J Electroceram (2010) 25:1–10
DOI 10.1007/s10832-009-9581-z

Effects of the material properties on piezoelectric PZT thick film micro cantilevers as sensors and self actuators

Jae Hong Park · Hwan Kim · Dae Sung Yoon · Soo Yoo Kwang · Jinhyung Lee · Tae Song Kim

Received: 4 June 2008 / Accepted: 19 May 2009 / Published online: 2 June 2009

Abstract In general, PZT thick films fabricated through screen printing show porosity ranging from 10% to 40%. Unfortunately, these high porosities of thick films greatly affect the electromechanical characteristics of PZT thick film cantilevers. In this paper, we report a systematic analysis on the effect of thick film porosity on the electromechanical characteristics of the PZT thick film cantilevers in order to make the PZT thick film cantilever a highly controllable micro mass sensor or micro self actuator. The theoretical calculations of mass sensitivity and actuating force of the optimal PZT thick film cantilevers are presented with respect to the material properties and geometry of PZT thick films, which are based on experimentally verified material properties and geometrical parameters. The 400×300 cantilever with 20% porosity of active material was evaluated to be reliable as an optimal mass sensor and self actuator. The thick film cantilever indicates both high mass sensitivity (~48 pg/Hz), the same as sensitive thin film cantilever sensors, and high actuating force (~1.7 N), similar to strong bulk cantilevers. From the results of the modeling, it was found that the harmonic oscillation response according to material properties including the porosity, and geometry of the fabricated thick film cantilever, is quite controllable and predictable, thus enhancing the actuating force and mass sensitivity. Also, it was confirmed that controlling the porosity of PZT thick films is more efficient than controlling the cantilever geometry to increase the cantilever resonating force. However, optimizing the geometric constituents is more effective than controlling the densification of PZT thick films to increase the mass sensitivity of the cantilevers.

Keywords Cantilever · Sensor · Actuator · Piezoelectric · Thick film · Porosity · Mass sensitivity · Actuating force

J. H. Park
Harvard-Massachusetts Institute of Technology Division of Health Sciences and Technology, Department of Medicine,
Brigham & Women's Hospital, Harvard Medical School,
65 Landsdowne Street,
Cambridge, MA 02139, USA

J. H. Park (✉) · D. S. Yoon · J. Lee · T. S. Kim (✉)
Nano-Bio System Research Center,
Korea Institute of Science and Technology,
Seoul 136-791, Korea
e-mail: jaehongp@mit.edu
e-mail: tskim@kist.re.kr

H. Kim
Department of Material Science and Engineering,
Seoul National University,
Seoul 151-744, Korea

D. S. Yoon
Department of Biomedical Engineering, Yonsei University,
Gangwon-do 220-710, Korea

S. Y. Kwang
Department of Materials Science and Engineering,
University of Seoul,
Seoul 130-743, Korea

T. S. Kim
Intelligent Microsystem Center, Nano-Bio System Research Center,
Korea Institute of Science and Technology,
Seoul 136-791, Korea

1 Introduction

The PZT thick film cantilever devices fabricated using the MEMS process are very attractive because they are appropriate for use as micro sensors for infinitesimal chemical, physical, or biological stimulus, or as micro actuators for flowing, delivering, or mixing target media.

These advantageous terms result from their high mass sensitivity or large actuating force, even in liquid dampers [1–5]. Nonetheless, the resonance and sensing properties of PZT thick film cantilever devices using resonance behavior have rarely been studied before, because not only the processing temperature of the PZT thick film is high enough to generate PbO condensation and reaction to undesirable glassy phase, but also micro-patterning using the etching process of PZT thick film is not easy or desirable [1–9].

In order to overcome these problems, some researchers have suggested that the screen printing method is capable of achieving reliable micro-dimension patterning and thickness over a range from several microns to tens of microns as just one drawing of PZT paste, and also that several other methods can realize the sintering of PZT at a low temperature [3, 5, 7–9]. As far as screen printing is concerned, unfortunately, complete densification cannot be obtained by screen printing alone because the PZT paste is deposited through the screen mesh and extra pressing processes are not appropriate to maintain the micro pattern. Accordingly, some methods that incorporate the screen printing method have been explored to increase the density of thick films. Those methods include the development of new piezoelectric materials, development of proper milling and mixing methods, addition of glass frit, and sol infiltration into the thick film [3–9].

Basic modeling for the mechanics for PZT-based cantilevers according to the geometric criterion have been proposed and analyzed well by several research groups [5–7]. In general, the material parameters of thick film, such as porosity and Young's modulus, as well as cantilever geometry, largely affect the resonance properties, such as actuating force or mass sensitivity, of the thick film cantilever. However, theoretical modeling on the influence of the material characteristics has not yet been reported elsewhere, even though it is valuable information. In particular, we consider that the material characteristics of thick film play important roles in the resonance properties for screen printed thick film cantilevers because it shows various porosities.

In this report, in order to evaluate, design, and control the PZT thick film cantilever as either a micro mass sensor or a micro self actuator, we investigate the influence of the level of densification (i.e. film porosity) on the resonance behavior (i.e. mass sensitivity and actuating force) of PZT thick film cantilevers using theoretical modeling. The theoretical calculations regarding the mass sensitivity and actuating force of PZT thick film cantilevers are presented with respect to the material properties (density and Young's modulus) of PZT thick films, which are based on experimentally verified parameters of material and geometrical constituents. Modeling of the resonance mechanics of a PZT coated cantilever according to the geometric criterion has also been performed successfully. The factors affecting the mechanical resonance behavior, such as actuating force and mass sensitivity, of the piezoelectric cantilever consist of geometric parameters (length, width, and thickness) and material parameters (density and Young's modulus), or electrical properties (capacitance and dielectric permittivity). From the result of this modeling, we confirm that the increase of Young's modulus due to the decrease of porosity of PZT thick films is more efficient than controlling the cantilever geometry to increase the cantilever actuating force, while optimizing the geometric constituents is more effective than controlling the densification of PZT thick films to increase the mass sensitivity of cantilevers.

2 Preliminary discussion and theory

Figure 1 describes the principle and mechanical structures of PZT thick film cantilever sensors or self actuators in dynamic resonant mode. Dynamic motion of cantilevers using alternating current needs a piezoelectric part (i.e. capacitor type PZT oscillator) and a non-piezoelectric part (cantilever type membrane). The piezoelectric thick film cantilever Combined (i.e. integrated) with both PZT oscillator and cantilever membrane moves and deflected up and down according to the applied AC frequencies. Consequently, the piezoelectric PZT cantilever generates the strongest transverse wave through the maximum deflection and oscillation, if the applied frequency on sweep matches exactly to the characteristic frequency of the whole piezoelectric PZT cantilever, whose characteristic frequency is decide by its geometric parameters such as length, width and thickness, and material parameters such as density and Young's modulus which depend on its porosity. The dependency and effect between the performances for proper sensors or self actuators of piezoelectric PZT thick film cantilevers and their parameters are presented in this research. Also the relationships including optimum values among the geometric or material parameters are considered as the following view points.

2.1 Resonance frequency shift

The spring constant of the vertical deflection of a load applied to the end of a rectangular shaped cantilever is represented by the equation below [10–14]:

$$K = \frac{F}{h} = \frac{Ewd^3}{4L^3}, \tag{1.1}$$

where K indicates total spring constant of cantilever, h is the deflection caused by the load, E denotes the cantilever's modulus of elasticity, and w, d, and L indicate the width, thickness, and length of the cantilever, respectively. The primary resonance frequency is:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{m^*}} = \frac{d}{2\pi(0.98)L^2}\sqrt{\frac{E}{\rho}}, \tag{1.2}$$

where ρ indicates the cantilever's density and m^* indicates the cantilever's effective mass. Effective mass (m^*) is associated with the beam mass and is represented by $m^*=n\, m_b$. n is the geometric factor of the beam. For example, for a diving board shaped rectangular cantilever, the n value is 0.24 [11, 12].

Assuming that the elements absorbed on the surface do not affect the spring constant of the cantilever, the resonance frequency expressed by the absorbed substances is as in the equation below:

$$\frac{\left(f_1^2 - f_2^2\right)}{f_1^2} = \frac{\Delta m}{m}. \tag{1.3}$$

f_1 indicates the primary resonance frequency before the reaction, and f_2 indicates the resonance frequency after the reaction. Δm and m indicate the absorbed mass and the mass of the primary cantilever beam before the reaction, respectively. If the loading amount of mass is limited to the end of the cantilever, the effective mass concept should be adopted in Eq. (1.3).

If absorption occurs in the entire cantilever, the spring constant of the cantilever and mass added from the absorption change, resulting in a resonant frequency shift.

$$df(m^*, K) = \left(\frac{\partial f}{\partial m^*}\right)dm^* + \left(\frac{\partial f}{\partial K^*}\right)dK = \frac{f}{2}\left(\frac{dK}{K} - \frac{dm^*}{m^*}\right). \tag{1.4}$$

The spring constant shift occurs for various reasons, and it is known to be caused by a change in the elastic constant on the thin film surface and cantilever's morphological change. Here, we consider an end loading experiment [2] in which the absorbed mass exists only on the end of the cantilever. For end loading, the effect on the surface stress of dK/K in Eq. (1.4) is minimized, and the resonant frequency shift is only subject to change by mass loading.

The harmonic resonance response of a unimorph cantilever is strongly dependent on structural constituents and material parameters, such as elastic constant and density. The resonant frequency of a piezoelectric unimorph cantilever clamped at one end can be described as in Eq. (2.1) with regard to mass sensing with a condition of resonance [1, 2, 10, 11, 15–18]:

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{Me}}, \tag{2.1}$$

$$f_n = \frac{I_n^2}{2\pi}\sqrt{\frac{K}{m^*}} = \frac{v_n^2}{2\pi L^2}\sqrt{\frac{D_p}{m}}, \tag{2.2}$$

and

$$D_p = \frac{\left\{E_{np}^2 h_{np}^4 + E_p^2 h_p^4 + E_{np} h_{np} E_p h_p \left(4h_{np}^2 + 6h_{np}h_p + 4h_p^2\right)\right\}}{12\left(E_{np}h_{np} + E_p h_p\right)}, \tag{2.3}$$

where m^* (kg/m^2), K (N/m), and D_p (N·m) are the effective mass, spring constant, and bending modulus per unit width, respectively, and f_n and ν_n are the nth-mode resonant frequency and nth-mode dimensionless eigen value that depends on the resonant mode of the cantilever, respectively. L (m) is the length of the cantilever, and ρ_p (kg/m^3), ρ_{np} (kg/m^3), h_p (m), h_{np} (m), E_n (N/m^2), and E_{np} (N/m^2) are the density, thickness, and Young's modulus of the piezoelectric material and non-piezoelectric materials, respectively.

2.2 Mass sensitivity

If discrete mass (m_d) is added or reacted to a rectangular cantilever, the effective mass of the cantilever absorb system can be described as $m_{eff}= m^* + m_d$. m^* indicates the effective mass of the cantilever. Therefore, the resonant frequency of cantilever can be shown as Eq. (3.1) below [12, 18]:

$$f = \frac{1}{2\pi}\sqrt{\frac{Ewd^3}{4L^3(m_d + 0.24\rho wdL)}}. \tag{3.1}$$

Gravimetric sensitivity, S_m, suggested by Ward *et al* [18] is a useful normalized parameter that helps compare the micro cantilever sensor with other gravimetric sensing devices in terms of sensor performance shown in Eq. (3.2):

$$S_m = \lim_{\Delta m \to 0} \frac{A}{f}\frac{\Delta f}{\Delta m} = \frac{A}{f}\frac{df}{dm}, \tag{3.2}$$

where Δm and dm indicate the absorbed masses at each active sensor area, and A indicates the absorbed area of the cantilever.

The principle of the mass sensing mechanism is based on the mechanical phenomenon where the resonant frequency of a micro cantilever decreases as mass is added to the cantilever beam surface. Therefore, the amount of mass loading on the cantilever can be determined from the shift in the resonant frequency of the cantilever. Recently, a theoretical model regarding the resonance behavior of a multi-layered cantilever has been proposed by Shih et al. [11]. For our piezoelectric cantilever, the resonant frequency can be expressed in terms of spring constant (K) and effective mass (m^*), as shown below [1, 2].

$$f_n = \frac{v_n^2}{2\pi(\sqrt{3/0.236})}\sqrt{\frac{K}{m^*}}, \tag{4.1}$$

$$K = \frac{3D_p w}{L^3}, \tag{4.2}$$

$$m = \rho_p h_p + \rho_{np} h_{np}, \tag{4.3}$$

$$m^* = 0.236\left(\rho_p h_p + \rho_{np} h_{np}\right) wL, \tag{4.4}$$

$$f_n^2 = \frac{v_n^4}{4\pi^2 L^4}\frac{D_p}{m} = \frac{I_n^4}{4\pi^2}\frac{K}{m^*} = \frac{v_n^4}{4\pi^2}\frac{K}{(3/0.236)m^*}, \tag{4.5}$$

and

$$f_n' = \frac{v_n^2}{2\pi(\sqrt{3/0.236})}\sqrt{\frac{K}{m^* + \Delta m}}, \tag{4.6}$$

where L is the length of the cantilever, w is the width of the PZT thick film cantilever, f_n is the nth-mode resonant frequency, and m^*, K and D_p are effective mass, spring constant, and bending modulus per unit width, respectively. ν_n is a dimensionless nth-mode eigen value that depends on the resonant mode of the cantilever. ρ_p, ρ_{np}, h_p, and h_{np} are the densities and thicknesses of the piezoelectric layer and non-piezoelectric layer, respectively.

3 Experimental, results and discussion

3.1 Properties of the active materials and thick film cantilevers

In general, screen printed green PZT thick film is composed of PZT powders and organic binders that enhance the mechanical strength of the film. In order to obtain a fully dense film from a green thick film, a high sintering temperature and sufficient sintering time are considered as essential requirements. According to previous works, an almost fully dense PZT bulk sample is obtained under special conditions of a sintering temperature of approximately 1250°C and a sintering time of more than 2 h [1, 3–5, 9]. Accordingly, PZT is seemingly incompatible with Si substrates because the melting point of Si (~1400°C) is close to the sintering temperature of PZT. Even though the combination of PZT and Si can be achieved by adjusting the sintering temperature, a critical PbO condensation problem remains for sintering PZT thick film on Si. Therefore, in order to realize the integration of PZT on a Si substrate without a PbO condensation or reaction between PZT and Si, it is necessary to decrease the sintering temperature to approximately 800°C. This has been accomplished by adding 10 mol% of the substituent, PZW ($Pb(Zn_{0.5}W_{0.5})O_3$), into the PZT ($Pb(Zr_{0.52}Ti_{0.48})O_3$) powder [1, 2, 9], controlling the particle size, and applying sol infiltration enhancement into the powder [8, 9].

In previous studies, all PZT thick films were fired at a low temperature of 800°C, enough to prohibit PbO evaporation. We also adopted a short sintering time of 10 min to hinder the interaction between PZT and Si [1, 2, 8, 9]. Figure 2 shows the SEM top view images of PZT thick film cantilevers with three different sizes in their length and width. These three different sized cantilevers were fabricated to investigate geometrical effects in this study. Figure 3 (a), (b) provide the top and common cross sectional views of cantilevers fabricated on only one wafer simultaneously. From Figs. 1 and 2, it would be announced that a series of cells is composed of cantilevers with a width of 400 µm and lengths of 380 µm, 480 µm, and 580 µm. The non-piezoelectric membrane supporting the PZT thick film has a Pt (500 nm)/TiO_2 (50 nm)/SiNx (1500 nm)/Si (10000 nm) structure. The thicknesses of the PZT and total non-piezoelectric membrane are approximately 22 µm and 12.3 µm, respectively. The porosity of the printed PZT thick

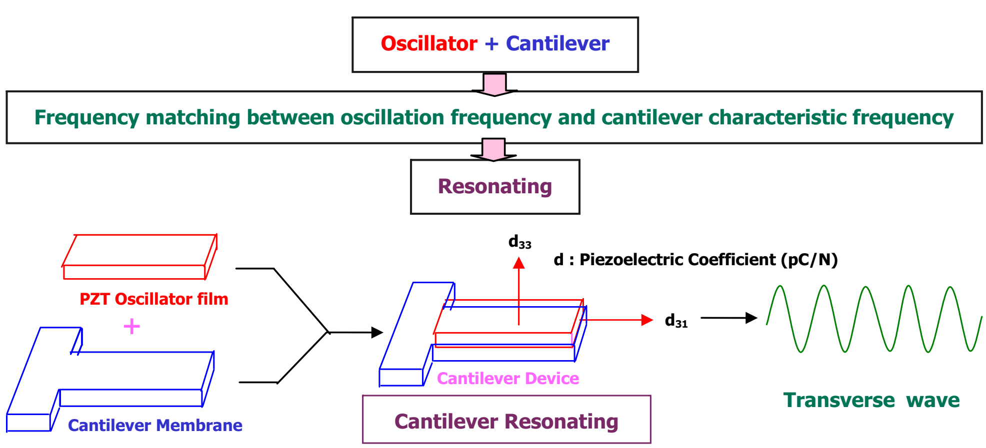

Fig. 1 Schematic setup for principle and mechanical structures of PZT thick film cantilever sensors or self actuators in dynamic resonant mode

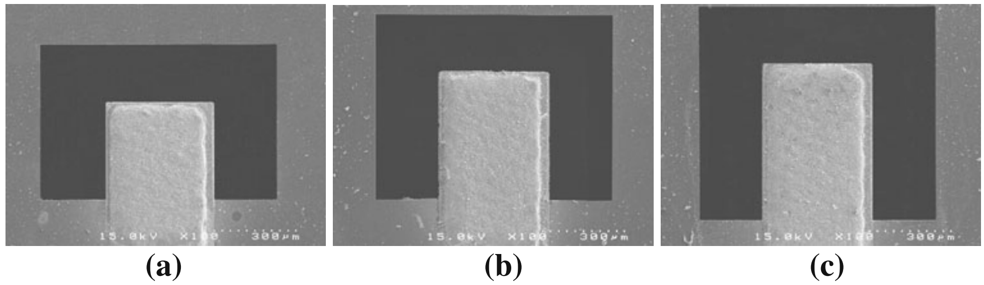

Fig. 2 SEM images for top views of PZT thick film cantilevers with dimensions of (**a**) 400 μm × 380 μm, (**b**) 400 μm × 480 μm, and (**c**) 400 μm × 580 μm

films is estimated to be approximately 30%, as shown in Fig. 3 (c) and (d). This considerable porosity is caused by an insufficient sintering temperature and time and also screen printing protocols from the mesh screening.

Nonetheless, screen printing of the PZT might be a strong candidate for patterning thick film micro devices because it is microscopically and directly patternable without extra patterning processes. Furthermore, this convenient process is compatible with MEMS processes. If harmonic oscillation of the screen printed thick film cantilever is able to be observed in air and liquid environments, then the screen printing approach will warrant further attention. In general, the efficient harmonic oscillation response is not easily obtained in a liquid environment with a weak actuating force. This phenomenon occurs because the peak intensity of the resonant peak is drastically decreased by the high effective mass of liquid, and the full-width-at-half-maximum (FWHM) becomes much broader by viscous damping. If Q factors in a liquid environment are demonstrated below 1~2, it can be estimated to have poor detectability [1, 19, 20]. We have attempted to observe the harmonic oscillation response of a PZT thick film cantilever in several liquid environments (i. e. conditions with various proportions of glycerol, from 0 to 100 wt%, in water) with various viscosities (0.01~6 P). The harmonic oscillation response (resonance frequency and mechanical displacement) was investigated using a LDV (Laser Doppler Vibrometer, NEO ARK Co, Japen.) as a laser dynamic interferometric vibrometer in water-glycerol mixture after electrical passivation with 100 μm thickness of parylene-C coating. Figure 4 shows the harmonic oscillation curves (a) and resonance frequencies and mechanical Q factors (b), for different fluid viscosities from 0.01 to 6 P, of the PZT thick film cantilever with a width of 400 μm and length of 480 μm driven in 15 $V_{p\text{-}p}$. The resolving quality of the resonant curve can be expressed as a quality factor Q [1, 21, 22]:

$$Q = 2\pi \frac{stored\ vibration\ energy}{total\ energy\ lost\ per\ cycle\ of\ vibration} = \frac{f_r}{\Delta f}, \tag{5.1}$$

where f_r is the resonant frequency and Δf is the FWHM of the resonant curve. In 100 wt% water, the thick film cantilever shows a very good Q of approximately 22.6. Even in 100 wt% glycerol with a viscosity of 6 P, the Q value is 3.5. In general, the viscosity of the whole serum ranges from 0.03 to 0.04 P according to the health condition. Accordingly, considering that Q factor of the PZT thick film resonant cantilever is 10.8 within a mixture of half water-half glycerol in weight (water:glycerol=50 wt%:50 wt%) with a viscosity of 0.04 P, it is worthwhile to discuss and consider that the PZT thick film cantilever has enough potential to be adopted to a resonance-type micro self-sensing sensor. Additionally, it provides greatly improved Q factors compared with those of thin film cantilevers [19, 20] in severer damping conditions than real serum conditions, even on a PZT active material with 30% porosity.

In previous reports, porosity data has been observed in a range of 10~40% with several *in situ* densification processes [1, 2, 8, 9]. Therefore, PZTs in this porosity range can be realized in our thick film system. Furthermore, controlling the organic binders, particle size of PZT powders and sol infiltration level attribute to adjusting the packing of the PZT powder. Therefore, we can expect various resonance properties, including Q factors, mass sensitivity for a mass sensor, and actuating force for a self actuator, according to the porosity change of the piezoelectric PZT films.

There is, however, some debate that remains between the cantilever noise force and the Q factor. Ordinarily, sensor performance is improved by reducing the noise of the preamplifier used to convert physical signals to electrical signals and by controlling other error sources, such as uncompensated thermal drift. However, there eventually comes a point where thermodynamics impose a barrier to further sensor improvement. For micro cantilevers optimized for use in force detection, the thermo-mechanical noise sets a limit to the ultimate force resolution [22, 23]. The minimum detectable force of a harmonic oscillator is given by Eq. (5.2) [22].

$$F_{\min} = \sqrt{\frac{2Kk_bTb}{\pi Q f_0}}, \tag{5.2}$$

where K is the spring constant, k_B is Boltzmann's constant, T is the absolute temperature, b is the measurement

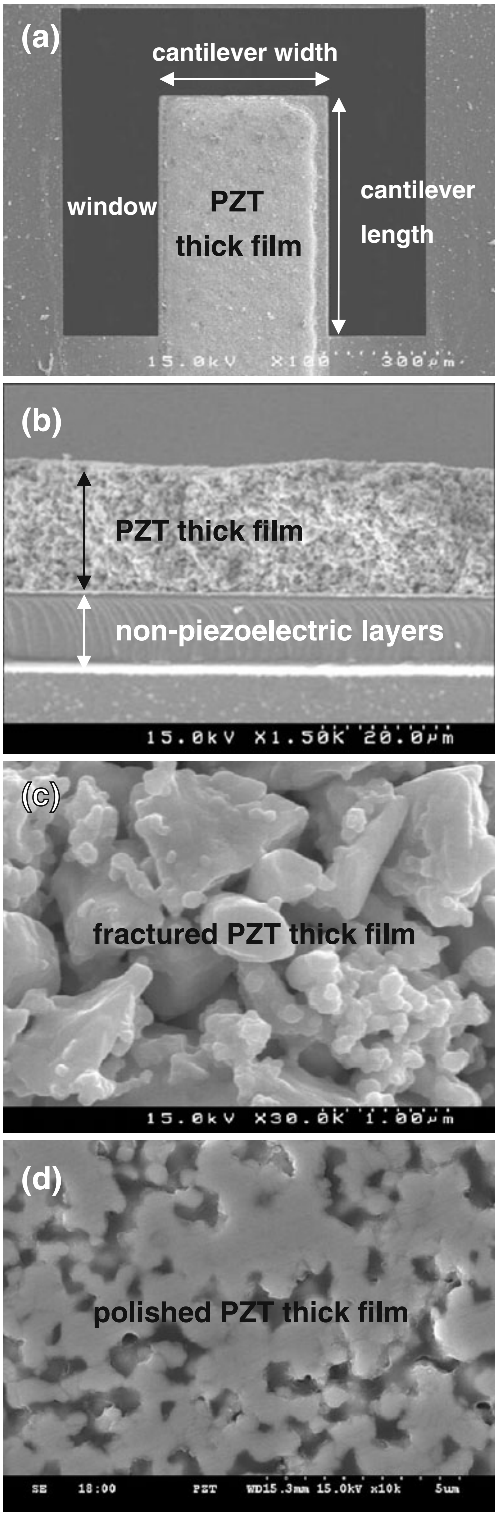

Fig. 3 SEM images of (**a**) the top view of PZT thick film cantilever, (**b**) the cross sectional view of PZT thick film and membrane for mechanical support, and (**c**) the fractured and (**d**) polished cross-sectional views of the PZT thick film

bandwidth, Q is the quality factor, and f_0 is the resonant frequency. As for Eq. (5.2), the minimal detectible force of harmonic oscillator appears to be inversely proportional to the root Q. However, the physical explanation of this phenomenon remains a subject of debate, because the quality factor (Q) and bandwidth (b) have also been shown to vary with the resonant frequencies (f_0) affected by cantilever dimensions, as well as material characteristics and empirical circumstances of the system. In Eq. (5.1), the total energy loss per cycle may be expressed as the sum of different loss sources with corresponding Q factors: internal material loss (Q_i), loss to the chip substrate through the cantilever support (Q_s), and viscous loss (Q_a) [21]. Accordingly, it can be assumed that the Q factors of resonant cantilevers strongly depend on cantilever constituents or conditions including geometrical, material, or environmental parameters. Even if piezoelectric materials such as PZT thick films are involved in the cantilever

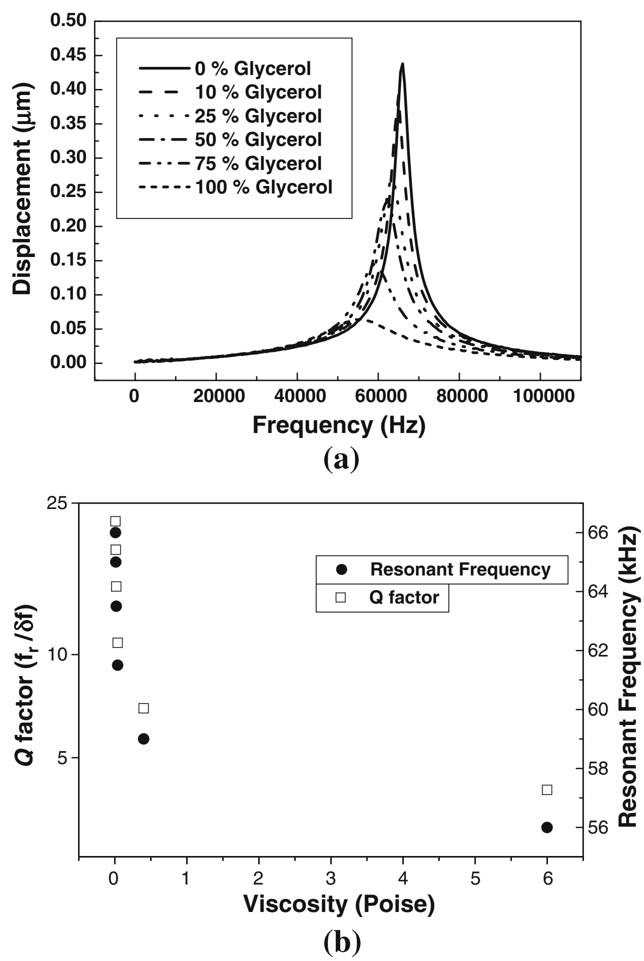

Fig. 4 (**a**) Harmonic oscillation curves, and (**b**) resonance frequencies and mechanical Q factors (log-scale formatted axis) according to viscosity variation from 0.01 to 6 P (i.e. from 0 wt% to 100 wt% of glycerol in water) of the PZT thick film cantilever with a width of 400 μm and length of 480 μm driven in 15 $V_{p\text{-}p}$

system, the dependency of the Q values on material characteristics might be more significant. It can be suggested that the assumption of an invariant Q or a maintained Q against the variation of constituents (material and geometrical parameters of the cantilever) is needed to evaluate mass sensitivity or actuating force. Nonetheless, it is still significantly ambiguous and difficult to analytically interpret the relation between the force of the resonant cantilever and Q factor with various constituent parameters. Also, it might not be precise and desirable to valuate the performance of a piezoelectric cantilever as one side of a sensor or an actuator in terms of the Q factor only, even though it provides a reference of the performance. Additionally, it is quite difficult to design an efficient model to simultaneously perform as a sensor and actuator. For that reason, we need to distinguish the dependency of performance by the mass sensitivity as a sensor and actuating force as a self actuator. Consequently, we will present an effective design for the PZT thick film cantilever as a mass sensor application or a self actuator application, through the investigation of the effects of material characteristics and geometric parameters on mass sensitivity and actuating force of the cantilever.

3.2 Calculation of resonance dynamics and mass sensitivity according to material and geometrical properties

The objective of this study is to design PZT thick film cantilevers that can exhibit a strong actuating force or a high sensitivity. PZT thick film cantilevers that have the properties required for a sensor or actuator might be applicable to not only high power self actuators, but also bio sensors capable of actuating and *in situ* sensing, for real time detection of bio materials in liquid damper. Therefore, to realize PZT thick film cantilevers, it is essential to consider suitable modeling of the PZT thick film cantilevers with respect to actuating force and mass sensitivity. Factors affecting the mechanical or resonant behavior, including actuating force and mass sensitivity of cantilevers actuated by piezoelectric materials, are geometric components (length, width, and thickness) and material parameters, such as mechanical properties (density and Young's modulus of each layer) or electrical properties (capacitance and dielectric permittivity). In general, the increase of Young's modulus of piezoelectrics (E_p) plays a positive role in mechanical behavior (i.e. actuating force and mass sensitivity) of the cantilever. For identical materials, however, both E_p and ρ_p change simultaneously with changes in porosity. Therefore, the effect of porosity on both mass sensitivity and actuating force must be considered.

The flexural resonant frequency after additional mass loading can be delineated as in Eq. (4.6), where $f_n^{'}$ indicates the nth-mode resonant frequency after an additional Au mass loading (Au mass loading at 10% of the area from the cantilever tip, which does not affect the spring constant of the cantilever, on the entire bottom side [2]). Accordingly, the mass change Δm can be estimated by Eq. (6.1):

$$\Delta m = \frac{v_n^4 K}{4\pi^2 \times (3/0.236)}\left(\frac{1}{f_n^{'2}} - \frac{1}{f_n^2}\right) = \frac{v_n^4 K}{501.845}\left(\frac{1}{f_n^{'2}} - \frac{1}{f_n^2}\right), \tag{6.1}$$

$$f_n^{'2} = \frac{1}{\frac{\Delta m}{K v_n^2} + \frac{1}{501.854 f_n^2}}, \tag{6.2}$$

and

$$\Delta f_n = f_n - f_n^{'} = \frac{v_n^2\sqrt{K}}{22.402}\left(\sqrt{\frac{1}{m^*}} - \sqrt{\frac{1}{m^* + \Delta m}}\right), \tag{6.3}$$

where f_n and $f_n^{'}$ are the nth-mode resonant frequencies before and after mass loading, respectively.

On the contrary, the blocking force of piezoelectric cantilevers can be defined as in Eq. (7.1) to (7.3) [24], which indicates the driving force on the dynamics of cantilever resonating.

$$F_{bl} = \frac{3wt^2E_p}{8L}\frac{2AB}{(AB+1)(1+B)}d_{31}E_3\,, \tag{7.1}$$

$$A = \frac{E_m}{E_p} = \frac{S_{11}^P}{S_{11}^m}\,, \tag{7.2}$$

and

$$B = \frac{t_m}{t_p}, \tag{7.3}$$

where L, w, and t are the cantilever length, width, and total thickness, respectively. d_{31} is the transverse piezoelectric coefficient and E_3 is the applied electric field.

Along with the Young's modulus of piezoelectrics (E_p), the most important electromechanical property of the piezoelectric cantilever is the transverse piezoelectric constant (d_{31}), which is closely related to the actuating force and displacement. A high d_{31} induces a high actuating force and large displacement of the thick film cantilever. Thus, a thick film cantilever with a high d_{31} is desirable to obtain strong harmonic oscillation in a liquid damper. One possible method to evaluate the piezoelectric constant (d_{31}) of the piezoelectric PZT cantilever is to use the constituent equation suggested by Smith and Choi [25]. The constituent equations for the electromechanical characterization of piezoelectric and heterogeneous unimorph cantilevers were derived under the assumption of a thermodynamic equilibrium state. According to the above condition, capacitance (C) can be expressed as in Eq. (8.1) and (8.2):

$$C = \frac{A}{h_p}\left[\varepsilon_{33}^{T} - \frac{d_{31}^{2} h_{np}\left\{s_{11}^{np}\left(h_p\right)^3 + s_{11}^{p}\left(h_{np}\right)^3\right\}}{K}\right], \tag{8.1}$$

and

$$K = 4S_{11}^{np}S_{11}^{p}h_{np}\left(h_p\right)^3 + 4S_{11}^{np}S_{11}^{p}\left(h_{np}\right)^3 h_p + \left(S_{11}^{p}\right)^2\left(h_{np}\right)^4 + \left(S_{11}^{np}\right)^2\left(h_p\right)^4 + 6S_{11}^{np}S_{11}^{p}\left(h_{np}\right)^2\left(h_p\right)^2, \tag{8.2}$$

where A,ε_{33}^{T}, and d_{31} are the area of the entire electrode, dielectric constant, and transverse piezoelectric coefficient, respectively. Also, the rule-of-mixture should be used to calculate the total electric permittivity of the porous structure [1, 26]. From the above results, it is known that the mechanical or resonant behavior of piezoelectric cantilevers depends on geometric factors and material parameters in a complicated manner with high order terms. In particular, mass sensitivity is more dominantly affected by the geometric components than the material parameters. However, actuating force is more greatly affected by the material parameters than the geometric components.

In general, both E_p and ρ_p of any material change with a variation in its porosity. However, both E_p and ρ_p provide opposite influences on the resonance behavior of the cantilever. Precisely, the increase of E_p among the mechanical parameters is a factor in the improvement of resonance behavior (i.e. both actuating force and mass sensitivity). However, an increase in ρ_p appears to degrade the mass sensitivity of the cantilever slightly, because an increase in density means an increase of mass in the same volume of the cantilever. Accordingly, the effect of porosity on both actuating force and mass sensitivity must be considered in order to design a proper cantilever with the expected mass sensitivity and/or high actuating force. Figure 5 and Table 1 present the effect of the material properties and parameters, and the cantilever geometry on the mass sensitivity and actuating force of piezoelectric PZT thick film cantilevers. As presented in Fig. 5 (a), the increase of porosity from 50% to 100% leads to a 10~20% increase, which is attributed to the decrease in the effective mass, of mass sensitivities of the cantilever beam. However, Fig. 5 (b) shows that each cantilever with the fully dense active material (0% porosity) improves the actuating forces (i.e. blocking forces) up to twofold of the original value, which is attributed to the drastic increase of E_p and d_{31}, compared with that of the highly porous active material with 50% porosity. In particular, the 400×300 cantilever with active material with 20% porosity, which is an empirically possible value of porosity that can be achieved through

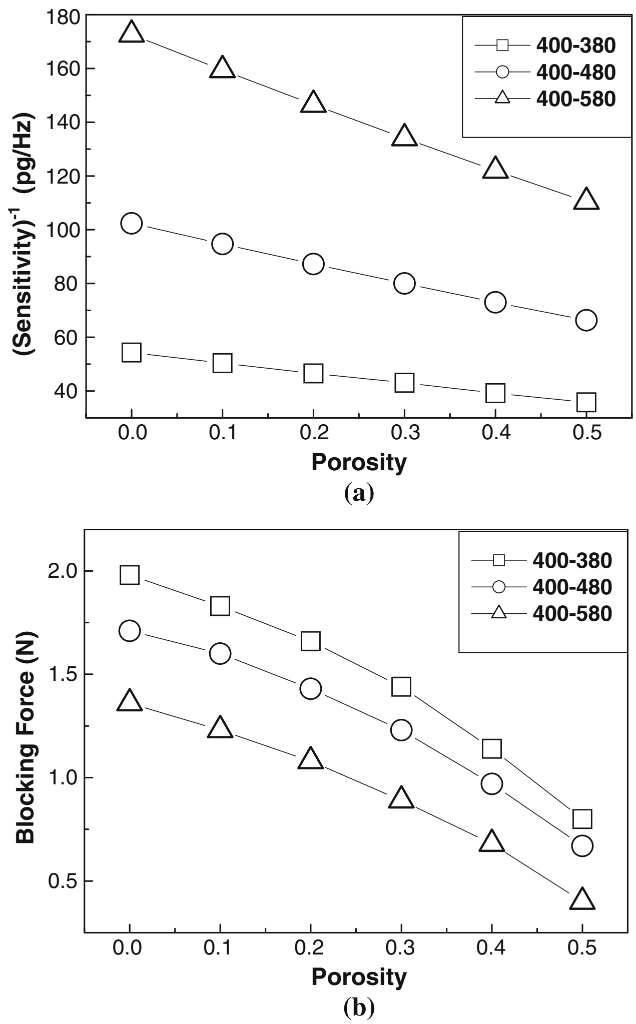

Fig. 5 (**a**) Mass sensitivity and (**b**) actuating force of PZT thick film cantilevers according to porosity of PZT thick films

particle size control or sol infiltration process [1, 8, 9], presents both a high mass sensitivity (48 pg/Hz), comparable to that of thin film cantilevers (~23 pg/Hz) [27], and a high actuating force (1.7 N), as high as that of bulk cantilevers (~2 N) [24].

Overall, it was found that the mass sensitivity of PZT thick film cantilevers depends more on the change of geometric constituents than the actuating force of those, as seen in the results. Also, the dependency of the mass sensitivity and the actuating force on the material parameters shows opposite inclinations to that of the geometric constituents. In other words, increasing the material parameters, E_p and d_{31}, through densification of PZT thick films is more efficient in increasing the actuating force of the cantilever than controlling the cantilever geometry. However, the optimization of geometric constituents is more effective in increasing the mass sensitivity of the cantilever than controlling densification.

Table 1 Data presenting Young's modulus, density of the PZT thick films, theoretical first-mode resonant frequencies before and after the 10 ng mass deposition, and blocking force driven at 15 V according to porosity and dimension of cantilevers, on the assumption of no spring constant change.

Cantilever dimension (μm)	Porosity of PZT thick films (%)	E_p (GPa)	ρ_p (kg/m^3)	$f_1^{theoretical}$ (Hz)	$f_1^{'\,theoretical}$ (Hz)	$\Delta f_1^{theoretical}$ (Hz)	(Sensitivity)$^{-1}$ (pg/Hz)	F_{bl} (N)
400×380	0	77.0	7500	151780.23	151761.82	18.41	54.31831	1.98
	10	69.3	6750	153030.43	153010.58	19.85	50.37783	1.83
	20	61.6	6000	154140.71	154119.22	21.49	46.53327	1.66
	30	53.9	5250	155020.46	154997.24	23.22	43.06623	1.44
	40	46.2	4500	155520.89	155495.38	25.51	39.20031	1.14
	50	38.5	3750	155380.33	155352.38	27.95	35.77818	0.80
400×480	0	77.0	7500	97136.98	97127.21	9.766	102.39607	1.71
	10	69.3	6750	97939.61	97929.05	10.56	94.71491	1.60
	20	61.6	6000	98652.62	98641.16	11.46	87.24481	1.43
	30	53.9	5250	99123.15	99110.65	12.50	79.99360	1.23
	40	46.2	4500	99530.28	99516.58	13.70	72.99803	0.97
	50	38.5	3750	99444.38	99429.30	15.08	66.30860	0.67
400×580	0	77.0	7500	67456.22	67450.43	5.79	172.62213	1.36
	10	69.3	6750	68013.86	68007.59	6.27	159.41336	1.23
	20	61.6	6000	68508.75	68501.93	6.82	146.54162	1.08
	30	53.9	5250	68898.23	68890.77	7.46	134.04826	0.89
	40	46.2	4500	69118.14	69109.94	8.20	121.98097	0.68
	50	38.5	3750	69058.84	69049.79	9.06	110.43622	0.40

Consequently, it was revealed that increasing E_p and d_{31} by decreasing the porosity is essential in cantilever design to realize PZT thick film cantilevers that are capable of a high mass sensitivity or a high actuating force. High actuating force and high mass sensitivity can originate from the density of the film. This means that the design of a micro cantilever with respect to porosity could provide a possibility of application to a strong harmonic oscillator or a high analytical sensor, even in a liquid damper. In addition, it is also possible to predict and simultaneously control both the resonance behavior and the mass sensitivity of the piezoelectric cantilever with optimum properties as a required for active or passive multi-transducer platforms in μ-TAS (Micro Total Analysis System) applications.

4 Conclusions

PZT ($Pb(Zr_{0.52}Ti_{0.48})O_3$) thick film cantilever devices, which are expected to advance micro mass sensors and micro self actuators, were successfully fabricated on a Pt/TiO_2/SiN_X/Si substrate using a screen printing method and MEMS processes. The porosity of the bare printed PZT was observed in a range from 10 to 40%, as in our previous works. Accordingly, we theoretically analyzed the effect of the geometry and porosity of the cantilever beams on mass sensitivity and actuating force and designed effective cantilever platforms for optimal practical application. The elastic and electromechanical properties, such as Young's modulus and transverse piezoelectric coefficient, were determined from microstructural and electromechanical analyses. We found that the mass sensitivity of the PZT thick film cantilever depends more on the geometric parameters than the actuating force. However, the increase of ρ_p appears to degrade the mass sensitivity of the cantilever slightly, because an increase in density means an increase of mass in the same volume of the cantilever. Furthermore, we found out that the 400×300 thick film cantilever with 20% porosity of active material was evaluated to be reliable as an optimal mass sensor and self actuator. The thick film cantilever indicates both high mass sensitivity (~48 pg/Hz), the same as sensitive thin film cantilever sensors, and high actuating force (~1.7 N), similar to strong bulk cantilevers.

Consequently, it was estimated that the design to increase E_p and d_{31} by decreasing porosity is desirable to increase the actuating force of dynamic mode cantilevers. Therefore, an optimal geometric design and proper densification of active materials make it possible to realize high mass sensitivity or high actuating force for the required application. This successful analysis opens up the possibility to predict and simultaneously control both the resonance behavior and the mass sensitivity of the piezoelectric thick film cantilever with optimum properties as a required for active or passive multi-transducer platforms in μ-TAS (Micro Total Analysis System) applications.

Acknowledgments The authors are grateful for the financial support from the Intelligent Microsystem Center sponsored by the Korea Ministry of Science and Technology as a part of the 21st Century's Frontier R&D Projects (Grant MS-01-133-01) and National Core Research Center for Nanomedical Technology sponsored by KOSEF (Grant R15-2004-024-00000-0). Also, this work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD), (Grant Number: KRF-2006-351-D00002).

References

1. J.H. Park, T.Y. Kwon, D.S. Yoon, H. Kim, T.S. Kim, Fabrication of microcantilever sensors actuated by piezoelectric Pb$(Zr_{0.52}Ti_{0.48})O_3$ thick films and determination of their electromechanical characteristics. Adv. Funct. Mater. **15**, 2021–2028 (2005). doi:10.1002/adfm.200500331
2. J.H. Park, T.Y. Kwon, H.J. Kim, S.R. Kim, D.S. Yoon, C.-I. Chun, H. Kim, T.S. Kim, Resonance properties and mass sensitivity of monolithic microcantilever sensors actuated by piezoelectric PZT thick film. J. Electroceram. **17**, 565–572 (2006). doi:10.1007/s10832-006-6290-8
3. S.P. Beeby, A. Blackburn, N.M. White, Processing of PZT piezoelectric thick films on silicon for microelectromechancial systems. J. Micromech. Microeng. **9**, 218–229 (1999). doi:10.1088/0960-1317/9/3/302
4. Y.-B. Jeon, T.-S. Chung, K.-S. No, Fabrication of PZT thick films on silicon substrates for piezoelectric actuator. J. Electroceram. **4** (1), 195–199 (2000). doi:10.1023/A:1009924113335
5. R.A. Dorey, S.B. Stringfellow, R.W. Whatmore, Effect of sintering aid and repeated sol infiltrations on the dielectric and piezoelectric properties of a PZT composite thick film. J. Eur. Ceram. Soc. **22**, 2921–2926 (2002). doi:10.1016/S0955-2219(02)00062-6
6. S. Le Dren, L. Simon, P. Gonnard, M. Troccaz, A. Nicolas, Investigation of factors affecting the preparation of PZT thick films. Mater. Res. Bull. **35**, 2037–2045 (2000). doi:10.1016/S0025-5408(00)00402-5
7. R.N. Torah, S.P. Beeby, N.M. White, Improving the piezoelectric properties of thick-film PZT: the influence of paste composition, powder milling process and electrode material. Sens. Actuators A Phys. **110**, 378–384 (2004). doi:10.1016/j.sna.2003.09.027
8. J.H. Park, J.H. Son, D.S. Yoon, T.S. Kim, H.-H. Park, H. Kim, Electrical properties of screen printed PZT thick films infiltrated with photo-sensitive sol compared with normal sol for cantilever type biochip. Integr. Ferroelectr. **69**, 163–171 (2005). doi:10.1080/10584580590898613
9. T.Y. Kwon, J.H. Park, Y.B. Kim, D.S. Yoon, C.I. Cheon, H.L. Lee, T.S. Kim, Preparation of piezoelectric $0.1Pb(Zn_{0.5}W_{0.5})O_3$-$0.9Pb(Zr_{0.5}Ti_{0.5})O_3$ solid solution and thick films for low temperature firing on a Si-substrate. J. Cryst. Growth **295**, 172–178 (2006). doi:10.1016/j.jcrysgro.2006.07.005
10. X. Li, W.Y. Shih, I.A. Aksay, W.-H. Shih, Electromechanical behavior of PZT-brass unimorphs. J. Am. Ceram. Soc. **82**, 1733–1740 (1999). doi:10.1111/j.1151-2916.1999.tb01993.x
11. W.Y. Shih, X. Li, H. Gu, W.-H. Shih, I.A. Aksay, Simultaneous liquid viscosity and density determination using piezoelectric unimorph cantilevers. J. Appl. Phys. **89**, 1497–1505 (2001). doi:10.1063/1.1287606
12. J.H. Lee, PZT nanomechanical cantilever studies for protein detection system, PhD Thesis, *Yonsei University*, 2004, pp. 16–20.
13. F.G. Brath, J.A.C. Humphrey, *Sensing in Biological Engineering* (Spronger Wien, NewYork, 2002)
14. D. Sarid, *Scanning force microscopy* (Oxford University Press, New York, 1994)
15. J.W. Yi, W.Y. Shih, W.-H. Shih, Effect of length, width, and mode on the mass detection sensitivity of piezoelectric unimorph cantilevers. J. Appl. Phys. **91**, 1680–1686 (2002). doi:10.1063/1.1427403
16. J.W. Yi, W.Y. Shih, R. Mutharasan, W.-H. Shih, In situ cell detection using piezoelectric PZT-stainless steel cantilevers. J. Appl. Phys. **93**, 619–625 (2003). doi:10.1063/1.1524022
17. J. Merhaut, *Theory of Electroacoustics* (McGraw-Hill, New York, 1981), p. 100
18. M.D. Ward, D.A. Butty, In situ interfacial mass detection with piezoelectric transducers. Science **249**, 1000–1007 (1990). doi:10.1126/science.249.4972.1000
19. G.Y. Chen, R.J. Warmack, T. Thundat, D.P. Allison, A. Huang, Resonance response of scanning force microscopy cantilevers. Rev. Sci. Instrum. **65**, 2532–2537 (1994). doi:10.1063/1.1144647
20. P.I. Oden, G.Y. Chen, R.A. Steele, R.J. Warmack, T. Thundat, Viscous drag measurements utilizing microfabricated cantilevers. Appl. Phys. Lett. **68**, 3814–3816 (1996). doi:10.1063/1.116626
21. R. Sandberg, K. Molhave, A. Boisen, W. Svendsen, Effect of gold coating on the Q-factor of a resonant cantilever. J. Micromech. Microeng. **15**, 2249–2253 (2005). doi:10.1088/0960-1317/15/12/006
22. K.Y. Yasumura, T.D. Stowe, E.M. Chow, T. Pfafman, T.W. Kenny, B.C. Stipe, D. Rugar, Quality factors in micron- and submicron-thick cantilevers. J. Microelectromech. Syst. **9**, 117–125 (2000). doi:10.1109/84.825786
23. T.B. Gabrielson, Mechanical-thermal noise in micromachined acoustic and vibration sensors. IEEE Trans. Electron. Dev. **40**, 903–909 (1993). doi:10.1109/16.210197
24. Q.-M. Wang, Q. Zhang, B. Xu, R. Liu, L.E. Cross, Nonlinear piezoelectric behavior of ceramic bending mode actuators under strong electric fields. J. Appl. Phys. **86**, 3352–3306 (1999). doi:10.1063/1.371213
25. J.G. Smith, W.-S. Choi, The constituent equations of piezoelectric heterogeneous bimorphs. IEEE Trans. Ultra. Ferro. Freq. Contr. **38**, 256–270 (1991). doi:10.1109/58.79611
26. B. Krause, G.-H. Koops, N.F.A. van der Vegt, M. Wessling, M. Wubbenhorst, J. van Turnhout, Ultralow-k dielectrics made by supercritical foaming of thin polymer films. Adv. Mater. **14**, 1041–1046 (2002). doi:10.1002/1521-4095(20020805)14:15<1041::AID-ADMA1041>3.0.CO;2-A
27. J.H. Lee, K.H. Yoon, T.S. Kim, Characterization of resonant behavior and sensitivity using micromachined PZT cantilever. Integr. Ferroelectr. **50**, 43–52 (2002)