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Electrodeposition of High Strength Au-Cu Alloys for MEMS Device

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Abstract

This paper describes electrodeposition of Au-Cu alloys for fabrication of MEMS device. The average grain size and copper content are both affected by the applied current density, and a wider range of the copper content is obtained by pulse current plating method. Micro-mechanical properties of the gold-based alloys are evaluated by compression test. The yield stress reaches 1.38 MPa for micro-pillar composed of 14.2 wt% of Cu and average grain size of 4.4 nm. Long-term vibration test is conducted to evaluate structure stability of micro-cantilever fabricated by the Au-Cu alloy electrodeposition method. The results confirm that the structure stability is enhanced with the Au-Cu alloy micro-cantilever.

1. Introduction

The use of electrodeposited gold as movable micro-components in micro-electro-mechanical systems (MEMS) devices has been demonstrated to allow enhancement in the sensitivity and miniaturization of the device [1]. Reliability of the MEMS components is highly dependent on mechanical properties of the material. For strengthening of electrodeposited metallic materials, alloying is an effective method because of solid solution strengthening mechanism [2]. In addition, further grain refinement of the electrodeposited alloy can be obtained by pulse current plating method to improve the mechanical strengthen according to the grain boundary strengthening mechanism (also called Hall-Petch relationship) [3].

Mechanical properties of materials having dimensions in micro- or smaller scale is known to have different behavior when compared to bulk-size specimens. The phenomenon is called sample size effect [4]. For applications as MEMS components, it is necessary to evaluate the mechanical properties using specimens in micro-scale.

In this work, electrodeposition of Au-Cu alloys and the micro-mechanical properties are studied for fabrication and design of micro-components in MEMS devices. Long-term vibration test of micro-cantilevers prepared by the Au-Cu alloy electrodeposition is also conduct to reveal the structure stability.

2. Experimental

Au–Cu alloy films with ~50 μm thickness were electroplated from a commercially available electrolyte by MATEX Co. Japan, which contained 17.3 g/L of $X3Au(SO_3)_2$ (X = Na, K), 1.26 g/L of $CuSO_4$, and EDTA as the additive with pH at 7.5. Direct constant current (DC) [2] and pulsed current (PC) [3] electrodeposition methods were used. For both the DC and the PC electrodeposition, the temperature was maintained at 50°C.The current density was varied from 2 to 9 mA/cm^2 for the DC electrodeposition. For the PC electrodeposition, the on-time (t_{on}) was fixed at 10 ms, while the current off-time (t_{off}) and the pulse on-time current density (J_p) were varied.

Crystal structures of the electrodeposited Au–Cu alloys were characterized by X-ray diffraction (XRD). The average grain size (d_g) were estimated from the XRD results and the Scherrer equation. The Scherrer equation is shown in the following:

$$d_g = \frac{\lambda}{\beta \cos \theta} \qquad (1)$$

where λ is the X-ray wavelength at 0.15418 nm, β is full width at half maximum of the (111) XRD diffraction peak in radians, θ is Bragg angle of the (111) peak. Copper content in the alloy film (w_{Cu}) was characterized by energy dispersive spectroscopy (EDS) equipped in a scanning electron microscope.

For the micro-compression test, Au-Cu micro-pillars with a square cross-section of 10 μm by 10 μm and the height at 20 μm were fabricated by focus ion beam (FIB). Uniaxial compression tests were conducted at a constant displacement rate of 0.1 μm/s using a testing machine specially designed for micro-specimens. Details of the micro-pillar fabrication and the micro-compression tests are reported in a previous study [5].

Micro-cantilevers with the design-width at 20 μm and the design-length ranged from 50 to 1000 μm were prepared by lithography and the DC electrodeposition. Then long-term vibration test was conducted to evaluate the structure stability.

3. Results and Discussion

As shown in Fig. 1, the d_g decreased from 8.8 to 5.3 nm when the current density was decreased from 2 to 6 mA/cm^2, and grain coarsening was observed when the current density increased beyond 6 mA/cm^2 for the DC electrodeposition. In the meanwhile, an increase in the w_{Cu} from 4.3 to 22.0 wt% was obtained when the current density was increased from 2 to 9 mA/cm^2. The w_{Cu} ranged from 3.5 to 26.7 wt% and a minimum d_g at 4.4 nm were attained by the PC electrodeposition. The PC electrodeposition was more effective in refinement the d_g, and the w_{Cu} distribution is also wider when compared with the DC electrodeposition. Nerveless, the results demonstrated the flexibility in controlling properties of the Au-Cu alloy films.

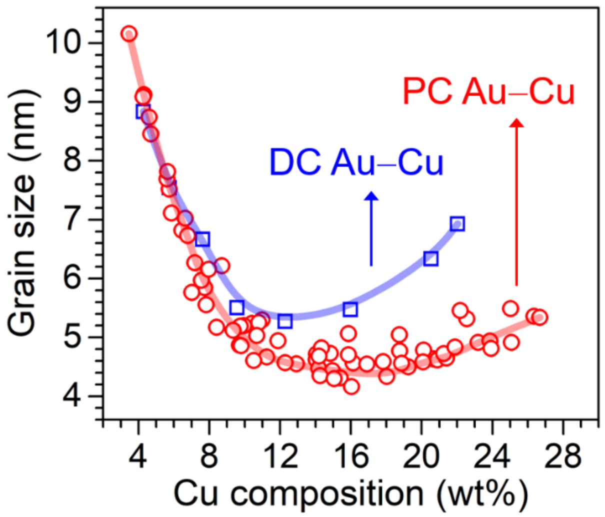

Fig. 1 Plots of relationship between grain size and composition for Au–Cu alloys deposited with varied electroplating conditions.

The Au-Cu micro-pillars with the w_{Cu} lower than 14.0 wt% showed barrel shape deformation after the compression test, which is a typical deformation behavior for specimens composed of polycrystals. Brittle fracture was observed for pillars having the w_{Cu} higher than 14.0 wt%.

The yield stresses (σ_y) obtained from the compression tests are summarized in Fig. 2. Generally, the σ_y increased as the d_g decreased. Basically, in Fig. 2(a), the σ_y had a linear relationship with inverse square root of the d_g, which corresponds well with the Hall-Petch relationship indicating the strengthening is mainly results of the grain boundary strengthening mechanism. In Fig. 2(b), the σ_y also increased with an increase in the w_{cu}. The results indicate solid solution strengthening also contributes to the increased in the σ_y. The highest σ_y at 1.38 MPa was attained from the pillar composed of 14.2 wt% of Cu and average grain size of 4.4 nm.

Structure stability of the Au-Cu micro-cantilevers was evaluated by first measuring height at the tip before and after the vibration test and then calculating the change in the tip height. The change in the tip height would an indicator for the structure stability. Results of the long-term vibration test of a 1000 μm long Au-Cu micro-cantilever were shown in Fig. 3, and the w_{Cu} was 2.3 wt%. A micro-cantilever composed of pure gold was also evaluated to be used as a comparison. The results confirmed that the structure stability is improved by alloying the gold-based micro-cantilever with only 2.3 wt% of copper.

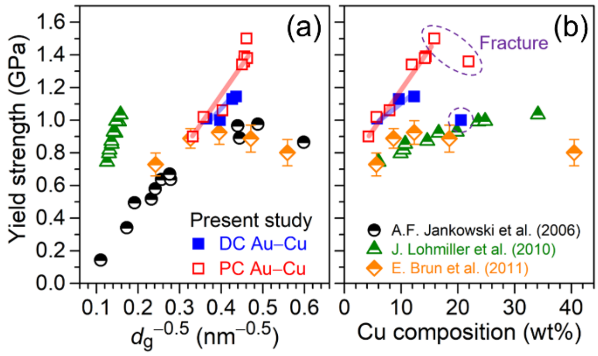

Fig. 2 Plot of (a) inverse-square root of the grain size versus the σ_y (Hall–Petch plot) and (b) the Cu composition versus the σ_y.

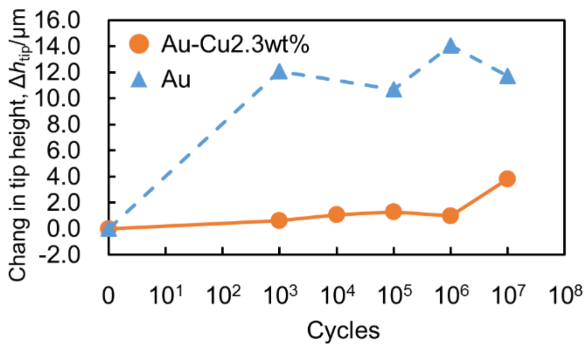

Fig. 3 Plot of (a) inverse-square root of the grain size versus the σ_y (Hall–Petch plot) and (b) the Cu composition versus the σ_y.

3. Conclusions

Au-Cu alloys with different average grain size and Cu content could be prepared by controlling the electrodeposition parameters. In addition, Cu alloying of gold-based micro-structures was found to be effective in improving the yield stress and the structure stability. The Au-Cu alloy electrodeposition is a promising method for fabrication of MEMS components.

Acknowledgements

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