Resonance-mode effect on piezoelectric microcantilever performance in air, with a focus on the torsional modes

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A high quality factor is preferred for a microresonator sensor to improve the sensitivity and resolution. In this paper we systematically investigate the performance of the microcantilever in different resonance modes, which are the first three flexural modes, the first lateral mode, and the first and the second torsional modes. An aluminum nitride-based piezoelectric cantilever is fabricated and tested under controlled pressure from an ultra-high vacuum to a normal atmosphere, using a custom-built vacuum chamber. From the experiment results, it can be seen that the torsional modes exhibit better quality factors than those of the flexural and lateral ones. Finally, an analytical model for the air damping characteristics of the torsional mode cantilever is derived and verified by comparing with experimental results.

Keywords: microcantilever, aluminum nitride, torsional mode, quality factor

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1. Introduction

Micromechanical resonators have been recently developed as sensor platforms for detecting small mass and force due to their tiny structures,[1] among which micropiezoelectric cantilevers have been attracting intensive attention as their advantages in low-cost fabrication and ultrahigh sensitivity.[2] Piezoelectric cantilevers are more attractive than other types, such as electrostatic,[3] electromagnetic[4] or optical-associated[5] resonators, as their self-exciting and self-sensing capability, low driven voltage and fully integration. To be compatible with complementary metal–oxide–semiconductor (CMOS) circuits as well as other microelectromechanical systems (MEMS) components, aluminum nitride (AlN) was selected as the active piezoelectric layer. Furthermore, both high piezoelectric coefficients and low intrinsic stress of the AlN film can be obtained by controlling the deposition parameters.[6]

The sensing resolution of the cantilever can be improved by enhancing the quality (Q) factor value, which is defined as the ratio of stored energy to dissipated energy. In general, a high Q factor results in a sharper resonance peak and leads to a better detectable resolution. The dissipated energy Q^{-1} for a cantilever resonator consists of internal energy loss and external loss. The internal loss is mainly related to internal friction in the structure Q_{TED}^{-1} (often referred to as thermal elastic damping (TED)) and that between each layer interface regions $Q_{\mathrm{in.f.}}^{-1}$, and the support loss at the anchor of the cantilever Q_{sup}^{-1}, while the external loss Q_{air}^{-1} is correlated to the radiation damping that depends on the coupling with the surrounding medium. For a cantilever operating in normal atmosphere, the external energy loss (air damping) is the main energy loss source instead of the internal energy loss.[7,8] In order to minimize the air damping, Blom *et al.*[9] and Naeli and Brand[10] investigated the dependence of Q factor on the cantilever geometry, while Xia and Li,[8] Lu *et al.*[11] and Dohn *et al.*[12] discussed different resonance-mode effects on the cantilever performance. Besides, Blom *et al.*[9] pointed out that the Q factor of the resonator in a higher order flexural mode is always superior to that in a lower one. Most of the previous researches[9–12] have focused on the air damping effect of flexural mode resonators on Q factor. In this paper the performances of microcantilevers in different orders of flexural, lateral (also known as in-plane), and torsional modes are systematically evaluated and compared.

In this paper we investigate the air damping effects of the micromechanical cantilevers in different resonance modes on the Q factor. Several typical modes of an AlN-based cantilever are measured under pressure controlled atmospheres. In our experiments, the torsional modes show better performances than the flexural or lateral modes, and the second torsional mode exhibits the highest Q factor. An analytical model is also developed to study the air damping characteristics in the torsional modes of the cantilever.

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2. Experiment

2.1. Device description

The microcantilever used in this work is shown in Fig. 1. The cantilever was fabricated using a low resistivity (less than 0.1 Ω·cm) p-type single crystal silicon (SCS) wafer. The SCS also served as the bottom electrode for the piezoelectric layer. The bottom silicon nitride (Si_xN_y) layer was used as a hard mask for etching the SCS substrate to a residual thickness of about 20 μm in the areas where the suspended cantilever would be placed. Then a 1-μm thick AlN film and a 300-nm thick gold (Au) film were deposited and etched to form a sandwiched piezo-electrode stack together with the SCS bottom electrode. Finally the resonant beam was released by the back side wet etching and front side dry etching process (cf. Fig. 2). The elimination of the bottom metal electrodes reduces the number of stacked layers and the stress in the cantilever, simplifying the fabrication process and suppressing the internal energy loss in the structure. The nominal dimensions of the cantilever are 2000 μm in length and 400 μm in width.

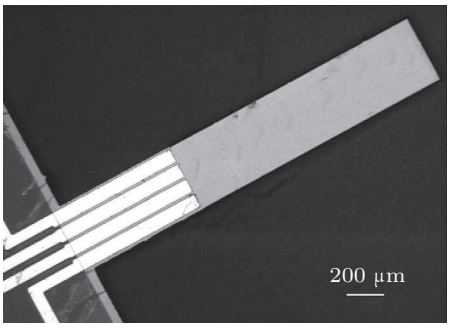


Fig. 1. Micrograph of the fabricated AlN-based piezoelectric cantilever.

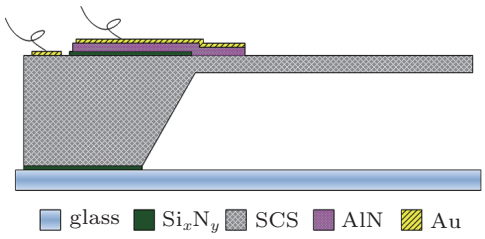


Fig. 2. (color online) Schematic cross section of the cantilever.

2.2. Measurement setup

The fabricated cantilever was tested under pressure controlled atmospheres from an ultrahigh vacuum (UHV) to a normal atmosphere, using a custom-built vacuum chamber. As reported in Ref. [13], the electrical crosstalk in the resonator makes the mechanical resonance less pronounced. Weak output from the AlN film requires a high precision pre-amplifier for detecting the resonance. An electrical compensation and readout circuit has been developed based on the method proposed in Ref. [14]. The experimental setup consists of the signal-readout circuit, placed in the vacuum chamber, and an HP4395A network analyzer as shown schematically in Fig. 3.

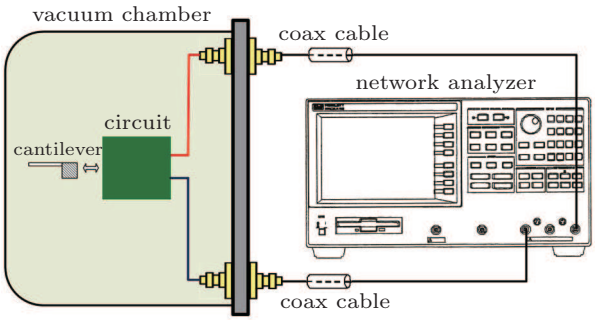


Fig. 3. (color online) Schematic plot of the measurement setup.

3. Quality factors of different modes

The first six resonance modes of the cantilever have been measured and characterized, which are the first, second, and third flexural modes, the first lateral mode, and the first and second torsional modes. Finite element analysis software COMSOL was used to assign the resonant modes to the observed peaks. A comparison between simulated and experimentally observed peaks is shown in Table 1. Figure 4 shows the resonance frequency response of the cantilever in normal atmosphere, the resonance mode shapes inserted in the figure were obtained by COMSOL software, depicting the displacement of the cantilever for each mode.

The Q factors of different modes were characterized under different pressures varying from 2×10^{-4} mbar to 1 bar (1 bar = 10^5 Pa). When the ambient pressure was even lower, no differences in the resonator output could be observed. The Q factors from the measurements are summarized in Fig. 5, from which one can find that the mode shape has a big effect on the performance of the resonator, and the torsional modes exhibit better Q factors.

Table 1. Comparison between experimentally observed resonance frequencies f_e and COMSOL simulated frequencies f_s.

Mode	1st flexural	2nd flexural	1st torsional	1st lateral	3rd flexural	2nd torsional
f_e/kHz	7.0	41.1	73.6	95.5	112.6	212.7
f_s/kHz	6.6	41.5	74.1	110.3	116.3	219.6
Error	5.71%	0.97%	0.68%	15.50%	3.29%	3.24%

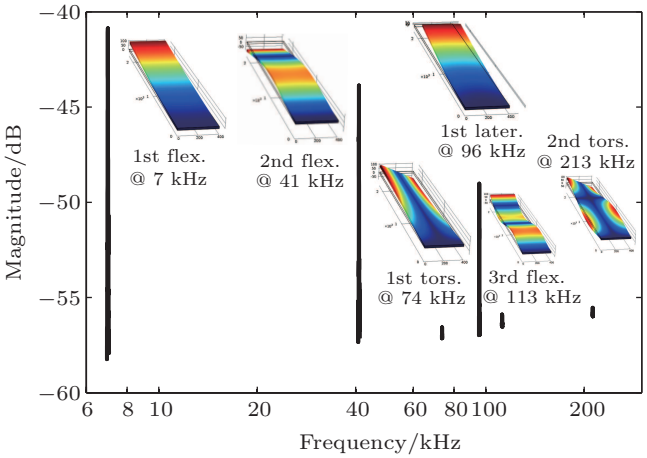


Fig. 4. (color online) Amplitude spectrum and mode shapes of the cantilever at normal atmosphere.

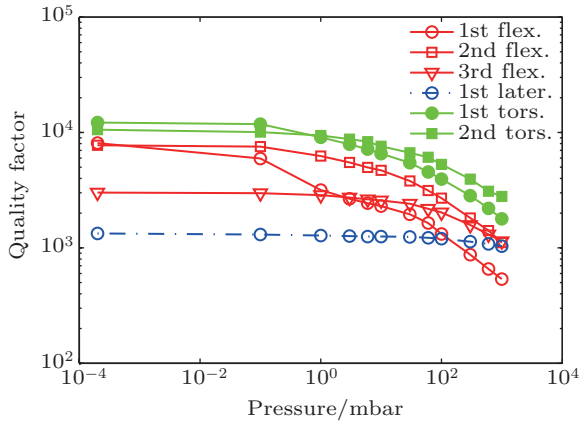


Fig. 5. (color online) Variations of Q factor with ambient pressure for different modes.

The values we obtained for quality factor Q_{air} due to air damping at atmosphere were 574, 1296, 1839 for the first, second, and third flexural modes respectively. These results show a general trend that Q_{air} is enhanced as the order of the flexural mode increases. However, the total Q factors do not follow that trend, since the internal energy loss in the 3rd flexural mode is much higher than those in the 1st and 2nd modes. For the 3rd flexural mode, the TED loss was found to play an important role in the internal losses. According to Ref. [15], the quality factor of a flexural vibrating cantilever limited by TED loss can be expressed as

$$Q_{\text{TED}} = \frac{\rho_{\text{b}} C_{\text{p}}}{\alpha_{\text{T}}^2 T E} \frac{f^2 + F_0^2}{f F_0}, \tag{1}$$

where ρ_{b}, C_{p}, α_{T}, and E are the density, heat capacity at constant pressure, linear thermal expansion, and elasticity modulus of the cantilever material, respectively; f is the cantilever resonance frequency; F_0 is the critical damping frequency, defined as $F_0 = \pi\kappa/2\rho_{\text{b}} C_{\text{p}} h^2$, with κ being the material thermal conductivity and h the cantilever thickness. Q_{TED} has a minimum at $f = F_0$, where the heat energy generated from the material internal friction dissipates completely. For the cantilever in this case, the critical frequency is calculated to be 235 kHz, the resonance frequency of the 3rd flexural mode is closer than those of other flexural modes, and the TED energy loss is much higher than the others.

The air damping energy loss in the lateral mode is expected to be lower, since the beam was shearing rather than compressing the air. However, the internal energy loss was found to be even heavier than that due to the air damping, leading to a low Q factor. It is mainly due to the larger support loss compared to other modes. The quality factor Q_{sup} is estimated to be[16]

$$Q_{\text{sup}} = k\,(L/H)^3\,, \tag{2}$$

where k is a coefficient ranging from 2.17 to near 0, L is the length of the cantilever, and H is the thickness of the vibration, here H is the width of the cantilever W.

The torsional modes exhibit the better Q factors than the other types of modes. This phenomenon is found to be inconsistent with that found in other literature.[8,17] Unlike the bending strain under flexural or lateral motion, in the silicon membrane and the top piezo-electrode stack strips, the generated shear strain under the torsional motion is immune to volume tension or compression. This can effectively suppress volume-change-induced energy dissipation, thereby contributing to lower internal mechanical damping.[18] In this resonator configuration, the reduced energy loss due to the piezoelectrode stack is assumed to be less than that due to the silicon membrane, since the stack is much thinner than the membrane. Moreover, the turning-fork-like antiphase movement between the double sides of the torsional cantilever is expected to feature a high quality factor in an air environment. Therefore, it is necessary to investigate the air damping effect of the torsional mode resonator to achieve better resonance behavior.

4. Air damping analysis of the cantilever in the torsional modes

The air can be considered to be incompressible because the wavelength of sound is much longer than the cantilever width. The velocity field $\boldsymbol{u}$ of the air is governed by the Navier–Stokes equation and the continuity equation for incompressible fluids[19]

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \text{grad})\,\boldsymbol{u} = -\frac{1}{\rho_{\text{a}}} \text{grad}\, P + \frac{\mu}{\rho_{\text{a}}} \Delta \boldsymbol{u}, \tag{3}$$

$$\text{div}\, \boldsymbol{u} = 0, \tag{4}$$

where μ, ρ_{a}, and P are the air effective viscosity coefficient, density, and pressure, respectively. The effective viscosity μ is used instead of the air dynamic viscosity μ_{a}, to extend the model to rarefied air. This concept is reasonable when the surrounding pressure range is in the viscous regime, which means the air pressure is not very low so that the air can still be considered as a continuum, i.e., when the Knudsen number K_{n} (defined as the ratio of the mean free path of the air

molecules to the width of the cantilever), is smaller than 0.1. Burgdorfer[20] obtained a simple form for the effective viscosity coefficient

$$\mu = \frac{\mu_a}{1+6K_n}. \tag{5}$$

Equations (3) and (4) cannot be solved in a closed form for the beam-shaped cantilever. However, Landau and Lifshitz[19] calculated the air drag force $\boldsymbol{F}$ for an oscillatory motion sphere with radius R straightforwardly from these equations, and the drag force is expressed as

$$\boldsymbol{F} = 6\pi\mu R\left(1+\frac{R}{\delta}\right)\boldsymbol{u} + 3\pi R^2\sqrt{\frac{2\mu\rho_a}{\omega}}\left(1+\frac{2R}{9\delta}\right)\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t}, \tag{6}$$

where ω is the angular vibrating velocity and δ is the boundary layer thickness, defined as $\delta = \sqrt{2\mu/(\rho_a\omega)}$. The air load effect can be characterized from the drag force $\boldsymbol{F}$, with a damping coefficient

$$c = 6\pi\mu R\left(1+\frac{R}{\delta}\right), \tag{7}$$

derived from the real part of $\boldsymbol{F}$, and the spring constant

$$k = -3\pi R^2\omega\sqrt{2\mu\rho_a\omega}\left(1+\frac{2R}{9\delta}\right), \tag{8}$$

obtained from the imaginary part of $\boldsymbol{F}$.

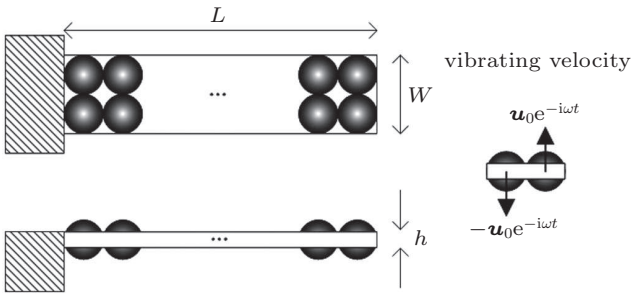


Fig. 6. Sphere-string model for analyzing the torsional mode air damping of the cantilever beam.

Based on the motion of a single sphere, Hosaka *et al.*[21] obtained the analytical air damping for the flexural mode beam-shaped resonator, by simplifying the beam into a string of coherently resonating spheres. For the torsional vibrating case, it is more appropriate to model the beam by a string of flat dishes[8] or two parallel strings of spheres. The first proposal was based on the calculation of the air drag force acting on a single dish, where the force was simplified into the real part of that on a sphere with the same radius, and then the air damping can be derived from the moment of force of the torsional vibrating dishes. This paper presents another approach to solve the problem using the second proposal, by assuming the beam to be comprised of two strings of opposite-vibrating spheres as shown in Fig. 6. Herein the damping coefficient of the torsional cantilever is calculated from the drag force on each single sphere, and can be expressed as

$$c_{air} = 6\pi\mu L\left(1+\frac{W}{4}\sqrt{\frac{\rho_a\omega}{2\mu}}\right). \tag{9}$$

Finally the quality factor associated with the air damping Q_{air} is calculated from

$$Q_{air} = \frac{Wh\rho_b\omega}{6\pi\mu\left(1+\frac{W}{4}\sqrt{\frac{\rho_a\omega}{2\mu}}\right)}. \tag{10}$$

The parameters used in this model are listed in Table 2. Figure 7 shows the measured and calculated Q factors of the two torsional modes resonances, each as a function of ambient pressure. The calculations were derived based on the drag force on individual moving spheres, and on the premise that the surrounding air pressure was in the viscous regime, it can be seen that the rough calculations show fairly good agreement with the measurement results.

Table 2. Parameters of the beam material (SCS) and air.

		Symbol	Unit	Value
	Temperature	T	K	300
Beam	Density	ρ_b	kg/m^3	2330
	Width	W	m	4×10^{-4}
	Thickness	h	m	2.3×10^{-5}
Air	Pressure	P	Pa	$10^2 \sim 10^5$
	Gas const.	R_c	$J/(\mathrm{mol\cdot K})$	8.314510
	Boltzmann constant	K_b	J/K	1.38×10^{-23}
	Molecule diameter	d_0	m	3.2×10^{-10}
	Molar mass	M	kg	2.896×10^{-2}
	Mean free path	λ	m	$K_bT/\left(\sqrt{2}\pi d_0^2 P\right)$
	Knudsen number	K_n		λgW
	Density	ρ_a	kg/m^3	$MP/(R_cT)$
	Viscosity	μ_a	Pa·s	$\rho_a\lambda\sqrt{R_cT/(3M)}$
	Effec. viscosity	μ	Pa·s	$\mu_a/(1+6K_n)$

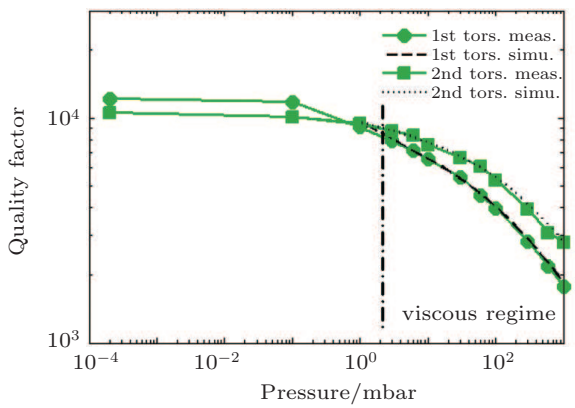


Fig. 7. (color online) Simulated and measured quality factors versus pressure for the torsional modes of the cantilever.

5. Conclusions

A piezoelectric cantilever employing AlN as an active film is fabricated and tested in a custom-built vacuum chamber under pressures ranging from 2×10^{-4} mbar to a normal atmosphere. The effects of different resonance modes on the cantilever performance in air are systematically measured and analyzed. An analytical model for the air damping effect on the torsional mode is derived and the obtained results agree well with the measurements. From both analytical results and the test data, it follows that the torsional modes of the cantilever are generally better than those of the flexural and lateral ones, and the second torsional mode exhibits the highest Q factor.

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