Sub-Picogram Resoluble Piezoresistive Cantilever Sensors with Optimized High-Mode Resonance Excitation

Dazhong Jin, Jian Liu, Xinxin Li*, Min Liu, Guomin Zuo, Yuelin Wang, Haitao Yu, ~~Xiaohong~~ Ge
and

***Abstract*-Ultra-sensitive mass sensor is in demand for bio/chemical molecular detection. A piezoresistive resonant cantilever sensor is developed with an optimized electro-magnetic excitation for high-mode flexure resonance. In our experiments, it has been proved that the quality factor of the resonant cantilever can be improved by this optimized high-mode resonance exciting technique. Experimental results show that the optimized excitation for the 2nd mode resonant sensor can effectively improve the mass-sensing resolution (in air) to *0.2pg*, thereby, improving the bio/chemical sensor performance.**

Background

Micromechanical resonant cantilever sensors with ultra-high mass sensitivity and pictogram-level (or better) resolution have attracted intensive interests for detection and recognition of single cell and individual bio/chemical molecules [1]. With precise optical deflection system, a single cell [2] and even a virus [3] has been detected in air. In ultrahigh vacuum the cantilevers showed atto-gram mass resolution [4], which almost approach the ultimate limit [5]. In the aforementioned investigations, effective mass and quality factor of the cantilever are main factors to determine the mass resolution. From another viewpoint, the mass resolution can be improved by enhancing the resonance frequency stability with feedback loop control [6]. A promising prospect has been preliminarily demonstrated that operating the cantilever in high resonant mode facilitates enhancement of Q factor and sensitivity [7]. However, this experiment was done by AFM mode with off-sensor optical position sensing detection (PSD). For portable bio/chemical sensing applications, it is important to integrate the signal read-out elements into the resonant cantilever [8].

In present work, we develop a sub-picogram resoluble mass sensor by using a high-mode resonant cantilever. With a vibration-peak localized electromagnetic excitation technique for 2nd flexure resonant mode, The resonant frequency signal is obtained by on-chip integrated piezoresistors and a close feedback electric close-loop. *0.2pg* mass resolution is measured.

Current Results

Shown in Fig. 1, both conventional 1st mode resonant cantilever (denoted as No.1) and optimal-excited 2nd mode cantilever (No.2) are designed and fabricated for comparison. NdFeB magnet is mounted in the sensor package to generate magnetic field for excitation. When *sine*-wave AC electric current is fed through the aluminum loop, the cantilevers vibrate under Lorentz force. The driving force for the No.1 cantilever is located at the cantilever-end, i.e. the 1st mode resonant peak location. For the No.2 cantilever, however, a paper-clip shaped aluminum loop is designed with two driving locations at the middle point and the end point, respectively. Shown in Fig. 1, the two resonant peaks in the 2nd mode shape function are 180^o out of phase each other. Accordingly, the two driving forces are always opposite in direction that match the 2nd mode shape. The optimized excitation is expected with a improved performance. The piezoresistors are put near the roots of the cantilevers, where the vibration induced stress is with maxim value (see Fig. 2). Identical dimension of 300×75×3μm^3 is designed for both the No.1 and No.2 cantilevers. The process is shown in Fig. 3.

In air, the resonance performances of the cantilevers are measured with an Agilent 4385A network analyzer. Shown in Fig. 4, the No.1 cantilever is with the 1st mode resonance frequency as 41.91kHz and the Q factor as 50. In the 2nd mode, the resonant frequency and the Q factor is 252.58kHz and 161, respectively. The No.2 cantilever's resonant frequency and Q factor are measured as 40.65kHz and 45 for the 1st mode, as well as, 227.21kHz and 322 for the 2nd mode. By analysis, compared to the 1st mode, the mass sensitivity of the 2nd mode can be improved by 5.584 and 6.265 times for No.1 cantilever and No.2 cantilever, respectively. On another hand, it is proved that Q factor can be enhanced by exciting the 2nd resonant mode for both the No.1 and No.2 cantilevers. More important, in the 2nd resonant mode, No.2 cantilever shows significant higher Q factor than the No.1 cantilever. This significant improvement of the No.2 cantilever is attributed to the optimized excitation for the 2nd mode resonance. For evaluating the mass resolution, the noise limited resonant-frequency stability is measured with a close-looped resonance-maintaining interface circuit shown in Fig. 5. The frequency stability is evaluated by using Allan variance analysis [9]. With the measured data shown in Fig. 6, the calculated mass resolutions are listed in Table 1. The No.2 cantilever resonating in the 2nd mode shows the minimum Allan variance and the highest mass-sensing resolution of *0.2pg*. Therefore, the performance of the resonant cantilever sensor is improved by the optimized 2nd mode excitation. With the sub-picogram resolution in air, the integrated piezoresistive cantilever is promising to be used for ultra-sensitive detection of bio/chemical molecules.

References

[1] N. V. Lavrik and P. G. Datskos, Cantilever transducers as a platform for chemical and biology sensors, Rev. Sci. Instru., 75(7)(2004) pp.2229-2253.

[2] B. Ilic et al, Single cell detection with micromechanical oscillators, J. Vac. Sci. Technol. B, 19(6)(2001) pp.2825-2828.

[3] A. Gupta, D. Akin, and R. Bashir, Single virus particle mass detection using microresonators with nanoscale thickness, Appl. Phys. Lett., 84(11)(2004) pp.1976-1978.

[4] T. Ono, Xinxin Li, H. Miyashita and M. Esashi, Mass sensing of adsorbed molecules in sub-picogram sample with ultrathin silicon resonator, Rec. Sci. Instrum., 74(3)(2003) pp.1240-1243.

[5] K. L. Ekinci, Y.T. Yang and M. L. Roukes, Ultimate limits to inertial mass sensing based upon nanoelectromechanical systems, J. Appl. Phys., 95(5)(2004) pp.2682-2689.

[6] A. Vidic, D. Then and Ch. Ziegler, A new cantilever system for gas and liquid sensing, Ultramicroscopy, 97(2003) pp.407-416.

[7] S. Dohn, R. Sandberg, W. Svendsen and A. Boisen, Enhanced functionality of cantilever based mass sensors using higher modes and functionlized particles, Transducers'05, pp.636-639.

[8] A. Boisen, J. Thaysen, H. Jensenius and O. Hansen, Environmental sensors based on micromachined cantilevers with integrated read-out, Ultramicroscopy, 82 (2000) pp.11-16.

[9] F. Walls and D. Allan, Measurements of frequency stability, Proc. IEEE, 74(1)(1986) pp. 162-168.

IEEE requires paper titles to be within quotes, i.e., "???". Also, volume of publication should be Italicized.

All authors are with State Key Lab of Transducer Technology, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, 865 Changning Road, Shanghai 200050, China.

*Contacting Author: Xinxin Li is with Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, China. (phone: +86-21 62131794; fax:+86-21 62513510; email: *xxli@mail.sim.ac.cn*).

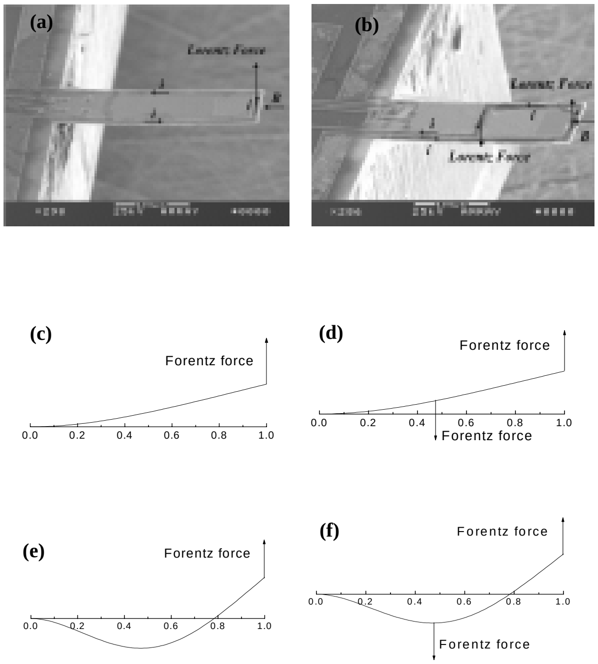

Fig. 1. (a) and (b), the SEM images showing the piezoresisiteve resonant cantilevers of No.1 and No.2, respectively. The aluminum loops for electromagnetic excitation are also shown. (c) and (d), the 1st flexure mode shape driven by the corresponding Lorentz forces on No.1 and No.2 cantilevers. (e) and (f): the 2nd mode shape for the No.1 cantilever and the No.2 cantilever excited by the Lorentz forces.

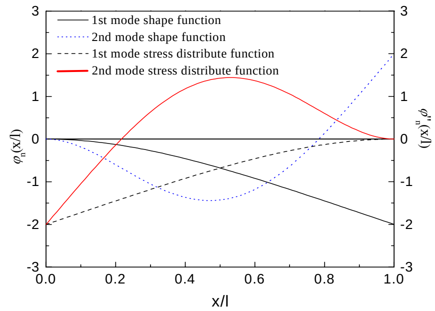

Fig. 2. The 1st and the 2nd mode-shape functions, $\varphi_n(x/l)$, and stress distributions, $\varphi''_n(x/l)$, of a resonant cantilever under the boundary condition of $\cos(\kappa_n l)\cosh(\kappa_n l) = -1$. The eigen-value ω_n is determined by $\kappa_1 l$=1.875 and $\kappa_2 l$=4.694.

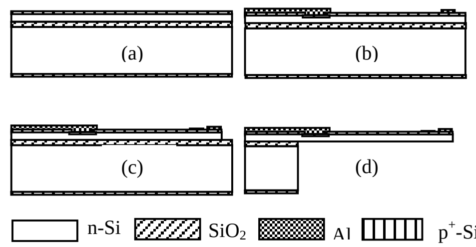

Fig. 3. Process flow for the integrated cantilever sensors.

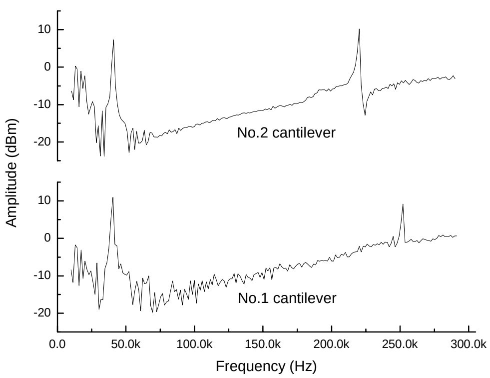

Fig. 4. Measured amplitude-frequency responses for the two cantilevers. The No.1 cantilever's resonance frequency and Q factor are 40.45kHz and 50 in the 1st resonant mode; 252.15kHz and 161 in the 2nd mode. The No.2 cantilever's resonance frequency and Q factor are 40.75kHz and 46 in the 1st mode; and 227.21kHz and 332 in the 2nd mode, respectively.

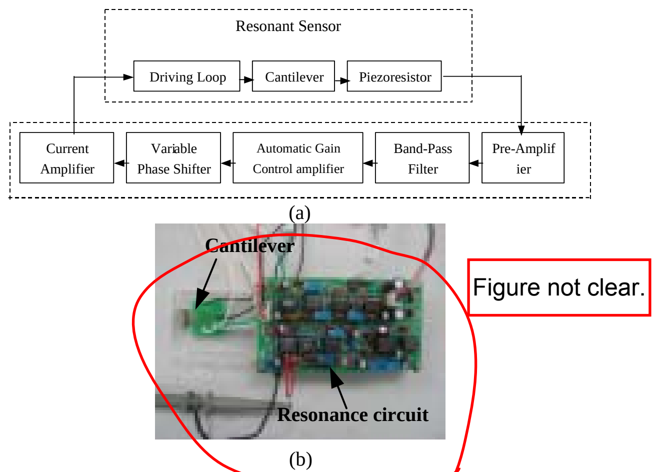

Fig. 5. (a), schematic diagram of the resonance maintaining circuit with a feedback close-loop. (b), photograph of the measured sensor with the interface circuit PCB connected.

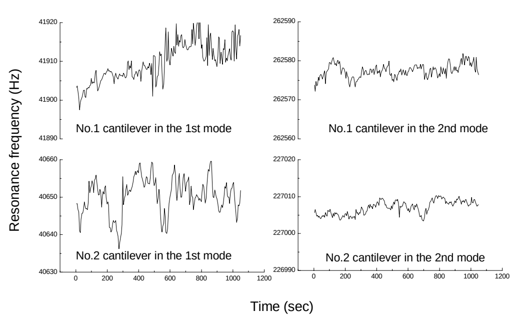

Fig. 6. Measured frequency stability for 1200 seconds. Both the No.1 and the No. 2 cantilevers are measured for both the 1st and the 2nd resonant modes.

Cantilever	First resonant mode				Second resonant mode			
	Resonance frequency (kHz)	Q factor	Allan variance	Mass resolution (pg)	Resonance frequency (kHz)	Q factor	Allan variance	Mass resolution (pg)
No.1	41.91	50	5.2×10^{-5}	5.5	262.58	161	3.1×10^{-6}	0.3
No.2	40.65	45	5.8×10^{-5}	6.1	227.00	322	2.3×10^{-6}	0.2

Table 1. The characteristics of the No.1 and the No.2 micromechanical resonant piezoresistive cantilevers for both the 1st and the 2nd resonant modes. By Allan variance analysis, the No.2 cantilever show the highest mass-sensing resolution of 0.2pg in the 2nd resonant mode. This is due to the paper-clip shaped aluminum loop for two-position Lorentz force excitation. The two driving positions match the two deflection peaks of the 2nd mode shape.