A novel antistiction method using harmonic excitation on the microstructure

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A novel antistiction method using harmonic excitation on the microstructure is presented. We exploit a simplified model consisting of a single-degree-of-freedom mass-damping-spring system to simulate the drying process of the microstructure. Based on this proposed method, we can predict the dynamic response of the microstructure including the resonant frequency and the damping characteristic of the drying system. And then adequate harmonic excitation is applied to release the microstructure during drying process. Silicon dioxide beams with 0.7-μm-thick, 16-μm-wide, 120-μm-long, 4 μm gap, were released successfully by this method. Theoretical predictions of the dynamic behavior of microstructures during the drying process agree well with experimental results. The proposed approach effectively improves the yield rate of the microstructure without additional masks and complicated process during the postetch release process. [DOI: 10.1116/1.1353542]

I. INTRODUCTION

Wet etching and drying process used to release microstructures is a common step in surface and bulk micromachining technology. The stiction phenomena, a major problem of postetch rinsing and drying procedure, may cause microstructures to fail or decrease the process yield. The sticking problem due to the reaction mechanism between rinse liquid and microstructures becomes a serious issue in fabricating microstructures. To evaluate and reduce the stiction phenomenon, a variety of analytical models and experiments concerning this issue have been reported.[1–9] The van der Waals forces, surface tension forces, electrostatic forces, and so forth[1,2] are regarded as several possible reasons to result in stiction. In short, the Laplace pressure and surface tension resulting from the rinse liquid between microstructures and the substrate are two dominant forces to initiate stiction during the drying process.

Various approaches have also been demonstrated to prevent the problem of stiction. For instance, changing the surface topology of the micromachined structure[3,4] can reduce the surface tension of drying liquid. To eliminate the initial contact between surfaces or to reduce the adhesion of microstructure using different rinsing solutions such as methanol, isopropanol, and prolonged water, are reported in Ref. 1. In Refs. 5 and 6, an alternative strategy to apply external forces including magnetic field and pulsed ultrasonic source to prevent the stiction of the microstructure are proposed. Although all of these approaches are quite effective in increasing process yield, they must be implemented at the expense of additional masks, complicated process, and facilities.

The existing articles only considered that the microstructure is statically deformed by the liquid during drying. In the present study, an external harmonic excitation is exploited to drive the microstructure during the drying process. Hence, a dynamical system is formed with the microstructure and the liquid. The occurrence of stiction will be affected by the dynamic response of this system. It is expected that the stiction of the microstructure can be prevented if the system is driven at its resonant frequency. In the following text, the analytical model is developed to predict the dynamic response of the excited dynamical system during the drying process. Experiments are also conducted to demonstrate the applications of the proposed technique.

II. ANALYTICAL MODEL OF THE DRYING PROCESS

The drying process of a microstructure right after the wet etching can be treated as an isobaric process in most circumstances (i.e., the pressure inside the liquid film is the same everywhere). The mechanisms of the drying process have been extensively derived.[1,3] Briefly, the Laplace pressure and surface tension on the microstructure are two primary forces to cause stiction during the drying process. In the present study, the drying of a micromachined cantilever under the excitation of a harmonic load is discussed. The analytical model is established in this section to study the dynamic response of the cantilever during drying process.

Figure 1 shows the model applied in this study to simulate the dynamic response of the microstructure during the drying process. According to the observation in the experiment, there is a liquid film accumulating between the substrate and the tip of the beam, as shown in Fig. 1(a), before being fully evaporated.[1] As indicated in Fig. 1(b), the gap d becomes $d-\Delta d$ after the beam deformed by the liquid film. The physical model of Figs. 1(a) and 1(b) is illustrated in Fig. 1(c) where the liquid film is represented by the equivalent spring, mass, and damper. In short, the equivalent spring effect mainly comes from the Laplace pressure of the liquid film and the equivalent damping effect is due to the squeeze of the liquid film. Moreover, the continuous beam model in Fig. 1(c) is simplified to the single-degree-of-freedom lumped model in Fig. 1(d). Based on this lumped model, the present study tends to describe the dynamic response of the

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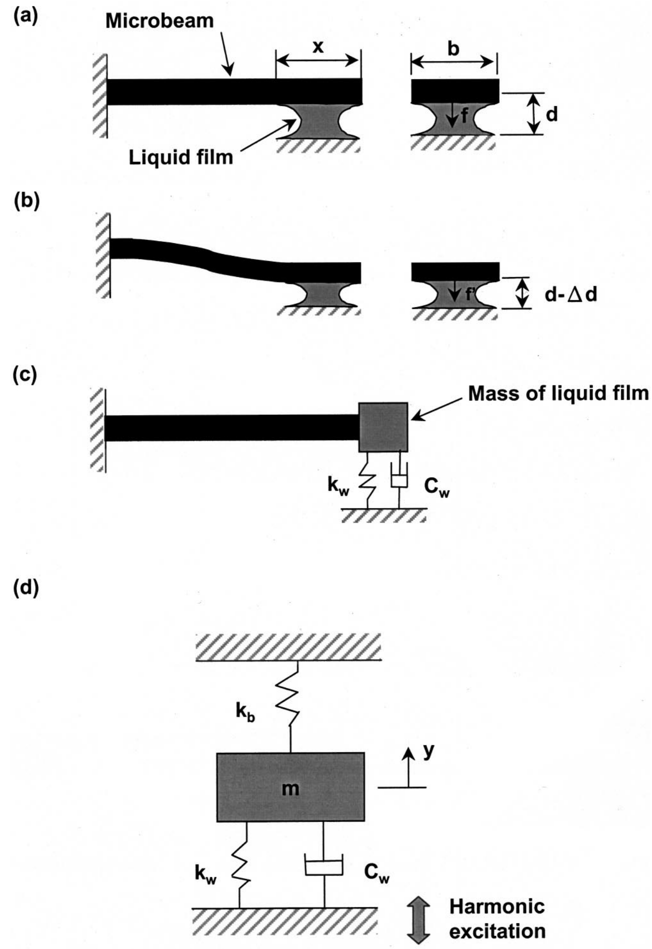

FIG. 1. The lumped dynamic model for the drying process of the microcantilever beam.: (a) the original situation of the drying system, (b) the deformation of the beam when the gap is changed, (c) the simplified model of liquid film, and (d) the simplified lumped dynamic model system.

bending mode of the cantilever in Fig. 1(a) by the second-order differential equation

$$m\ddot{y}+c_w\dot{y}+(k_w+k_b)y=F. \tag{1}$$

The parameters c_w and k_w represent the equivalent damping constant and spring constant of the liquid film. The parameters k_b and y are the equivalent spring constant of the beam and the dynamic response of the lumped mass in Fig. 1(d), respectively. As shown in Fig. 1(a), the spring constant k_w is calculated at the situation that necking has occurred and an inside meniscus has formed. Hence, the Laplace pressure is generally the dominant load acting on the microstructure, and the radius of the meniscus is assumed to be uniform along the boundary of the liquid film.[1] To simplify the drying process of the microbeam, the radius of the meniscus is assumed to be half of the gap d in this model. Therefore, the force f caused by the Laplace pressure can be expressed as[1]

$$f=\frac{2\gamma bx}{d}, \tag{2}$$

where γ is the surface tension coefficient of liquid, b is the width of the cantilever beam, and x is the length of the liquid film contacting with the cantilever beam as indicated in Fig. 1(a). As shown in Fig. 1(b), the force caused by the Laplace pressure becomes f' after the gap changes from d to $d-\Delta d$. The spring constant k_w due to the Laplace pressure will be determined by

$$k_w=\Delta f/\Delta d, \tag{3}$$

where $\Delta f=f'-f$. According to Eqs. (2) and (3), the parameter k_w of the liquid film is expressed as

$$k_w=4\gamma bx/d^2. \tag{4}$$

On the other hand, the equivalent damping effect is due to the squeeze of the liquid film. According to Refs. 10 and 11, the damping constant c_w of the liquid film is expressed as

$$c_w=\mu b^3x/d^3, \tag{5}$$

where μ is the viscosity of the liquid film.

The dynamic response y of the simplified lumped model in Fig. 1(d) is determined after substituting Eqs. (4) and (5) into Eq. (1). It is obtained from Eqs. (4) and (5) that the spring and damping constants vary with the shape of the liquid film. Since the liquid film is evaporated during drying process, its shape will change with the drying time. In conclusion, the vapor rate of the liquid film and the drying time are critical parameters in analyzing the dynamic response of the beam. This study assumed that the gap d and length x decrease linearly with the drying time. The total drying time was divided into 20 steps; therefore, the analytical results in Figs. 2 and 3 were determined at each time step. Figure 2 displays the dynamic response of the 0.7-μm-thick, 16-μm-wide silicon dioxide cantilevers with two different beam lengths during the drying process. The gap d in this model is 4 μm. In Fig. 2, the resonant frequency increases with drying time. This is due to the variation of the shape of the liquid film during drying. It is also obtained from Fig. 2 that the resonant frequencies of the beams with different lengths are very close. Thus, the liquid film remarkably influences the natural frequency of the dynamical system in Fig. 1(d).

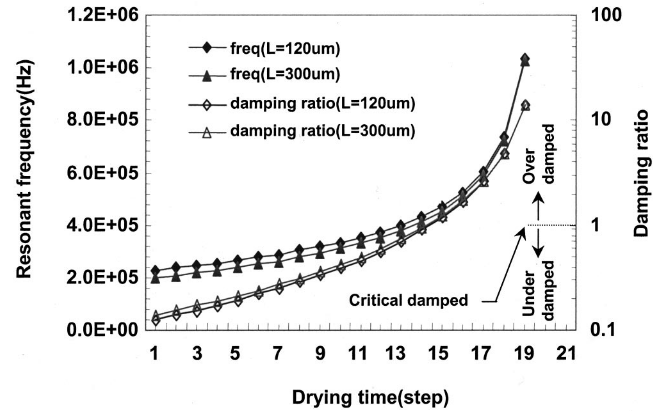

FIG. 2. The resonant frequency and damping characteristic of 0.7-μm-thick, 4-μm-gap, 16-μm-wide silicon dioxide beam with two different lengths (120 and 300 μm) during the drying process.

According to the results in Fig. 2, the system is initially underdamped, then becomes critically damped, and finally is

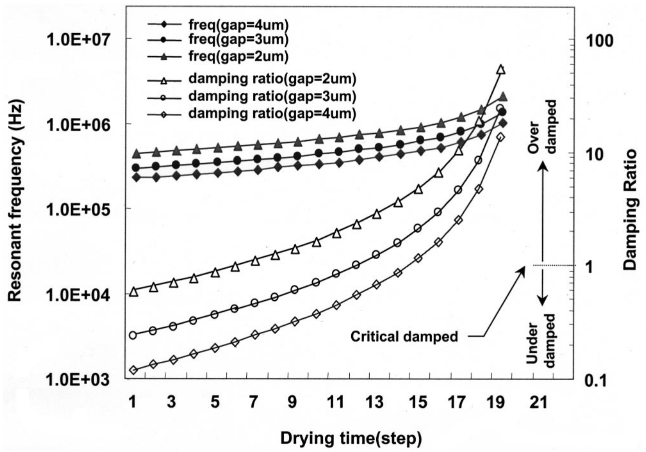

FIG. 3. The resonant frequency and damping ratio characteristic of 0.7-μm-thick, 16-μm-wide, and 120-μm-long silicon dioxide beam with three distinct gaps (4, 3, and 2 μm) during the drying process.

overdamped when the drying time increased. Consequently, the damping constant increases when the cantilever beam approaches the substrate. During the underdamped condition, the system will experience an extremely large dynamic response when it is excited at the resonant frequency. Hence the stiction can be prevented. On the other hand, the beam will not oscillate when the system in Fig. 1 is overdamped, and then the proposed approach cannot prevent the stiction problem. The results in Fig. 2 revealed that the cantilever beam could be separated with the liquid film by the harmonic excitation during drying process.

The relation between the gap d and the dynamic response of the system is also studied. Figure 3 shows the variation of the resonant frequencies and the damping ratio with the drying time for three different gap sizes. The silicon dioxide beam analyzed in Fig. 3 is 0.7 μm thick, 16 μm wide, and 120 μm long. The results shown in Fig. 3 indicate that the resonant frequency of the system will be decreased when the size of the gap is increased. In addition, it is more difficult to release the beam with a smaller gap through the harmonic excitation approach since they are overdamped for most of the drying time. The analytical model that is proposed in this section is also applicable to other microstructures. We can predict the dynamic response of the microstructure during the drying process and adequately choose the frequency of harmonic excitation to prevent the stiction of the microstructure.

III. EXPERIMENT AND RESULTS

A. Fabrication processes and experimental setup

In application of the proposed antistiction technique, we fabricated silicon dioxide cantilever beams on a (111) silicon substrate. As shown in Fig. 4(a), the thermal oxide film was grown on the (111) wafer at first. In Fig. 4(b), the oxide film was patterned into cantilevers with various lengths and widths by buffered HF after photolithography. The silicon substrate was then etched by reactive ion etching (RIE) to define the gap d between the beams and the substrate. After anisotropic etching in KOH solution, the dioxide beams were released from the substrate, as illustrated in Fig. 4(d). Figure 5 shows a scanning electron microscope (SEM) photograph of typical cantilever beams fabricated through the processes in Fig. 4. The advantage of the fabrication processes is that

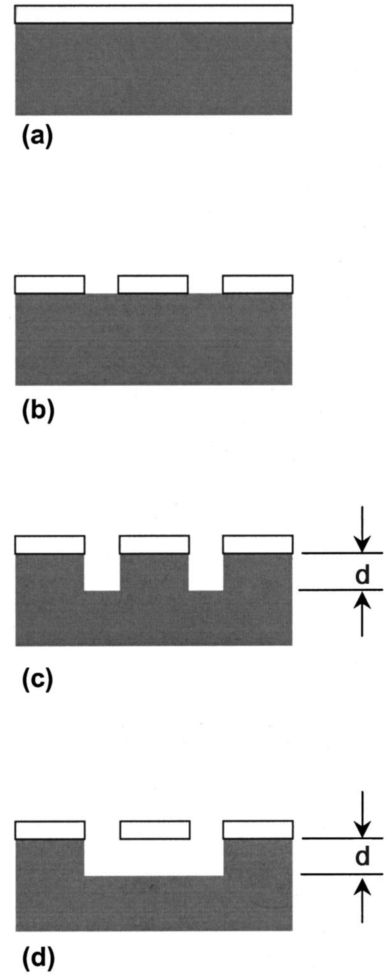

FIG. 4. Fabrication process of the silicon dioxide cantilever beams on the (111) single crystal silicon substrate.

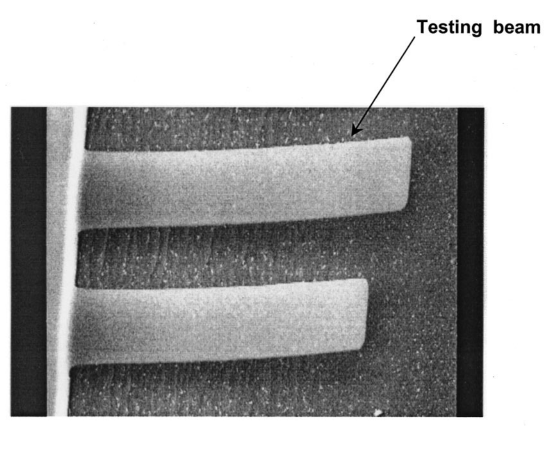

FIG. 5. The SEM photograph of the silicon dioxide cantilever beams.

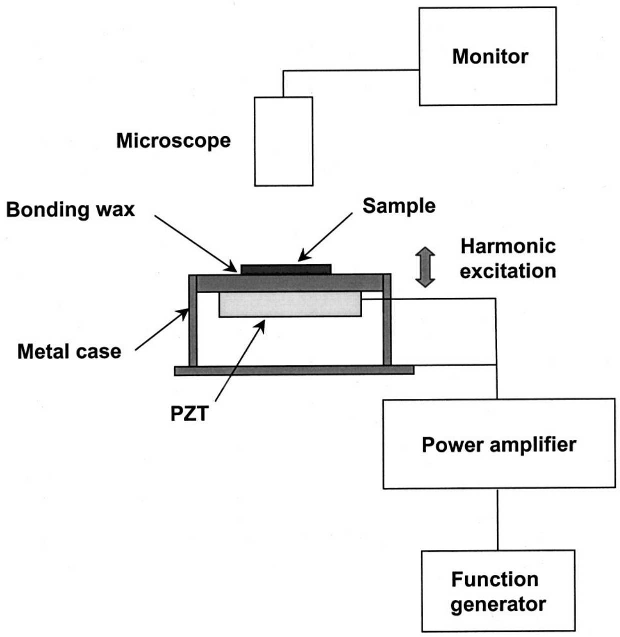

FIG. 6. A schematic diagram of the experimental setup.

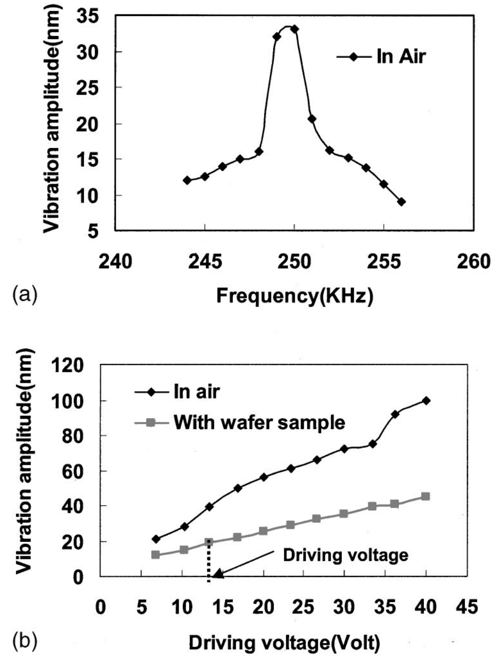

FIG. 7. The vibration characteristic of the PZT actuator, (a) the relation between vibration amplitude and frequency. (b) The relation between vibration amplitude and driving voltage, which the actuator is driving at 250 kHz resonant frequency with and without wafer.

the gap between the beams and the substrate can be easily defined by RIE. In addition, the processes require only one mask.

The substrate was then tested using the setup illustrated in Fig. 6. The sample was mounted on a PZT actuator (28 mm in diameter and 8 mm in thickness) by wax. The PZT actuator performed as a shaker to provide high frequency excitation to the test sample. Hence, the PZT actuator must be operated in the thickness-extension mode to perform as a base excitation source. As shown in Fig. 6, the signal used to drive the PZT actuator was generated by the function generator and then enlarged by a power amplifier. Finally, the dynamic response of the beams during the drying process can be observed and recorded by the microscope and video recorder.

B. Result

The sample containing the microstructures and the deionized water experienced drying under the atmospheric pressure and the room temperature. In order to be compared with the analytical results, the experiment focused on the dynamic response of the 120-μm-long, 16-μm-wide, and 0.7-μm-thick cantilever. Moreover, the gap defined by the RIE was 4 μm in depth. The PZT actuator drove the silicon wafer after the liquid had applied on the beams. Based on the simulation in Fig. 2, a PZT actuator, whose natural frequency of the first thickness-extension mode is near 250 kHz, was selected to excite the cantilevers at their underdamped condition during drying. As shown in Fig. 7(a), the first thickness-extension mode of the PZT actuator measured by a laser Doppler vibrometer approximates 250 kHz. Figure 7(b) shows the variation of the vibration amplitude of the PZT actuator with the driving voltage. It is obtained that the PZT actuator was approximately proportional to the driving

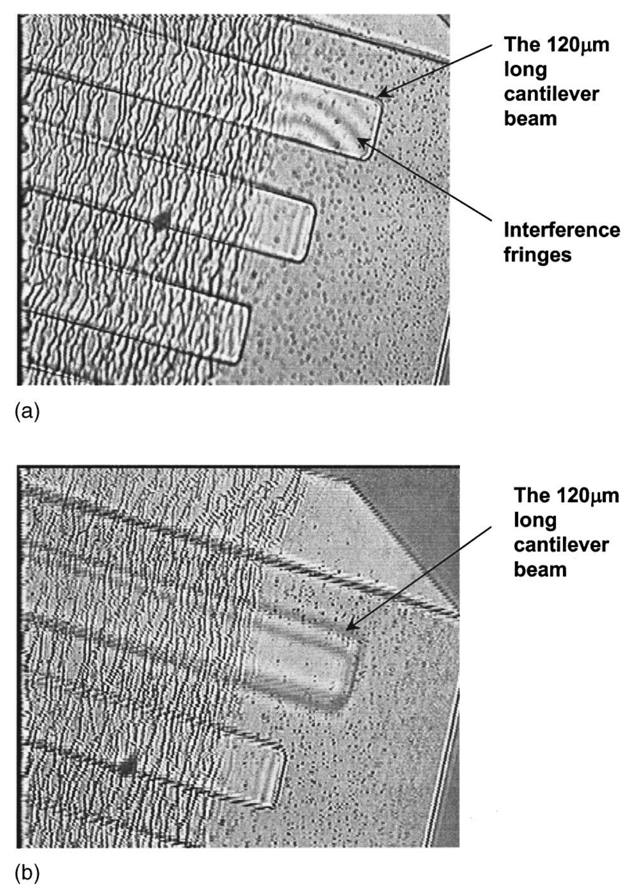

FIG. 8. The pictures of the drying process of cantilever beam. (a) The oxide beam with liquid film without harmonic exciting force before separation from the substrate. (b) The beam was separated successfully from liquid film with harmonic exciting force.

TABLE I. Summary released results of the cantilever beams with a PZT actuator driving force and no exciting force.

		First test	Second test	Third test
Drying with harmonic excitation	Drying time	60 s	10 s	110 s
	Result	Released	Released	Released
Drying without harmonic excitation	Drying time	More than 30 min	More than 30 min	More than 30 min
	Result	Permanently stuck	Permanently stuck	Permanently stuck

voltage when operating at 250 kHz. Thus, the energy transferring from the PZT actuator to the cantilever beam can be evaluated. The driving voltage of the PZT actuator was selected as 14 V to prevent the impact between the cantilever and the silicon substrate. After excited by a 250 kHz harmonic load for 10–110 s, the beam was released from the substrate, as shown in Fig. 8(b). As compared with the photo in Fig. 8(a), the existence of interference fringes is observed at the tip of the beam. It shows that the beam was stuck on the substrate by the liquid film after drying if without PZT excitation. Table I summarizes the results of the drying test for cantilever beams with and without the excitation of a PZT actuator. The beams were stuck on the substrate permanently if they were not driven by the harmonic excitation. On the other hand, beams excited by the PZT actuator were released successfully after a very short period. The experimental results agree well with the analytical ones. Briefly, a significantly dynamic response will be induced to separate the cantilever beams and the substrate when the resonant frequency of the underdamped drying process corresponds to the frequency of harmonic excitation. This method will prevent the stiction problem and enhance the yield rate of the drying process of the microstructures.

IV. CONCLUSION

In this research, a novel technique to prevent the sticking of the microstructure during the drying process was studied. The lumped model regarding the micromachined structure and the liquid film was established to predict the dynamic response of the system. According to the Laplace pressure and the squeeze film effect, the spring and the damping constants in the model were determined. When an underdamped dynamical system was driven at its resonant frequency, the tip of the beam experienced a large response, so that the liquid film accumulating at the tip of the beam was destroyed. The stiction of the microstructure consequently can be prevented. The application of this technique was also demonstrated by the experiment. Such a model effectively improved the yield rate of the microstructures without additional masks and complicated process during postetch release process. And this approach is also applicable to other microstructures.

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