Physics

Physics Research Publications

Purdue University

Year 2004

Enhanced mass sensing using torsional
and lateral resonances in microcantilevers

L. B. Sharos

A. Raman

S. Crittenden

R. Reifenberger

This paper is posted at Purdue e-Pubs.

<http://docs.lib.purdue.edu/physics.articles/364>

Enhanced mass sensing using torsional and lateral resonances in microcantilevers

L. B. Sharos and A. Raman^{a)}

School of Mechanical Engineering, Purdue University, W. Lafayette, Indiana 47907

S. Crittenden and R. Reifengerger

Center for Sensing Science and Technology, Purdue University, W. Lafayette, Indiana 47907

(Received 30 January 2004; accepted 8 April 2004; published online 19 May 2004)

We present a method to detect, with enhanced sensitivity, a target mass particle attached eccentrically to a microcantilever by measuring multiple three-dimensional modes in the microcantilever vibration spectrum. Peaks in the spectrum reveal a complex coupling between the bending, torsional, and lateral motions and detailed finite element models assist in their interpretation. The mass sensitivities of the torsional and lateral mode frequencies are an order of magnitude greater, and their Q factors significantly higher, than that of the conventionally used fundamental bending mode. These modes offer significantly enhanced mass sensing capabilities within the realm of existing microcantilever technology. © 2004 American Institute of Physics. [DOI: 10.1063/1.1759379]

The ability to rapidly detect small quantities of targeted materials in either gas or liquid environments provides a constant challenge in sensing science and technology. Sensor concepts must be developed in an effort to both increase the lower sensitivity limits as well as shorten the response time to sense many targets simultaneously without interference. A technique of current interest is the use of scanning probe microcantilevers, initially developed for imaging purposes in scanning force microscopy (SEM), for sensing applications. The use of microcantilevers as chemical sensors was described by Chen *et al.*¹ who realized that static bending induced by differential surface stress, or changes in the resonant frequency induced by mass uptake, could be sensed with standard scanning probe instrumentation adapted to monitor adsorption of a targeted species. This early work has been followed by a number of reports which have demonstrated sensing applications using microcantilever static deflection and frequency shift for sensing in the gas^{2,3} and liquid^{4–6} environments. Recent studies have shown that microcantilevers can be fabricated which have sensitivities into the attogram regime.⁷

Clearly, techniques which enhance sensitivity in vibrating microcantilevers are of interest. In what follows, we show that, by a careful analysis of torsional and lateral modes of cantilevers, an order of magnitude improvement in sensitivity and resolution can be achieved using conventional microcantilevers without the need for designs or advanced fabrication.

For this proof of concept experiment, commercially available silicon diving-board microcantilevers (test microcantilevers henceforth) from NovaScan,⁸ with a fundamental bending frequency of ~ 21 kHz, were chosen because of their ready availability and the maximum reliable piezodriving frequency (800 kHz) of the lock-in amplifier used in the experiment. To determine the mass sensitivity of each test microcantilever, a known mass is mounted⁹ to the free end

corner, see Fig. 1(a), and the modal frequencies with and without the added mass are determined. The test masses are uniform borosilicate glass microspheres with a mass of approximately 10 pg^{10} equaling roughly the mass of ten bacteria.

Due to the length scale of the test microcantilevers and masses, all manipulation was performed under an Epiphot 200 dark-field optical microscope with a set of Newport 460A Series micropositioners. The glass microspheres are manipulated through electrostatic force by etched tungsten wires with $\sim 1 \text{ }\mu\text{m}$ radius of curvature at the tip. The electrostatic and van der Waals forces between the test microcantilever and the glass microsphere are sufficient to hold the microsphere in place.

The test microcantilevers are mounted inside a Nanotec ElectronicaTM scanning probe microscopy system and the bending and torsional microcantilever vibrations are monitored using a four-quadrant photodetector as the driving frequency of the vertically base excited piezocrystal actuator is swept using a lock-in amplifier. Initially, the torsional and vertical bending vibration spectra of a test microcantilever are determined by performing a broad frequency sweep from 0 to 500 kHz at 100 Hz intervals [see Figs. 1(b) and 1(c)]. Subsequently, a Visual Basic code collected and stored the magnitude and phase output from the lock-in amplifier at each frequency interval. Each of the first five modal frequencies is then examined separately with 1 Hz interval sweeps between the half magnitude frequency points.

The interpretation of the measured peaks in the vertical bending and torsional vibration spectrum is complex. To facilitate this identification, a detailed finite element (FE) model was created and a modal analysis was performed in ANSYS 7.1 using the geometrically exact measurements of the microcantilever including the probe tip.¹¹ The ordering of the mode shapes and the frequencies at which they occur is quite sensitive to small imperfections in the microcantilever geometry and one cannot simply generalize the shape as a standard diving-board microcantilever with a rectangular cross-

^{a)}Electronic mail: raman@ecn.purdue.edu

FIG. 1. (a) SEM of cantilever (nominal width of $35\ \mu\text{m}$) with attached glass microsphere (nominal diameter of $2\ \mu\text{m}$). (b) Vertical and (c) torsional displacement of test microcantilever NSC No. 12 without an attached microsphere.

section. The FE predictions matched closely¹² most of the measured peaks in the vibration spectrum.¹³ Further, the FE analysis revealed that both the vertical and lateral bending motions couple to torsional motions [as seen in the FE mode shapes in Fig. 1(c)] due to the eccentric center of mass of the microcantilever and the probe tip.¹⁴ This was also observed in the experiments; in Figs. 1(b) and 1(c) the first torsional mode appears in the vertical deflection spectrum and the second and third vertical bending modes appear in the torsional deflection spectrum. Indeed, it is precisely this coupling induced by geometric imperfections that allows the torsional and lateral bending modes to be excited by a vertical excitation from the piezocrystal. Note further that strong modal coupling is observed [Figs. 1(b) and 1(c)] and predicted between the first torsional and third bending modes. This phenomenon is explained clearly using the theory of eigenvalue veering.^{15,16} According to the theory, previously uncoupled vibration modes with closely spaced frequencies are ex-

FIG. 2. Shift in spectrum after glass microsphere has been added. Squares = initial, triangle = with added microsphere, and asterisk = after microsphere is removed. For the purposes of clarity, only one symbol is plotted every 50 data points.

pected to couple strongly in the presence of eccentric attached masses and asymmetric cantilever geometry. Finally, consider the relative magnitudes of the different peaks in the measured forced vibration spectrum of the microcantilever in Figs. 1(b) and 1(c). The relative magnitudes of the second and third vertical bending modes are a sensitive function of the cantilever slope¹⁷ in specific mode shapes and the positioning of the laser spot ($\sim 30\ \mu\text{m}$ diameter) relative to the vibration nodes of the specific mode. Indeed, it is possible to carefully position the laser spot so as to maximize the contribution of any chosen vertical bending mode. The data presented in Figs. 1 and 2 were acquired by optimizing the laser position to maximize the response of higher frequency modes.

After carefully characterizing the bare cantilever, a glass microsphere is mounted on the free end of the test microcantilever as in Fig. 1 to purposefully bias the torsional modal frequency and the experiment was rerun to determine a set of modal frequencies. Lastly, the glass microsphere is removed and a final set of data is collected. These experiments are repeated for a set of six nominally identical microcantilevers.

First, the addition of the test mass to the edge of the test microcantilever near the free end decreased all the modal frequencies as expected; see Fig. 2. Note that when the microsphere is removed, the frequencies consistently return to those before the microsphere was added. The magnitudes of the resonance peaks usually change before the microsphere is added and after it is removed. This is due to the unavoidable small variations in the microcantilever and laser spot orientation that occur when the cantilever chip is taken out of the atomic force microscope (AFM) and replaced.¹⁸

Relevant data from the six cantilevers are summarized in Fig. 3 which shows that the first torsional and first lateral bending frequencies are significantly more sensitive to the added mass than the fundamental bending frequency. Note that the third vertical bending mode frequency also offers very high mass sensitivity. This is likely due in part to its high natural frequency and also its strong coupling with the torsional mode. An unbiased estimate of the Q factor of each modal frequency is precisely calculated using the circle fit method¹⁹ to determine the resolution of the mass sensitivity

FIG. 3. Plot of frequency shift and Q for six different NSC test microcantilevers.

for a given modal frequency.²⁰ The Q factors for each of the five modal frequencies are shown in Fig. 3 for all test microcantilevers used. It is apparent that the Q factors of the first torsional and the first lateral modes are significantly higher than that of the fundamental bending mode and generally higher than that of the third bending mode. The inherent differences in Q factors of these modes are likely due to the motion specific nature of the surrounding fluid-microcantilever interactions.^{21,22}

Data from Fig. 3 also reveals that the average mass detection sensitivities for the third bending mode, first torsional mode, first lateral mode, second vertical bending mode, and first vertical bending mode based on the average glass microsphere diameter¹⁰ are, respectively, 37 ± 12 , 80 ± 33 , 104 ± 39 , 286 ± 92 , and 987 ± 350 femtogram/Hz for the first five test microcantilevers. These sensitivities of course can be improved by optimizing the microcantilever dimensions for sensing rather than scanning applications.

In conclusion, the use of torsional and lateral modes of diving-board microcantilevers offers an order of magnitude improvement in sensitivity and resolution for target mass detection in comparison to the fundamental bending mode. Moreover, we anticipate that this idea can be extended to triangular cantilevers. Clearly, the deliberate excitation and measurement of torsional modes by the off-center binding of

biological targets to suitably patterned and functionalized microcantilevers, seems like a particularly promising consequence of this work.

This work was partially supported by NASA Grant No. NCC 2-1363. The authors would also like to thank Y. E. Kim, the director of Purdue's Center for Sensing Science and Technology, for his continued interest in this work.

¹G. Y. Chen, T. Thundat, E. A. Wachter, and R. J. Warmack, *J. Appl. Phys.* **77**, 3618 (1995).

²H. Jensenius, J. Thaysen, A. A. Rasmussen, L. H. Veje, O. Hansen, and A. Boisen, *Appl. Phys. Lett.* **76**, 2615 (2000).

³T. Thundat and L. Maya, *Surf. Sci.* **430**, L546 (1999).

⁴R. Raiteri, M. Grattarola, H. J. Butt, and P. Skladal, *Sens. Actuators B* **79**, 115 (2001).

⁵J. Fritz, M. K. Baller, H. P. Lang, H. Rothuizen, P. Vettiger, E. Meyer, H. Guntherodt, C. Gerber, and J. K. Gimzewski, *Science* **288**, 316 (2000).

⁶M. Su, S. Li, and V. P. Dravid, *Appl. Phys. Lett.* **82**, 3562 (2003).

⁷T. Ono, X. Li, H. Miyashita, and M. Esashi, *Rev. Sci. Instrum.* **74**, 1240 (2003).

⁸NSC12 microcantilever dimensions: Length $\sim 315 \mu\text{m}$, width $\sim 35 \mu\text{m}$, thickness $\sim 2 \mu\text{m}$.

⁹S. Prescesky, M. Parameswaran, A. Rawicz, R. F. B. Turner, and U. Reichl, *Can. J. Phys.* **70**, 1178 (1992).

¹⁰Borosilicate microspheres, purchased from Duke Scientific Corporation (Palo Alto, CA), have a certified mean diameter of $2 \mu\text{m} \pm 0.5 \mu\text{m}$, a standard deviation of $0.7 \mu\text{m}$, a coefficient of variation of 35%, and a mass of approximately 10 pg. The microspheres were certified by a certificate of calibration traceable to the National Institute of Standards and Technology on October 10, 2001. www.duke-scientific.com

¹¹The exact dimensions of the specific microcantilever were determined by taking several scanning electron microscopy (SEM) pictures from different angles in the presence of a test gauge structure to accurately calibrate the SEM photos. The FE method took into account the width variation of the microcantilever along its length, the asymmetric corner notches at the free end of the microcantilever, and approximated the probe tip as a conical protrusion. Following a detailed convergence study 50 523 ten node Tetrahedral-187 elements were used. The material and geometric properties chosen for the model were: $E = 169 \text{ GPa}$, $\rho = 2329 \text{ kg/m}^3$, length = $316.06 \mu\text{m}$, width varied linearly from fixed to free end $34\text{--}36.34 \mu\text{m}$, thickness = $1.622 \mu\text{m}$. The nominal spring constant for this cantilever is $\sim 0.2 \text{ N/m}$.

¹²The percent difference between experimental and FE results: First bending = 0.6%, second bending = 7.3%, first torsion = 16.1%, third bending = 0.6%, first lateral = 4%.

¹³S. Zurn, M. Hsieh, G. Smith, D. Markus, M. Zang, G. Hughes, Y. Nam, M. Arik, and D. Polla, *Smart Mater. Struct.* **10**, 252 (2001).

¹⁴M. Reinstaedtler, U. Rabe, V. Scherer, J. A. Turner, and W. Arnold, *Surf. Sci.* **532**, 1152 (2003).

¹⁵N. C. Perkins and C. D. Mote, Jr., *J. Sound Vib.* **106**, 451 (1986).

¹⁶P. T. Chen and J. H. Ginsberg, *J. Vibr. Acoust.* **114**, 141 (1992).

¹⁷Note that the photodetector output is proportional not to the deflection, but rather the slope of the microcantilever at the laser spot location.

¹⁸A side experiment conducted demonstrated that the spectrum peaks magnitude vary by up to two to three times when a bare microcantilever is repeatedly removed and replaced in the AFM. This is due to inevitable variation in cantilever chip orientation and the position of the laser spot.

¹⁹The circle fit method calculates the Q factor of each mode based on the magnitude and phase of the response measured at all 1 Hz increments over the entire half magnitude bandwidth of the specific peak. It is significantly more accurate than the half-power method.

²⁰D. J. Ewins, *Modal Testing: Theory, Practice, and Application*, 2nd ed. (Research Studies Press Ltd., Baldock, Hertfordshire, England, 2000), pp. 306–318.

²¹J. W. M. Chon, P. Mulvaney, and J. E. Sader, *J. Appl. Phys.* **87**, 3978 (2000).

²²C. P. Green and J. E. Sader, *J. Appl. Phys.* **92**, 6262 (2002).