RESONANT MEMS FOR HIGH RESOLUTION ATOMIC FORCE AND DISPLACEMENT MEASUREMENTS IN LIQUID

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ABSTRACT

This work presents resonant microstructures capable of resolving subatomic features and/or measurement of atomic level forces in liquid media. It has previously been shown that forces in the micro- and nano-Newton range applied to laterally flexible extensional-mode micro-resonators lead to significant resonant frequency shifts [1]. In this work a similar principle has been applied to rotational mode disk resonators capable of maintaining relatively high quality factors in liquid. Preliminary results indicate about 10-fold improvement in combined displacement-force resolution in liquid compared to typical piezoresistive cantilevers. Using integrated comb-drive electrostatic actuators, displacement and force resolutions as high as 200fm and 1nN have been demonstrated. Using softer resonant structures or application of the force through a leveraging mechanism, force sensitivities in the pN range can be achieved while maintaining sub-nm spatial resolution.

INTRODUCTION

Sub-nanometer displacement and force measurements are an indispensable part of modern biological sciences including the study of cell mechanobiology, interaction forces within various biomolecules, nanomechanical properties of biological samples, monitoring of protein dynamics, and imaging biological samples in their native environments [2, 3]. To date, the most powerful tool to study biological systems is frequency-modulation atomic force microscopy (FM-AFM) utilizing optical lever. Due to significant quality factor drop of conventional AFM cantilevers in air and liquid (limited to 100 and 10, respectively), true atomic resolution imaging and force measurements in air and especially in liquid remain a formidable challenge [4]. Employing sophisticated instrumentation and readout electronics along with application of proper modifications within commercially available AFMs, subatomic displacement and force resolutions have been demonstrated in liquid. For instance, using small oscillation amplitude (0.16-0.33) of a ~40N/m cantilever, vertical resolution of 2-6pm has been shown [5]. Piezoresistive sensing, on the other hand, enables integration of sensing elements on the AFM cantilevers, significantly simplifying the experimental setup by eliminating the need for external sensing elements, precise system alignment and complex circuitry for operation [6]. However, such methods require complex fabrication processes and cannot compete with some of the conventional technologies in terms of sensitivity [7-9]. Taking advantage of high performance of microscale rotational mode disk resonators in liquid, this work presents an integrated, convenient (with fully electronic readout) and potentially transformative force-displacement measurement technique that can be deployed in various environments (vacuum, air, and liquid) with higher sensitivity.

DEVICE DESCRIPTION

Figure 1 illustrates SEM view of one of the test structures used in this work that is comprised of a disk resonator coupled to a comb-drive electrostatic actuator. The structures are fully made of single crystalline silicon and are fabricated on silicon-on-insulator (SOI) substrates with device and buried oxide layer thicknesses of 15 μ m and 5 μ m, respectively. The long narrow tangential beams on

Figure 1: SEM view of a 2.3MHz in-plane disk resonant force-displacement sensor capable of operating in liquid. The inset on the bottom left depicts the finite element modal analysis of the rotational resonant mode of the disk structure.

the two sides of the disk are responsible for both thermal actuation and piezoresistive detection of the resonator vibrations. Upon periodic electro-thermal excitation of the resonator with the appropriate frequency, the disk starts vibrating in its rotational resonance mode [10] (as depicted in the inset of Fig. 1). The comb drive actuator has 55 interdigitated electrode pairs separated by photolithography defined 2.3 μ m wide air-gaps and can simulate the effect of an external force applied to the resonant force sensor. The force from the actuator can slightly deform the resonator structure, and consequently change its effective mechanical stiffness and therefore resonance frequency.

RESULTS AND DISCUSSION

Resonant structures with different dimensions were tested in both air and xylene showing Q factors as high as ~4000 and ~80, respectively. Xylene, which is an organic nonconductive liquid, was used to allow application of relatively large actuation voltages to the electrostatic actuator. Figure 2 shows how the frequency response of the 2.3MHz resonator of Fig. 1 changes under constant bias current in both air and liquid, while increasing the external electrostatic force. The change in resonance frequency of the resonant force-displacement sensor of Fig. 1 as a function of the external force is illustrated in Fig. 3, showing force and displacement sensitivities of 0.88Hz/nN (0.38ppm/nN) and 21Hz/nm (9ppm/nm) in liquid. With a conservative frequency measurement accuracy of 1Hz this leads to force and displacement resolutions of 1nN and 40pm, respectively. Interestingly, the results show that sensitivities in liquid are ~2X larger than in air leading to 2-fold better force and displacement resolutions ($\epsilon_r=2.2$ has been taken into account for Xylene). This is believed to be due to the increased effect of structural deformations on viscous damping. Table 1 summarizes the results obtained from a number of similar devices with different dimensions demonstrating

Figure 2: Measured frequency responses for the 2.3MHz thermal-piezoresistive resonator of Fig. 1 in air and xylene with different applied external forces. Red and blue plots refer to air and liquid testing conditions, respectively. The results indicate $\sim 2X$ higher force-displacement sensitivities in liquid than in air. Dielectric constant of $\epsilon_r=2.2$ for xylene has been used in electrostatic force calculations.

Figure 3: Measured frequency of the resonator of Fig. 1 as a function of the applied local force.

displacement and force resolutions as high as 200fm and 1nN. It should be noted that force resolution and displacement resolution of such sensors are directly related via the structural stiffness at the point where the external force is applied. Accordingly, force resolution can be improved at the expense of losing displacement resolution (by decreasing the structural stiffness at the point of force application) and vice versa. To have a fair comparison with other atomic force measurement techniques, therefore, resolution figure-of-merit (FOM) is defined as the force resolution-displacement resolution product. As shown in Figure 4, the proposed approach provides $\sim 10X$ better FOM in liquid (40nN.pn) compared to typical piezoresistive cantilevers (400nN.pn) [7].

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Table 1: Summary of in-liquid measurement results obtained from devices with different dimensions (spotted in Fig. 4).

Device#	Dimensions (L $\times$ w)	Force Resolution	Stiffness (kN/m)	Displacement Resolution	FOM (nN.pn)
1	180 $\mu\text{m}\times 2\mu\text{m}$	1nN	0.025	40pm	40
2	30 $\mu\text{m}\times 2\mu\text{m}$	25nN	12.5	2pm	50
3	10 $\mu\text{m}\times 2\mu\text{m}$	100nN	500	200fm	50

Figure 4: Comparison of current work performance with other approaches in terms of their FOM (force-displacement product). The blue and red axes represent force and displacement resolution, respectively. A blue cross-bar with a larger shift towards left depicts a better combined force/displacement performance (lower FOM). The numbers 1 to 3 show the force and displacement sensing performance of the three disk resonant sensors of Table 1.

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