Structure Stability of High Aspect Ratio Ti/Au Two-Layer Cantilevers for Applications in MEMS Accelerometers

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Abstract

This paper reports the structure stability of Ti/Au two-layer micro-cantilevers with various aspect ratios based on the results obtained from a 3D optical microscope and FEM simulation. The cantilevers were fabricated by MEMS fabrication process. The movable structure stability was investigated by observing shape of the Ti/Au two-layer micro-cantilevers with the Ti layer thickness of 0.1 μm , and the Au layer thicknesses of 3 μm , 10 μm and 12 μm . The length was varied from 100 to 1000 μm . The results of the tip deflection observed from the 3D optical microscope were similar to those of the FEM simulation. The experimental results of the micro-cantilevers with the Au thickness of 12 μm indicated the highest structure stability. In conclusion, these results revealed that the Ti/Au two-layer structure can enhance the stability and reliability of the movable structure.

Keywords: Ti/Au, High Aspect Ratio, Cantilever, Structure Stability, COMSOL

1. Introduction

Gold materials are widely known to have high chemical stability, corrosion resistance, electrical conductivity and density. They are all advantageous when applied as electronic components and device fabrication process techniques [1-3]. Recently, complementary metal-oxide-semiconductor-micro-electrical-mechanical system (CMOS-MEMS) technology has been developed to design electronic devices with an improved performance [4,5]. Thus, we have developed the high sensitive micro-electro-mechanical system (MEMS) inertia sensor and the integrated CMOS-MEMS accelerometer using gold material as proof mass [6-8]. In order to realize the CMOS-MEMS structure, a post-CMOS process that would not affect the CMOS properties is required. Electroplating is a promising post-CMOS process to fabricate the MEMS devices [8] because of the simple process conditions and low temperature process, which is important since heat is one of the major concerns affecting properties of the CMOS. In addition, properties of the plated materials can be precisely controlled by the electrochemical parameters. Therefore, gold electroplating can be applied in fabrication of the movable structures in the MEMS accelerometer.

The reliability of the gold materials in micro-scale should be evaluated for practical applications in the MEMS. The reliability can be determined by the mechanical properties and structure stability of the materials. There are several reports on mechanical properties of the gold materials [9,10]. However, there are very limited reports on the structure stability of the gold materials, especially for the dimensions in micro-scale.

Based on Euler-Bernoulli beam theory [11], the structure stability is highly related to Young's modulus of the material used to fabricate the movable structures. Young's modulus of gold is 78.5 GPa [12], which is considered to be low when compared to the other commonly used materials in electronic devices, such as Cu (128 GPa) and Si (165 GPa) [13]. The structure stability is expected to be higher using two-layer structure composed of a material having Young's modulus higher than that of gold. Young's modulus of titanium is 120.2 GPa [12]. The structure stability has been reported to be improved using a thin titanium layer as the bottom layer in a two-layer Ti/Au structure [6-8]. In addition, the titanium layer can also be used to improve adhesion of the gold layer on SiO₂.

There is still no report on the structure stability of the Ti/Au two-layer structure with different aspect ratios. Therefore, this paper presents the structure stability of the Ti/Au two-layer cantilevers with different aspect ratios by varying the length and the gold thickness. The evaluations were carried out based on the results obtained from a 3D optical microscope and finite element method (FEM) simulation (COMSOL Multiphysics software).

2. Experimental Method

2.1 Structure design and fabrication process of the Ti/Au micro-cantilevers

Fig. 1 shows a schematic view of the Ti/Au two-layer micro-cantilever. The titanium layer was formed by evaporation to be used as the adhesive layer on SiO₂. Then a thin layer of gold was evaporated to be used as the seed layer in gold

electroplating. The series of lithography and electroplating processes were conducted to fabricate the micro-cantilevers. More details of the lithography and electroplating processes could be found in a previous study [8]. The micro-cantilevers were annealed at 310 °C during fabrication process.

Micro-cantilevers with different dimensions were prepared, details are given in table 1. Length (l) of the micro-cantilevers was varied from 100 μm to 1000 μm . Width (w) of the micro-cantilevers was 10 μm . Thickness of the Ti layer (t_{Ti}) was 0.1 μm . Thickness of the Au layer (t_{Au}) was either 3 μm , 10 μm or 12 μm . Distance between each micro-cantilever was 100 μm .

2.2 Evaluation of the Ti/Au micro-cantilevers

Structure stability of the micro-cantilevers was evaluated by observing the micro-cantilevers using a scanning electron microscope (SEM, S-4300SE, Hitachi) and a 3D optical microscope (OM, VHX-5000, Keyence) equipped with a 3D measurement function. Structure stability was quantified by the difference between the height of the cantilever at the tip and the height of the cantilever at the fixed end or Δh . The height (h) was defined as the distance from the top surface of the micro-cantilevers to the surface of the substrate, as shown in Fig. 1. The height was determined by the Keyence OM.

2.3 FEM simulation for Ti/Au micro-cantilevers

FEM simulation was carried out by using the simulation software COMSOL Multiphysics to analyze the deformation behaviors of micro-cantilevers. The micro-cantilever was modeled on a beam part by using original material constant which

is provided by COMSOL. Constraint condition was used as a fixed-end to monitor tip deflections, and symmetry condition was applied along the length of the micro-cantilever to reduce a computation time. The equations of linear elastic material was selected in the category of solid mechanics. The properties of linear elastic materials such as Young's modulus, thermal expansion coefficient, Poisson's ratio and density were applied in the simulation. The effect of the increase in the temperature from 20 to 310°C on deformation behaviors of the micro-cantilevers was simulated.

3. Results and Discussion

Fig. 2(a) shows an optical micrograph of top view of the Ti/Au micro-cantilevers (type A, which thickness of the Au layer is 3 μm). More details of the fixed-end were observed from the SEM image, as shown in Fig. 2(b). The fixed-end was composed of multiple layers of the Ti/Au two-layer structure. From the top view, there was no obvious deformation in the directions parallel to the substrate surface. The result is expected since deformation in the directions parallel to the substrate surface is mostly caused by inadequate fabrication process or poor handling of the samples.

The deformation was expected to occur in a direction perpendicular to the substrate surface. Therefore, height of the micro-cantilevers at different point away from the fixed-end was measured by the OM, shown in Fig. 3. In general, the micro-cantilevers had a downward deflection because of the weight of the micro-cantilevers. This is the why the titanium layer is used as the bottom layer. Figure 3(a) shows that the structure stability was the worst for the $t_{\text{Au}} = 3 \mu\text{m}$ micro-cantilevers. The structure stability was

high when the thickness was increased to 10 μm and 12 μm even when the lengths were at 1000 μm , as shown in Fig. 3(b) and (c). The deformation was found to be higher with an increase in length of the micro-cantilevers. This is because shear force at the fixed-end would increase with an increase in the length according to the Euler–Bernoulli beam theory for cantilever beam with uniformly distributed load [6]. The equations of Euler–Bernoulli beam theory for cantilever beams with uniformly distributed load are listed as follows:

$$\text{Shear force at the fixed-end } (Q): Q = ql \quad (1)$$

$$\text{Deflection at the tip } (z): z = \frac{ql^4}{8EI} \quad (2)$$

$$\text{Second moment of area } (I): I = \frac{(t_{Au} + t_{Ti})^3 w}{12} \quad (3)$$

where q is the distributed load, in other words a force per unit length, l is length of the cantilever, E is the Young's modulus, t_{Au} is thickness of the Au layer, t_{Ti} is thickness of the Ti layer, and w is width of the cantilever. According to the theory, bending or deflection at the tip of the cantilever (z) is lowered with an increase in the Au layer thickness. Therefore, the increase in thickness of Au layer of the micro-cantilevers led to a lower tip deflection and better structure stability.

A simulation was carried out using the simulation software COMSOL simulation to analyze the deformation of the micro-cantilevers. The effects of the increase in the temperature from 20 to 310 $^{\circ}\text{C}$ on deformation of the micro-cantilevers were simulated. The properties of linear elastic materials such as Young's modulus, thermal expansion

coefficient, Poisson's ratio and density were used in the simulation. The results of COMSOL simulation for the micro-cantilevers with a length of 100 μm and a Au thickness of 3 μm , 10 μm and 12 μm are shown in Fig. 4. For all of the three micro-cantilevers, downward tip deflections were observed. The deflections were considered to be mainly caused by the difference in thermal expansion coefficient between Ti ($8.6 \times 10^{-6} \text{ K}^{-1}$) and Au ($14 \times 10^{-6} \text{ K}^{-1}$).

Table 2 shows information of the tip deflection obtained by the OM and COMSOL simulation. Each deformation value showed the same trend, which are all downward and the deflection magnitude decreased with an increase in the Au thickness. The results obtained from the simulation were all more negative than those observed by the OM, but the simulation results were still close to the OM results. The difference indicated that there are other factors involved in deformation of the micro-cantilevers. For example, titanium oxidizes easily during the fabrication process, and TiO_2 could be formed on the Ti surface after the annealing treatment. Young's modulus of TiO_2 is 270 GPa [14], which is much higher than the value of Au and Ti. Also, the high annealing temperature can accelerate formation of an intermetallic layer at the Ti/Au interface. Therefore, information of the TiO_2 layer, intermetallic layer, and heat-treatment conditions should be included in the COMSOL simulation to provide more precise results.

4. Conclusions

The structure stability of the two-layer Ti/Au micro-cantilevers with different aspect ratios was evaluated. The experimental results showed that the structure stability was lowered with an increased in the length and a decrease in the gold layer thickness. The structure stability was high for all of the micro-cantilevers with a Au thickness of 10 μm and 12 μm . On the other hand, FEM simulation was also conducted to study the structure stability. The deflection observed in the simulation was suggested to be mainly caused by the difference in thermal expansion coefficient between Ti and Au. Both the results obtained from the OM and the simulation showed downward tip deflection for the micro-cantilevers. The simulation showed higher magnitude of the tip deflection. This is suggested to be caused by the formations of the TiO_2 at the surface to Ti layer and the intermetallic layer at the Ti/Au interface, which were not considered in the simulation. Furthermore, the results confirmed that the Ti/Au two-layer structure with optimized Au thickness has high potential to be applied as reliable movable structures in MEMS devices.

Acknowledgments

This work has been supported by CREST Project by the Japan Science and Technology Agency (JST).

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Figure 3 Deflection curve in the height for the micro-cantilevers with different lengths of 1000, 500, and 100 μm and Au thickness of (a) 3 μm , (b) 10 μm and (c) 12 μm , respectively.

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Table 1 Design parameters of the micro-cantilevers.

		<i>l</i>	<i>w</i>	<i>t</i> _{Au}	<i>t</i> _{Ti}
Cantilever	A	100 μm ~ 1000 μm	10 μm	3 μm	0.1 μm
	B			10 μm	
	C			12 μm	

Table 2 Comparison of the tip deflection of the micro-cantilevers with the length of 100 μm and the Au thickness of 3 μm , 10 μm and 12 μm obtained by the OM and COMSOL simulation.

Au thickness	Deformation (Δh)	
	OM	COMSOL
3 μm	-1.05 μm	-2.1 μm
10 μm	-0.26 μm	-0.7 μm
12 μm	-0.27 μm	-0.6 μm

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Graphical Abstract

Two-layer Ti/Au micro-cantilever

Height profile of the cantilevers

Au thickness of 12 μm gives the highest stability

COMSOL Multiphysics simulation

Au thickness ($l=100\text{ }\mu\text{m}$)	Deformation	
	OM	COMSOL
3 μm	-1.05 μm	-2.1 μm
10 μm	-0.26 μm	-0.7 μm
12 μm	-0.27 μm	-0.6 μm