Sensors and Actuators A 147 (2008) 203–209

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Using electric actuation and detection of oscillations in microcantilevers for pressure measurements

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A R T I C L E I N F O

Article history:
Received 12 February 2008
Received in revised form 2 April 2008
Accepted 20 April 2008
Available online 8 May 2008

Keywords:
Microcantilever
Electrostatic
Harmonic resonance
Pressure
Q-factor
Gas environments

A B S T R A C T

Response characteristics of a microcantilever, such as resonant frequency, amplitude, phase and quality factor, can be used for absolute pressure measurements in the range of 10^{-4} to 10^{3} Torr. To this end, it would be very convenient to have the resonance of the microcantilever actuated and detected electrostatically. Herein, we report the nonlinear dynamics of microcantilevers under varying pressure and different gases using the harmonic detection of resonance (HDR) technique [J. Gaillard, M.J. Skove, R. Ciocan, A.M. Rao, Electrical detection of oscillations in microcantilevers and nanocantilevers, Rev. Sci. Instrum. 77 (2006) 073907]. The HDR technique exploits nonlinearities in the cantilever-counter electrode system to allow electrostatic actuation and detection of the responses of the microcantilever to the pressure and gas composition. In particular, the 2nd and 3rd harmonics of the measured charge on the cantilever are investigated. The microcantilever demonstrates a quality factor of ∼10,000 at 10^{-3} Torr, and a usable response in the range from 10^{-3} to 10^{3} Torr. The use of different harmonics can enable us to adjust the range of pressures over which the sensor has an efficacious response, enhancing its sensitivity to a particular environment. The experimental results are in reasonable agreement with theoretical calculations, despite the nonlinearities involved.

Published by Elsevier B.V.

1. Introduction

Cantilever structures are the simplest structures that can be easily micro-machined, mass produced and integrated into micro- or nano-electromechanical systems (MEMS/NEMS) [1]. The microcantilever's response includes any variable that changes the vibration of the cantilever, and is measured as a change in the resonance frequency, amplitude, phase and/or quality factor. These variables may also be reflected in the harmonic structure of the response. In this paper, we discuss only the properties at the 1st mode of vibration of the cantilever. We are working with gases for which we expect no physical or chemical absorption or effects due to their dielectric constant. Further, all the measurements are at room temperature and the damping of the vibrating cantilever is caused by both the internal friction in the cantilever (intrinsic damping) and the surrounding gas.

Silicon microcantilevers have been extensively studied as sensors for pressure, temperature, mass and viscosity measurements [2–8]. Many of the reported results are focused on the resonance response as a function of pressure in different regimes—the intrinsic regime, the molecular flow regime, the viscous regime, and transition regimes in between. In the intrinsic regime (10^{-8} to 10^{-6} Torr) due to the low air pressure, air damping is insignificant compared to the intrinsic damping of the vibrating cantilever itself. Hence the resonant frequency ω_0 and the quality factor Q are nearly independent of air pressure p. In the molecular region (10^{-6} to 10^{-1} Torr), the collisions of air molecules with the vibrating cantilever cause the damping. For the viscous region ($p > 10^{-1}$ Torr), the velocity of the cantilever is always much smaller than the speed of sound in the medium and hence we can consider air as a viscous fluid. However, there can be turbulence, in which case the damping is roughly proportional to the square of velocity [9]. In this investigation, laminar flow with negligible turbulence is assumed. The dependence of Q on p can be explained by the Christian model [10], which emphasizes that the Q is proportional to $1/p$ in the molecular region. Blom et al. mainly focuses on dividing the viscous regime into two zones, one with Q independent of p and the other with Q proportional to $1/\sqrt{p}$ [8]. The main focus of this work is to conduct a characteristic study of a resonating cantilever as a function of chamber pressure over six decades (10^{-3} to 760 Torr) using a technique outlined briefly in the following paragraph [11]. The effect of different gases: He, Ar, H_2, and air were also measured and the results are in agreement with theory. In a separate study, we compare the 2nd and 3rd

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0924-4247/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.sna.2008.04.017

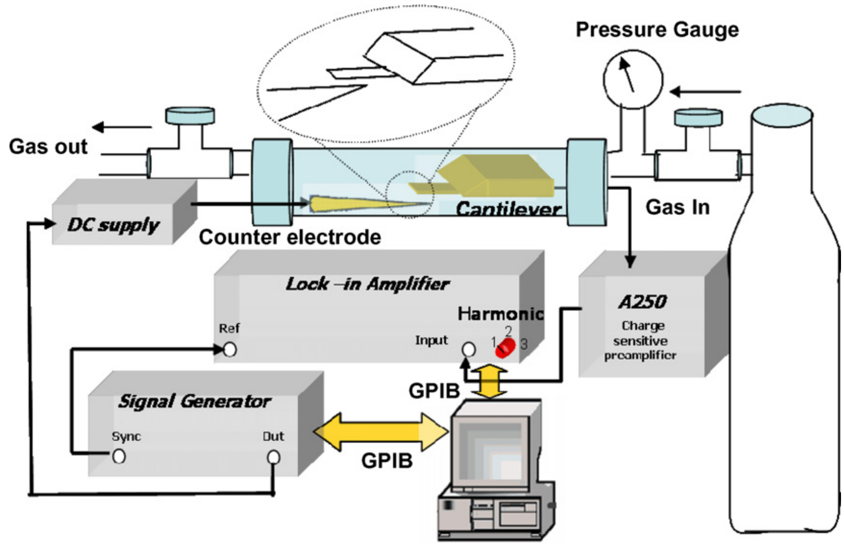

Fig. 1. A schematic of the experimental set up for our harmonic detection of resonance method. The cantilever is forced by an ac voltage from the signal generator and a dc voltage from the dc supply. The charge induced on the cantilever is a function of the forcing voltages and the position of the cantilever. This charge is amplified and then particular harmonics of the frequency of the forcing ac voltage measured by the lock-in amplifier. The inset shows the geometry of the cantilever with respect to that of the W tip.

harmonic responses of a silicon microcantilever as a function of *p*.

Recently, we have developed an electrical readout system using a technique called the harmonic detection of resonance (HDR) [11–13]. The microcantilever is electrostatically actuated by applying an ac voltage (V_{ac}) with a dc offset (V_{dc}) to the counter electrode which is a tungsten (W) tip. The W wire was etched in NaOH to form a sharp conical W tip [14]. The cantilever is aligned such that the long axis of the cantilever intersects the axis of the conical tip, and the plane of the cantilever is parallel to the nearby surface of the conical tip (see inset in Fig. 1). The electrical signal due to the modulated charge created on the cantilever by the dynamic capacitance as well as the electrostatic driving signal is measured by an A250 charge sensitive preamplifier. The charge on a microcantilever has a rich harmonic structure and measuring it at higher harmonics avoids the parasitic capacitance problem. The lock-in amplifier detects the output of the A250 at the higher harmonics of the oscillator frequency, which in turn is referenced to the signal generator (Fig. 1). Using HDR, we have measured mechanical resonances in silicon microcantilevers in 2nd, 3rd and 4th harmonics [11].

2. Quality factor (*Q*)

For a harmonic oscillator, the usual definition of the quality factor *Q* is

$$Q = \frac{2\pi U_i}{U_d} = \frac{2\pi\,(\text{stored vibration energy})}{\text{energy dissipated per period}}$$

It is usually measured at the 1st harmonic of the power curve near resonance in a linear system, that is, a simple harmonic oscillator (SHO). In the HDR method, we do not have a simple harmonic oscillator, nor is it easy to measure the first harmonic response, which is usually overwhelmed by parasitic capacitance signals. For an SHO, *Q* is also equal to ω_0 divided by the full width at half maximum of the resonance peak of a power vs. frequency plot. We will use the following definition for the experimental quality factor Q_E for any harmonic and for cantilever motions that are nearly that of a SHO as well as motions in which the position of the cantilever affect the spring constant and driving force.

$$Q_E = \frac{\omega_0}{\text{FWHM}} \tag{1}$$

where ω_0 is the resonant frequency and FWHM is the full width at half maximum of the resonant peak of a squared amplitude vs. frequency plot. Although this is not the standard *Q*, as shown below it is generally consistent with results predicted for a standard *Q*.

Following Pippard [15] for a damped SHO, the quality factor is identical to Q_E defined above

$$Q_E = \frac{1}{2}\frac{\omega'}{\omega''},$$

where

$$\omega'' = \frac{b}{2m}$$

and

$$\omega' = \sqrt{\omega_0^2 - 2(b/2m)^2} = \sqrt{\left(\frac{k}{m}\right) - 2\left(\frac{b}{2m}\right)^2},$$

m is effective mass of the 1st mode of vibration of the cantilever, *b* measures the damping and k is the spring constant.

Since we can measure ω_0 and Q_E, we should be able to calculate the damping, *b*. Note that we will have to plot the square of the amplitude vs. frequency to get Q_E. Thus

$$Q_E = \frac{1}{2}\frac{\omega'}{\omega''} = \frac{1}{2}\frac{\sqrt{\omega_0^2 - 2(b/2m)^2}}{b/2m}, \quad \left(\frac{b}{2m}\right)^2 = \frac{\omega_0^2}{4Q_E^2 + 2}$$

Since in our case $Q_E \gg 50$, we can neglect the 2 in the denominator on the right side,

$$b \approx m\frac{\omega_0}{Q_E} \tag{2}$$

Since we can measure directly ω_0 and Q_E, and estimate *m* reasonably well, we can estimate the damping, *b*, with the caveat that our systems are not linear and we use harmonics other than the first.