Sensors and Actuators A 232 (2015) 1–7

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Resonant-mode effect on fluidic damping of piezoelectric microcantilevers vibrating in an infinite viscous gaseous environment

Huacheng Qiu [a,b,*], Dara Feili [a], Xuezhong Wu [b], Helmut Seidel [a]

[a] Saarland University, Chair of Micromechanics, Microfluidics/Microactuators, 66123 Saarbrücken, Germany
[b] National University of Defense Technology, College of Mechanical Engineering and Automation, 410073 Hunan Province, China

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form 5 May 2015
Accepted 5 May 2015
Available online 15 May 2015

Keywords:
Microcantilevers
Resonant mode
Fluidic damping
Viscous fluid
Piezoelectric

ABSTRACT

High quality factors are preferable for resonating microcantilever sensors in order to improve sensitivity and resolution. In this paper we investigate the performance of microcantilevers in different resonant modes vibrating in infinite gaseous environments. Aluminum nitride based piezoelectric microcantilevers are fabricated and tested under controlled pressure from high vacuum to atmospheric pressure in N_2 environment, using a custom-built vacuum chamber. From the experiment results it can be seen that the torsional modes exhibit larger quality factors than those of the flexural and lateral ones, and the lateral modes have the lowest *Q* factors, which are limited mainly by the high intrinsic damping. Finally, analytical models for the fluidic damping characteristics of beam-shaped resonators at different resonant modes are derived and show good agreement with experimental results in the higher pressure regime.

1. Introduction

Micromechanical resonating cantilevers are used in a large variety of applications, particularly as sensors for the measurement of fluid properties, such as density, viscosity, temperature, pressure or flow velocity [1]. In most applications the sensing resolution of the cantilevers can be improved by enhancing the quality (*Q*) factor value, which is defined as the ratio of stored energy to dissipated energy per cycle. In general, a higher *Q* factor results in a sharper resonance peak and leads to a better detectable resolution. It is therefore desirable to understand and analyze the mechanisms of energy loss.

For a cantilever resonator operating in fluidic environment, the dissipated energy consists of intrinsic energy losses $Q^{-1}_{intrinsic}$ inside the solid-state material(s) of the resonator and of external losses due to fluidic damping by the surrounding medium $Q^{-1}_{fluidic}$. In order to minimize the fluidic damping, Blom et al. [2], Naeli and Brand [3], as well as Lübbe et al. [4] investigated the dependence of the *Q* factor on the cantilever geometry and on the surrounding medium. These studies focused on the fluidic damping effects of resonators operating in their fundamental flexural mode. More recently, attention begins to be paid to resonators operating at higher resonant modes [5–10]. So far, in individual studies, individual resonant modes of cantilevers are developed and used. With the results obtained from different cantilever designs and different experimental conditions, it is difficult to compare them and to judge which modes are superior.

In this work the performance of microcantilevers in different orders of flexural, lateral and torsional modes is systematically evaluated and compared. The experiments are carried out by using aluminum nitride (AlN) based piezoelectrically driven microcantilevers. Cantilevers with different geometries have been fabricated and tested in N_2 environment under pressures varying from 10^{-4} to 10^3 mbar. Several typical modes of the cantilevers are detected and characterized. In the following sections of this paper, detailed measurements of the frequency responses are presented first. Next, the analysis about the fluidic damping characteristics of the flexural modes and torsional modes of cantilevers are carried out based on assuming an incompressible fluid that can be described by continuum theory. The analytical predictions are in reasonable agreement with the measurements for the first few modes, but start to underestimate the fluidic damping as mode number and resonance frequency increase. At last, the influence of the fluid's compressibility is discussed.

---

* Corresponding author at: Saarland University, Chair of Micromechanics, Microfluidics/Microactuators, University Campus, Building A5 1, Room 1.10, D-66123 Saarbrücken, Germany. Tel.: +49 0681 3024182; fax: +49 0681 3024699.
E-mail address: h.qiu@lmm.uni-saarland.de (H. Qiu).

http://dx.doi.org/10.1016/j.sna.2015.05.003
0924-4247/

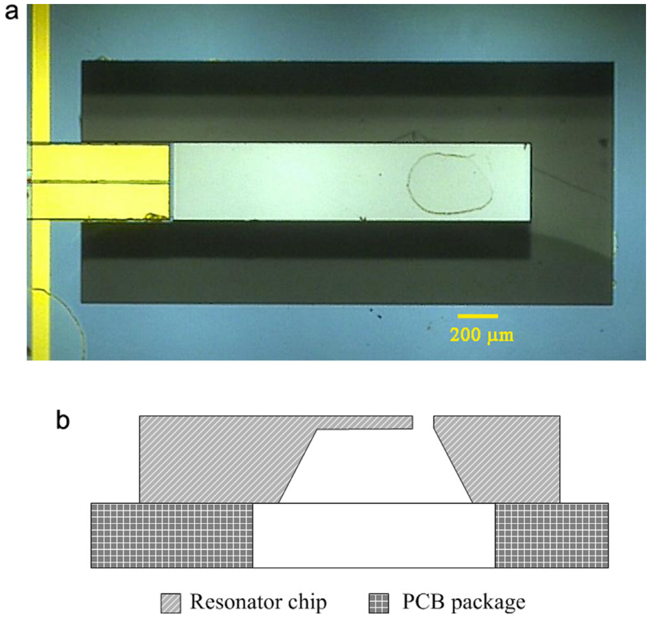

Fig. 1. AlN-based piezoelectric microcantilever, (a) micrograph and (b) schematic cross sectional view of the packaged chip.

2. Experiment

2.1. Device fabrication and packaging

Fig. 1(a) shows one example of the microcantilevers used in the experiments. A piezo-electrode stack (consisting of a 1 μm thick AlN layer and a 300 nm thick gold top electrode) was sputter deposited on top of the cantilever beam. The stack was divided into two identical strips: one is used for excitation and the other one for detection. A comprehensive description of the fabrication process can be found in [11]. To minimize "squeeze film" damping effects induced from any nearby surface, the cantilever chip was die-mounted on a pre-drilled printed circuit board (PCB) package, as schematically shown in Fig. 1(b). In this package, the resonator is suspended several millimeters away from any bottom surface, so the influence of the bottom surface on the resonance spectrum is assumed to be negligible.

2.2. Measurement setup

The fabricated resonators were housed in a custom-built vacuum chamber, and characterized under controlled pressures varying from high vacuum (HV) to normal atmosphere. The pressure in the chamber can be controlled precisely by back filling with nitrogen. In order to complete the measurement by all-electrical excitation and detection, an electronic circuit (which is described in [11]) was developed and placed in the chamber together with the resonator.

2.3. Measurement results

A cantilever resonator, with dimensions of 400 μm width, 2200 μm length and 22 μm thickness, was tested first. To excite the resonator in higher modes, the applied driving voltage frequency was scanned from 5 to 250 kHz. Seven resonant modes of the cantilever have been detected and characterized, which are the first to fourth flexural modes, the first lateral mode, and the first and second torsional modes, respectively. Finite element analysis software COMSOL was used to assign the resonant modes to the observed peaks. The real resonator was covered by a thin piezo-electrode stack to excite and detect the resonance. To simplify the computation, in the COMSOL simulation (as well as analytical solutions in Section 3), the resonator structure is assumed as a pure silicon block, the piezo-electrode stack is eliminated by simply increasing the silicon membrane thickness, to get an equivalent spring constant. A comparison between simulated and experimentally observed frequencies in HV is shown in Table 1. Fig. 2 shows the resonance frequencies and amplitudes of the cantilever in normal atmospheric N_2. The resonant mode shapes inserted in the figure were obtained by COMSOL software, depicting the displacement of the cantilever for each mode.

The Q factors of different modes were characterized under different pressures varying from 10^{-4} mbar (HV) to 1000 mbar (atmosphere). When the ambient pressure was reduced to even lower values no differences in the resonator output could be observed. So the results at 10^{-4} mbar pressure are assumed to be representative for the intrinsic damping of the resonator. The Q factors from the measurements are summarized in Fig. 3, from which one can find that the mode shape has a big effect on the performance of the resonator.

The values of the quality factors $Q_{fluidic}$ due to gas damping at atmospheric pressure, which can be obtained from the measured Q factors by separating mathematically the intrinsic Q factors $Q_{intrinsic}$, are 543, 1318 and 1890 for the first, second, and third flexural modes, respectively. These results show a general trend that $Q_{fluidic}$ is increasing as the order of the flexural mode gets higher. However, $Q_{fluidic}$ slightly reduces to 1645 at the fourth flexural mode. Besides, the total Q factors at third and fourth flexural modes are much lower than $Q_{fluidic}$, since the intrinsic energy loss ${Q_{intrinsic}}^{-1}$ is found to increase as the mode number increases. For the 3rd and 4th flexural modes, the thermoelastic damping (TED) loss was found to play an important role in the internal losses. According to [12,13], Q_{TED} has a minimum when vibrating at thermal relaxation frequency F_0, where the heat energy generated from the material internal friction dissipates completely. For the cantilever in this case, F_0 is calculated to be around 235 kHz, the resonance frequency of the 3rd (112.6 kHz) and 4th (225.5 kHz) flexural modes are closer than those of other flexural modes, and the TED energy loss is much higher than for the others.

The torsional modes exhibit higher Q factors than all other types of modes over the whole observed pressure range. Unlike the bending strain under flexural or lateral motion in the silicon membrane and the top piezo-electrode stack strips, the generated shear strain under torsional motion is unaffected by volume tension or compression. This can effectively suppress volume-change-induced energy dissipation in the solid materials [14], and leads to a higher intrinsic Q factor. Moreover, the tuning-fork-like antiphase movement induces a large part of gas flow between the two sides of the torsional cantilever, unlike vibrating in the flexural mode, the gas does not need to move around the whole cantilever width. This causes less energy dissipation induced by the gas volume change, and is expected to feature a high quality factor in fluidic environment.

The Q factor of the lateral mode stays almost constant over the whole pressure range and only starts to decrease moderately when the pressure gets close to 1000 mbar. The fluidic damping energy loss in the lateral mode is expected to be lower, since the beam is shearing with its width and only compressing the gas with its much smaller thickness. However, the intrinsic energy loss was found to be the highest for all observed modes, so that the effect of fluidic damping is only observed at pressures close to 1000 mbar. The high intrinsic loss is expected to be mainly due to the larger support loss as compared to other modes [15].

Other two cantilevers, with dimensions of 200 μm × 1200 μm × 18.4 μm and 200 μm × 2200 μm × 17.6 μm were tested and