

QUALITY FACTOR OF PZT THIN FILM TRANSDUCED MICRO CANTILEVERS

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ABSTRACT

In this paper, quality factor (Q-factor) of piezoelectric $\text{Pb}(\text{Zr},\text{Ti})\text{O}_3$ (PZT) thin film transduced micro cantilevers were investigated under atmospheric pressure. The mechanisms for energy loss during cantilever vibration were analyzed and discussed. It was found that Q-factor increases with the increase of PZT thickness while keeping other cantilever geometries unchanged. Shorter cantilever, especially when cantilever length to width ratio less than 2, results in preferred larger Q-factor, which can be as high as 450 when using $1.04\mu\text{m}$ -thick PZT film as the electromechanical conversion medium. Moreover, our results indicate that dielectric loss in PZT film and thermoelectric loss are significant as well as air damping even when PZT cantilever was actuated at atmospheric conditions.

Keywords: quality factor, PZT film, micro cantilever, micro resonator, MEMS

To achieve ultra-high resonator sensitivity, high quality factor (Q-factor) is most desirable in resonator design and fabrication. However, up to date, Q-factor of piezoelectrically transduced micro resonator is still lower than that of conventional capacitive type even under atmospheric pressure [7][8], where air damping is believed much larger than other energy dissipation mechanisms. It limits its application on occasions when both ultra-high sensitivity and atmospheric environment are required, such as chemical vapor/molecule detection [4] and living cells observation [9].

In this paper, in order to better understand the energy dissipation mechanisms in piezoelectrically transduced micro resonators at atmospheric conditions, which is believed more complex due to electromechanical coupling in piezoelectric thin film and multi-layered device structure, $\text{Pb}(\text{Ti}, \text{Zr})\text{O}_3$ (PZT) thin film transduced micro cantilevers with different PZT thicknesses and cantilever geometry were fabricated. Then their Q-factors under atmospheric pressure were investigated and compared. Here, (100) oriented PZT thin film was chosen as the electromechanical conversion medium due to its excellent mechanical and piezoelectric properties. Furthermore, the affections of cantilever structure as well as PZT film on performance of PZT cantilever were analyzed and discussed.

1. INTRODUCTION

Piezoelectrically transduced micro resonators have become an attractive research topic in recent years since it has potential applications in ultra-small mass detectors, bio-sensors, RF filters and high frequency micro oscillators [1]~[5]. Compared with electrostatically actuated and sensed capacitive silicon micro resonator [6][7], piezoelectrically transduced micro resonator exhibits better impedance matching with electronics so that sub-100nm gap spacing can be avoided in device fabrication. Piezoelectrically transduced micro resonator also provides better power handing capability than capacitive type since low driving-voltage of several hundreds of millivolts is enough for resonator actuation [4], which facilitates the integration of micro resonators with CMOS signal processing circuits.

2. EXPERIMENTS

Fig.1 shows the structure of our PZT thin film transduced micro cantilever. It is composed of SiO_2 structure layer, Platinum(Pt)/Titanium(Ti) bottom electrode (Ti was used as adhesion layer between SiO_2 and Pt), PZT thin film, Ti/Pt/Ti top electrode and SiO_2 electric passivation layer. The fabrication process starts from thermal oxidized silicon wafer. The thickness of SiO_2 is $2.3\mu\text{m}$. Fig.2 shows the detailed process flow. First, 200nm/50nm-thick Pt/Ti film was sputtered on thermal oxidized silicon wafer as bottom electrode,

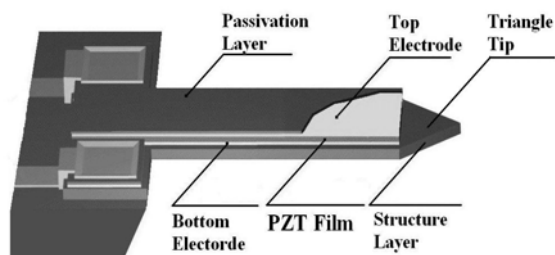


Fig.1 Structure of our piezoelectric PZT thin film transduced micro cantilever.

strongly (100) oriented PZT thin film with different film thickness (390nm, 650nm and 1.04 μ m) was deposited by sol-gel method on Pt/Ti/SiO₂/Si substrate as described in literature [10], another 200nm/50nm-thick Pt/Ti film was sputtered on PZT film as top electrode (Fig.2 (a)); Then, Pt/Ti electrode layer and PZT thin film were patterned by Electron Cyclotron Resonance (ECR) etching and wet-chemical etching, respectively (Fig.2 (b)); After that, 200nm-thick SiO₂ passivation layer was deposited by sputtering (Fig.2 (c)); Reactive Ion Etching (RIE) was used to define electric contact hole and cantilever geometry (Fig.2 (d)); Then, 200nm/50nm-thick Ti/Pt/Ti layer was deposited again by sputtering and

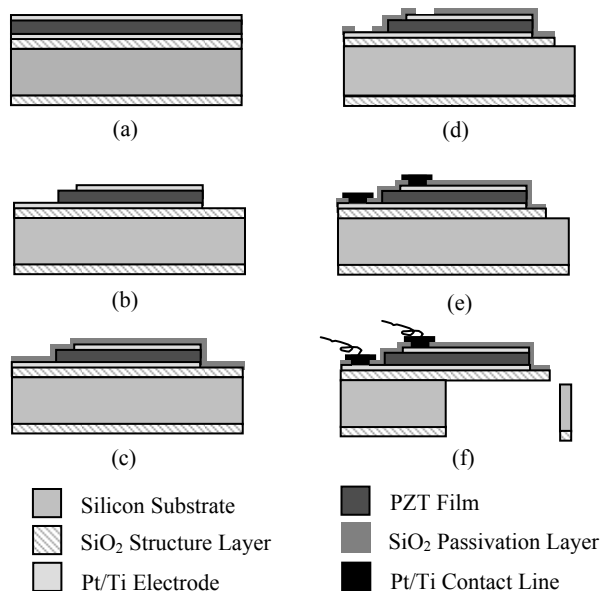


Fig.2 PZT cantilever fabrication process: (a) Pt/Ti bottom electrode layer, PZT film and Pt/Ti top electrode layer deposition; (b) PZT film and top/bottom electrode layer patterning; (c) SiO₂ passivation layer deposition; (d) electrode contact hole and cantilever shape patterning; (e) electric contact line deposition and patterning; and (f) cantilever release.

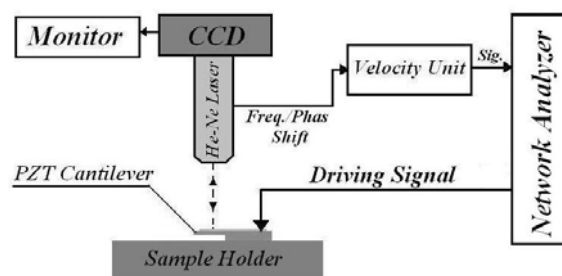


Fig.3 Schematic drawing of our PZT thin film transduced micro cantilevers' Q-factor measurement system.

patterned by ECR to form electric contact line (Fig.2(e)); Finally, the cantilever was released by Deep RIE as shown in Fig.2(f). The length of the cantilever L was 150 μ m, 200 μ m and 250 μ m, while maintain the width of the cantilever w at 90 μ m.

In this study, Q-factor of the PZT cantilever was defined as the ratio of cantilever resonant frequency $f_{\text{resonance}}$ to bandwidth at -3dB power $\Delta f_{-3\text{dB}}$:

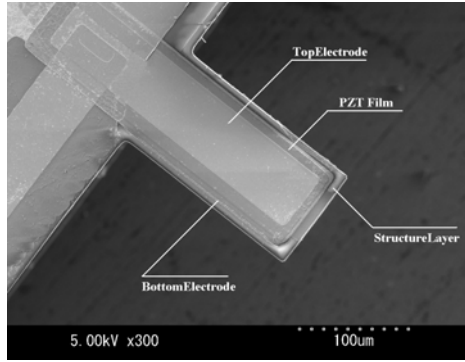
$$Q = \frac{f_{\text{resonance}}}{\Delta f_{-3\text{dB}}} \quad \text{Eq.1}$$

Although PZT cantilever has self-sensing function as well as self-actuation, Q-factor of the cantilevers were detected by a Laser Doppler Vibrometer (LT7901, GRAPHTEC Co.) then analyzed by a Network Analyzer (HP4395A, Agilent Technologies Inc.) to avoid extra noise from following PZT induced current detection circuits and make the measured results comparable. Fig.3 shows the schematic drawing of our Q-factor measurement system.

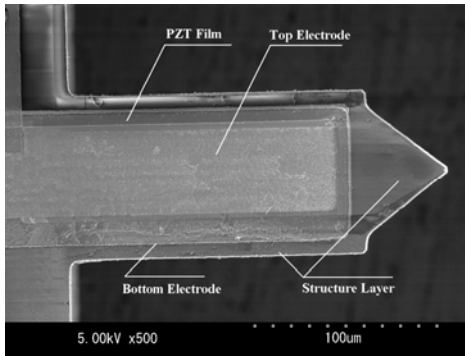
3. RESULTS AND DISSCUSSION

In this study, two kinds of PZT cantilevers were fabricated, which marked as A (without triangle tip) and B (with 50 μ m-long triangle tip), respectively. Fig.4 shows the SEM images of the fabricated PZT cantilever. Type A is commonly used for the application of molecule sensing while type B is often used for micro probe structures. The measured resonance-peak of the 150 μ m-long B-type cantilever when actuated by integrated 390nm-thick PZT film was shown in Fig.5.

In order to investigate the Q-factor dependence on cantilever geometry as well as PZT thickness, measured Q-factors of these cantilevers were summarized in Fig.6. Obviously, cantilever exhibits preferred larger Q-factor when actuated by thicker PZT film, which increases almost 2 times when PZT thickness varies from 390nm to 1.04 μ m. Besides, shorter cantilever without triangle tip results in larger Q-factor, especially when cantilever



(a)



(b)

Fig.4 SEM images of the fabricated PZT cantilever (a) Type A: without triangle tip and (b) Type B: with 50 μ m-long triangle tip.

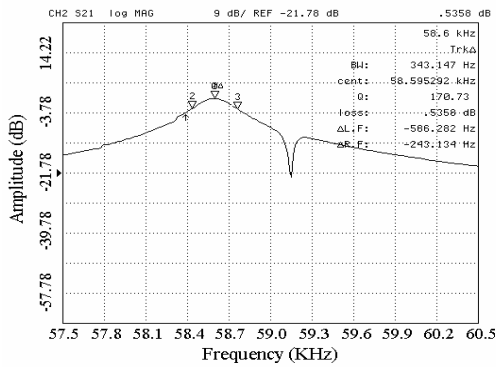


Fig.5 Measured resonance-peak of the 150 μ m-long B-type cantilever when actuated by integrated 390nm-thick PZT film.

length to width ratio $L/w < 2$. At the shortest length (cantilever-150A), Q-factor was found as high as 450 when using 1.04 μ m-thick PZT film as the electromechanical conversion medium. It is coincide with the theoretical analysis on single-layered silicon cantilever by F.R.Blom et al. [11], which concluded that thick and short cantilever seems to be more appropriate to obtain a large Q-factor.

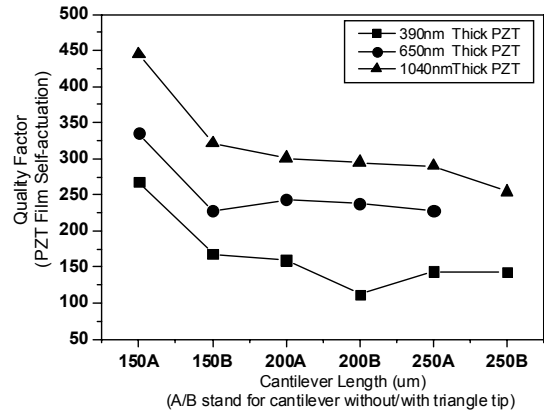


Fig.6 Measured Q-factors of the PZT thin film transduced micro cantilevers with different PZT thicknesses and cantilever geometries when self-actuated under atmospheric pressure.

Since the measurement was performed under atmospheric pressure, air damping is believed essential to energy consumption than other mechanisms [11], such as thermoelastic loss [12], support loss [13] and surface loss [14]. Accordingly, Q-factor of the PZT cantilever will be proportional to its peak kinetic energy E_{peak} during vibration, which can be expressed as follows:

$$E_{peak} = \frac{1}{2} K_r A^2 \quad \text{Eq.2}$$

where A is the vibration amplitude and K_r is elastic constant of the cantilever. For multi-layered cantilever, K_r is determined by:

$$K_r = \frac{3}{L^3} \sum_{i=1}^n Y_i w_i t_i \left\{ \frac{t_i^2}{12} + [Z_{nt} - (\sum_{j=1}^i t_j - \frac{t_i}{2})]^2 \right\} \quad \text{Eq.3}$$

where Y_i is Young's modulus of layer i ; t_i is thickness of layer i ; w_i is width of layer i and Z_{nt} is the distance from zero-stress interface in PZT cantilever to its top surface, which can be calculated from equation $Z_{nt} = \frac{\sum_{i=1}^n Y_i t_i [\sum_{j=1}^i t_j - \frac{t_i}{2}]}{\sum_{i=1}^n Y_i t_i}$. Therefore, thicker PZT film and shorter cantilever length will contribute to larger cantilever Q-factor through improving cantilever elastic constant K_r . It is believed one of the major reasons for Q-factor dependence at atmospheric conditions as shown in Fig.6.

Besides, we found by wafer-bending stress measurement method that residual stress in PZT film

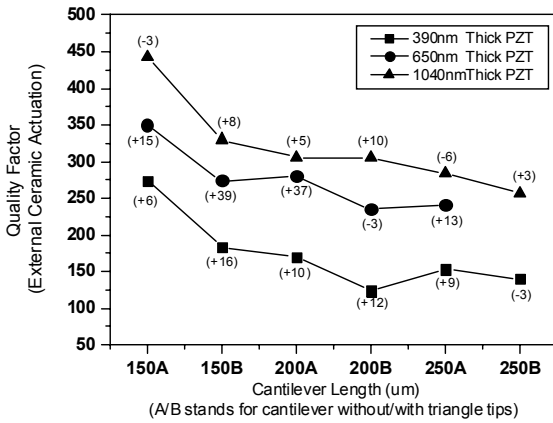


Fig.7 Measured Q-factors of PZT film transduced micro cantilevers under atmospheric pressure when actuated by external vibrator. The bracketed number indicates the differential value to the results when actuated by integrated PZT thin film.

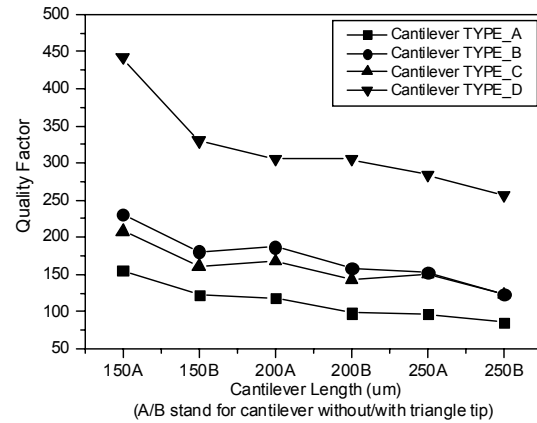


Fig.8 Measured Q-factors of the fabricated cantilevers which composed of different layer: TYPE_A: SiO₂ cantilever; TYPE_B: SiO₂+Pt/Ti cantilever; TYPE_C: SiO₂+Pt/Ti+PZT (1.04μm-thick) cantilever; TYPE_D: complete layered PZT (1.04μm-thick) cantilever as shown in Fig.4.

decreases notably when the film thickness increases from 390nm to 1.04μm. It gives us another possible reason on PZT thickness dependent as shown in Fig.6. Further experiments are under consideration to prove this analysis.

Other than air damping, dielectric loss in PZT thin film is another important energy dissipation mechanism for PZT transduced micro cantilevers. According to Don L.DeVoe's study, transfer function of PZT transduced resonator can be expressed as follows [2]:

$$Y_{21} = j\omega\gamma_1 \frac{Z(j\omega)}{F(j\omega)} \gamma_2 \quad \text{Eq.4}$$

where γ_1 stands for the electromechanical conversion from driving signal to PZT induced mechanical force F for actuation; γ_2 stands for the electromechanical conversion from cantilever deformation Z to PZT induced piezoelectric current output for sensation; and $Z(j\omega)/F(j\omega)$ describes the transfer of mechanical force F to cantilever deformation Z . In order to investigate the affections of dielectric loss in PZT thin film during electromechanical conversion, the fabricated cantilevers were actuated by an external vibrator and the measured Q-factors under atmospheric pressure were shown in Fig.7. Similar Q-factor dependence on PZT thickness as well as cantilever geometries can be found in the curve, whereas, the differential value in bracket indicates that Q-factor of the cantilever increases a few percent when actuated by external vibrator. When cantilever was actuated by integrated PZT thin film, electromechanical conversion of both γ_1 for actuation and γ_2 for sensation

will be involved, while actuated by external vibrator, only γ_2 for sensation will exist. This difference in measured Q-factor reveals that dielectric loss in PZT thin film during electromechanical conversion from driving signal to cantilever deformation is noticeable even under atmospheric conditions.

Moreover, it seems that differential value in the brackets as shown in Fig.7 decreases with the increase of PZT thickness. Characterization on PZT film's electric properties, piezoelectric properties and microstructures at different film thickness may give us reasonable explanation, while it's still under going.

For multi-layered piezoelectric transduced resonators, thermoelastic damping can be quite significant because internal friction seems easier to happen near interfaces of each layer as well as within crystallographic defects [12][15]. Fig.8 shows the measured Q-factor of the fabricated cantilever with different layer structures. Similar Q-factor dependence as shown in Fig.6 can be found in SiO₂ cantilever (TYPE_A) and SiO₂+Pt/Ti cantilever (TYPE_B), while after 1.04μm-thick PZT film deposition, Q-factor of the SiO₂+Pt/Ti+PZT cantilever (TYPE_C) decreases even the thickness of the cantilever increases from 2.5μm to 3.5μm. These differences in the Q-factor can be explained by including the contributions of thermoelastic damping especially in polycrystalline PZT ceramic thin films. After covered by Pt/Ti top electrode and SiO₂ electric passivation layer, Q-factor of the PZT cantilever (TYPE_D) increases again due to improved cantilever elastic constant K_r , which includes both Young's modulus and thickness as shown in Eq.3.

Recent advances in sensor technology suggests sensor

array to provide more useful and reliable information by multiplicity responses from individual element [16]. Piezoelectrically transduced micro resonator is one of the most promising candidates for array application due to its ability to serve as both actuator and sensor. This paper gives us a preliminary impression on energy dissipation mechanisms in piezoelectric PZT thin film transduced micro cantilevers. Further study, especially in reduced pressure to find the intrinsic Q-factor of the PZT cantilever, is keeps going to describe the principle more precisely. Moreover, as described in literature [11], cantilever thickness and width should be chosen as small as possible to obtain a large critical pressure P_c . In that case, Q-factor reaches a pressure-independent value in viscous region. How to optimize the device design is still challenging and needs our further efforts.

4. CONCLUSIONS

In this paper, piezoelectric PZT thin film transduced micro cantilevers with different cantilever geometries and PZT thicknesses were fabricated to investigate its energy dissipation mechanisms at atmospheric conditions. It was found that Q-factors of the cantilever can be increased by increasing the thickness of the PZT thin film. Besides, dielectric loss in PZT thin film as well as thermoelastic loss is quite significant even when PZT cantilever was actuated at atmospheric pressure. These results will help us better understand the energy dissipation mechanism in piezoelectrically transduced micro resonators, and then facilitates its design.

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