevers. The released hollow shells are artificially colored for clarity. The etch-hole is visible near the tip of the cantilever in panel (b). The hollow cantilevers are mechanically robust, recovering from sharp bending by a micromanipulator probe without damage (e and f).

Figure 2: Thermal noise spectra (top) and driven resonance response (bottom) of a solid (left) and hollow (right) cantilever with a length of 140 μm, width of 37.5 μm, height of 4 μm, and thickness of 70 nm. The thermomechanical noise peak is more prominent in hollow cantilevers because the reduction in the quality factor is more than compensated by the reduction in the spring constant.

those of hollow cantilever as a function of the ALD Al_2O_3 thickness.

Figure 3: Ratios of the resonance frequency, quality factor, and spring constant of a solid cantilever to those of a hollow cantilever of the same dimensions. The circles with error bars and dashed lines show the experimental data while the solid curves show theoretical predictions.

Ratio with a value larger than 1 indicates that the parameter is reduced in a hollow cantilever relative to that of its solid counterpart. The reduced spring constant and frequency values agreed with the theoretical predictions obtained by approximating the cantilevers as a hollow beam with a rectangular cross-section. The frequency reduction was by a factor of $\sim 1.5\times$ and, as expected, largely independent of Al_2O_3 thickness.

Experimentally, the quality factor in the air was typically reduced by a factor of 10, although theoretical models [4,5] predicted even higher reduction, up to $50\times$ for an Al_2O_3 thickness of 20 nm. The spring constant of the hollow cantilevers ranged from 0.3 to 1.4 N/m, a reduction by a factor of up to $100\times$. The greatly reduced spring constant offers enhanced sensitivity in biological and chemical sensing applications. In addition, the cantilevers demonstrate extreme mechanical robustness under bending deformations (Figures 1e and 1f), similar to our previously reported hollow mechanical metamaterials [6,7].

Finally, as a result of the greatly reduced quality factor in air and only a small change in the resonance frequency (Fig. 3), the ringdown time, $\tau_r = Q/2\pi f$ was approximately five times smaller in hollow cantilevers. Figure 4 shows how the smaller ringdown time enhances the spatial resolution of the tapping mode AFM. At the scan rate of 4.88 lines/second (left panels), the tip spends ~ 400 microseconds acquiring data for each pixel, which is sufficiently long to reach a steady state for both hollow and solid cantilevers. However, at a scan rate of 9.77 Hz (right panels), the pixel dwell time is reduced to ~ 200 microseconds, which becomes comparable to the ringdown time of the solid cantilever measured experimentally: $\tau_{r,\text{solid}} = 372/(2\pi(287 \text{ kHz})) = 206$ microseconds. As a result, the image obtained with a solid cantilever becomes distorted, especially in the areas of abrupt topography changes. In contrast, the hollow cantilever has a ringdown time that is more than five times smaller $\tau_{r,\text{hollow}} = 43/(2\pi(190 \text{ kHz})) = 36$ microseconds and can still resolve the topography. Since the ringdown time is the inverse of the resonator bandwidth, the hollow cantilevers offer greatly increased bandwidths and, therefore, increased data acquisition rates. Similar bandwidth enhancements can be achieved for other resonator geometries and for other resonant sensor applications (e.g., chemical gas sensing, ultrasound transduction, etc.).

Figure 4: AFM scan images with scan size of $5 \mu\text{m}$ of a corner of a rectangular calibration grid hole with 200 nm depth using solid and hollow cantilevers at scan rates of 4.88 Hz and 9.77 Hz. The inset images show the zoomed-in view of the edges. At higher scan rate, the solid cantilever does not respond to the probe velocity as quickly as the hollow cantilever, resulting in a distorted edge profile (top right panel).

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