Measurement of Yield Strength for Electroplated Nickel Film Using Micro-cantilever

Hyoung-Sik Moon†, Jooh-Wan Kim* and Young-Min Kim*

Abstract - We report highly improved yield strength of nickel thin film, prepared using electroplating. The micro-scaled nickel cantilever is found to have significantly higher yield strength than bulk nickel. For the yield strength test, the heights of the micro-scaled cantilever were varied up to 60 μm and electrostatic force was used for actuation. Stress of the bent cantilever was estimated using the FEM large deflection model. The yield strength of the thin nickel film is found to be over five times higher than that of the bulk nickel previously published. Results from this study indicate that metal microstructures can be used for MEMS applications requiring large deflection.

Keywords: Large deflection, MEMS, Nickel electroplating, Yield strength, Young's modulus

1. Introduction

Cantilever type microstructures have been widely used for various MEMS applications. Examples of these are the 2D optical router and RF switches for communication networks, the micro accelerometer, gyroscope, AFM (Atomic Force Microscope) tip as well as numerous other sensors [1-3]. When selecting the appropriate materials to realize such devices, mechanical properties of the material should be seriously considered. To date, metal microstructures have been used only for very limited displacement because of their low yield strength, which has been assumed to be similar to that of bulk metal. For large displacement applications, polysilicon has been chosen as a building material for its high yield strength [4, 5]. However, use of polysilicon frequently requires wafer bonding, in which alignment and high temperature processing are critically needed. In this work, we investigate the feasibility of using a thin metal on MEMS applications requiring large displacement. Mechanical characteristics of a micro-scaled thin nickel film are estimated by measuring dynamic behavior of a nickel-electroplated cantilever and using a finite elements method with a large deflection model.

2. Devices Fabrication

Fig. 1 shows a schematic view of the micro cantilevers fabricated in this work. The fabrication flow of a micro-cantilever is displayed in Fig. 2. At first 1000Å /2500Å /1500Å Ti/Cu/Ti is thermally evaporated on a glass substrate as a seed layer for electroplating and for the bottom electrode (a). The 1500Å Ti layer acts as a protecting layer for the Cu oxidation and will be etched immediately prior to post plating. The evaporated layers are patterned/etched to define the bottom electrode and the electroplating seed layer. Ammonium copper sulfate is used for etching copper and 5% buffered HF for titanium. After defining the seed and the bottom electrode, a 2-3 μm thick Spin-on-Glass (ACUGLASS T-12B. Honeywell) is deposited as an insulating layer to prevent the device from being electrically shorted during actuation (b). Next, a 60 μm high electroplating mold is formed using a commercially available photoresist, AZ9260 (c). Electroplating is performed in nickel sulfamate bath at 50°C (d). Compared to electroplated nickel film obtained in the watt bath, one obtained in the sulfamate bath has low internal stress and good ductility [6]. The composition of the plating bath is listed in Table 1.

Sodium lauryl sulfate is added to reduce pits on the surface of the electroplated device. The electroplating is continued until the mold is completely filled up. Next a 6000Å Cu film is evaporated to provide a seed layer for the second electroplating (e). Following evaporation, the

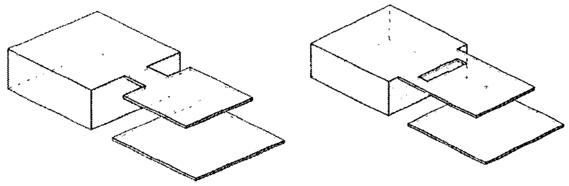
(a) (b)

Fig. 1 Schematic view of micro-cantilevers. (a) single neck (b) double neck.

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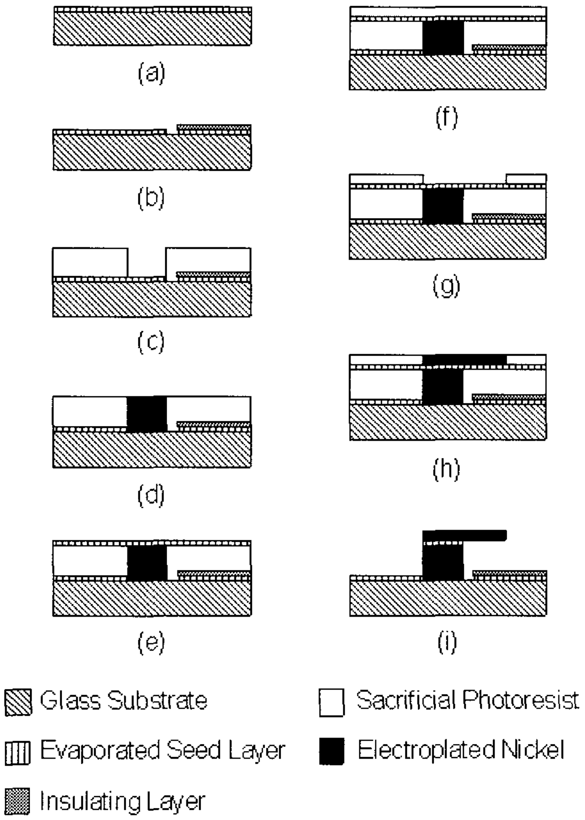

Fig. 2 Micro-cantilever fabrication flow. See the text for details.

second photoresist patterning is performed to make a cantilever plating mold (f), (g), which is followed by the second nickel electroplating. The thickness of the cantilever can be precisely controlled by plating time and current density. During the second nickel plating, a 3 μm thick nickel cantilever is fabricated (h). To release the cantilever from the substrate, the sacrificial photoresist and the 6000Å Cu film are removed using acetone and the ammonium copper sulfate. The ammonium copper sulfate is found to have an excellent selectivity over nickel.

Table 1 The composition of nickel sulfamate electroplating bath.

Component	Quantity
$Ni(SO_3NH_2)_2 \cdot 4H_2O$	500 g/l
H_3BO_3	30 g/l
$NiCl_2 \cdot 6H_2O$	10 g/l
Sodium Lauryl Sulfate	0.5 g/l

Thanks to height of the post and good elasticity of the nickel, stiction can be avoided when a methanol rinse is used (i). Fig. 3 and Fig. 4 show SEM images of a 500 μm x 500 μm cantilever, which is formed on a 50 μm high nickel post.

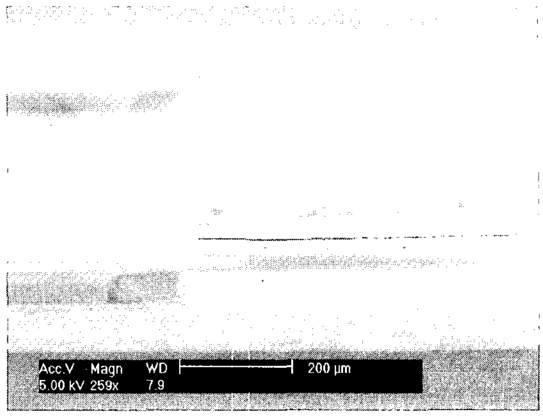

Fig. 3 SEM image of a micro-cantilever fabricated in this work. (Side view)

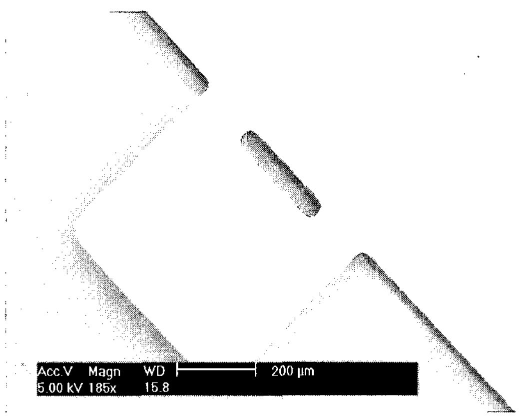

Fig. 4 SEM image of a micro-cantilever fabricated in this work. (Top view)

3. Results and Discussion

Fig. 5 presents the measurement setup for cantilever deflection. A laser beam is focused on the top of the cantilever and the reflected beam from the cantilever is measured using a position sensitive photodetector (PSD). As an actuation voltage is applied, the cantilever deflects downward and the position of the reflected beam shifts. Relative position change of the beam is converted into a voltage shift, which is measured using an oscilloscope.

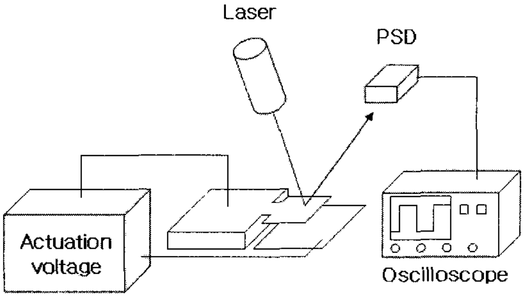

Fig. 5 Experimental setup for measuring mechanical behavior of cantilever.

Tested cantilevers are fabricated to have a 300μm x 300μm area, a 100μm x 100μm single supporting neck and a thickness of 3μm with varying height of nickel post from 20μm to 60μm. Fig. 6 shows the dynamic behavior of the cantilever when a 320 V step voltage is applied. The voltage measured at the oscilloscope represents the relative position shift of the reflected beam. As the cantilever moves downward, the measured voltage increases as indicated in Fig. 6.

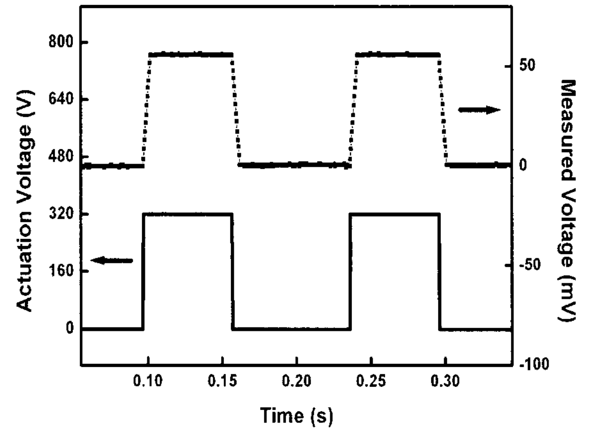

Fig. 6 Operation characteristics of a cantilever measured by PSD. The tested cantilever is supported by a single neck. The dotted line indicates measured voltage from PSD and the solid line shows actuation voltage.

If there is a reduction in the amount of the cantilever deflection after some period of actuation, it is the result of plastic deformation of the cantilever undergoing higher stress than the yield strength. To confirm the yield strength of the thin nickel film, the cantilever is bent to 60 μm many times, but the plastic deformation is not observed. Note unchanged voltage in Fig. 6 when the cantilever is released. To estimate the maximum stress loaded on the cantilever, stress distribution inside the bent cantilever has been simulated using the ANSYS finite element method (FEM). The stresses are simulated using both fine 2D shell and 3D plain models, and the results are found to be in good agreement. The simulated stress map indicates that the maximum stress is mainly loaded at the neck as shown in Fig. 7.

The maximum stress value is simulated as the deflection is varied from 20μm to 60μm. The estimated maximum stress is presented in Fig. 8. Assumed are Young's modulus of 160GPa [8] and poison ratio of 0.31 of the thin nickel film. Based on Fig. 6 and Fig. 8, it is known that the plastic deformation has not occurred in the single neck cantilever when the cantilever is loaded at 595 MPa. The result indicates that the yield strength of the nickel film must be higher than 595MPa.

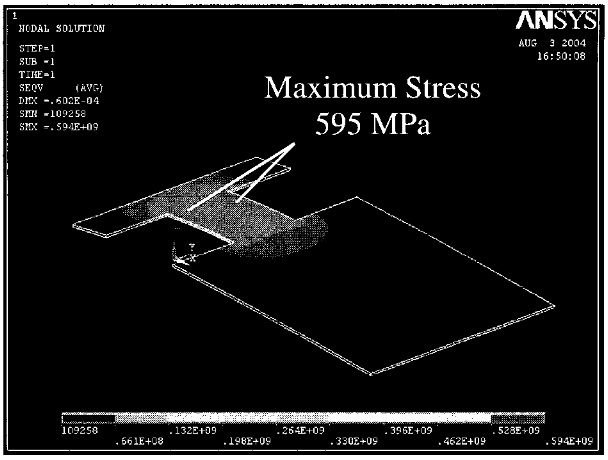

Fig. 7 Simulated stress distribution inside the cantilever using ANSYS. Cantilever is 300 μm x 300 μm and supported by a single neck of 100μm x 100μm with a thickness of 3 μm. The maximum stress is calculated when deflection distance is 60μm.

To increase the maximum stress loaded on the cantilever, the length of the supporting neck is reduced. Also, two supporting necks, instead of a single neck, are fabricated on a 65μm high post for superior process yield. The two supporting necks are found to suppress unexpected physical tilting during the releasing process. The neck sizes are 30μm x 50μm for device (a) and 15μm x 30μm for device (b), respectively.

Fig. 9 illustrates pull-in voltage change of the cantilevers as the actuation is repeated. The pull-in voltage was carefully measured while increasing the actuation voltage until the pull-in of the cantilever was observed in the microscope. Immediately after the pull-in was observed, the applied voltage was down to zero. The pull-in voltages of each device are 420V (a) and 410V (b).

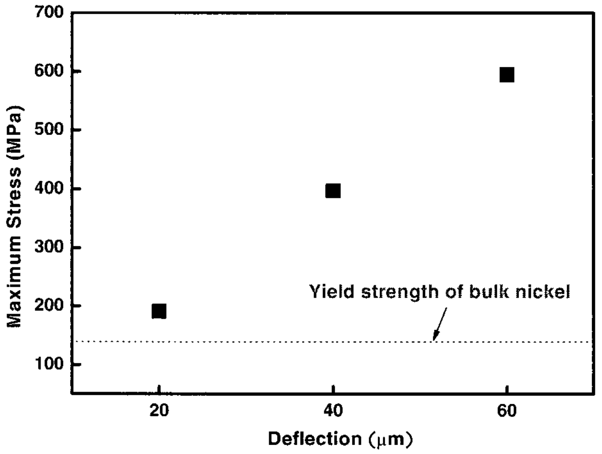

Fig. 8 Calculated maximum stress inside cantilever using nonlinear deflection model. The tested cantilever is the same as in Fig. 7.

After the first pull-in of the cantilever, the actuation voltage is observed to decrease, indicating that the released cantilevers did not restore their initial height because of the plastic deformation. The decreased gap between the cantilever and the bottom electrode was independently confirmed using an optical microscope. Using the ANSYS with a large deflection model, the maximum stress developed during the first pull-down was estimated for the two cantilevers. The estimated maximum stresses were 810MPa for device (a) and 1.04GPa for device (b). The decreased pull-in voltage after the first actuation implies that the yield strength of the nickel film should be below 810MPa. During the actuation series, the pull-in voltage continuously decreases and approaches to 305V (a) and 300V (b), as shown in Fig. 9. Using the optical microscope, the decreased gaps were measured at 55μm (a) and 50μm (b). Based on the unchanged pull-in voltage, the maximum stress developed in the pull-in cantilevers is believed to be lower than the yield strength.

The maximum stresses are calculated as 615MPa (a) and 750MPa (b), which bind the lower limit of the yield strength. According to the results obtained above, the yield strength of the electro-plated nickel should be bounded between 750MPa and 810MPa, which matches with previously published ones [9, 10]. Good agreement with the value obtained in the micro-tensile test [10], which is free of strain-hardening effect, indicates the strain-hardening effect may not be significant in the plated nickel thin film.

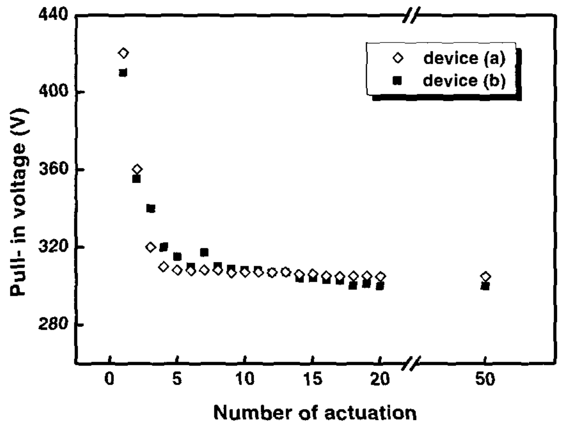

Fig. 9 Pull-in voltage change during cyclic actuations. Each cantilever is supported by two supporting necks. Significant voltage drop is observed in the first few actuations, implying plastic deformation of the cantilever.

Use of the simple cantilever structure enables measurement of the yield strength in-situ with high accuracy, which could not be done in [9, 10]. Note that the yield strength of the thin nickel film is much higher than one of bulk published, 140MPa [11]. Compared to the yield strength of polysilicon, which was reported as 1.2GPa [12], the yield strength of the electroplated thin nickel film is found to be almost half that of the polysilicon.

4. Conclusion

Using electroplated nickel cantilevers, the yield strength of the thin nickel film was measured. Nickel film of a few microns in thickness was found to have much higher yield strength than bulk nickel. The yield strength of the film showed to be almost half that of the polysilicon. Based on the results obtained from this study, metals can be considered as a building material for MEMS applications requiring large deflection, where only polysilicon or crystalline silicon has been perceived to be usable.

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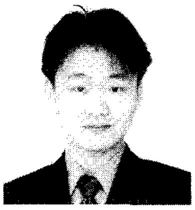

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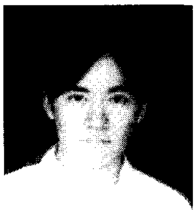

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