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ScienceDirect
Sensors and Actuators A 141 (2008) 43–51
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Analysis of resonating microcantilevers operating in a viscous liquid environment

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Received 14 March 2007; received in revised form 2 July 2007; accepted 12 July 2007
Available online 20 July 2007

Abstract

The characteristics of resonant cantilevers in viscous liquids are analyzed. Various rectangular cantilevers geometries are studied in pure water, glycerol and ethanol solutions of different concentrations, and the results are described in terms of the added displaced liquid mass and the liquid damping force for both, the resonance frequency and the quality factor (Q-factor). Experimental results using a set of magnetically actuated resonant cantilevers vibrating in the out-of-plane ("weak-axis bending") mode are presented and compared to theoretical calculations. The importance of the study is in the use of resonant cantilevers as biochemical sensors in liquid environments.

Keywords: CMOS sensor; Liquid-phase operation; Resonant cantilever

1. Introduction

Several sensor technologies are being investigated for gas- or liquid-phase detection. In recent years, interest in cantilever-based chemical and bio-chemical sensing systems has risen due to their projected high sensitivity [1–3]. The large ratio of surface area-to-mass makes the microcantilever extremely sensitive to surface processes. For bio-chemical detection, the microcantilever is usually coated with a bio-chemically sensitive layer, which selectively absorbs the analyte molecules of interest. Two possible modes of operation exist: (a) the static mode and (b) the resonant mode. In the static mode, the analyte adsorption on the cantilever surface gives rise to surface stress and, thus, to a bending of the cantilever [1,2]. In the resonant mode, the cantilever is driven at its fundamental resonance frequency (or one of the harmonic frequencies), and an increase of the cantilever mass due to analyte absorption causes a decrease of the cantilever resonance frequency [3]. In this paper, only the resonant mode will be considered. When operated in liquid environments, the mechanical properties of the fluid, i.e., density and viscosity, will influence the cantilever's dynamic behavior.

In the resonant mode of operation, an important transducer parameter is the mechanical quality factor. When operating frequency-output sensors, such as microcantilevers, in an oscillator configuration, the frequency stability and, consequently, the limit of detection (LOD) are directly dependent on the quality factor. Since bio-chemical sensors operate in either, the gas or the liquid phase, the quality factor of the resonant microcantilever is not as high as that of microcantilevers operating in vacuum [4]. When a microcantilever is placed in a gas atmosphere, the resonance frequency is usually reduced by a few percent or less, whereas the quality factor is decreased by orders of magnitude with respect to its value in vacuum [5]. The immersion of the cantilever in a liquid results in even more pronounced changes in the frequency response with the quality factor being another order of magnitude lower in comparison to the gas phase. The reduced value of the quality factor is due to energy dissipation

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0924-4247/$ – see front matter
doi:10.1016/j.sna.2007.07.010

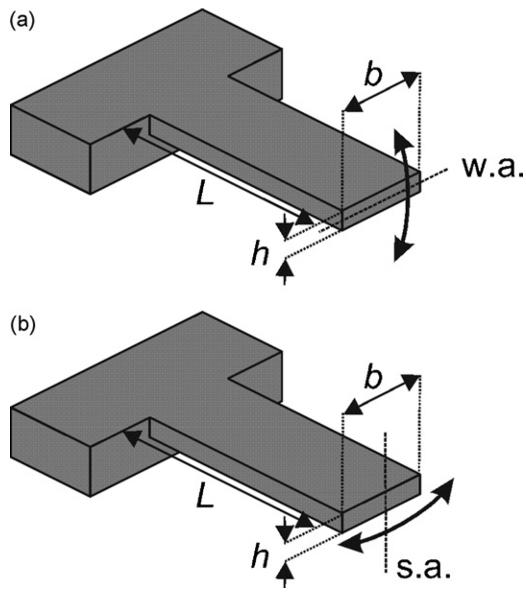

Fig. 1. (a) Out-of-plane bending. (b) In-plane bending mode of vibration (w.a. and s.a. denote the "weak" and "strong" axis of the cantilever).

in the surrounding medium and directly affects the sensitivity and detection limit of this type of sensor.

The aim of this paper is to study the out-of-plane vibration mode (for various rectangular cantilever geometries), which is the most commonly used mode in cantilever research. This mode relies on the out-of-plane bending of the cantilever, for which the flexural stiffness is minimal (Fig. 1a). Another vibration mode is the in-plane vibration mode (Fig. 1b). The advantages of this mode are minimized dissipation losses to the surrounding fluid and maximized flexural stiffness. A consequence of the high flexural stiffness is that this mode is very difficult to excite. We therefore limit ourselves to the out-of-plane vibration mode.

In the first part of the paper, relevant theoretical results are presented for microcantilever beam vibrations. These results include equations for the resonance frequency, the forces associated with the surrounding fluid, the quality factor, and the frequency shift caused by an added mass on the beam surface based on a lumped-element model. In the experimental part of this paper, measurements of various cantilevers vibrating in viscous fluids featuring different viscosities are compared with theoretical results. These measurements have been performed with magnetically actuated microcantilevers, fabricated in CMOS technology with post-CMOS micromachining. As will be shown, the sensor dynamics in the liquid are strongly dependent on the cantilever width.

2. Microcantilever mechanics

2.1. Fluid losses, resonance frequency and quality factor

When a microcantilever vibrates in a viscous fluid, the fluid offers resistance to the motion of the beam, which can be described by an external force acting on the cantilever [6]. This force can be expressed in two terms. The first term is a dissipative force per unit length, which results from the fact that the motion of the fluid is not necessarily in phase with the cantilever motion. It is called the fluid damping force and is proportional to the cantilever velocity. The second term is proportional to the cantilever acceleration and results from the fluid being forced into motion with the cantilever. This term is due to the inertia of the fluid mass displaced by the motion of the cantilever. Combining these two terms, the total fluid force, F_{fluid}, per unit length of the cantilever can be written as [6]:

$$F_{\text{fluid}} = -g_1\dot{w} - g_2\ddot{w} \tag{1}$$

where $w = w(x, t)$ is the deflection at an arbitrary location, x, on the beam axis. In Eq. (1), g_1 is the fluid damping coefficient and g_2 is the added fluid mass per unit length of the beam. More details on these two factors will be given later in this paper.

Using the expression of the fluid force given in Eq. (1), the resonance frequency, f_r, of the microcantilever immersed in a viscous fluid can be related to its undamped natural frequency in vacuum, f_0 [7]:

$$f_r = f_0 \frac{1}{\sqrt{1 + Lg_2/m}} \sqrt{1 - \frac{1}{2Q_{\text{tot(liq)}}^2}} \tag{2}$$

with L being the cantilever length and m representing the cantilever mass. $Q_{\text{tot(liq)}}$ is the quality factor of the immersed cantilever taking into account all losses in the fluid as well as the intrinsic losses in the microstructure. It should be noted that the term "natural frequency" is used to denote the frequency, at which a free, unforced vibration may occur, whereas the term "resonance frequency" refers to the maximum-amplitude frequency of a forced vibration. Under identical environmental conditions, the resonance frequency is always smaller than the natural frequency due to internal losses in the cantilever structure.

For a composite cantilever, such as a CMOS cantilever used in the experiments performed in this work, the undamped natural frequency, f_0, can be expressed as follows:

$$f_0 = \frac{1}{2\pi}\left(\frac{\lambda_0}{L}\right)^2 \sqrt{\frac{\sum_i \hat{E}_i I_i}{b\sum_i \rho_i h_i}} \tag{3}$$

with $\lambda_0 = 1.875$ denoting the fundamental flexural mode and b being the cantilever width. Eq. (3) is derived from the classical beam bending theory. The parameters ρ_i and h_i are the density and thickness of the respective layers of the composite cantilever. I_i represents the individual moments of inertia of the different layers with respect to the neutral axis of the beam. The apparent Young's moduli of the respective cantilever layers are denoted $\hat{E}_i$.

The quality factor, $Q_{\text{tot(liq)}}$, of a liquid-immersed microstructure takes into account the fluid damping as well as internal damping effects caused by, e.g., support losses. Expressing the quality factor as the sum of its two main components yields:

$$\frac{1}{Q_{\text{tot(liq)}}} = \frac{1}{Q_{\text{int}}} + \frac{1}{Q_{\text{fluid}}} \tag{4}$$

with Q_{int} being the intrinsic quality factor of the microstructure and Q_{fluid} the fluid contribution to the quality factor, i.e.,