Modeling Electrothermal Plastic Deformation Self-Assembly

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ABSTRACT

Self-assembly of three-dimensional microstructures has been achieved using EPDA (Electrothermal Plastic Deformation Assembly). The EPDA process, in this case, is dependent on gold yielding within a gold and polysilicon bimorph. The bimorph is heated such that the gold plastically deforms via creep under compressive stress from actuation. When the bimorph cools the residual stress within the plastically deformed gold pulls the bimorph into a new power-off position. New simulation results and measurements of the electrothermal plastic deformation process are presented for a gold and polysilicon bimorph. Reliable simulation will assist with device designs for optical and RF applications. A FEA (Finite Element Analysis) model and a single gold and polysilicon bimorph are used evaluate the plastic deformation process. Joule heating is used to actuate the device in air and vacuum. By applying consecutive voltage pulses and measuring the power-off position of the device, the time dependent plastic deformation is measured. A temperature dependent primary creep material model for gold is developed using the measured data, and simulations of the deformation process compare well with measured results.

1 INTRODUCTION

Microstructures assembled perpendicular to the plane of fabrication have unique properties and potential applications within optical and RF devices. Since the planar nature of micro machining prohibits true three-dimensional fabrication, device design must permit some level of assembly to achieve this. Several design techniques have been used to assemble these structures, including hinged structures [1], high temperature reshaping of polysilicon [2], and stress-induced self-assembly mechanisms [3]. By introducing unique processing, Plastic Deformation Magnetic Assembly has achieved batch device assembly [4]. In addition, directed assembly of micro systems is proving to be effective [5]. Sarkar *et al.* [6] has introduced EPDA, a technique used to assemble a mirror into a position perpendicular to the substrate as shown in Fig. 1. The EPDA process, in this case, is dependent on gold deformation within a gold and polysilicon bimorph. The bimorph is heated such that the gold plastically deforms by stress relaxation, or creep, under the compressive stress from actuation at elevated temperatures. When the bimorph cools the residual stress within the plastically deformed gold pulls the bimorph into a new power-off position. Using a combination of bimorphs and structural beams (Fig. 2), devices have been designed to achieve motions up to 90° which can be actuated after plastic deformation.

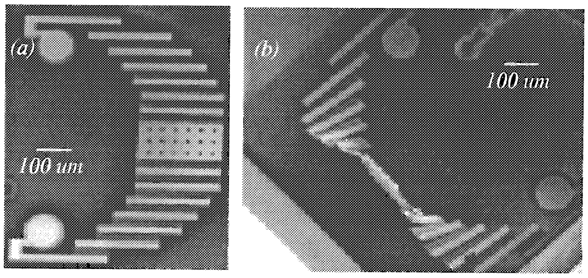

Figure 1: SEM images showing: (a) initial fabricated position; and (b) final position of a scanning micromirror assembled using EPDA.

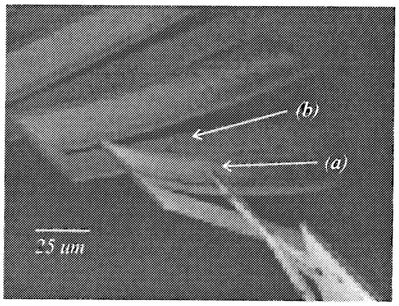

Figure 2: SEM image of: (a) a plastically deformed gold and polysilicon bimorph; and (b) corresponding polysilicon beam.

Elastic deformation analysis of multi-layered structures to thermal loading has been approached by numerous authors. Dunn *et al.* [7] have summarized much of this work and have used gold and polysilicon plate structures to validate their models. Finot and Suresh [8] provide a comprehensive analysis of the thermomechanical response of multi-layers, and have presented the effects of plasticity on large deformations using simulations. The model used in the plasticity evaluation considers that one of the layers follows an elastic/perfectly plastic response, which is entirely stress dependent. More long-term testing by Zhang and Dunn [9] has investigated stress relaxation of a gold and polysilicon plate over several hundred hours of thermal loading with experimental results. These authors use the power-law creep to represent the time and stress dependent relaxation within gold. Similar work is also presented by Shen and Suresh [10] using aluminum and silicon multi-layered thin films. Harris and King [11] use transmission electron microscope observations to study creep in polycrystalline thin films of gold. The work gives a more detailed model of creep mechanisms within gold films by including temperature dependence.

In this work we study the EPDA process by measuring the time dependent plastic deformation within a test structure at several temperatures. The outcome of this investigation provides a technique and appropriate material properties to simulate the stress relaxation, or creep, process within the gold using the finite element method.

2 EXPERIMENTAL

A single gold and polysilicon bimorph is used to evaluate the plastic deformation process. The single bimorph is fabricated using polysilicon MUMPs [12], removed from the wafer and packaged such that it is suspended in air as shown in Fig. 3. The attachment pads are 4.25 μm thick using a trapped oxide layer for additional strength, while the heater is 1.5 μm thick polysilicon and the bimorph is 0.5 μm of gold on 1.5 μm of polysilicon, extending 200 μm at a width of 20 μm. Joule heating is used to actuate the device by passing current through the polysilicon heater, which then heats the bimorph by conduction. To measure the plastic deformation process, controlled voltage pulses are applied to the device and the power-off position after each pulse is measured. The devices are first measured in vacuum to characterize the deformation process and then measured in air to validate the technique.

In the first measurements conducted in vacuum, SEM images are used to measure the plastic deformation as a function of time and applied voltage. The image in Fig. 4 shows how a reference point is used to measure the power off position within the scanning electron system. Since convective cooling effects are negligible, the temperature remains constant along the bimorph and the stress and strain can be predicted using the tip deflection and analytical techniques given in [8]. The temperature is predicted from the applied power using a finite element model discussed later. Using these techniques, data is collected and used to identify parameters within a creep model for gold.

Next the device is placed in ambient conditions under a UMECH^{TM} MEMS Motion Analyzer [13] to measure the response at a region of interest along its length. As illustrated in Fig. 5, the bimorph is held sideways and a region of interest is tracked using vision and image processing algorithms. The device is first powered at a level that does not induce deformation in order to measure static power versus displacement. After this, the device is powered at higher voltage levels to track the time dependent deformation process in air.

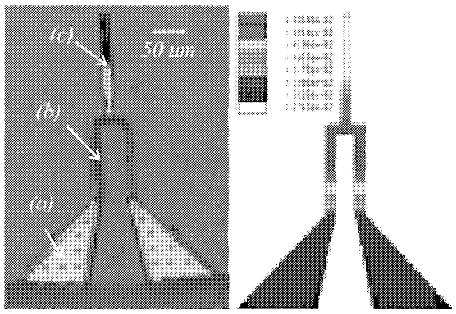

Figure 3: (left) Test structure consisting of: (a) attachment pads; (b) polysilicon heater; and (c) gold/polysilicon bimorph. (right) Simulated thermal distribution (K) within device.

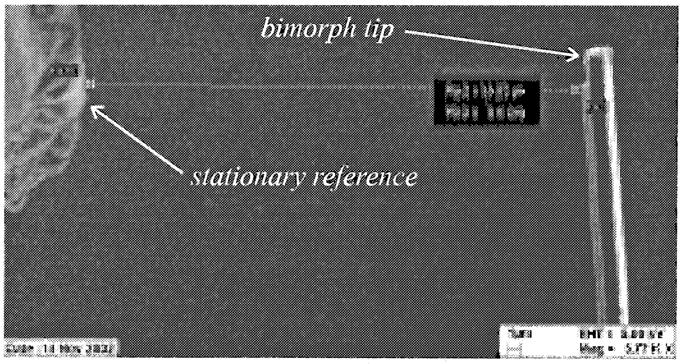

Figure 4: SEM of bimorph tip being measured from reference point to characterize the plastic deformation process.

3 MODEL AND SIMULATIONS

A 3D FEA model of the bimorph test structure, also shown in Fig. 3, is used to predict the temperature within the bimorph and to validate the material model developed. All simulation are performed using ANSYS^{TM} commercial finite element software.

To predict the temperature profile along the bimorph a thermal modeling technique and polysilicon electrother-

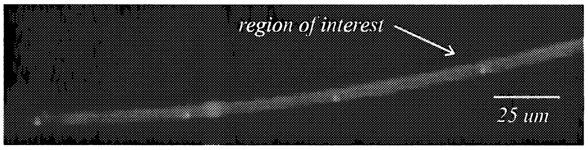

Figure 5: UMECH image showing region of interest used to measure the deflection of the gold and polysilicon bimorph. The bimorph is turned 90° to the camera.

mal material properties presented in [14] are used. Results from the thermal solution are applied as loads to the structural simulation to predict actuator motion. Fig. 6 compares measured data to the power versus displacement simulation. These results validate the modeling technique and material properties used in the simulation when the device is operating in the elastic range and in ambient conditions.

Temperature and strain hardening effects are considered to influence the plastic deformation mechanisms within gold. The work conducted by Harris and King [11] provides evidence of temperature dependent behavior, while the strain hardening effect is explained by an increase in dislocation density within the thin film as they collect at the film boundaries. As a result, the temperature dependent strain hardening primary creep equation is used to represent the time dependent plastic deformation within the gold. The form of this model is,

$$\dot{\epsilon}_{cr} = C_1 \sigma^{C_2} \epsilon_{cr}^{C_3} e^{-C_4/T} \tag{1}$$

where ϵ_{cr} is the creep strain, σ is the stress in MPa, T is the temperature in K, and the parameters C_{1-4} control the shape of the function. Measured data collected in vacuum is used to identify these parameters. Using the analytical techniques in [8] a script is written to simulate the creep behavior within the gold and a procedure is applied to find the parameters C_{1-3} that minimize the variance between measured and calculated response. This is done at several temperatures and parameter C_4 is extracted using an exponential fit; Table 1 summarizes the results of this procedure. Since the limited number of temperature dependent data points yields variation in the exponential fit, the creep model used in the FEA simulation uses a reduced form of Eqn. (1)

$$\dot{\epsilon}_{cr} = C_1^{'} \sigma^{C_2} \epsilon_{cr}^{C_3} \tag{2}$$

where $C_1^{'}$ is a function of temperature. Table 2 contains the temperature dependent values of $C_1^{'}$ used in simulation, while Fig. 7 compares the simulation results to measurement results in vacuum. The temperature dependent form of Eqn. (2) was found to represent the experimental data better.

Finally, the FEA model is enhanced to include convective cooling by air and compared with experimental data. Fig. 8 compares simulation results to data collected using the UMECH^{TM} in an ambient air environment at three power levels.

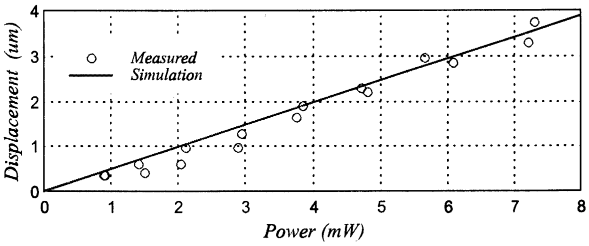

Figure 6: Comparison between measured and simulated response at the region of interest under static excitation in air.

Table 1: Parameters in the creep model extracted from vacuum measurements.

Parameter	Value
C_1	3.0×10^{-23}
C_2	6.719
C_3	-0.0436
C_4	-8.5×10^{-3}

Table 2: Temperature dependent $C_1^{'}$ parameter, used in the FEA simulation.

Temperature (K)	Parameter Value
386.69	2.69×10^{-14}
411.12	2.60×10^{-14}
447.60	9.84×10^{-14}
482.78	1.37×10^{-14}
535.03	6.14×10^{-16}
597.92	7.38×10^{-18}
640.52	1.04×10^{-17}

4 DISCUSSION

In general the plastic deformation mechanism is attributed to temperature, stress, and strain dependent behavior. Correspondence between simulation results and measured values, indicate that the strain hardening primary creep function has captured significant portions of the plastic deformation mechanisms within the gold. Furthermore, the extracted stress exponent, C_2 in Table 1 is in agreement with the value of 5.0 found in Zhang and Dunn [9]. Although the temperature dependence of Eqn. (1) has an exponential form, it was found that parameters extracted from experimental data did

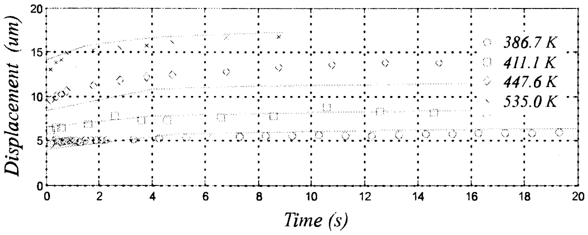

Figure 7: FEA simulation of power-off bimorph tip position, compared with measurement results in vacuum at four temperatures.

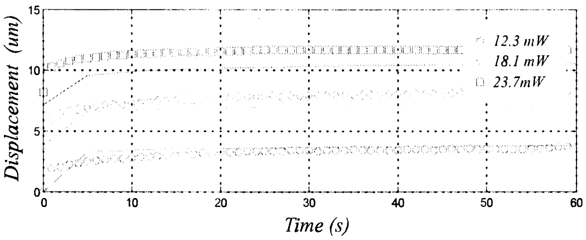

Figure 8: FEA simulation of power-off bimorph tip position, compared with measurement results in air at three applied power levels.

not agree well with this function. Instead, Eqn. (2) and temperature dependent parameters C_1^i describe the actual system better.

Measurements in vacuum indicate a higher creep rate than simulated at approximately 450 K. This behavior is attributed to the deviation between measured and simulated results in air at 23.7 mW.

In conclusion we feel these results have provided a simulation means whereby we can predict plastic deformation under electrothermal actuation and in response to large temperature changes.

5 ACKNOWLEDGMENTS

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REFERENCES

[1] K. Pister, M. Judy, S. Burgett, and R. Fearing, "Microfabricated hinges," *Sensors and Actuators*, vol. Vol. A33 No. 3, pp. 249–256, 1992.

[2] Y. Fukuta, D. Collard, T. Akiyama, E. Yang, and H. Fujita, "Microactuated self-assembling of 3d polysilicon structures with reshaping technology," in *Tenth Annual International Workshop on Micro Electro Mechanical Systems*, (Nagoya, Japan), pp. 477–481, IEEE, 1997.

[3] Y. Ho, M. Wu, H. Lin, and W. Fang, "A robust and reliable stress-induced self-assembly mechanism for optical devices," in *International Conference on Optical MEMS*, (Lugano, Switzerland), IEEE/LEOS, 2002.

[4] J. Zou, J. Chen, and C. Liu, "Plastic deformation magnetic assembly (PDMA) of 3d microstructures: Technology development and application," in *Proceedings of Transducers '01, the 11th International Conference on Solid-State Sensors and Actuators*, (Munich, Germany), 2001.

[5] M. Ellis, G. Skidmore, A. Geisberger, K. Tsui, N. Sarkar, and J. Randall, "Microfabricated silicon mechanical connectors and micro assembly," in *Nanotech 2002*, (Houston, TX), American Institute of Aeronautics and Astronautics, 2002.

[6] N. Sarkar, A.Geisberger, A. Rohani, W. Weimer, M. Ellis, G. Skidmore, and S. Chaudhuri, "Electrothermal plastic deformation self-assembly of 3-d optical microstructures," in *2002 IEEE/LEOS International Conference on Optical MEMS*, (Lugano, Switzerland), IEEE, 2002.

[7] M. Dunn, Y. Zhang, and V. Bright, "Deformation and structural stability of layered plate microstructures subject to thermal loading," *Journal of Microelectromechanical Systems*, vol. Vol. 11, No. 4, pp. 372–384, 2002.

[8] M. Finot and S. Suresh, "Small and large deformation of thick and thin-film multi-layers: Effects of layer geometry, plasticity and compositional gradients," *Journal of the Mechanics and Physics of Solids*, vol. Vol. 44, No. 5, pp. 683–721, 1996.

[9] Y. Zhang and M. Dunn, "Stress relaxation of Gold/Polysilicon layered MEMS microstructures subject to thermal loading," in *ASME International Mechanical Engineering Congress and Exposition*, (New York, NY), ASME, 2001.

[10] Y. Shen and S. Suresh, "Thermal cycling and stress relaxation response of si-al and si-al-SiO2 layered thin films," *Acta Metall. Mater.*, vol. Vol. 43, No. 11, pp. 3915–3926, 1995.

[11] K. Harris and A. King, "Direct observation of diffusional creep VIA TEM in polycrystalline thin films of gold," *Acta mater.*, vol. Vol. 46, No. 17, pp. 6195–6203, 1998.

[12] D. Koester, R. Mahadevan, B. Hardy, and K. Markus, *Mumps Design Handbook.* Cronos Integrated Microsystems, Morrisville, NC., 2000.

[13] M. Mermelstein, *UMECH Manual.* UMECH Technologies LLC, 2001.

[14] A. Geisberger, N. Sarkar, K. Tuck, C. Nistorica, K. Tsui, M. Ellis, and G. Skidmore, "Electrothermal actuator modeling and experimental validation," in *TEXMEMS IV*, (Lubbock, TX), July 11, 2002.