Nano-bending method to identify the residual stresses of MEMS films

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ABSTRACT

Nano-bending method is presented to quantify the residual stress in the surface micromachined MEMS. The present method assesses the residual stress by measuring the bending stiffness of MEMS bridge which is stiffened or softened by the tensile residual stress or by the compressive residual stress, respectively. The nano-indenter system is utilized to apply a nano-bending force and measure the displacement of the MEMS bridge. The present nano-bending method evaluates the anchor stiffness and the bending rigidity of the surface micromachined MEMS beams to remove the uncertainty from the anchor geometry and the material properties. The experimental results for the surface micromachined MEMS with 2.3 μm poly-silicon demonstrate the reliability and the accuracy of the present nano-bending method.

Keywords: residual stress, MEMS, nano-indenter, thin film, poly-silicon

1 INTRODUCTION

The residual stresses in the surface micromachined MEMS frequently degrade the reliability of the MEMS devices. The present study contributes to the development of robust measurement method to quantify the residual stresses of the surface micromachined MEMS.

A great deal of efforts has been forward to developing reliable and accurate methods to access the residual stresses in thin films. The oldest one, but the most popular method, is the Stoney equation that utilizes the wafer curvature due to the residual stress in deposited film [1]. The X-ray diffraction has been used to measure the spacing between crystallographic planes in a crystal film [2]. The Raman spectrography is to assess the residual stress by utilizing the frequency change of monochromatic light (typically a laser) entering sample material under residual stress [3].

As the integrated circuit process and MEMS technology have accelerated the miniaturization of devices, the demand for the knowledge about the local value of the residual stress grows. To identify the local stress state on a wafer, various approaches have been tried using micro test devices. Micro bridges and micro rings with interconnecting bars are utilized to measure the tensile and the compressive residual stresses, respectively [4]. The local deformation of the anchors of the surface micromachined cantilevers and entire beam deflections are investigated to understand the mean stress and the stress gradient in deposited film [5]. Mechanical amplifier is devised to amplify the in-plane displacement due to residual stress [6].

The present study proposes the nano-bending method to quantify the residual stress in the surface micromachined MEMS. The fundamental is based on the measurement of the bending stiffness of the surface micromachined MEMS bridges which is stiffened or softened by the tensile residual stress or the compressive residual stress, respectively. The tensile residual stresses of micro bridges significantly increase the bending stiffness of them while the compressive residual stress considerably decreases thir bending stiffness. Analyzing the alternation of the bending stiffness, the residual stress can be measure with high accuracy. A robust analytic model is developed in the present study in order to assess the effect of the residual stress from the change of the bending stiffness

Prior to the measurement of the residual stress, the anchor stiffness and the bending rigidity are obtained from the nano-bending test for MEMS cantilevers to remove the uncertainty in the geometry of the anchor and the material properties.

The residual stress is identified from the measurement of the bending stiffness of the MEMS bridge. The analytic model is used as the reference system to calculate the residual stress from the measured stiffness. The anchor stiffness and the bending rigidity are used to represent the effects of the anchor geometry and the material properties. The nano-indenter system is adopted as the external nano-bending load system.

The present nano-bending method does not need any electrical components and it does not require any pre or post treatment. Therefore, in-situ measurement can be done during the conventional surface micromachining process. Since the size of the test specimen is very small, the obtained residual stress is local value at a local point. The straightforward load-displacement relationship from the nano-indenter system makes the experiment easy.

The experimental results for the surface micromachined MEMS with 2.3 μm poly-silicon demonstrate the reliability and the accuracy of the present nano-bending method.

2 ANALYTIC MODEL

The analytic model of the MEMS bridges is established incorporating the residual stress effect. This analysis model is used as a reference to obtain the residual stress from the measured bending stiffness of the MEMS bridge.

Prior to the nano-bending experiment for the MEMS bridge, the anchor stiffness and the bending rigidity are obtained from the nano-bending experiment for the surface micromachined cantilevers. An analytic model of the MEMS cantilevers with finite anchor stiffness is developed providing reference for the experiment.

Finite element analysis is conducted to verify the analytic models. The effects of the anchor geometry and the residual stress on the MEMS cantilevers and bridges are studied through numerical simulations.

2.1 Surface micromachined MEMS cantilevers

Figure 1-(a) show a surface micromachined MEMS cantilever with length l. The nano-bending load from the nano-indenter system is symbolized as P. The anchor geometry is formed during removing the sacrificial layer beneath the cantilevers in the fabrication process. Figure 1-(b) shows the analytic model of the MEMS cantilever with the finite anchor stiffness K_θ. If the anchor stiffness is infinitive, the simplified model with rigid boundary is shown in the figure 1-(c). However, general surface micromachined structures are considerably affected by the anchor stiffness. Therefore, the present study adopts the analytic model in the figure 1-(b) for the MEMS cantilever.

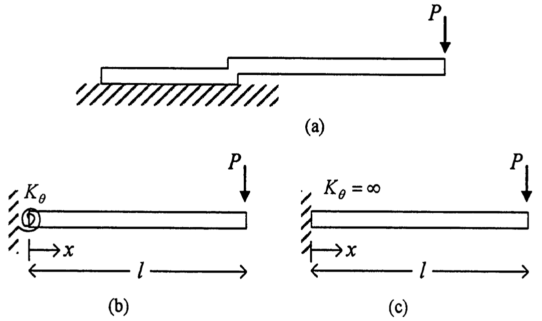

Figure 1: (a) Surface micromachined MEMS cantilever with the anchor geometry; (b) Analytic model of MEMS cantilever with finite anchor stiffness; (c) Analytic model of MEMS cantilever with rigid boundary

The displacement at the tip of the present analytic model is obtained as follows:

$$w_p = w\big|_{x=l} = \frac{P}{K} = \left(\frac{l^3}{3EI} + \frac{l^2}{K_\theta} \right) P \tag{1}$$

where EI is the bending rigidity of the beam.

If the effect of the anchor stiffness is ignored, the displacement in Eq. (1) is simplified such as:

$$\lim_{K_\theta \to \infty} w_p = \frac{l^3}{3EI} P \tag{2}$$

which is same with the result from the conventional cantilever model with rigid boundary shown in the figure 1-(c).

Note that the bending rigidity EI and the anchor stiffness K_θ are independent of the length of beam. Therefore the bending rigidity and the anchor stiffness can be acquired through the nano-bending test for two micro cantilevers with different length as shown in the following Equation.

$$\begin{Bmatrix} \dfrac{1}{EI} \\ \dfrac{1}{K_\theta} \end{Bmatrix} = \begin{bmatrix} l_{(1)}^3/3 & l_{(1)}^2 \\ l_{(2)}^3/3 & l_{(2)}^2 \end{bmatrix}^{-1} \begin{Bmatrix} 1/K_{(1)}^* \\ 1/K_{(2)}^* \end{Bmatrix} \tag{3}$$

In Eq. (3), the superscript '*' means the quantities obtained from the experiments and the subscript (1) and (2) represent two cantilevers with different length. The matrix computation in Eq. (3) results in EI and K_θ.

Figure 2 shows the bending stiffness of MEMS cantilevers calculated from the analytic models and FEA simulations. The stiffness is divided by the reference stiffness from Eq. (2). It is clear from the figure that the contribution of the finite anchor stiffness is considerable particularly in the short cantilevers.

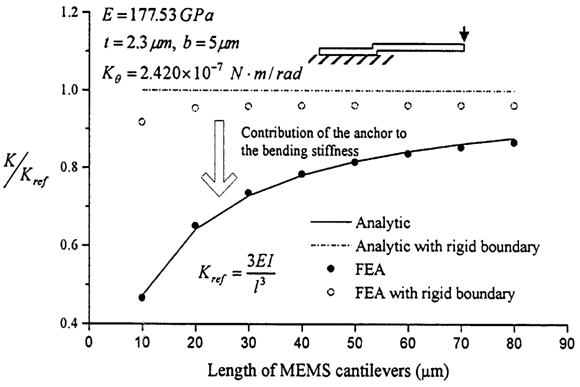

Figure 2: The bending stiffness of MEMS cantilevers with various length

2.2 Surface micromachined MEMS bridges

Figure 3-(a) shows schematic drawing of doubly supported MEMS bridge under nano-bending force. Figure 3-(b) illustrates the free body of diagram in an arbitrary section of the bridge. The nano-bending force is symbolized as P and the reaction moment at the boundary is expressed as M_o. The axial force N_x is produced by the residual stress σ_r as follows:

$$N_x = -\sigma_r bt \tag{4}$$

where b and t denote the width and the thickness of micro bridges, respectively.

The analytic model for the MEMS bridge is shown in figure 4-(a). The contribution of the anchor geometry is modeled as the anchor stiffness K_θ in the present analytic model. The analytic model with rigid boundary is illustrated in figure 4-(b), which have been conventionally adopted in the previous researches [7].

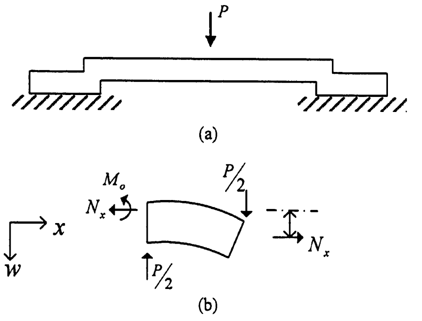

Figure 3: (a) Schematic sketch of micro bridges under nano-indenter load at the center; (b) free body of diagram

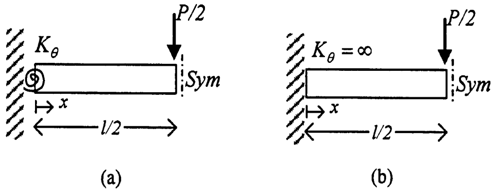

Figure 4: (a) Analytic model of MEMS bridge with finite anchor stiffness subjected to the nano-bending force; (b) Analytic model of MEMS bridge with rigid boundary subjected to the nano-bending force

After applying appropriate boundary conditions and the symmetry condition at the center of the beam, the bending stiffness of MEMS bridge with compressive residual stress is expressed as:

$$K = -\frac{4EIk^3\left(EIk\cos\frac{kl}{2} + K_\theta \sin\frac{kl}{2}\right)}{-4K_\theta + \left(4K_\theta + EIk^2 l\right)\cos\frac{kl}{2} + \left(-2EIk + klK_\theta\right)\sin\frac{kl}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

and the bending stiffness of MEMS bridge with tensile residual stress is:

$$K = \frac{4EIk^3\left(EIk\cosh\frac{kl}{2} + K_\theta \sinh\frac{kl}{2}\right)}{4K_\theta + \left(-4K_\theta + EIk^2 l\right)\cosh\frac{kl}{2} + \left(-2EIk + klK_\theta\right)\sinh\frac{kl}{2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

In Eqs. (5,6), the complex parameter k is defined as follows:

$$k \equiv \sqrt{\frac{|\sigma_r| bt}{EI}} \tag{7}$$

The bending stiffness of MEMS bridge is obtained as numerical values from the nano-bending experiment. Then, the unknown parameters in Eqs. (5,6) are the bending rigidity EI, the anchor stiffness K_θ, and the complex parameter k. Among them, the bending rigidity and the anchor stiffness are achieved from the nano-bending experiment for the MEMS cantilevers. Therefore, the complex parameter k remains the only unknown quantity in Eqs. (5,6).

After solving Eqs. (5,6) for k, the complex parameter k is obtained as a numerical value. Recalling Eq. (7), the residual stress can be acquired as follows:

$$\sigma_r = \frac{k^2 EI}{bt} \tag{8}$$

The sign of the residual stress is positive if it is compressive and vice versa if it is tensile.

Figure 5 shows the load-displacement relationship of the MEMS bridge with the length of 90 μm. The present analytic model agrees well with the FEA simulation. The effect of the anchor geometry is clearly demonstrated. As the displacement exceeds the linear range, the geometrically nonlinearity grows. The stiffness data in the experiment is obtained in the linear range.

Figure 6 shows the stiffness of MEMS bridge with the length of 90 μm. It is apparent in the figures that the residual stress in MEMS bridge leads to considerable change of the stiffness.

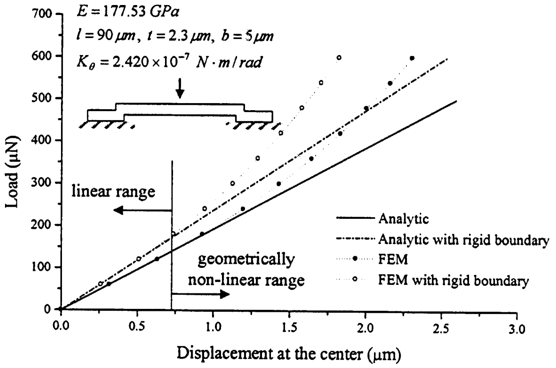

Figure 5: Load-displacement relationship of MEMS bridge with the length of 90 μm

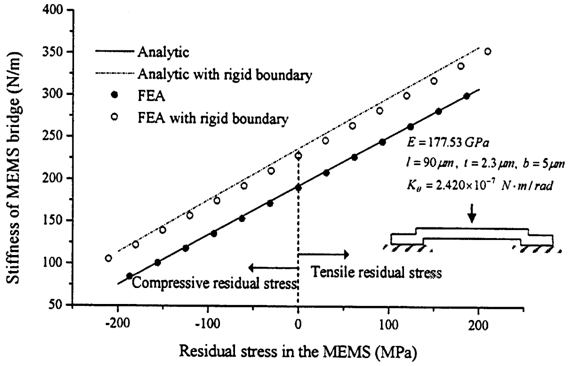

Figure 6: Residual stress effect on the stiffness of MEMS bridge with length L=90 um

3 EXPERIMENTS

3.1 Experimental procedure

Figure 7 summarizes the experimental process of the present nano-bending method. The specimens consisting of MEMS cantilevers and MEMS bridges are prepared by the surface micromachining process with 2.3 μm poly-silicon. The bending rigidity EI and the anchor stiffness K_θ are acquired from the nano-bending experiment for the MEMS cantilevers. Then the nano-bending experiment for the MEMS bridge is carried out to obtain their stiffness. Comparing the stiffness with the reference stiffness determines the stress type; the compressive residual stress and the tensile residual stress. After determining the complex parameter k by applying the experimental results to the analytic model, the residual stress can be obtained from the definition of k.

3.2 Fabrication

The MEMS beams are fabricated on the basis of the surface micromachining technology. At first, after cleaning the substrate the TEOS layer is deposited using PECVD process. Then, LPCVD poly-silicon is deposited following the patterning process for the anchor. RTA (Rapid thermal annealing) process with six cases of temperature is followed to obtain diverse specimens with various residual stresses. Then, the ploy-silicon is etched to make beam geometry. Finally the TEOS sacrificial layer is removed in the HF solution. Figure 8 displays the SEM pictures of the fabricated MEMS beams. Table 1 shows the six cases of the prepared specimens with different temperature of the RTA process.

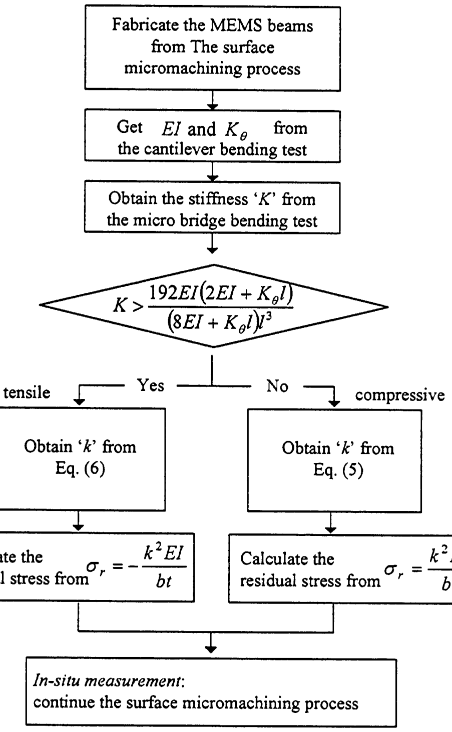

Figure 7: The experimental flow of the present nano-bending test to quantify the residual stress in the MEMS structures

Specimens	spec. A	spec. B	spec. C	spec. D	spec. E	spec. F
RTA temperature (℃)	as depo.	900	950	1000	1050	1100

Table 1: Specimens with different temperature of RTA (Rapid thermal annealing) process

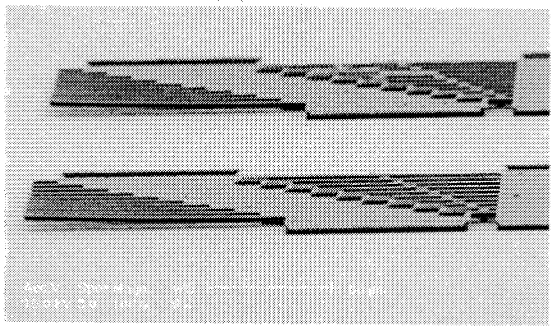

Figure 8: Fabricated MEMS cantilevers and bridges from the surface micromachining process

3.3 Nano-bending experiment for MEMS cantilevers

The present nano-bending method is applied to the MEMS cantilevers. The aim of the present experiment is to obtain the bending rigidity EI and the anchor stiffness K_θ. Among the MEMS cantilevers, two beams with the length of 20 μm and 30 μm are selected for the experiment. Five tests for each case of the length are conducted for every specimen in Table1. The load-displacement data shown in figure 9 are analyzed to obtain the stiffness of MEMS cantilevers. The bending stiffness of the MEMS cantilevers are achieved from the inclination of the load-displacement graphs and are displayed in figure 10. Then, the bending rigidity and the anchor stiffness are achieved as shown in figure 11.

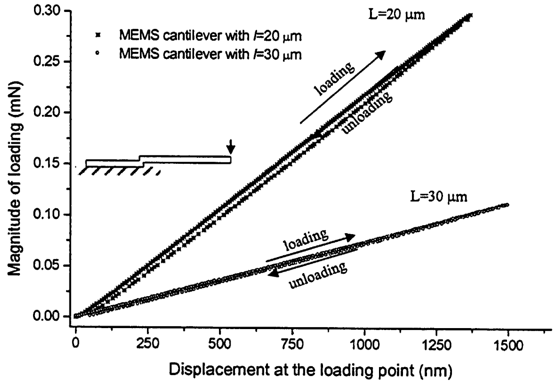

Figure 9: Load-displacement relationships of MEMS cantilevers with the length of 20 μm and 30 μm

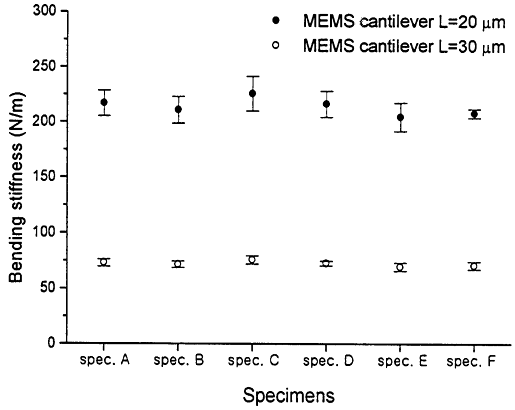

Figure 10: Bending stiffness of the MEMS cantilevers from six cases of wafers with different RTA temperature

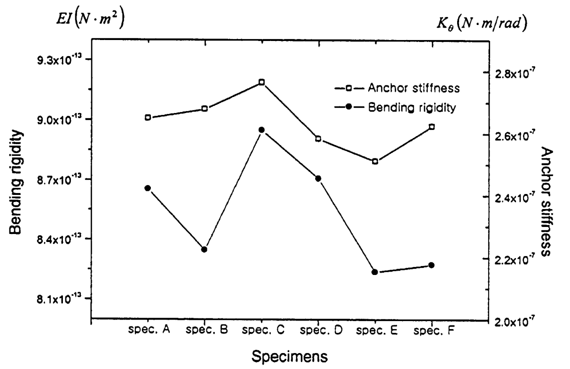

Figure 11: Bending rigidity and anchor stiffness of the MEMS cantilevers

3.4 Nano-bending experiment for MEMS bridges

The nano-bending method is applied to the MEMS bridges to quantify the residual stress. Two beams with the length of 90 μm and 100 μm are selected for the experiment. The experiments are performed about ten times for bridges with same length in every specimen.

The load-displacement relationships of the MEMS bridges with the length of 100 μm are depicted in figure 12. It is apparent that the six cases of the MEMS beams exhibit different behaviors. The geometrically non-linear effect is observed in both figures as expected from the FEA simulations in figure 5.

The bending stiffness of the MEMS bridges are obtained from the load-displacement relationship as shown in figure 13. The results demonstrate that the bending stiffness of MEMS bridge significantly changes due to the temperature of the RTA process.

Then, Eq. (5) and Eq. (6) are utilized to calculate the residual stress. The bending rigidity and the anchor stiffness previously obtained from the MEMS cantilevers are used in obtaining the residual stress. Figure 14 demonstrates the decreasing residual stress as the temperature of the RTA process increases. It is clear from the figure that the present nano-bending method is reliable measurement technique to evaluate the residual stress in MEMS structures.

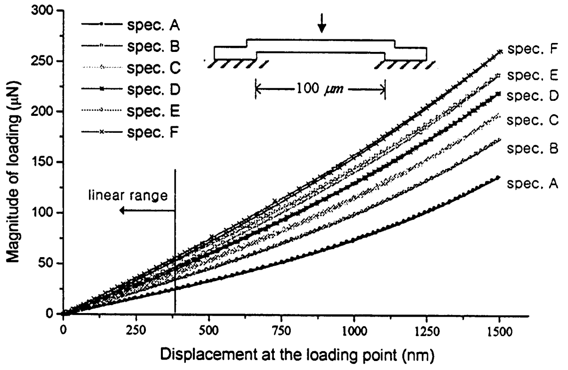

Figure 12: Load-displacement relationships of MEMS bridges with the length of 100 μm

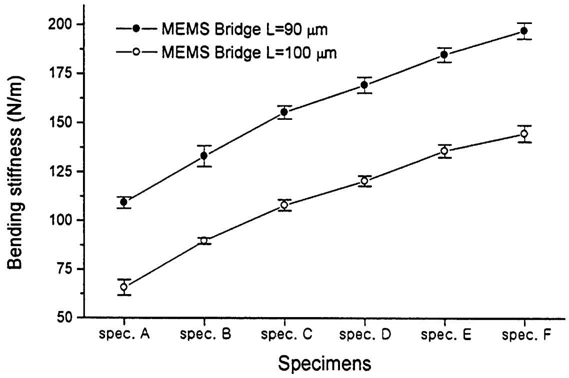

Figure 13: Bending stiffness of the MEMS bridge

4 CONCLUSION

The nano-bending method is proposed to quantify the residual stress in the MEMS structure. The present study provides robust analytic model to assess the residual stress effect from the measured bending stiffness of the MEMS beams. Finite element analysis is performed to verify the analytic model. The anchor stiffness and the bending rigidity of the surface micromachined MEMS beams are identified through the nano-bending experiment for the MEMS cantilevers. Finally, the residual stress in the surface-micromachined MEMS is obtained from the nano-bending experiment for the MEMS bridge.

The experiments are performed for the surface micromachined MEMS with 2.3 μm poly-silicon. Six cases of specimens are prepared with different temperature of the RTA process. The experimental result demonstrates the reliability and the accuracy of the present nano-bending method for the quantification of the residual stress in the MEMS structure.

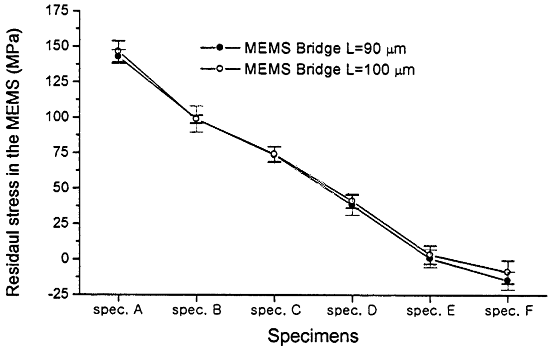

Figure 14: Residual stress obtained from the bending stiffness of MEMS bridges

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