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Residual Stress Measurement of Micro Gold Electroplated Structure

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ABSTRACT

In this paper, a simple method to measure the residual stress in microstructure is presented. In order to find the residual stress in micro-machined beam, the first natural frequency of the beam that has the residual stress inside is analyzed using Rayleigh's energy method. Micro gold electroplated structure is fabricated by surface micro-machining process including electroplating. The made structure is an approximate shape of clamped-clamped beam and its 1st natural frequency is measured by resonance method. For the better estimation of the residual stress, an equivalent length of micro-fabricated beam to ideal beam is calculated by FEM. The residual stress was estimated from the equivalent length and the measured natural frequency. It was found that a tensile stress was residue in the micro beam structure.

Keywords : Microstructure, Surface micro-machining, Gold electroplating, Residual stress

1. Introduction

Precise design of a microstructure is needed in MEMS for the reliable performance of micro machine. Especially, when we design a mechanical structure, exact mechanical properties of the structure material are required. The mechanical properties are dependent on the micro-machining process Therefore, many researches to measure the strength like the yield strength and the stiffness like the young's modulus are on going. After the microstructure is fabricated according to the design, it is desirable that residual stresses inside microstructure should be as small as possible for the reliable operation of micro machine. Therefore, the measurement method for the residual stress produced during micro-fabrication process have been studied(3). To measure the mechanical properties and residual stress, the nano-hardness test(4), the micro tension test(1), the cantilever beam resonance test(5), and the membrane bulge test(6) etc. have been used.

Gold electroplating has been mainly used in elector and electric component industry, but a few in micro electro mechanical systems. Since gold has a good affinity for organism cell, it is expected for the gold electroplating to be widely used in micro bio and medical instrument field in future.

In this paper, we proposed the measuring method of the residual stress as the basic study for the control of residual stress in micro-fabricated structure. To measure the residual stress, we made a microstructure whose shape is a clamped-clamped beam and then measured a natural frequency of the microstructure by using a resonance method. Consequently, by analyzing the measured frequency in Rayleigh's energy method, we tried to found the approximate magnitude of the residual stress of the micro-fabricated beam.

2. Measurement theory of residual stress

If there is a tensile residual stress in a clamped-clamped beam structure, the natural frequency of the beam is increased. It may be because the stiffness of the micro beam is increased by the tensile stress in the beam. By using the Rayleigh's energy method, we can approximately derive the first mode natural frequency of the beam in which there is a tensile stress. When an ideal shaped beam in which Euler's beam theory can be applied vibrates in the direction of beam thickness, the maximum kinetic energy $T_{\max}$ of the beam is as follows:

$$T_{\max} = 2\pi^2 f^2 \rho A \int_0^l Y^2(x)dx \qquad (1)$$

where, f is a natural frequency, A is a cross-section area, x is a location variable in the length direction of the beam, l is a whole length of the beam, ρ is a density of the beam material, and $Y(x)$ is a displacement function of the beam in the thickness direction at the position of x. A maximum potential energy U_{max} is composed of the energies resulted from a bending moment and a tensile stress, and is expressed as follows:

$$U_{\max} = \frac{EI}{2}\int_0^l \left(\frac{d^2Y(x)}{dx^2}\right)^2 dx + \frac{\sigma A}{2}\int_0^l \left(\frac{dY(x)}{dx}\right)^2 dx \qquad (2)$$

where, I is a bending potential moment, E is an elastic modulus. We assume that there is a constant tensile stress σ in a whole cross section of a beam.

We assumed that a displacement function $Y(x)$ is $cos(2\pi x/l)-1$ that satisfies a boundary condition and is an approximate first mode shape. Then, by the condition that maximum kinetic energy and maximum potential energy are equal ($T_{max}=U_{max}$), we can derive the 1st mode natural frequency f[Hz] of the beam as follows:

$$f^2 = \frac{1}{3}\left(\frac{\sigma}{\rho l^2} + \frac{\pi^2}{3}\frac{Et^2}{\rho l^4}\right) \qquad (3)$$

where, t is a beam thickness. By substituting the measured natural frequency and elastic modulus of the beam material into Equation (3), we can obtain the value of the tensile residual stress in the micro beam.

3. Fabrication of micro gold-structure

Fig.1 is the half shape of the micro clamped-clamped beam structure designed to measure a residual stress. And Fig.2 is the fabrication process of the designed micro gold structure by using the electroplating. We applied a double electroplating process of Ni-Au to make a dynamic structure that is apart from a substrate and vibrates vertically above the substrate. During the fabrication process, Ni was used as sacrificial layer and gold was used as structure layer. In order to fabricate an anchor, we used over electroplating method that is isotropic process.

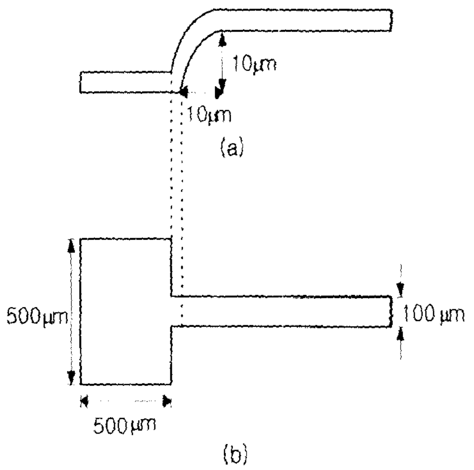
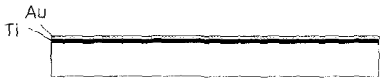


Fig. 1 (a) Side view and (b) plane view of specimen

Firstly, we used n-type silicon as a substrate in which thermal oxidation layer is deposited with 5000Å thickness. We deposited Ti(200Å)-Au(1000Å) used as seed layer on the substrate by thermal evaporation(Fig.2(a)). For the improvement of bonding property, the deposition was done with heating the substrate about 200℃. Next, for the gold electroplating used as the seed layer of sacrificial nickel layer electroplating, photo resist (AZ5214E) was patterned with thickness of 1.5㎛ to be used as an electroplating mold and thin gold layer was deposited in the thickness of 3000Å. The reason of electroplating this gold layer is that over electroplating of sacrificial nickel layer is hard to perform on the thermal evaporated layer.

When the electroplating was finished, the PR was removed and the Au-Ti seed layers were etched away continuously until the electrodes were isolated (Fig. 2(c)). Then the thick PR was spin-coated to form an electroplating mold used for sacrificial nickel electroplating (Fig. 2(d)). In order to form a sacrificial layer, the nickel was electroplated in the electroplating mold with a thickness of about 30 ㎛. During this process, the initial current only flowed to the drive electrode (Fig. 2(c)), not the anchor electrode by patterning the paths of the current. This process enabled the electroplating to take place in the drive electrode only, not in the anchor electrode because an oxidation layer isolated the substrate. However, in the part unbounded by the electroplating mold, the nickel grew in a horizontal direction as shown in Fig. 2(e) due to the isotropic characteristics.

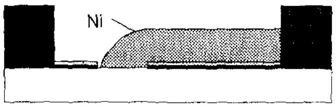


(a) seed layer deposition

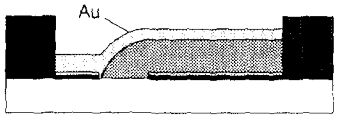
(b) PR patterning & short electroplating for plating base lines

(c) wet etching of evaporated gold and titanium seed layer & PR strip

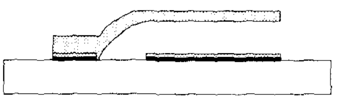
(d) thick PR coating & UV lithography for electroplating mould



(e) sacrificial nickel electroplating



(f) structural gold electroplating



(g) mould strip & releasing

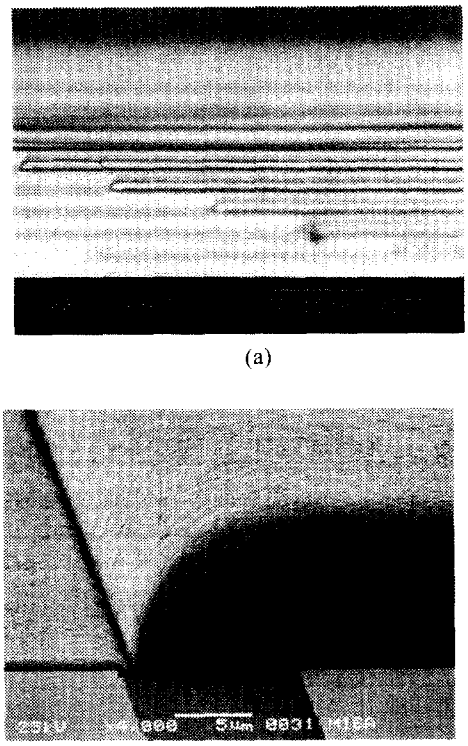
Fig. 2 Fabrication process of microstructure

The nickel electroplating was continuously performed until the electroplated nickel reached the anchor electrode, and then gold electroplating of the desired thickness was performed. The finally obtained shape is shown in Fig. 2(f). This process required a caution. Once the side-growing nickel reaches the anchor electrode and is electrically connected, the anchor electrode is also nickel electroplated. If the anchor is nickel electroplated, the micro beam is detached from the anchor when the sacrificial layer is etched away. We set the current density at 2 ㎃/㎠ during the electroplating process.

Finally, we etched the nickel sacrificial layer with 38% hydrochloric acid solution and washed it with DI water and IPA. After drying the microstructure, we obtained a micro beam (Fig. 2(g)). We used a sulfamate as the nickel electroplating solution and a commercial non-cyanide (NEUTRONEX210, EEJA) as the gold electroplating solution.

We micro-fabricated a number of micro clamped-clamped beam structures with various beam lengths. SEM photographs of the micro-fabricated beams are shown in Fig. 3. Micro beams with lengths of over 700 ㎛ showed the sticking of the beam to the substrate surface due to the adhesion between them which occurred in the process of micro-fabrication. In Fig. 3(b), the part where the beam connects to the substrate is bent. Through more careful observation of the picture, it can be seen that the bent area is not a perfect arc as designed in Fig.1. The height is 10 ㎛, but the width is only 7 ㎛.

The final shape of the electroplated anchor depends on that how long the isotropic process is kept on. Theoretically, if the isotropic nickel electroplating progressed perfectly, the lengths of both sides would be exactly the same of 10 ㎛. However, it seemed that nickel electroplating progressed faster in the vertical direction than in the horizontal direction. Hence the thickness of the beam in the horizontal direction is greater than that of in the vertical direction. This is affected by what additive is mixed with the electroplating solution. For example, if a saccharine is added in the electroplating solution, the progress of electroplating in the vertical direction is more dominant. Nevertheless, controlling the curvature of the shape is an extremely difficult process.



(a)

(b)

Fig. 3 SEM photographs of (a) whole view of released gold microstructures and (b) magnified view of anchor part of it

4. Experimental

The drive and measurement system used in the resonance test for the micro cramped-cramped beam structure is shown in Fig. 4. While changing the periodic frequency of electrostatic force exerted vertically on the beam, we measured the amount of vibration displacement of the beam by using a laser displacement meter. We observed the area where the maximum displacement could be occurred during the resonation, based on the theoretical vibration mode. We measured the 1st resonance frequency by monitoring the rapid resonance displacement with the variation of the periodic frequency of electrostatic force.

A beam diameter of the laser displacement meter used in this experiment is of about 20 ㎛ and the maximum measurable displacement is of 10 ㎜ and the accuracy is of 0.01 ㎛. The most of micro fabricated beam structures had no problem with measuring the resonance frequency. However, since the maximum measurable frequency with the laser meter was 50 ㎑, we had to use only the micro beam structures which had the 1st resonance frequency under than 25 ㎑. Therefore, for the measurement of residual stress, we used the micro beam structure with a flat area of 400 ㎛ in length, 100 ㎛ in width, 2.8 ㎛ in thickness, and 10 ㎛ in gap from the surface. Besides the laser meter with the measurement accuracy of 0.01 ㎑, we also performed the detection of the resonance through an optical microscope.

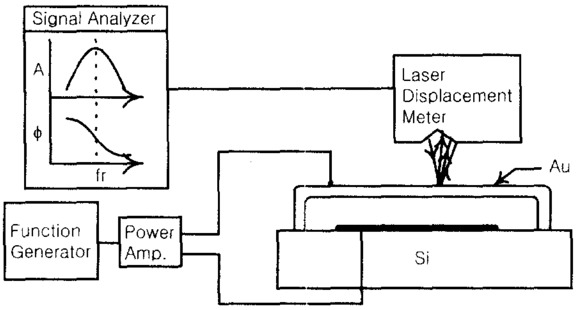


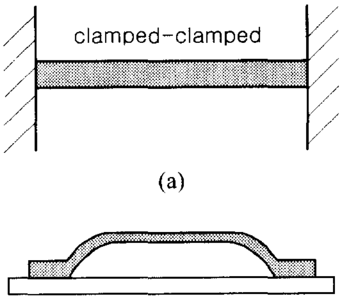
Fig. 4 Schematic of measurement system for resonance frequency

5. Results

Natural frequency was measured by using a resonance test device. For the measurement, we applied an electrostatic force of which voltage periodically changes from 0 V to 120 V to the microstructure as an external driving force using the AC power source. We measured resonance frequency of the microstructure with variation of the frequency of the electrostatic force. As a result, the measured first mode natural frequency was 36.0 ㎑.

The value of the elastic modulus (E) is to be kwon to estimate the magnitude of the residual stress by substituting the measured natural frequency into Equation (3). According to the result of our previous test(8) in which we obtained the magnitude of the elastic modulus by resonance test of the micro beam micro-fabricated by the same gold electroplating process, the elastic modulus was 43 ㎬ when the current density was 2 ㎃/㎠. The residual stress could be obtained by using this magnitude of the elastic modulus.

Equation (3), which was derived to estimate the residual stress, is correct when the beam is totally flat as shown in Fig. 5(a). However, the anchor part of the actually micro-fabricated structure is not flat as shown in Fig. 5(b) and this must be causing the spring effect(9). In order to apply Equation (3) to the actually micro-fabricated beam structure without error, we proposed an equivalent length (l_e) of the actual beam corresponding to the theoretical shape of the beam. First, in the case of no residual stress inside the beam, we obtained the first mode natural frequency for the shape of the actually micro-fabricated beam by using a commercial FEM program (ANSYS) as shown in Fig. 6. For the analysis, we used 81.2 ㎬ as an elastic modulus and 19.32 g/㎤ as a density, which are the material properties of general gold bulk material, and then obtained 34.692 ㎑ as the first mode natural frequency.



(a)

(b)

Fig. 5 (a) Ideal and (b) micro-fabricated bridge type micro beams

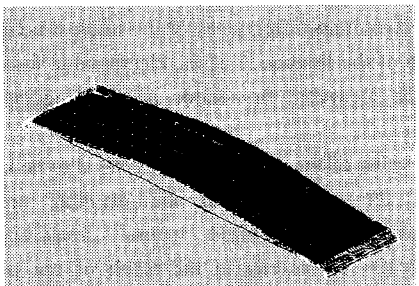


Fig. 6 The 1st mode shape of micro beam by FEM

The first mode natural frequency of the clamped-clamped beam of the ideal shape with no residual stress could be obtained by using the Euler's beam theory as follows:

$$f = \frac{4.730041^2 t}{4\pi l^2}\sqrt{\frac{E}{3\rho}} \tag{4}$$

The length of the beam in the ideal shape which has the same natural frequency as that obtained by the FEM analysis is calculated from Equation (4) and the result is 412.5 ㎛. We assumed this result as the equivalent length (412.5 ㎛) of the actual beam and used it instead the actual length (400 ㎛) for the estimation of the residual stress. This procedure is summarized in Table 1.

Table 1. Calculation of equivalent beam length (l_e)

Method	Given values	Calculated value
FEM (ANSYS)	t = 2.8 ㎛, l = 400 ㎛, ρ =19.32 g/㎤, E = 81.2 ㎬	f = 34.692 ㎑
Equation (4)	t = 2.8 ㎛, f = 34.692 ㎑, ρ =19.32 g/㎤, E = 81.2 ㎬	l_e = 412.5 ㎛

We assumed that the beam length is 412.5 ㎛, the elastic modulus is 43 ㎬, and the density of a micro material is 19.32 g/㎤. We substituted 36.0 ㎑, the measured value of natural frequency, into Equation (3). As a result, we obtained 6.26 ㎫ as the mean value of tensile residual stress in the microstructure. Therefore, when the microstructure is micro-fabricated by the gold electroplating process, the significant residual tensile stress occurs. In order that a micro machine fabricated by such the surface micro-machining method performs precisely and reliably, the research about reducing the residual stress formed during the micro-fabrication process is needed.

The mechanical properties and residual stress of the micro electroplated structure depend significantly on the process conditions of the micro electroplating. Besides, the repeatability of the measuring method of the residual stress is usually not good. The accuracy of the estimated residual stress should be dependent on whether the density of the electroplated gold is not different from that of a general bulk gold or not. In order to improve the accuracy, we must to measure the real density of the micro electroplated gold and use it to residual stress estimation. In addition, it is more desirable to micro-fabricate the beam structure of which the anchor part is as flat as possible, although this process is to be difficult, and estimate the magnitude of the residual stress using the real beam length than using the equivalent length analysis.

6. Conclusions

In this paper, we proposed the simple method to obtain the approximate magnitude of the residual stress of the micro gold structure fabricated by electroplating process. The natural frequency of the microstructure can be affected by the residual stress produced during the micro-fabrication process of it. By using the Rayleigh's energy method, we derived theoretically the approximate equation of the first mode natural frequency of the beam structure with the tensile stress inside. To apply the derived equation, we used a surface micro-machining process, which includes the electroplating, to fabricate a micro gold structure in the shape of a clamped-clamped beam. We also used resonance test to measure the natural frequency of the micro-fabricated structure. We estimated the magnitude of the residual stress from the measured resonance frequency. For the more accurate estimation, we used the equivalent length of the actual beam shape corresponding to the ideal beam shape. As a result, it is found that the tensile residual stress exists in the microstructure.

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