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POSITION-DEPENDENT OPTICAL BACK-ACTION IN CANTILEVER RESONATORS

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Micro- and nano-mechanical cantilever beams are being proposed for a multitude of applications in the sensing community, e.g. the detection of physical or chemical adsorption onto their surface [1]. They can be operated by monitoring their static deflection or the shift in their resonance frequency. It is generally accepted that frequency measurements constitute a much more accurate and stable technique, both because amplitude noise does not directly affect them and because frequency is a magnitude that can be detected very accurately [2, 3].

It is then of the utmost importance to elucidate the different mechanisms that can pose the ultimate limits for frequency-based detection [3], as for example the back-action of the detection mechanism [4-7]. Here, we study how optical detection affects the resonance frequency of cantilever beams and how the magnitude of this effect depends on the position across the cantilever where a laser spot (e.g. the detecting laser) is located.

We select one of the most common materials for the production of our structures: non-stoichiometric (silicon-rich) silicon nitride (SiNx). Our final structures (Fig. 1) have similar dimensions to other examples found in the literature [8, 9] with thickness (t) of 500 nm, width (w) of 100 µm and length (L) between 400 and 700 µm. Fabrication is performed following a simple 2 steps process: patterning of the cantilever shapes in the front-side and release from the backside in KOH. Characterization is performed in vacuum ($P \leq 10^{-5}$ mbar), at room temperature, using a piezoshaker actuator and a Polytec laser-Doppler vibrometer to detect the motion. In order to have a more stable experiment, we use the detecting laser with minimum power (1 µW) focused at the free end of the cantilever; and we introduce a second "heating" laser (100 µW) that we move across the cantilever surface (Fig. 1, inset). Frequency is monitored simultaneously for the three first out-of-plane flexural modes, and the heating laser is alternatively switched on-off with a frequency of 0.2 Hz in order to perform a differential measurement of its effect. The results are shown in Fig. 2, evidencing a non-uniform response across the cantilever that is fundamentally different depending on the mode shape.

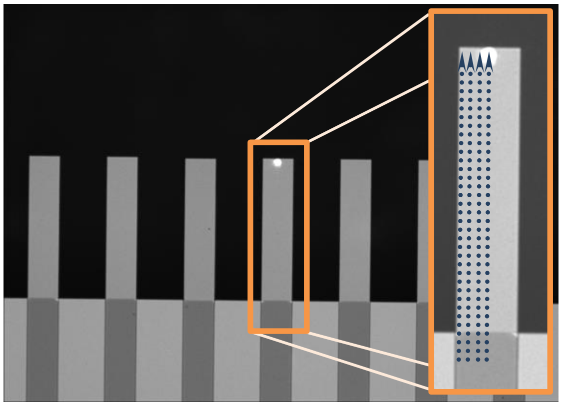

Figure 1: Optical micrograph showing the array of cantilevers used in the experiment. The detecting laser (1 µW) is focused at the free-end of the cantilever to be tested. A second laser (heating laser, 100 µW) is then scanned through the cantilever (see dotted arrows).

In order to provide a qualitative explanation for this behavior, we extract some fundamental material properties from an experiment using a Peltier

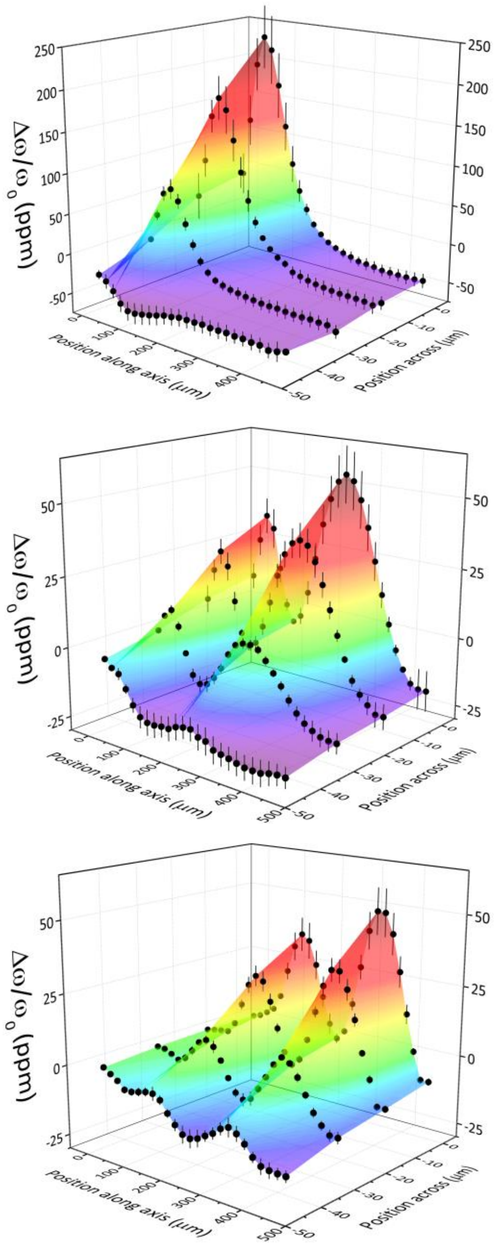

Figure 2: Relative frequency shift (in parts per million, ppm) of the three first out-of-plane flexural modes of the cantilevers shown in Fig. 1.

controlled heater (obtaining $\frac{\Delta\omega}{\omega_0}/\Delta T$, data not shown) and its comparison with Finite Element (FE) simulations for the frequency shift. We obtain: $\frac{\Delta E}{E}/\Delta T \approx -40\ \text{ppm/K}$, $CTE \approx 1\ \text{ppm/K}$, and $\sigma_0 \approx$ 185 MPa (tensile). Then, we perform another round of FE simulations to reproduce the laser-heating experiment (see Fig. 3). Our results show that changes in the material properties due to heating are not enough to reproduce the non-uniform behavior of SiNx cantilevers. Instead, we observe that the effect of localized stress gradient distribution needs to be taken into account. Our work then provides further proof to confirm that (surface) stress affects cantilevers' resonance frequencies, which is a particular topic that has shown quite controversy since the 1970s when it was first reported [10].

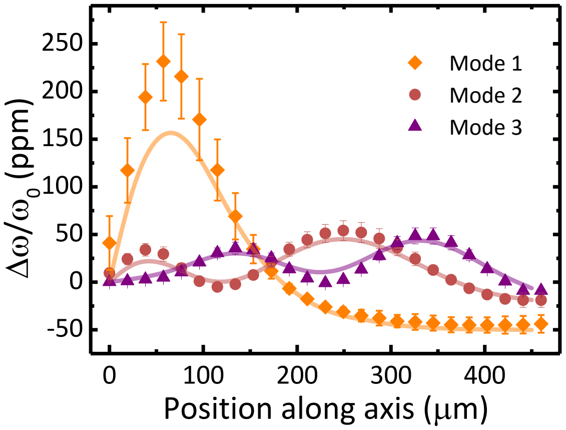

Figure 3 Experimentally measured (scattered data with error bars) relative frequency shift upon laser illumination, together with FE simulated results (lines) for each one of the three first out-of-plane flexural modes.

It is important to stress the significance of the results shown in Fig. 2, as they provide a roadmap to minimize optical back-action in resonant cantilever sensing experiments. For example if the laser power is not very stable, one would like to focus the detecting laser around the "nodal" points in Fig. 2. On the other hand, if the system is more prone to vibrations that might affect the laser position across the cantilever, then focusing around the peaks of Fig. 2 would minimize back-action and thus improve frequency noise.

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