A new micro-rotating structure

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Abstract. This paper presents a new micro-rotating structure for the local measurement of residual strain in thin films. Compared with a conventional rotating structure, the new structure doesn’t have a rotating point, but has lower residual strain distribution after deformation, a more precise test model, and larger measurement range. An analytical expression to calculate the residual strain is given so that the residual strain can be easily evaluated from the deflection of the rotating beam. Finite-element method (FEM) was also used both to optimize the design and to calibrate the new structure. Residual strains in LPCVD polysilicon films were determined by the new structure and compared with measurements by the conventional rotating structure. The two methods lead to comparable results.

1. Introduction

With the increasing use of surface micromachining for the fabrication of sensors and actuators, there is the need for a greater understanding of residual strain within deposited thin films. In many applications, low tensile strain is required to ensure that etched structures remain flat. In cases where compressive strain exists, structures may buckle after etching. It is, therefore, important to be able to measure the residual strain in order to optimize the process.

Many different techniques to perform these measurements have been developed during past years [1-5]. The most simple and useful approach uses strain sensors designed to operate passively [6]. These are basically undercut structures that deform measurably under the residual strain of the material. The passive strain sensors that were developed in the past include bridges and rings that buckle under compressive and tensile stresses, respectively, T-shaped structures with wide, long center beams, and thinner, deformable cross beams that provide a measure of the deformation either directly or by titling a long cantilever, and bridges with an intermediate lateral displacement that rotates a long pointer when deformed. The passive strain sensors are attractive because they can provide quantitative readout from an observation of the deformation under a microscope [7].

Figure 1 shows a conventional micro-rotating structure, introduced by Goosen et al. initially to measure residual strain in the thin films [6]. The micro-rotating structure was designed in such a fashion that when a film is freed from an underlying sacrificial layer, the residual strain in the film is released and hence the rotating beam is deflected. Consequently, residual strain can be evaluated at different locations on a silicon wafer. In addition, the micro-rotating structures have the ability to measure a large range of residual tensile or compressive strain. This technique is compatible with the sacrificed fabrication process and allows in situ residual strain measurements in the thin films [8].
In all conventional micro-rotating structures, necks were designed to decrease the width of the connection between the actuating beam and the rotating beam. These two necks, also named rotating points, were introduced to enhance the sensitivity of the structure. However, these two rotating points also introduce some troubles simultaneously. Because the rotating points have high strain concentration after the structure deformed, they are easy to be broken [8]. So the rotating points reduce both percent of pass and measuring range of conventional micro-rotating structures. At the meantime, there is no effectively analytical formula for the conventional micro-rotating structure.

This paper presents a new micro-rotating structure. Compared with conventional micro-rotating structures, the new structure has no rotating point. The widths of actuating beams of the new structure are uniform and less than that of conventional actuating beam [9]. Figure 2 shows a schematical representation of the new micro-rotating structure.

2. Theoretical Model

2.1. Analytical Modeling.

The new micro-rotating structure is a statically indeterminate structure with the degree of indeterminacy being 3, which can be modeled analytically using the force method. The force method is first used here to analyze the displacement and rotation at the end of left actuating beam due to the three redundant, X1, X2 and X3, as shown in Figure 3. Here X1 stands for a unit horizontal force; X2 stands for a unit vertical force; and X3 stands for a unit couple force. The virtual work method is then utilized to calculate the deflection of the left actuating beam tip. Following the force method [10][11], the three redundant X1, X2 and X3 can be obtained by solving a set of simultaneous equations:
where terms $\delta_i$ represent flexibility coefficients, which can be obtained by the diagram product of the bending moments. They are given by, respectively.

\[
\begin{bmatrix}
\delta_{11} & \delta_{12} & \delta_{13} \\
\delta_{21} & \delta_{22} & \delta_{23} \\
\delta_{31} & \delta_{32} & \delta_{33}
\end{bmatrix}
\begin{bmatrix}
X_1 \\
X_2 \\
X_3
\end{bmatrix}
= \begin{bmatrix}
L_a \cdot \varepsilon \\
(2L_a + W_T) \cdot \varepsilon \\
0
\end{bmatrix}
\] (1)

| $\delta_{11}$ | $\delta_{12}$ | $\delta_{13}$ | $\delta_{21}$ | $\delta_{22}$ | $\delta_{23}$ | $\delta_{31}$ | $\delta_{32}$ | $\delta_{33}$ |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $16L_a^3 + 18W_TL_a^2 + 6W_T^2L_a$ | $3L_a^3L_a + 2L_aL_WW_T$ | $2L_a^2 + L_WW_T$ | $0$ | $0$ | $3L_a^2 + 2W_TL_a$ | $-L_aL_w$ | $2L_a^2 + L_WW_T$ | $\frac{2L_a^2 + L_WW_T}{EI}$ |

where $E$ is the Young’s modulus of film, $G$ is the shear modulus of film, $\varepsilon$ is the residual strain of film, $I (=TW^3/12)$ is the moment of inertia, $EI$ represents the flexural rigidity of the beams, $T$ is the thickness of the beams, $K$ is a modifying factor of section of beam, for rectangle beam here, $K=1.24$ [9]. The other parameters are as shown in Figure 3. The three redundant $X_1$, $X_2$ and $X_3$ can be obtained by Eq. (1). Once they are solved, the bending moment of the actuating beam due to residual strain can be obtained. According to the method of the virtual work, the deflection in the point C, where actuating beam connects indicating beam, can be obtained as follow:

Horizontal displacement:

\[
\Delta_H = \frac{X_2 \cdot L_a}{E \cdot A} - L_a \cdot \varepsilon
\] (2)

Vertical displacement:

\[
\Delta_V = \frac{L_a^3 \cdot X_1}{3E \cdot I} + \frac{L_a^2}{2E \cdot I} \left[ X_1(L_a + W_T) - X_2L_a - W_T \right]
\] (3)

Rotary displacement:

\[
\Delta_\theta = \frac{L_a^2X_1}{2EI} + \frac{L_aX_1(L_a - W_T) - X_2L_a - W_T}{EI}
\] (4)

According Eq. (3), (4) and (5), the deflection in the tip of indicating beam can be obtained as follows:

\[
\Delta = L_r \cdot \Delta_\theta + \Delta_H
\] (5)

It follows from Eq. (6) that the deflection in the tip of indicating beam is a function of physical dimensions of microstructure and residual strain in film, but it has nothing with the thickness or Young’s modulus of film.

Eq. (6) also means that the residual strain is a function of deflection of indicating beam.

\[
\varepsilon = \varepsilon(\Delta)
\] (6)

From Eq. (7) we can obtain residual strain in the film by measuring the deflection of indicating beam of the new micro-rotating structure.

2.2. Error Modeling

A first-order error analysis can be carried out by examining Eq. (6). $\Delta$ and $W$, the reading of the deflection of the indicating beam and the width of beams respectively, are the main source of error while other parameters have negligible error effects. The residual strain error can be represented as

\[
d\varepsilon = \frac{\partial \varepsilon}{\partial \Delta} d\Delta + \frac{\partial \varepsilon}{\partial W} dW
\] (7)
The resolution of $\Delta$ is mainly determined by the resolution of the microscope and the design of the output, which may be a vernier gauge [7]. With well design parameters, a best resolution of $0.2\mu$m and uncertainty of $0.1\mu$m can be achieved for $\Delta$. The resolution of $W$ is determined by mask and etching condition.

3. FEM simulations and structure design

In order to confirm the analytical results above and compare the performances of the new micro-rotating structure with the conventional micro-rotating structure, numerical analysis of the new structure and conventional structure were performed with commercialized finite-element modeling (FEM) software, ANSYS®. Residual strain in the model was introduced by the standard technique of applying a uniform temperature change with a uniform temperature coefficient.

$$\varepsilon = \Delta T \cdot \alpha$$

where $\Delta T$ is temperature change and $\alpha$ is the thermal expansion coefficient of the polysilicon film.

The material parameters used in our FEM were as follow: Young’s modulus, $E$, is 180GPa; Since the Poisson ratio of employed materials usually varies only slightly from 0.2 to 0.3, and its effect on the residual strain is nearly negligible, we keep it as a constant, i.e. $\nu = 0.22$; $\alpha = 2.7\mu$$/^\circ$C; the thickness of film is $1\mu$m. And the element selected in ANSYS® software for simulation is plane183. The geometric parameters of micro-rotating structures were listed in table 1.

| Geometric | New Structure | Conventional Structure |
|-----------|---------------|------------------------|
| $L_a$     | 200           | 200                    |
| $W_a$     | 5             | 5                      |
| $L_r$     | 202.5         | 202.5                  |
| $W_r$     | 11            | 5                      |
| $L_g$     | 15            | 15                     |
| $W_o$     | 2             | 2                      |
| $L_o$     | 2             | 2                      |

According to linear elasticity [11], the residual displacement and hence the deflection is directly proportional to the residual strain. Therefore, we expect that the tip deflection is directly proportional to $\varepsilon$. Figure 4 shows that the deflection of indicating beam is proportional to residual strain and the analytic modeling of new micro-rotating structure agrees with FEM and the sensitivity of the new micro-rotating structure is not less than that of the conventional structure.

![Figure 4](image1.png)

**Figure 4.** The deflection of rotating beam as one function of residual strain

![Figure 5](image2.png)

**Figure 5.** FEA representation of residual stress distributions in the new structure after deformation.
Figure 5 show the distribution of residual stress in the new micro-rotating structure after release of residual strain which is 0.0016. It can be obtained from FEM results that the new structure’s residual stress on deformed is 0.25 of the conventional structure’s residual stress. FEM results also show that the conventional micro-rotating structures are easier to be broken than the new structures due to high stress concentration.

4. Experiment
To validate the new micro-rotating structure, both the new and conventional micro-rotating structures were fabricated by using the standard surface micromachining process provided by Peking University. The experiment results indicate that the sensitivity of the new structure (0.0048μm/με) is a little less than that of the conventional structure (0.0050μm/με).

After the residual strain (261.5με) of the polysilicon film is released, maximum strain value in the deformed new micro-rotating structure is 692με, which is only 30% of the conventional structure. So the new micro-rotating structure is steadier and has the ability to locally measure a larger range of tensile or compressive residual strain in the thin films with appropriate sensitivities.

5. Concluding remarks
This work presents a new micro-rotating structure of strain sensor for both tensile and compressive strain measurements. A formula to calculate the residual strain from the deflection of the rotating beam is developed. The residual strains, therefore, can be easily evaluated from the deflection. The FEM simulation and experiment results indicate that new micro-rotating structure has the ability to locally measure a large range of tensile or compressive residual strain in the thin films with appropriate sensitivities.

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