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Research paper

Enhancement in structure stability of gold micro-cantilever by constrained fixed-end in MEMS devices

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A B S T R A C T

This paper reports effects of the constraint condition at fixed end of the Ti/Au-layered micro-cantilever on the structure stability. Two types of constraint at the fixed end were used. One was constraining only bottom surface of the fixed end, and the other was constraining both top and bottom surfaces of the fixed end. The evaluation was conducted by observing the deformation by a 3D optical microscope and FEM simulation using the COMSOL Multiphysics software. From optical microscope observations, the top and bottom constrained micro-cantilevers showed a lower deflection at the tip, and the average deformation was also lowered. The FEM simulation revealed similar results as the optical microscope results. The fixed end was found to deform along as the body of the micro-cantilever deformed from the FEM simulation. Hence, the constraint condition at the fixed end contributes greatly to the overall structure stability of the Ti/Au micro-cantilevers.

1. Introduction

Micro-electromechanical systems (MEMS) accelerometers composed of gold-based movable structures [1,2] are reported to have higher sensitivity than the conventional silicon-based design because of the high density. Density of gold (19.3×10^3 kg/m^3 at 298 K) is about 10 times higher than that of silicon (2.33×10^3 kg/m^3 at 298 K) [3]. The sensitivity is affected by the Brownian noise, and the Brownian noise is greatly influence by total mass of the proof mass in the MEMS accelerometer [4]. Hence, application of a high density material, such as gold, as the main component is advantageous in improving the sensitivity and further miniaturization of the device. However, gold is known to be a relatively soft metallic material. Yield stress of bulk gold is reported to be 55–200 MPa [5], and the Young's modulus is 70 GPa [6]. On the other hand, fracture strength of silicon is 1–3 GPa [7], and the Young's modulus is 130–188 GPa [8]. Hence, the structure stability becomes a concern when gold-based material is applied as the movable structures based on Euler-Bernoulli beam theory [9].

In order to utilize gold's high density and improve the structure stability, a multiple Ti/Au-layered design is proposed for the gold-based movable structures [10]. Yield stress (480 MPa) [11] and Young's modulus (111.5 GPa) [6] of bulk titanium are both higher than those of gold, therefore, overall mechanical properties are expected to be improved using this Ti/Au-layered design. For the Ti/Au-layered design, a titanium layer is firstly evaporated on the substrate before deposition of a gold seed layer. Then, lithography process and gold electroplating are applied to fabricated gold structures with various dimensions. After an annealing process, the difference in thermal expansion coefficient of the materials composing the two layers would cause a deflection at tip of the cantilever, which is known as the bimetallic effect [12,13]. In a previous study, structure stability of the Ti/Au-layered micro-cantilevers was evaluated by observing tip deflection of the micro-cantilevers with different thickness of the electroplated gold layer [14]. As expected, the structure stability became worse, which is the tip deflection increased, as length of the micro-cantilever increased. On the other hand, the structure stability improved with an increased in the gold layer thickness.

In practical applications of the Ti/Au micro-cantilever in MEMS devices, constraint conditions at fixed-end of the micro-cantilever structure could vary. Top surface at the fixed end could be free and exposing to air and the bottom surface is constrained to a structure. Also, both the top and bottom surface could be constrained and sandwiched between two other structures. Constraint conditions at the fixed end can affect deformation behavior and structure stability of the Ti/Au micro-cantilever, which would influence practical implantation of the Ti/Au layered structure in MEMS devices. Therefore, in this study, effects of constraint conditions at the fixed end, such as a

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constraint on bottom surface of the fixed end only and constraints on both the top and the bottom surfaces, on the structure stability of micro-cantilever composed of Ti/Au layered structure will be reported. The evaluations would be carried out by measuring the tip deflection using results obtained from a 3D optical microscope (OM) and finite element method (FEM).

2. Experimental method

2.1. Design parameter of micro-cantilevers

A schematic diagram of the Ti/Au micro-cantilever is shown in Fig. 1. More details of the fabrication processes could be found in a previous study [10]. Two types of the micro-cantilever were studied. Type I was with a constraint on the bottom surface of the fixed end only. Type II was with constraints on both the top and the bottom surface of the fixed end. Fig. 2 shows SEM images of the Ti/Au-layered micro-cantilevers fabricated by a series of lithography and electroplating processes. Micro-cantilevers with different dimensions were prepared. Width (w) of the micro-cantilevers was 15 μm. Thickness of the Au gold layer (t_{Au}) was 15 μm. Thickness of the titanium layer (t_{Ti}) was 0.1 μm. Various length (l) of the micro-cantilevers were used, which were 50, 100 and 200 μm.

2.2. Experimental apparatus and procedures

Structure stability of the Au/Ti micro-cantilevers were evaluated by observing height profile of the micro-cantilevers using a scanning electron microscope (SEM, S-4300SE, Hitachi high technologies Co., Ltd) and a 3D optical microscope (OM, VHX-5000, Keyence) equipped with a 3D measurement function. Height of top surface of the micro-cantilever (h_x) at a position x away from the fixed end was determined along long-side of the micro-cantilever in a step size (d) of 0.1 μm by the OM. The structure stability is quantified by calculating the height difference along the micro-cantilever body (Δh_x), which is the difference

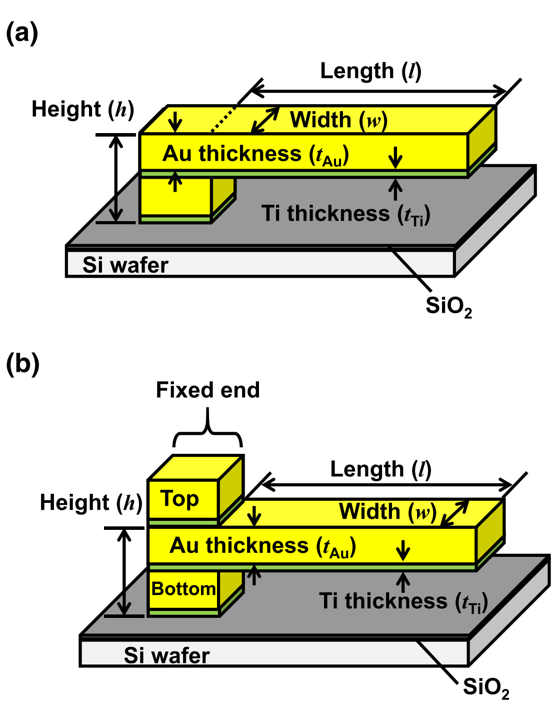

Fig. 1. Schematic diagrams of the (a) type I and the (b) type II Ti/Au micro-cantilevers.

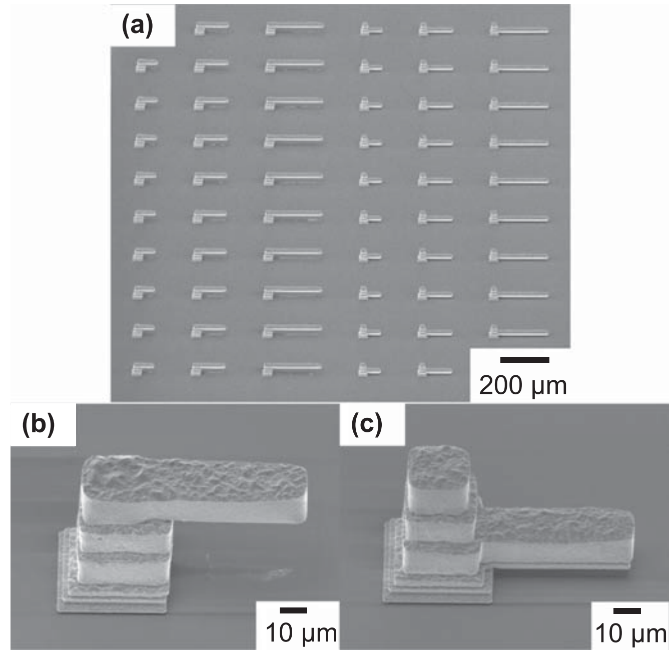

Fig. 2. SEM image of the (a) Ti/Au micro-cantilevers array with the length varied from 50 μm to 200 μm, width of 15 μm and Au thickness of 15 μm, the (b) type I and the (c) type II Ti/Au micro-cantilevers with a length of 50 μm, width of 15 μm and Au thickness of 15 μm.

between the h_x and the height at the fixed end (h_0). The equation is shown in the following:

$$\Delta h_x = h_x - h_0 \tag{1}$$

For the type II micro-cantilevers, because of the constraint on top surface of the fixed end, height of the top surface of the micro-cantilever body at a location very close to the fixed end was used as the h_0. The deflection at the tip (Δh_l) and average deformation of the micro-cantilever ($\Delta h_{ave,l}$) were also calculated. The equation for $\Delta h_{ave,l}$ is shown in the following:

$$\Delta h_{ave,l} = \frac{\sum_{x=1}^{l/d} (\Delta h_x \times d)}{l} \tag{2}$$

where l is total length of the micro-cantilever. d is step size of the measurement, which is 0.1 μm determined by the OM.

2.3. FEM simulation parameters

FEM simulations were carried out using a simulation software (COMSOL Multiphysics) to analyze deformation behaviors of the Au/Ti micro-cantilevers. The micro-cantilever analyzed was composed of two sections, one was the fixed end section and the other was the beam body. For the type I micro-cantilevers, the fixed-end was modeled as having the same width, which is 15 μm, as the beam body. On the other hand, for the type II micro-cantilevers, width of the fixed-end was set to be 30 μm. For the type I, only bottom surface of the fixed-end was restrained. For the type II, both of upper and lower surface of the fixed-end were restrained. The equations of linear elastic material were selected in the category of solid mechanics. Constants of linear elastic materials such as Young's modulus, thermal expansion coefficient, Poisson's ratio and density were applied in the simulation. The constants were provided by the database embedded in the COMSOL Multiphysics [6]. Young's modulus of titanium and gold were 115.7 and 70 GPa, respectively. Thermal expansion coefficient of titanium and gold are 8.6×10^{-6} and 14.2×10^{-6} K^{-1}, respectively. The effect