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Abstract: Thermally excited and piezoresistively detected bulk-micromachined cantilevers vibrating in their in-plane flexural resonance mode are presented. By shearing the surrounding fluid rather than exerting normal stress on it, the in-plane mode cantilevers exhibit reduced added fluid mass effects and improved quality factors in a fluid environment. In this paper, different cantilever geometries with in-plane resonance frequencies from 50 kHz to 2.2 MHz have been tested, with quality factors as high as 4200 in air and 67 in water.

Keywords: Cantilever, liquid operation, piezoresistive detection, resonant sensor.

Micromachined cantilever beams with rectangular cross section are widely used in scanning probe microscopy (SPM) [1] and have been explored to implement biochemical sensors [2]–[9]. In these applications, the cantilevers are operated either in a static bending regime or in a dynamic mode, in which the measurand affects a resonance frequency of the cantilever [2], [3]. In the latter case, research has focused predominantly on cantilevers vibrating in an out-of-plane bending mode. Thereby, the cantilevers often do not utilize integrated excitation and detection schemes; instead, vibrations are excited and sensed externally using, e.g., piezoelectric actuators and optical detection systems [7]–[9], which partially negates the miniaturization advantages gained from using microsensors.

In sensing applications where cantilever dynamic-mode operation is used, the quality factor Q of the resonance mode limits the sensor resolution. For this reason, several recent studies have measured and modeled the Q-factors of cantilevers vibrating in out-of-plane bending modes [10]–[13]. While Q-factors up to 1500 have been measured for the first out-of-plane bending mode in air [10], liquid operation becomes challenging because of the substantial viscous damping by the fluid. Other than low Q-factors, typically not exceeding 10–20 in water [6], a substantial reduction of the out-of-plane resonance frequency of typically 50% is observed in liquid due to the large effective mass of the accelerated fluid. In addition, cantilevers that push against the fluid are more sensitive to viscosity and density changes in the liquid itself [6].

This raises the question of how the performance of (cantileverbased) resonant microsensors operating in liquid environment can be improved. One promising approach is the use of so-called suspended microchannel resonators [7], in which the fluid is routed through a channel inside the resonator, while the resonator itself can be operated in air or even vacuum. Current implementations of this technology are, however, limited to flow rates up to 0.1–1 μL/min because of the small channel cross section and require an external optical setup for vibration sensing. Alternatively, vibration modes that are less affected by the surrounding fluid can be explored. Examples include piezoelectric acoustic-wave devices [14] and, in particular, the well-known quartz crystal microbalance [15] and flexural-plate-wave devices [16]. However, these devices generally require more complex fabrication sequences, including the deposition of piezoelectric materials, and are often not easily amenable to miniaturization and batch fabrication.

In this paper, we explore silicon cantilevers vibrating in in-plane bending modes to improve the Q-factor [17]. Cantilevers vibrating in in-plane bending modes (also referred to as lateral or strong-axis bending mode) have been employed in SPM to measure friction forces and lateral stiffness [1], [18], again utilizing external excitation and sensing schemes. In contrast, this paper demonstrates an integrated method for exciting the first in-plane (lateral) bending mode of micromachined silicon cantilevers with rectangular cross section. Moreover, the first systematic study of Q-factors of such cantilevers operating in air and liquid is presented. Thus, this paper sets the stage for the development of a robust liquid sensing platform based on cantilevers using the first in-plane resonance mode.

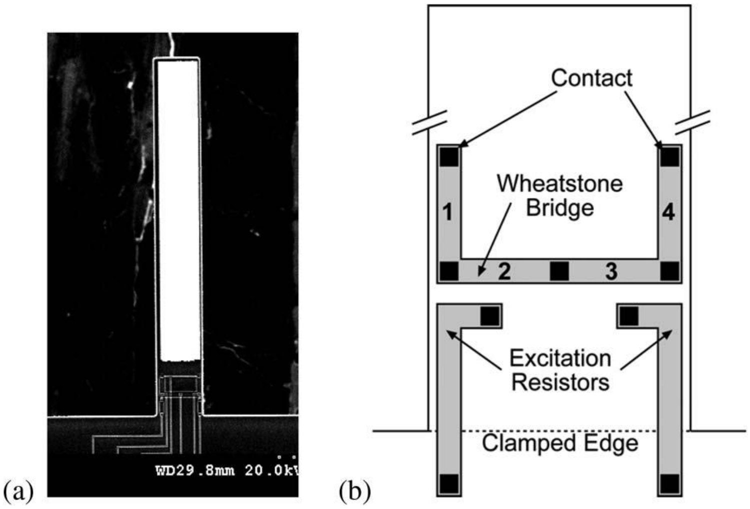


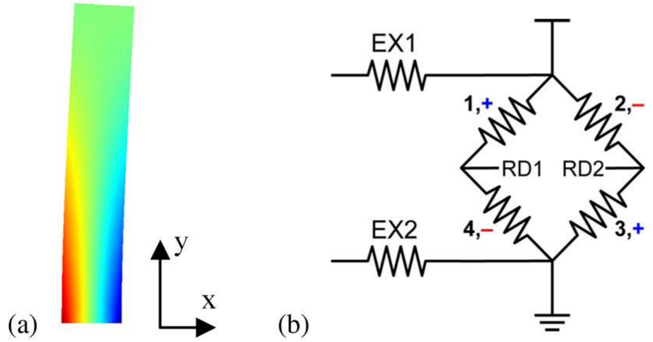
Fig. 1. (a) SEM photograph of 60-μm-wide and 400-μm-long cantilever(coated with gold for biochemical sensing applications). (b) Schematic layoutof heating resistors and U-shaped Wheatstone bridge with piezoresistors 1–4.

Rectangular silicon cantilevers [Fig. 1(a)] with widths of 45, 60, 75, and 90 μm and lengths of 200, 400, 600, 800, and 1000 μm were fabricated using a CMOS-compatible bulk-micromachining process, which is outlined elsewhere [19]. Epitaxial silicon wafers (epi-wafers) with an n-type device layer were used as starting materials, with the thickness of the epitaxial layer defining the thickness of the released cantilevers. If not noted otherwise, all cantilevers tested in this paper have a nominal silicon thickness of 12 μm. Thermal excitation and piezoresistive detection were chosen as the driving and sensing mechanisms, respectively, because they can easily be integrated with the use of diffused resistors. For liquid operation, the aluminum lines connecting the diffused resistors were covered with a 1.2-μmthick triple-layer passivation sandwich, alternating plasma-enhanced chemical vapor deposited oxide and nitride films to mitigate the effects of pinholes and control the overall mechanical stress in the passivation stack.

Two diffused p-type silicon resistors located at the clamped edge of the cantilevers are integrated as electrothermal excitation elements. For excitation of the in-plane mode, one of the heating resistors is driven by an ac voltage superimposed on a dc voltage to avoid frequency doubling.

To reject common-mode signals, such as a uniform temperature modulation, a full Wheatstone bridge configuration is chosen for the sensing piezoresistors with all resistors located on the cantilever. To facilitate the closed-loop operation of the cantilevers in a future sensing application, it is important that the Wheatstone bridge not only responds to the in-plane mode but also suppresses signals stemming from out-of-plane and torsional modes as much as possible. In the current design, this is achieved by utilizing the characteristic stress patterns of the different mode shapes (Fig. 2) and a U-shaped layout of the bridge [Fig. 1(b)], with two resistors along the cantilever edge and two resistors spanning the cantilever width. All four resistors are of equal length-to-width ratio and thus nominally have the same resistance.

1st In-Plane Mode



1st Out-of-Plane Mode

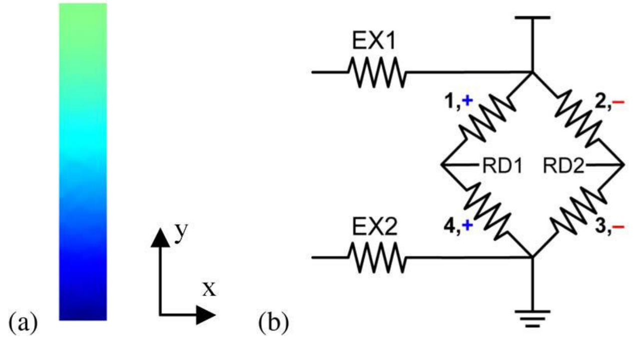


Fig. 2. (a) Distribution of bending stress component σ_y in the y-direction assimulated using the FEM software COMSOL for a 400 × 75 μm cantilever vibrating in the first in-plane and the first out-of-plane resonance mode. (b) Signs of expected resistance change of the piezoresistors (see Fig. 1) in case of the first in-plane and the first out-of-plane mode, assuming that resistor 1 experiences a positive resistance change. EX1 and EX2 are the heating resistors for thermal excitation. RD1 and RD2 are the read-out connections.

Fig. 2 shows the simulated bending stress component σ_γ (in the length direction of the cantilever) for the first out-of-plane bending and the first in-plane bending mode. It should be noted that, for both modes, σ_γ is the dominant stress component. As a result, piezoresistors 1 and 4 experience —to first order— a longitudinal stress, while piezoresistors 2 and 3 experience a transverse stress. Using the longitudinal and transverse piezoresistive coefficients π_ι and π_t, respectively, one finds

$$\frac{\Delta R}{R}\Big|_{1,4} \approx \pi_\iota \sigma_\gamma \; \frac{\Delta R}{R}\Big| \approx \pi_\iota \sigma_\gamma .$$

Considering that the piezoresistors are p-type resistors and arranged parallel and perpendicular to the (110) crystal direction of the (100) wafer, π_ι and π_t have similar magnitude but opposite signs [20]. Fig. 2 shows the resulting signs of the resistance changes in the Wheatstone bridge (the resistance change of resistor 1 is assumed to be positive) for both the first in-plane and out-of-plane modes, with the in-plane mode yielding a much stronger signal compared to the out-of-plane mode.

Twenty different cantilever geometries with in-plane resonance frequencies ranging from 50 kHz to 2.2 MHz (in air) were fabricated and tested in both air and water. The cantilevers were mounted in ceramic dual-in-line packages, and a polymer ring was glued to each cantilever die after wire bonding to allow for a drop of water to be placed on top of the bulk-micromachined opening. Open-loop frequency transfer characteristics were recorded in both air and water.

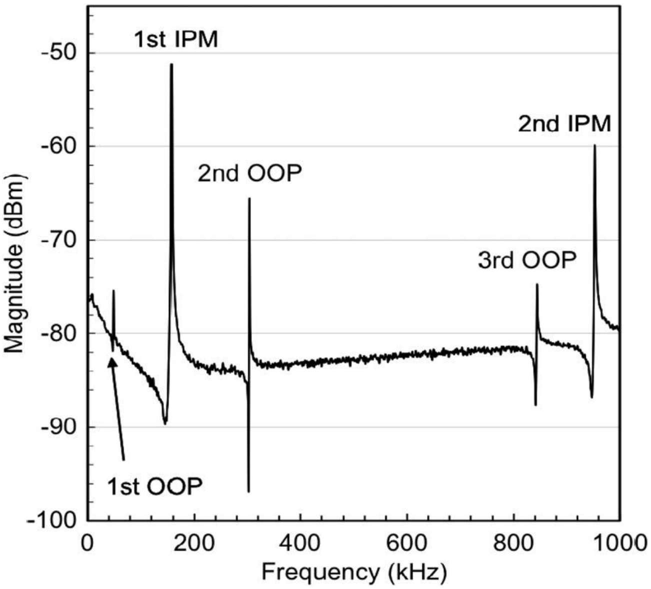


Fig. 3. Open-loop frequency transfer characteristic for a 600-μm-long,45-μm-wide, and 12-μm-thick cantilever in air. Each mode is labeled, i.e., IPM = in-plane mode and OOP = out-of-plane mode.

As an example, Fig. 3 shows the open-loop frequency response for a 600 × 45 μm cantilever in air. The resonance modes were identified with accompanying finite-element method (FEM) simulations, and as expected from the bridge design, the first in-plane resonance at 157 kHz yields the strongest piezoresistive output signal. When placed in an amplifying feedback loop, the cantilever will be preferentially excited at this mode. Short-term frequency stability measurements based on the Allan variance method yield values in the 10^{-8} range in air and 10^{-6} range in water.

To investigate the excitation efficiency, the vibration amplitudes of a 600 × 45 μm cantilever with 6-μm silicon thickness (covered with a 3000-Å gold layer) were optically measured using a Polytec MSA-500 Micro System Analyzer. With driving voltages V_{dc} = 2 V and V_{ac} = 0.3 V_p, the first out-of-plane resonance at 32.5 kHz yields a tip amplitude of 118 nm (Q = 500), while the first in-plane mode at 144.5 kHz exhibits a peak amplitude of 750 nm (Q = 1630) in air. Clearly, the thermal excitation is more efficient in exciting the in-plane resonance mode.

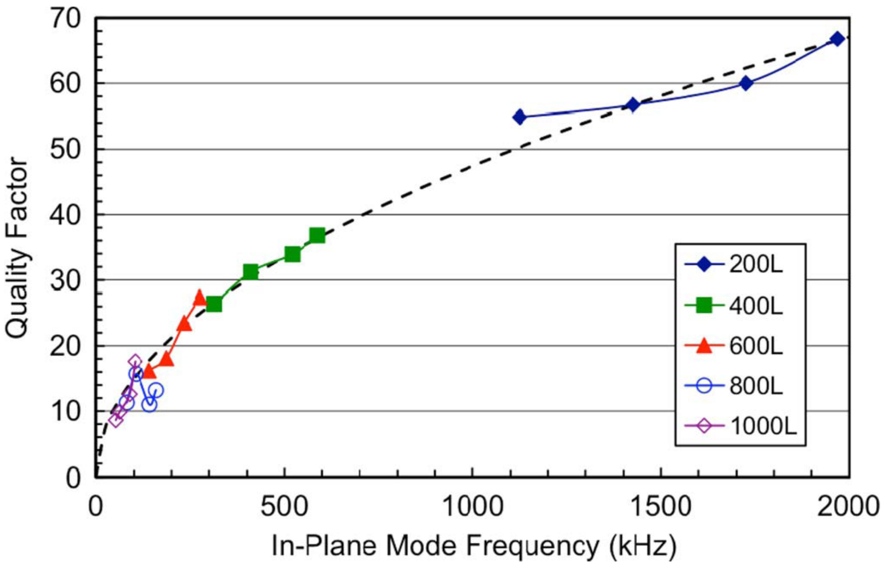


Fig. 4. Quality factor in water as a function of the measured in-plane mode frequency for cantilevers with 12-μm silicon thickness.

The quality factor and frequency of the first in-plane mode of all 20 cantilevers were extracted from the transfer characteristics measured in both air and water. The resonance frequencies are only lowered by 5%–10% in water compared to the values in air. This is a major advantage of the in-plane (lateral) mode as compared to the out-of-plane mode, where the added mass effect results in a reduction of resonance frequency as high as 50% [6] (for the devices tested in this paper, the first out-of-plane mode is undetectable in liquid because of the piezoresistor layout). Fig. 4 shows the quality factor in water as a function of the in-plane resonance frequency. The quality factor increases roughly with the square root of the frequency for cantilevers of the same thickness, and the highest quality factor measured in liquid was 67 for a 200 × 90 × 12 μm device. In air, a maximum Q-factor of 4200 was measured for the first in-plane resonance of a 400 × 90 × 12 μm cantilever. The Q-factor of the shorter cantilevers is reduced in air because of support losses.

In conclusion, the use of in-plane rather than out-of-plane bending modes of cantilevers offers significantly improved quality factors in both air and water. The in-plane modes can be excited electrothermally and detected preferentially using integrated piezoresistors in a U-shape bridge layout. The cantilevers with integrated driving and sensing schemes are expected to be used as sensitive biochemical sensor platforms with detection limits in the parts-per-billion range in aqueous environments.

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