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Control the Shape of Buckling Micromachined Beam using Plasma Chemistry Bonding Technology

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In this study, we report a novel method for controlling the shape of a micromachined bridge (clamped-clamped beam) by plasma surface modification. In short, the microbridge can be tuned to either buckle upward or downward using plasma treatment. To demonstrate the feasibility of this approach, NH_3 plasma treatments were employed to control the direction of buckling amplitude for a SiO_2 microbridge. Furthermore, the shape of a buckling microbridge can also be adjusted by the same technique. The buckling profiles predicted by finite element analysis are in agreement with those determined from the measurement. [DOI: 10.1143/JJAP.45.8479]

KEYWORDS: buckle, plasma treatment, residual stress, micro bridge, MEMS

1. Introduction

Micromachined bridges are one of the most commonly used structures in the micro-electro-mechanical-system (MEMS) fields. It is easy to fabricate buckled micromachined bridges by directly applying compressive thin film residual stress resulting from fabrication. Such a buckling behavior can also be exploited to fabricate out-of-plane three-dimensional micromechanical structures. The buckling of a micromachined beam has various applications, such as in relays,[1] valves,[2] and material property test keys.[3] In general, the ideal clamped-clamped beam may buckle upward or downward randomly. Moreover, the initial excitation of the structures by some additional loads, such as gradient residual stresses, may influence the buckling amplitude direction.[4] It is difficult to predict the buckling amplitude orientation of the micromachined bridge, such that the applications of buckling beam are limited.

It is a convenient approach to apply plasma to change the physical or chemical properties of a thin film surface. This technique, called plasma treatment, is easy to integrate with microfabrication. Presently, the plasma treatment is extensively employed in semiconductor manufacturing for surface cleaning and modifications.[5] The modification of thin film's mechanical properties using plasma treatment has been investigated in refs. 6 and 7. It is feasible to exploit the effects of plasma treatments to tune the residual stresses of thin films.[8] Thus, a cantilever beam shape is tuned by varying the plasma treatment region and conditions.[8]

In this study, the plasma treatment technique has been employed to modulate the residual stress of thin film, so as to control the buckling amplitude orientation of the micromachined bridge, and to tune the shape of the buckling beams. In application, the variations in buckling and shape of a SiO_2 bridge with NH_3 plasma treatments were investigated. The changes in chemical bonding and mechanical properties of SiO_2 after plasma treatment were characterized by X-ray photoelectron spectroscopy (XPS), secondary ion mass spectrometry (SIMS), scanning electron microscopy (SEM), and optical interferometry.

2. Concept

In general, thin film residual stresses consist of both uniform stress and gradient stress components.[9] The buckling of a micromachined bridge is mainly due to the uniform compression. On the other hand, the gradient residual stress will lead to the bending of a micromachined cantilever. In ref. 8, the plasma treatment has been employed to give an equivalent gradient residual stress on thin film, and the micromachined structure made of the thin film is under an equivalent bending moment. Thus, the radius of the curvature of the bending cantilever is changed. Moreover, the cantilever beam shape is also tuned by varying the plasma treatment region.[8] In this study, we intend to exploit the characteristics of plasma treatment to apply an equivalent bending moment on micromachined structures, so as to tune the buckling amplitude orientation and shape of a micromachined bridge.

The concept of this study is shown in Fig. 1. The plasma treatment is applied to part of the microbridge, as indicated by the dark color regions in Fig. 1. Thus, the equivalent bending moment will apply in these plasma-treated regions. In this case, the equivalent bending moment will cause the plasma-treated microstructure to bend in a concave downward manner. As shown in Fig. 1(a), the plasma-treated regions are located at both sides of the microbridge, so that the microbridge has an initial deflection in a concave upward manner after plasma treatment. In Fig. 1(b), the plasma treatment region is located at the center of the microbridge, so that the center of the microbridge has an initial deflection concave downward after plasma treatment. Since the buckling amplitude orientation is determined by the initial beam profile, the microbridge in Fig. 1(a) will buckle downward and the microbridge in Fig. 1(b) will buckle upward. Briefly, the buckling amplitude orientation in an upward or downward manner can be controlled using the plasma treatment regions. In Fig. 1(c), the plasma treatment region is located between the center and the boundary of the microbridge. The peak of the buckling beam is no longer located at its center, and the beam shape is slightly changed. In short, the concept of partially prebending structures by plasma treatment is exploited not only to determine the orientation but also to tune the shape of the buckling beam.

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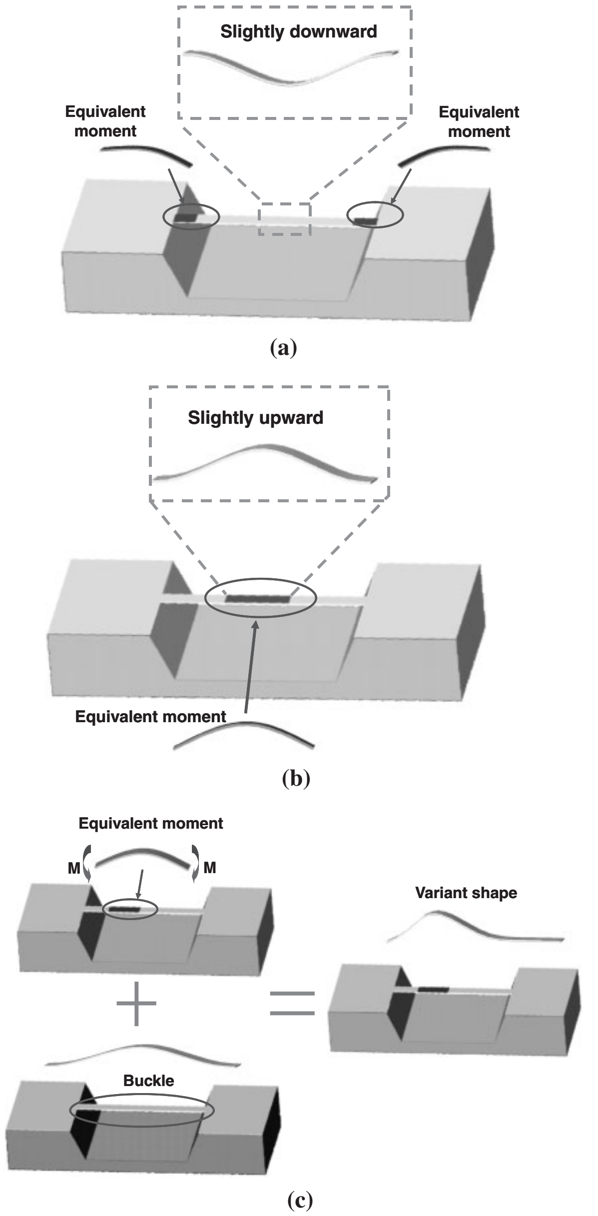


Fig. 1. Explanation of plasma treatment effect on buckling amplitude orientation and shape.

3. Experimental Methods

To demonstrate this concept, thermal oxide bridges were fabricated and then treated with various NH_3 plasmas. The process is schematically shown in Fig. 2. In Fig. 2, AA′ represent the cross sections along the beam length. A 0.8-μm-thick SiO_2 layer was thermally grown on (100) Si wafer at 1050 °C. The SiO_2 thin film was patterned by photolithography and reactive ion etching (RIE) as shown in Fig. 2(a). The aluminum film was defined using the lift-off process in Fig. 2(b). Lift-off process was chosen so as not to change the SiO_2 film properties during aluminum deposition. This aluminum film acted as the mask to define the region for the following NH_3 plasma treatments. The NH_3 plasma treatment was operated in a plasma-enhanced chemical vapor deposition (PECVD) reaction chamber. The plasma conditions of NH_3 were 250 °C/500 mTorr at a 200 W RF power for 1 h. The frequency of the RF power was 13.56 MHz. Since there was no DC bias, the ion was not accelerated. Fig. 2(c) shows the pattern formed by the NH_3 plasma treated SiO_2 film after removing the aluminum mask. The aluminum mask was removed using a ($H_3PO_4 : HNO_3 : CH_3COOH : H_2O$) HNA etchant at 75 °C. Finally, the Si substrate was removed anisotropically using a 15% tetramethyl ammonium hydroxide (TMAH) solution at 75 °C, so that the bridge made of SiO_2 film was fully suspended, as shown in Fig. 2(d). The test SiO_2 bridge was 300 μm long and 30 μm wide. Moreover, 15 SiO_2 bridges were characterized for each test to show the feasibility and repeatability of the present approach.

The static deflection test was employed in this study to characterize the mechanical behaviors of the bridge after the processes. Moreover, the chemical properties of thin films, such as chemical composition, were investigated by X-ray photoelectron spectroscopy (XPS) and secondary ion mass spectrometry (SIMS). Analysis of the XPS spectra typically involved background subtraction using the Shirley method[10] followed by nonlinear least squares fitting to a mixed Gaussian–Lorentzian peak shape. The variations of the chemical properties with the depth of thin film were also characterized.

4. Results and Discussion

The chemical bonding of thin film after plasma treatment was characterized by XPS and SIMS depth profiles. Thus, the correlation of the mechanical properties and chemical bonding of thin film were determined. Figure 3 shows the XPS spectra of the SiO_2 film for N 1 s and Si 2p lines after plasma treatment. The peak in Fig. 3(a) indicates that the Si–N bond[11] was formed after NH_3 plasma treatment. As shown in Fig. 3(b), the binding energy of the Si 2p electrons for the samples without plasma treatment is near 103.2 eV.[12] The SiO_2 film treated with NH_3 plasma was composed of two different environments in Si 2p line: Si–O at 103.55 eV and Si–N at 102.05 eV.[13] In addition, the binding energy of the sample after NH_3 plasma treatment was slightly changed. It implies that some of the Si–O bonds were replaced by the Si–N bond, so that part of the oxidation state of silicon was less than four.

As shown in Fig. 4, the SIMS depth profile of the NH_3 plasma treated SiO_2 film was investigated. Thus, the variation of the chemical composition with the depth of SiO_2 film was determined. Figure 4 shows the depth of SiO_2 film as three regions with different nitrogen concentrations. I, II, and III indicate the regions of higher nitrogen concentration, lower nitrogen concentration, and no nitrogen, respectively. The nitrogen implantation depth for NH_3 plasma treatments was 200 nm. In region III (from 200 to 320 nm depth), the nitrogen concentration of the SiO_2 film was not influenced by the plasma treatments. In conclusion, an equivalent gradient residual stress may result from the formation of Si–N chemical bonds on the surface (200 nm deep) of SiO_2 film; moreover, gradient stress can be easily tuned by varying the NH_3 plasma.

The SEM image in Fig. 5 shows the deflection profiles of the bridge after being tuned by NH_3 plasma treatment. The plasma treatment regions are indicated in the right hand side of Fig. 5. The difference in the buckling amplitude orientation for the bridge is visible in the SEM image. The deflection profiles of the bridge measured by an optical

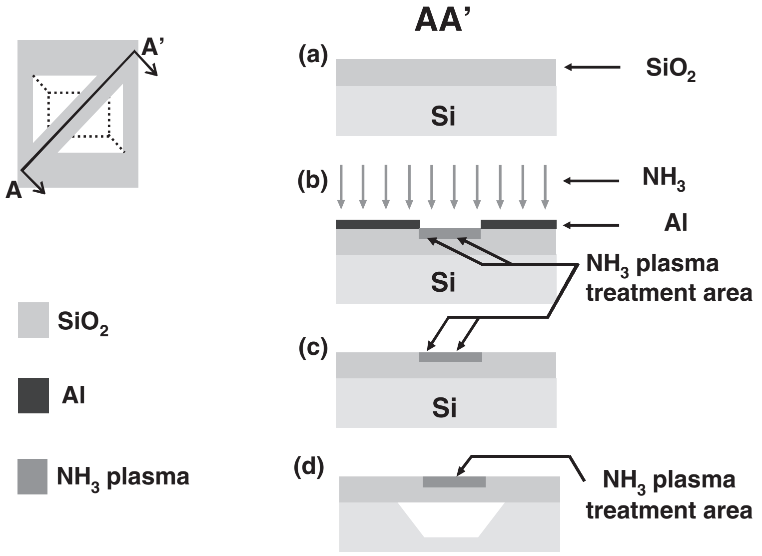
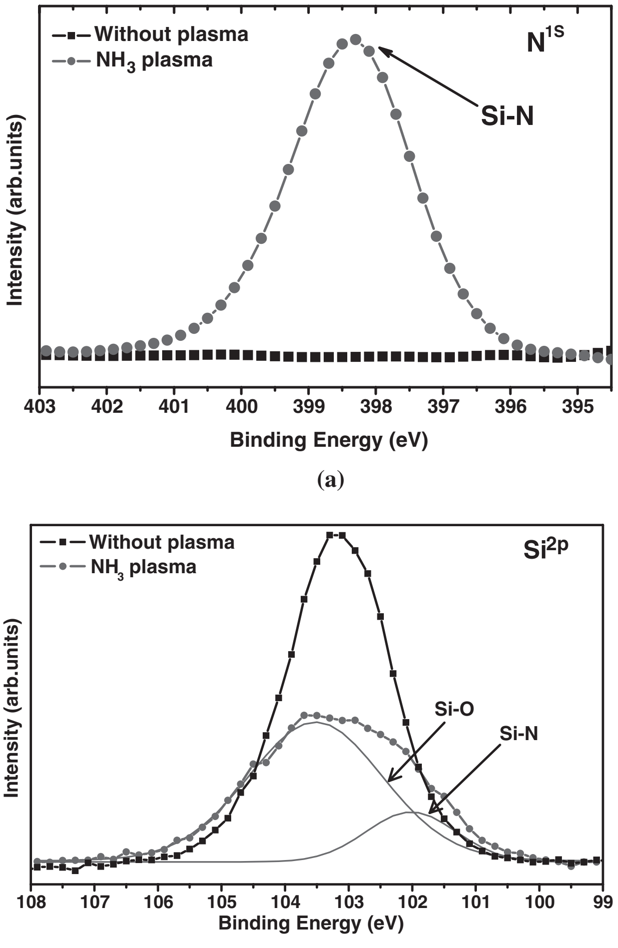


Fig. 2. Present fabrication process steps.



(a)

(b)

Fig. 3. XPS spectra of SiO_2 film at (a) N 1 s and (b) Si 2p lines for NH_3 plasma treatment.

interferometer are shown in Fig. 6. The measurement results show that the bridge buckled downward [Fig. 6(a)] and buckling upward [Fig. 6(b)] when it was treated by the NH_3 plasma at both sides of the bridge and at the center region, respectively. The buckling amplitudes were about 12 µm. The data bars in Fig. 7 denote the percentage of the buckling amplitude orientations for fifteen 300 µm-long microbridges with different NH_3 plasma treatment regions and lengths. The positive and negative *y*-axes in Fig. 7 represent the

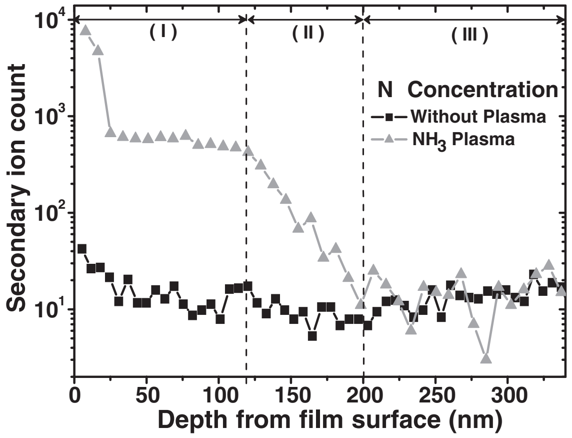
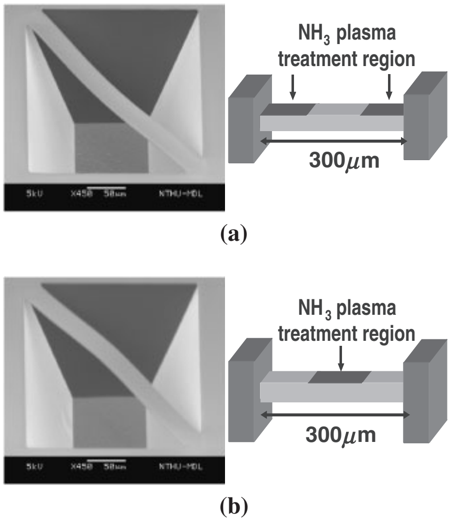


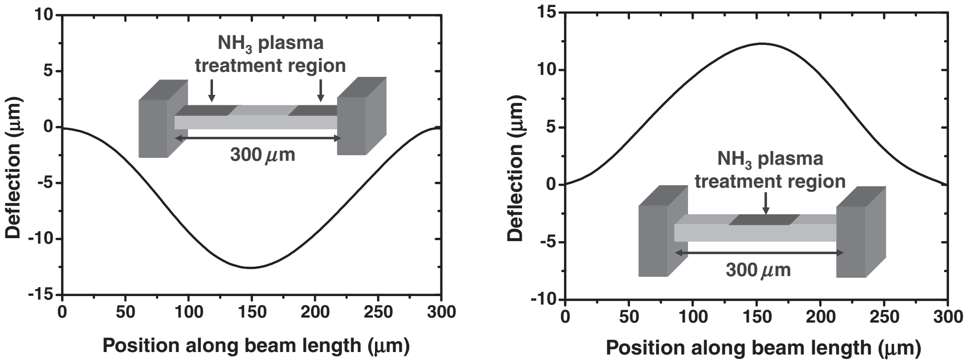
Fig. 4. SIMS depth profiles of SiO_2 films with plasma treatments.



(a)

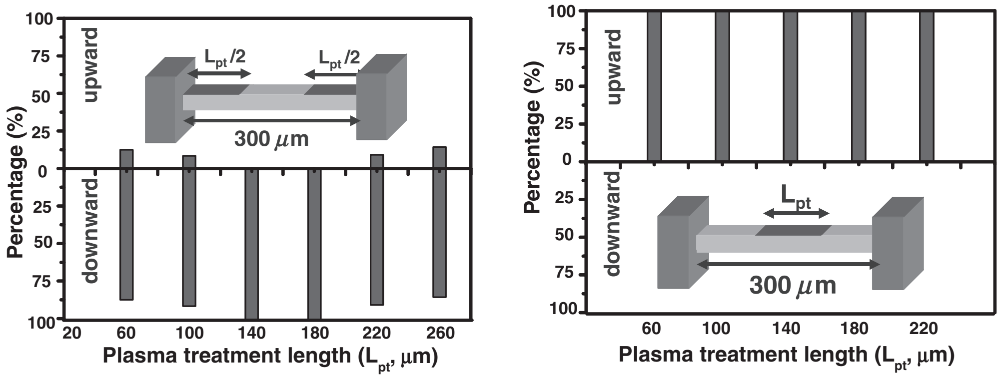
(b)

Fig. 5. SEM images of bridge for NH_3 plasma treatments at various regions: (a) at both sides of bridge and (b) at center region.



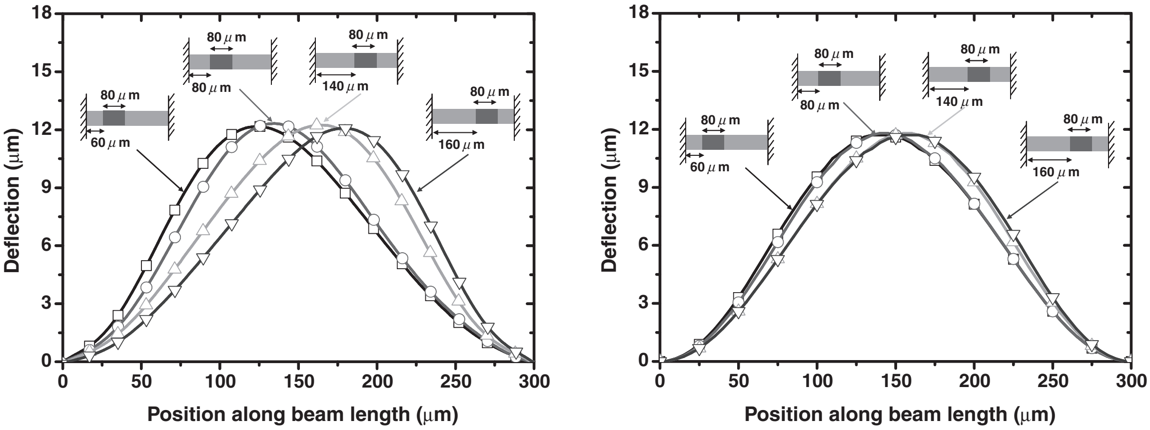
(a) (b)

Fig. 6. Deflection profiles of bridge with NH_3 plasma treatments at various regions.



(a) (b)

Fig. 7. Distribution of buckling amplitude orientation after plasma treatment: (a) at both sides of bridge and (b) at center region.



(a) (b)

Fig. 8. Comparison of (a) experiment and (b) FEM analysis results.

upward and downward directions, respectively. The bridges in Fig. 7(a) were treated by plasma at both sides with net treatment length L_{pt} ranging from 60 μm to 260 μm. Thus, more than 90% of the 15 tested bridges were buckled downward. The bridges in Fig. 7(b) were treated by plasma at the central region with L_{pt} ranging from 60 μm to 220 μm. All of the 15 tested bridges were buckled upward. The experiment results successfully demonstrated that the buckling amplitude orientation of the bridge can be tuned by varying the NH_3 plasma treatment regions.

Figure 8 shows the tuning of buckling beam shape using the plasma treatment technique. In this experiment, the length of plasma treatment region L_{pt} was 80 μm, and the distance L_{pb} between the plasma treatment region and the boundary of the beam ranged from 60 μm to 160 μm. The measurement results in Fig. 8(a) show that the peaks of the microbridge vary with L_{pb}; and the deflection beam profiles are no longer symmetrical at the beam center after plasma treatment. This characteristic can be predicted by the finite element simulation, as shown in Fig. 8(b). The thin film residual stresses in this model were determined using the approach in ref. 9. As a comparison, the measured thin film gradient stresses before and after plasma treatment are 13.6 and −37.4 MPa, respectively.8) In addition, a 300 MPa uniform residual stress, which is a typical value for thermal oxide, was employed in the model.14,15) The elastic modulus and Poisson's ratio used in the FEM model were 77 MPa and 0.23, respectively. Thus, the plasma treatment technique can be employed to tune the shape of the buckling beams.

5. Conclusions

In this study, we present a novel method to tune and control the shape of a micromachined bridge by plasma surface modification. Thus, the buckling amplitude orientation and the shape of the buckling microbridge can be predicted. This is particularly important in designing microstructures, such that the number of applications of microbridges can be significantly increased. In applications, SiO_2 microbridges with different lengths were fabricated using bulk micromachining. NH_3 plasma was employed to treat the microbridge at different regions. The experiment results successfully demonstrate that the partial pre-bending of a microbridge by plasma treatment can be exploited not only to determine the amplitude orientation but also to tune the shape of a buckling beam. It is believed that the plasma treatment technology for controlling the buckling behavior of microbridges is very practical and feasible.

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