Available online at www.sciencedirect.com
ScienceDirect
Sensors and Actuators A 136 (2007) 417–425
SENSORS AND ACTUATORS A PHYSICAL
www.elsevier.com/locate/sna

Behaviour of forbidden modes in the impedance characterization and modeling of piezoelectric microcantilevers

Javier Vázquez*, Pablo Sanz, José Luis Sánchez-Rojas

Universidad de Castilla-La Mancha, Departamento de Ingenieria Eléctrica, Electrónica, Automática y Comunicaciones, Av. Camilo José Cela s/n, 13071 Ciudad Real, Spain

Received 9 February 2006; received in revised form 30 October 2006; accepted 2 November 2006
Available online 6 December 2006

Abstract

A systematic impedance analysis of the resonance response obtained from commercial piezoelectric scanning force microscopy (SFM) cantilevers, comprising both experimental and simulation work, has been carried out. A finite element model (FEM) has been developed and fitted using experimental data, from which valuable conclusions have been reached. Although non-fundamental modes are less used in sensing applications, they have been emphasized in this work. Two main arguments justify a deeper study of these higher order modes. First, an SFM cantilever acting as a gravimetric sensor and driven at a non-fundamental resonance frequency shows a real potential to enhance its mass detection sensitivity when compared with its performance in the usual driving scheme at the fundamental frequency. Secondly, the characterization of some non-fundamental modes, torsionally shaped, reveals an unexpected behaviour that should be known and understood previously to any gravimetric sensor design using torsional modes. Results show that modes of torsional nature cannot be detected electrically because they are not even excited by the applied ac field. Moreover, torsional modes, successfully excited by an external harmonic mechanical stimulus, cannot be detected electrically either. An explanation to this phenomenon, based on the redistribution and cancellation of surface reaction charges, is given in detail and supported by simulation results.

Keywords: Microcantilever; MEMS simulation; Resonance; Piezoelectric; Impedance; Chemical sensor

1. Introduction

One of the most extended and widely known uses of cantilever beams to date is as scanning probe in atomic force microscopy. The performance of conventional silicon probes, operating in the tapping mode by means of an attached piezoelectric actuator, has been enhanced with the introduction of fast scanning structures where the piezoelectric element is sandwiched between two electrodes. SFM imaging is not, however, the unique application of such devices, and intensive research has been carried out in recent years oriented to investigate the cantilever performance in other fields. It has demonstrated a great potential, for example, as gravimetric sensor in chemical and biochemical applications, where a very thin layer of molecules deposited on the active surface of the device induces a measurable shift in its resonance frequency, when it is properly excited. Numerous publications have contributed to bring forward the state of the art of the piezoelectric cantilever as a gravimetric sensor in the last years. A brief review of them includes, chronologically listed, references [1–12], which settle a starting point for our work. The approach in the experimental part of our study is fully electric, unlike the common optical techniques, which are based on a two-port scheme comprising both electrical excitation and photodiode detection, and need a more sophisticated set up. The piezoelectric nature of the SFM probes utilized justifies the choice of an impedance analyzer as single excitation–detection port, which turns out to be easier to set up and operate, and it allows to evaluate the spectral resonance response in a broad frequency range.

In addition to this, a solid theoretical background around the electromechanical behaviour of piezoelectric heterogeneous bimorphs as a function of frequency has already been established, mainly by Smits et al. [13–17]. In particular, the relation between four sinusoidal driving parameters and their canonical

* Corresponding author.
E-mail address: javier.vazquez@uclm.es (J. Vázquez).

0924-4247/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2006.11.005

conjugates is determined in the form of a four by four dynamic admittance matrix, whose elements have a built-in resonance factor [15].

On the other hand, little attention has been paid to date to higher order modes of commercial AFM cantilevers. Chen et al. set up a theoretical approach to fill partially this gap [18], which can be of practical interest for certain applications. For example, the AFM probes utilized in our experiments have a fundamental resonance of nominally 50 kHz, but, according to the supplier technical data [19], tapping mode imaging is best performed on the second resonance, which is nominally of 210 kHz. Yet another argument supports the interest in a detailed study of non-fundamental resonance modes, which is explained as follows. Since length and width of AFM cantilevers are of the same order of magnitude, it is suitable to fall back on a mode plate theory instead of an elementary theory of bending thin beams in order to evaluate the resonance frequencies. For a given piezoelectric cantilever bimorph of length a, width b, mass density per unit area ρ and flexural rigidity D, which is clamped on one edge and free on the other three, the ith order natural frequency can be evaluated from the following equation:

$$\omega_i a^2 \sqrt{\frac{\rho}{D}} = c_i \tag{1}$$

being c_i a parameter which depends on the ratio aspect. If $a/b = 2$ and the Poisson's ratio ν (which influences the flexural rigidity) is set to 0.3, the frequency parameter c_i equals 3.47, 14.93, 21.61, 94.49 and 48.71 for $i = 1, \ldots, 5$, respectively. The values are obtained after a Rayleigh–Ritz analysis and the evaluation of products of beam functions, as can be found in reference [20]. An inspection to the series shows that the values associated to higher order modes are usually larger than that of lower order modes (although the trend is not increasing mode by mode, as flexural, torsional and mixed flexural–torsional modes are present in the series). This holds, besides, for every ratio aspect, regardless of the particular frequency parameter series. Eq. (1) can be rearranged in terms of the cantilever mass m and solved for the frequency, resulting:

$$\omega_i = \frac{c_i}{a^{3/2}} \sqrt{\frac{Db}{m}} \tag{2}$$

If adsorbates are deposited uniformly on the beam surface, the resultant mass change, δm, induces a shift in the resonant frequency. Since the added mass may alter the flexural rigidity D, a new D' should be introduced after the mass adsorption, and thus the frequency shift can be expressed as

$$\delta\omega_i = \frac{c_i \sqrt{b}}{a^{3/2}} \left(\sqrt{\frac{D}{m}} - \sqrt{\frac{D'}{m + \delta m}} \right) \tag{3}$$

which is proportional to c_i, regardless of the change in flexural rigidity (which is in principle not necessarily negligible). As a consequence, the frequency shift $\delta\omega_i$ becomes larger for non-fundamental modes than for the fundamental one and, in turn, the sensor sensitivity improves. Note that for the particular case where D' is such that the term into brackets vanishes or is very close to zero, $\delta\omega_i$ would be small even for modes with a high frequency parameter c_i.

It is worth mentioning that the presented scheme has been developed for a rectangular plate, which includes no tip at its end, as a real AFM cantilever does. The presence of the little tip modifies slightly the frequency parameters given above, but the general conclusion which motivates a detailed study of non-fundamental resonance modes remains the same.

2. Experimental work

2.1. Structure of the piezoelectric microcantilever

Silicon probes are commercially available and were manufactured by Veeco. Each probe consists of a phosphorus-doped silicon layer terminated in a sharp-etched tip for scanning purposes (which is not relevant in our study). A 3.5-μm thick ZnO piezoelectric film, sandwiched between two 0.25-μm Ti/Au electrodes, is grown on a nominal 4-μm thick silicon layer. The length and the width of the rectangular fraction of the beam that is free to vibrate is close to 347 and 240 μm, respectively. (Both

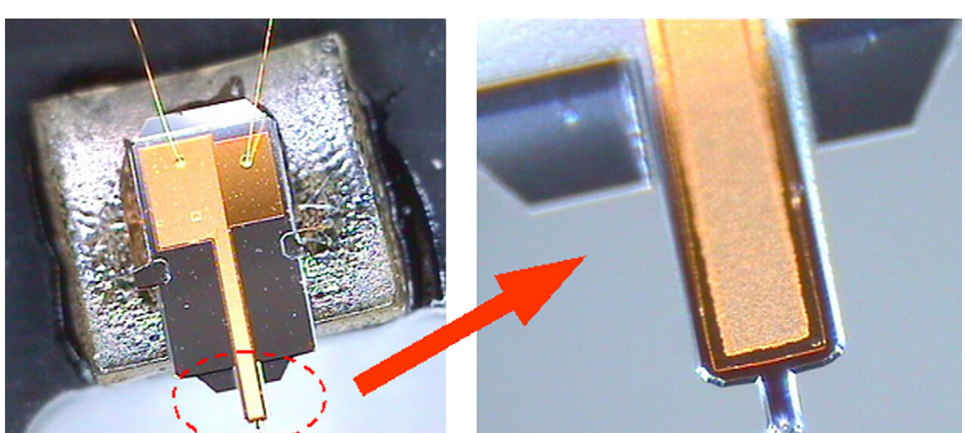

Fig. 1. SFM cantilever beam fabricated by Veeco.