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Tuning the quality factor of bulk micromachined structures using squeezed-film damping

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Abstract This report demonstrates the tuning the quality factor of a micromachined structure using the air damping of a small squeezed-film area (300 μm^2 to 800 μm^2). Two micromachining processes have successfully been established to fabricate novel stationary structures using thin films and bulk silicon, in which the stationary structure and a vibrating micromachined cantilever form a squeezed-film region. Measurements showed that, under the assistant of bulk silicon stationary structure, the quality factor of the vibrating beam decreased by 48% when the squeezed-film area was increased from 300 μm^2 to 800 μm^2 under a 760-torr ambient pressure. Moreover, even when the ambient pressure was only 20 mtorr, the quality factor of the beam still decreased by 20% for the same increase in area. Under the assistant of thin film stationary structure, the quality factor of the vibrating beam decreased by 35% when the squeezed-film area was increased from 300 μm^2 to 500 μm^2 under a 760-torr ambient pressure. Consequently, the proposed two stationary structures can be exploited to significantly alter the quality factor of dynamic systems.

1
Introduction

The performance of many MEMS devices can be improved by tuning the quality factor of the dynamic system. For instance, a high quality factor can increase the scanning angle of a micromachined optical scanner [1], a high-quality-factor MEMS resonator has been exploited to increase the performance of an RF filter [2], and the sensitivity of a micromachined microphone improves by increasing the quality factor of the vibrating diaphragm [3]. On the other hand, the damping can be used to reduce the oscillation of an accelerometer at resonance [4], and damping is required to reduce the settling time of various types of sensor and actuator, such as an optical switch [5].

Electrostatic force has frequently been employed to tune the quality factor of MEMS devices [6]. However, this comes with a requirement for additional feedback-control circuitry. The dynamic characteristics of micromachined structures, such as resonant frequency and damping coefficient, are usually influenced by air. For instance, the air between a surface micromachined plate and the substrate will be squeezed by out-of-plane motion of the plate. This squeezed-film effect will introduce an equivalent damper and spring [7–9], and hence affects the resonant frequencies of the micromachined plate. The squeeze film effect is seldom occurred in the bulk micromachined structures. However, air may appear as an equivalent mass and damping in bulk micromachined structures, and hence influences their dynamic characteristics [10, 11].

The air damping of micromachined structures has been studied extensively, but most research has focused on the effects induced by the motion of large-area structures. In contrast, this study investigated the squeezed-film effects in small-area structures by measuring the quality factor of a vibrating cantilever. Moreover, this study attempted to employ the squeezed-film effect to tune the quality factor of bulk micromachined structures. To this end, two novel stationary structures were devised and realized to produce the squeezed-film effect in bulk micromachined structures. To enhance the possibility of integrating various micromachined devices, the study has successfully established the surface and bulk micromachining processes for stationary structures.

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Design and analysis

The two micromachined structures illustrated in Fig. 1 were used to tune the quality factor of dynamic systems. In Fig. 1a, a bulk stationary structure made out of silicon substrate is used to introduce the squeezed-film effect in a vibrating beam. This effect is caused by variations in the air-gap thickness h inside the squeezed-film region during the vibration of the cantilever. The area of the squeezed-film region ($A = W \times L_d$) is determined by the width W of the cantilever and the length L_d of the stationary structure. The air gap is determined by the thickness h of a sacrificial thin film. Similarly, the surface micromachined stationary structure in Fig. 1b is also employed to form a squeezed-air region associated with a vibrating beam. The quality

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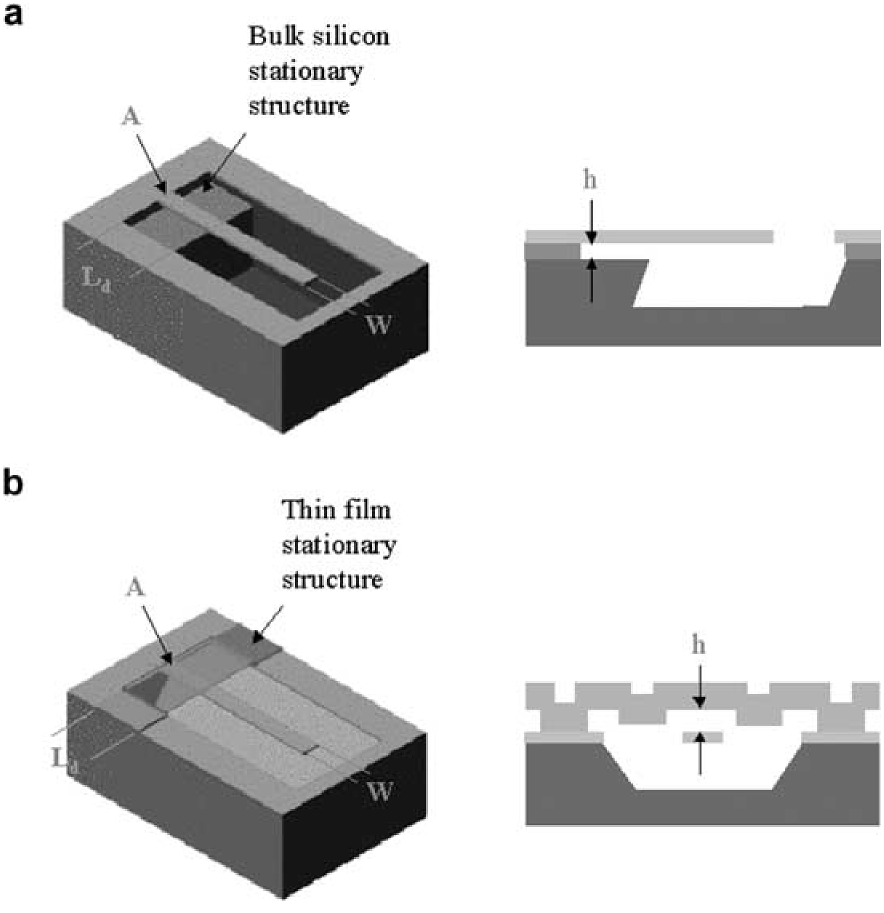

Fig. 1. Two micromachined stationary structures: **a** bulk silicon stationary structure, and **b** thin-film stationary structure

factor of the vibrating structure can be tuned by varying the dimensions of the stationary structures and the thickness of the sacrificial thin film.

This study employs the simplified model in Fig. 2 to predict the quality factor of the proposed design [12].

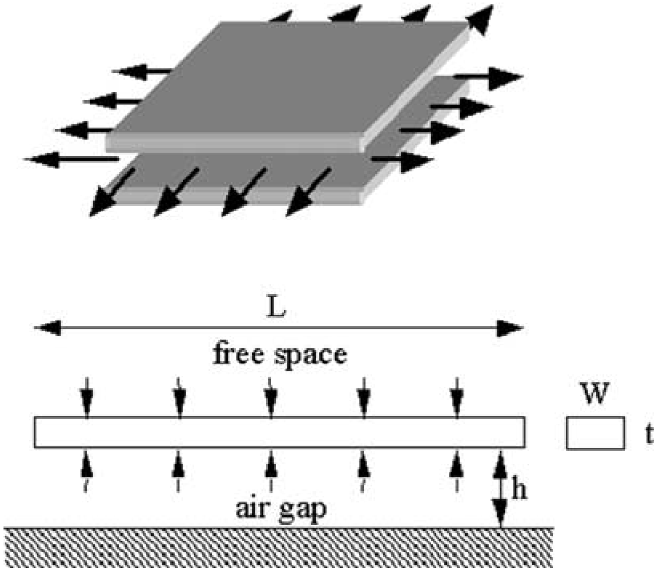

Fig. 2. A simplified squeezed-film model. The model shows a rigid plate with length *L*, width *W*, and thickness *t* vibrating above a stationary rigid surface, which will squeeze the air inside gap *h*

Fig. 2 shows a rigid plate of length L, width W, and thickness t vibrating above a stationary rigid surface. The air inside the gap of height h will be squeezed by vertical motion of the plate. If the vibration frequency of the plate is ω and the ambient pressure is P_a, the damping coefficient C due to the squeezed-film effect can be expressed as [13]

$$C = \frac{64\sigma P_a L W}{\pi^6 \varpi h} \sum_{\substack{m,n \\ \text{odd}}} \frac{m^2 + (n/\beta)^2}{(mn)^2\left\{\left[m^2 + (n/\beta)^2\right]^2 + \sigma^2/\pi^4\right\}} \tag{1}$$

where $\beta = L/W$ is the length per unit width for the beam (i.e., the aspect ratio of the squeezed-film region). The parameter σ in Eq. (1) is the squeeze number: $\sigma = (12\mu W^2\omega)/(P_a h^2)$, where μ is the viscosity of the air. In general, the damping effect of the squeezed air is greater for a smaller vibration frequency ω of the plate.

The movement of the air will change from viscous flow to free molecular flow at low ambient pressures [14]. According to [15], Eq. (1) can be applied to determine the damping coefficient C in different ambient pressures if the viscosity μ of the air is modified as μ_{eff}:

$$\mu_{\text{eff}} = \frac{\mu_0}{1 + 9.638 k_n^{1.159}} \tag{2}$$

where μ_0 is the viscosity at 1 atm. In addition, the dimensionless number $K_n = \lambda/h$ is the Knudsen number,

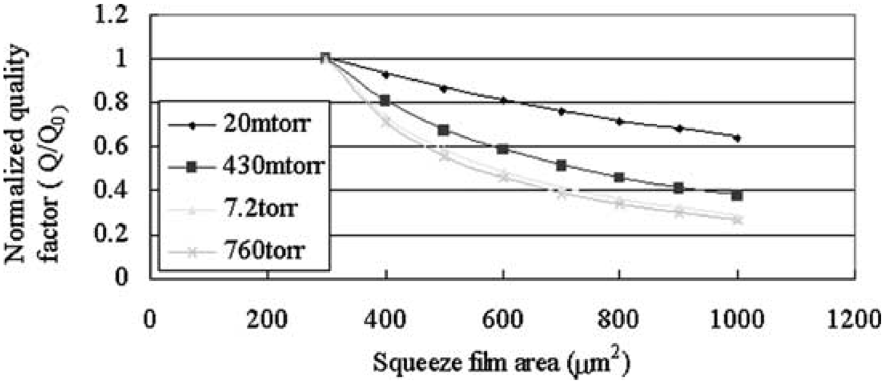

Fig. 3. Experimental results of the variation of the normalized quality factor (Q/Q_0) with the squeezed-film area when the ambient pressure (P_a) was at 760 torr, 7.2 torr, 430 mtorr, and 20 mtorr

where λ is the mean free path of the air. Apparently, the damping coefficient not only varies with the dimensions of the beam (L, W) and the air gap (h), but also with the ambient pressure P_a.

Using the above analytical model, the variation in the quality factor with the squeezed-film area for four different ambient pressures was studied. In the analysis, the viscosity of the air was $\mu = 1.8 \times 10^{-5}$ N · s/m^2, the air gap

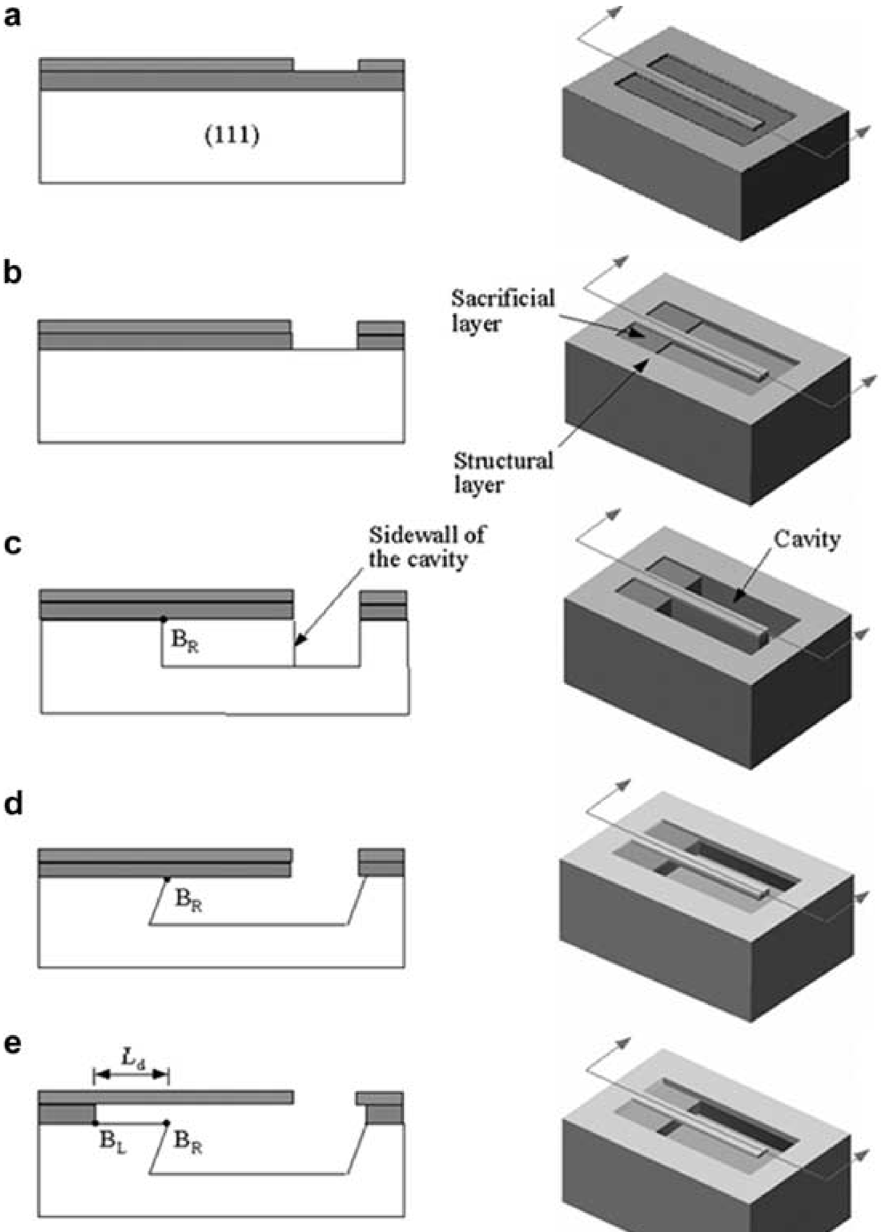

Fig. 4. The novel fabrication processes to realize the bulk silicon stationary structure. The positions B_R and B_L are determined by deep reactive ion etching and wet etching, respectively. The squeezed-film region between B_R and B_L has a length L_d

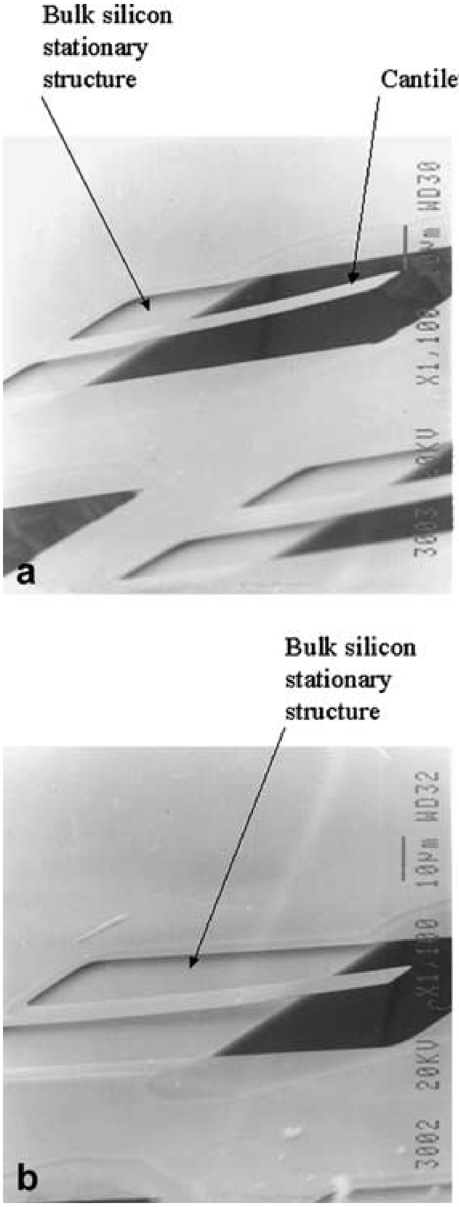

Fig. 5. Typical fabrication results of the bulk silicon stationary structure with two different values of L_d

was $h = 2\ \mu$m, the plate width was $W = 10\ \mu$m, and the plate length ranged from 30 μm to 100 μm (i.e., the area A ranged from 300 μm^2 to 1000 μm^2, and parameter β ranged from 3 to 10). Fig. 3 shows the variation of the quality factor with the squeeze film area A. In this figure, the quality factor Q was normalized to the quality factor Q_0 at $A = 300\ \mu$m^2. It shows that the quality factor decreases by 74% (from 3.4 at Q_0 to 0.9) and by 72% (from 125 at Q_0 to 35) as the squeezed-film area increased from 300 μm^2 to 1000 μm^2 when the ambient pressure is 760 torr and 7.2 torr, respectively. Moreover, it shows that the quality factor still changes by 36% (from 25200 to 16200) when P_a is only 20 mtorr. These results demonstrate that the quality factor of the structure can be significantly tuned by variations in the small squeezed-film area even under conditions of a very low ambient pressure.

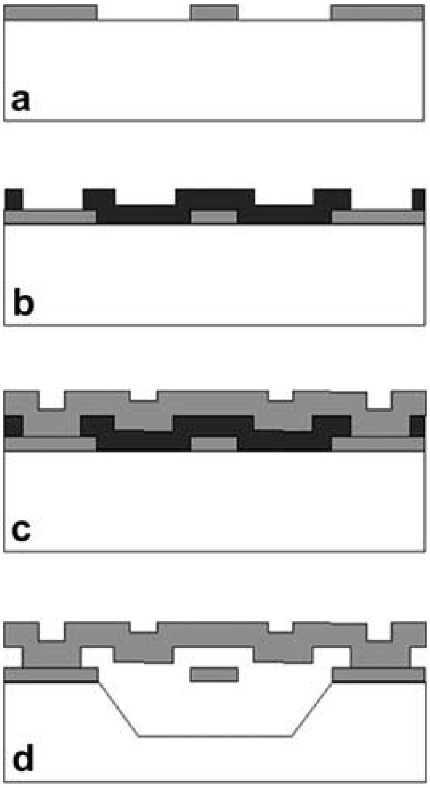

Fig. 6. The novel fabrication processes to realize the thin film stationary structure

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Experiment and results

In application of this technique, two micromachining processes have been developed to fabricate the bulk silicon and thin film stationary structures. The processes used to fabricate the bulk silicon stationary structure are shown in Fig. 4. Figure 4a shows that a sacrificial layer was first deposited on (111) silicon substrate. The air gap h was determined by the thickness of the sacrificial layer. A structure layer was deposited on the sacrificial layer and then patterned, as illustrated in Fig. 4b, after which the unprotected silicon substrate indicated in Fig. 4b was removed anisotropically by deep reactive-ion etching to produce a cavity (Fig. 4c). This process not only defined the position of point B_R but also enabled the subsequent wet chemical anisotropic etching on the (111) wafer that undercut the cantilever anisotropically from the sidewall of the cavity. This undercutting process fully removed the substrate under the cantilever, and was stopped by the (111) crystal planes of the substrate, as shown in Fig. 4d. Finally the sacrificial layer was etched isotropically to form the air gap. The position of point B_L in Fig. 4e was defined by carefully controlling the etching time; thus, length L_d of the air-squeezing region was determined. The SEM photographs in Fig. 5a, b show two typical fabrication results. The micrographs show micromachined cantilevers of two different lengths formed on top of bulk silicon stationary structures.

The processes involved in fabricating the thin film stationary structure are shown in Fig. 6. Figure 6a shows that a thin film was first deposited and patterned on a (100) silicon substrate, which defined the shape of the micromachined structure and the region of bulk silicon etching. After that, a typical surface micromachining processes was employed to fabricate the thin film stationary plate, as shown in Fig. 6b, c. The air gap h was determined by the thickness of the sacrificial layer, and the length L_d of the squeezed-film region was determined by the length of the thin film structure. Figure 6d shows that the movable structure was released after the sacrificial layer and the bulk silicon underneath were etched away. The SEM photograph in Fig. 7a shows a typical example of the fabricated micromachined cantilever under a thin film stationary structure. The air gap between the cantilever and the thin film stationary structure can be clearly seen in the higher-magnification micrograph in Fig. 7b.

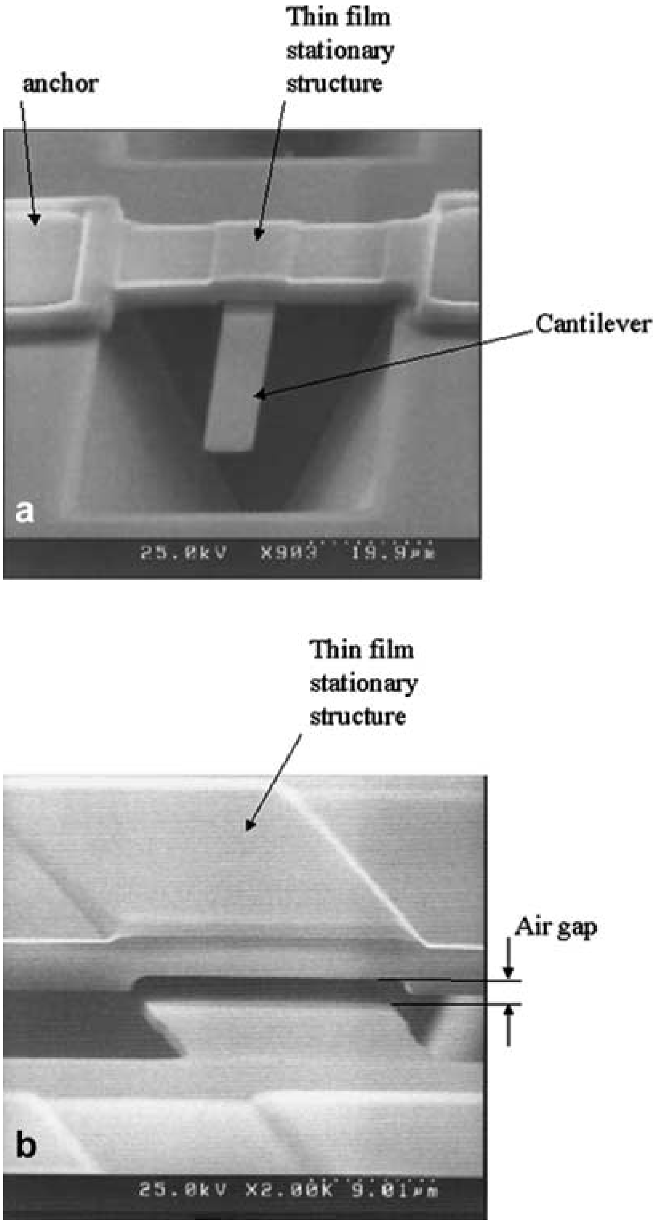

Fig. 7. Typical fabrication results of the thin film stationary structure

The test setup to measure the quality factor of the micromachined structures is shown in Fig. 8. The ambient pressure was controlled by a vacuum chamber during the test. A piezoelectric shaker was employed to excite the samples, and the resulting dynamic response of the test cantilever was measured by a laser Doppler vibrometer (LDV). The quality factor of the vibrating beam was determined by the bandwidth of its frequency response. The width W of the cantilever was typically 10 μm. Since the length L_d of the test cantilevers varied from 30 to 80 μm, the squeezed-film area ($W \times L_d$) ranging from 300 μm^2 to 800 μm^2. The data in Fig. 9 show how the quality factor varied with the area of the squeezed-film region for the bulk silicon approach (i.e., the case shown in Fig. 5). In this figure, the quality factor Q was also normalized to the quality factor Q_0 for $A = 300$ μm^2. The measurements were made at four different ambient pressures P_a: 760 torr, 7.2 torr, 430 mtorr, and 20 mtorr. The quality factor of the vibrating beam was 19.0 when $P_a = 760$ torr and when there was no bulk silicon stationary structure underneath. The quality factor reduced markedly from 14.4 (Q_0) to 7.6 when the area of the squeezed-film region increased from 300 μm^2 to 800 μm^2 under the same ambient pressure ($P_a = 760$ torr). When the ambient pressure was only 20 mtorr, the quality factor of the beam still decreased from 12100 (Q_0) to 9500 when the area of the squeezed-film region increased from 300 μm^2 to 800 μm^2.

The data in Fig. 10 show how the normalized quality factor (Q/Q_0, again, Q_0 represents the quality factor for $A = 300$ μm^2) varied with the area of the squeezed-film region for the thin film approach (i.e., the case shown in Fig. 7). The measurements were conducted at the same four different ambient pressures: 760 torr, 7.2 torr, 430 mtorr, and 20 mtorr. Since the cantilever was curved due to residual stress from the fabrication, the length of the thin film stationary plate was limited to $L_d < 50$ μm to prevent contact between the structures during dynamic testing. Thus the squeezed-film area for the thin film stationary plate case was limited to 500 μm^2. When the squeezed-film area increased from 300 μm^2 to 500 μm^2, the quality factor of the vibrating beam decreased from 17.4 (Q_0) to 11.3 when $P_a = 760$ torr, and decreased from 7230 (Q_0) to 6970 when $P_a = 20$ mtorr.

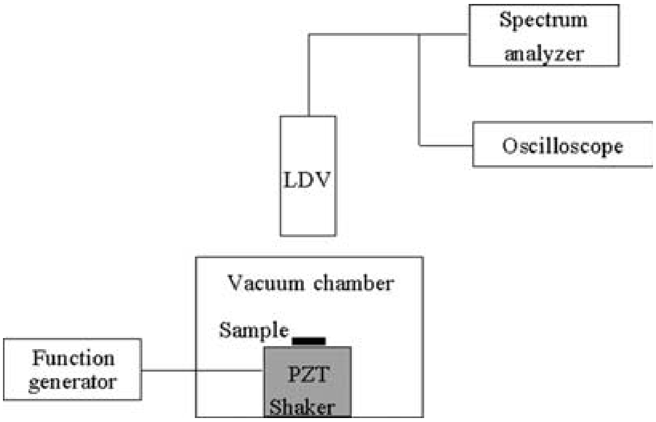

Fig. 8. The test setup

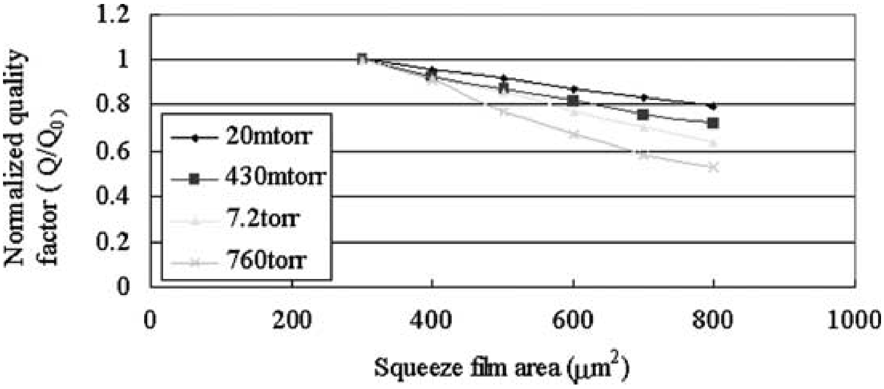

Fig. 9. Experimental results of the variation of the quality factor with the area of the squeezed-film region for the bulk silicon approach

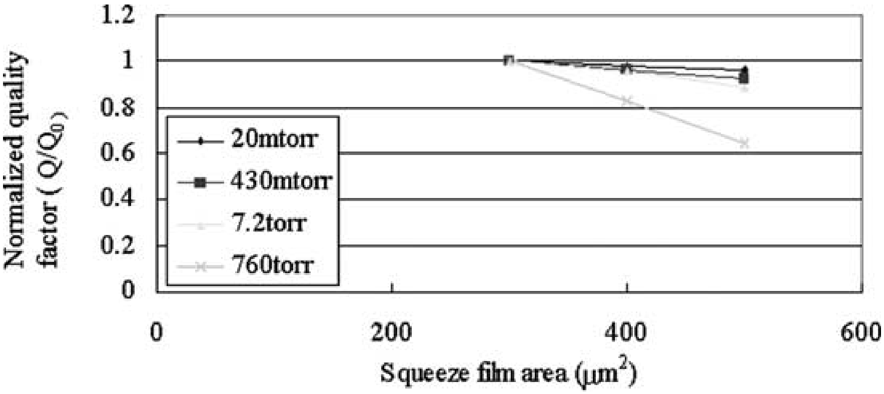

Fig. 10. Experimental results of the variation of the quality factor with the area of the squeezed-film region for the thin-film approach

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Discussions and conclusions

Two micromachining processes have been successfully established for fabricating novel stationary structures using thin films and bulk silicon. Using these processes, a squeezed-film region can be formed between a stationary structure and a vibrating micromachined cantilever. Measurements showed that, under the assistant of bulk stationary structure, the quality factor of the vibrating beam decreased by 48% when the squeezed-film area increased from 300 μm^2 to 800 μm^2 under a 760-torr ambient pressure. Even when the ambient pressure was only 20 mtorr, the quality factor of the beam still decreased 20% for the same change in area. Moreover, under the assistant of thin film stationary structure, the quality factor of the vibrating beam decreased by 35% when the squeezed-film area increased from 300 μm^2 to 500 μm^2 under a 760-torr ambient pressure. Accordingly, the proposed stationary structures can be employed to tune the quality factor of bulk micromachined structures by incorporating squeezed-film effect.

For a specific squeezed-film area ($A = 600$ μm^2), the quality factor was increased from 10 to 14 when the beam width W was increased from 10 μm to 20 μm, as indicated in Fig. 11. It is easier for the air underneath the cantilever to be pumped in and out when the beam is narrow, in which case the air acts more like a damper. In contrast, the air underneath a relatively wide cantilever will be more trapped, and this squeezed air acts more like a spring rather than a damper.

Figure 12 shows a comparison between the predicted and measured quality factors for different squeezed-film areas. The discrepancy between the predicted and measured results is 40–60%. The model in Fig. 2 considers the moving beam as a rigid body that also does not tilt relative to the substrate surface; therefore, the air gap between the structures was uniform. In contrast, the beam in the experiment was a flexible structure and experienced a bending deflection during the vibration test, and hence the air gap between the structures was not uniform. This difference in air-gap properties is the primary reason for the difference between the predicted and measured quality factors. In addition, the initial deflection of the micromachined beam resulting from the residual stress in the thin film may also have influenced the quality factor in the experiments. To predict the quality factor of the proposed design, the simplified dynamic model in Sect. 2 need to be further improved.

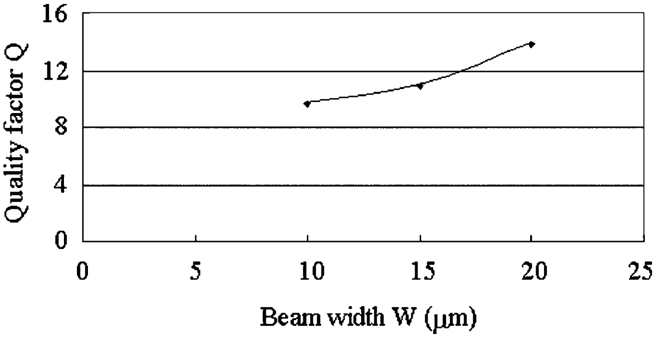

Fig. 11. Experimental results of the variation of the quality factor with the beam width W when the area of the squeezed-film region was $A = 600$ μm^2

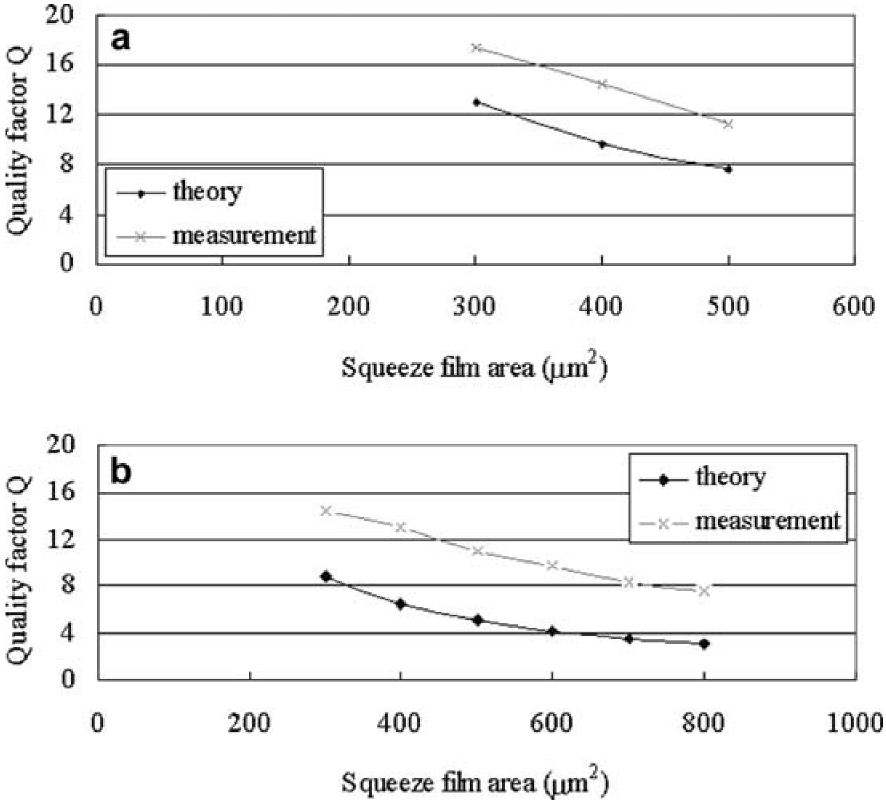

Fig. 12. Comparison of the predicted and measured quality factors for different squeezed-film areas

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