3-D Simulation of Thermal Multimorph Actuator based on MUMPs process

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Abstract: This paper describes the three dimension model and simulation results of a thermal actuator based on polyMUMPs process, known as thermal multimorph actuator. The device has potential application in micro-transducers such as atomic force microscope (AFM) tip and scanning tunneling microscope (STM) tip. This device made of a multi-layer materials stack together with consisted of polysilicon, SiO_2 and gold. A mask layout design, three dimension model and simulation results are reported and discussed.

Keywords: MEMS, thermal, actuator, bimorph, micro-heater

1. INTRODUCTION

Micro-Electro-Mechanical Systems (MEMS) technology has generated a significant a mount of interest in the government and business sectors. This interest is focused on the potential performance and cost advantages with micro-scale devices fabricated based on a silicon processing technology.

Thermal multimorph actuator is one of many kinds of thermal actuator based on MEMS technology that suitable for AFM tips application and many other applications. The present time, thermal multimorph actuators are used to handle the thermal tips for high-density data storage. Although it can exhibit large forces and linearity but it is high power requirements and low bandwidths [1].

The usual method be used to explain the MEMS devices behavior is finite element analysis (FEA). Many kinds of software can be applied to MEMS devices as long as a good understanding of device mechanism and approximated results.

FEA is an important tool for designing the MEMS devices. Low-cost, high performance MEMS devices require integrated electronics/MEMS processes, which have led to the development of surface micromachining technologies having the additional capability of including multilayer surface micromachined devices [2].

FEA is a numerical procedure that can be used to obtain thermal distribution and to predict the coupled thermal, electrical and mechanical properties for this device.

2. DEVICE DESIGN

A 2-D mask defines the layer geometry of each patterning step in the fabrication of MEMS devices. Masks levels have been defined within the layout tool; certain types of design errors are checked with design rule checking software. The design rule checking software checks such geometric features such as minimum feature resolution, minimum spacing between adjacent elements, etch release hole spacing etc. Design rule checking helps improve MEMS device yield by flagging geometric features that will likely result in process or design problems [2].

The actuator consists of two types of materials stack together, silicon dioxide and gold with an embedded polysilicon wire. The first layer formed below is silicon nitride as an insulator. The polysilicon wire encapsulated in silicon dioxide and gold layer are stacking together as shown in the cross section figure 1.

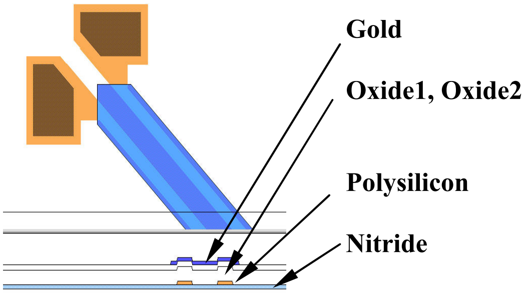


Fig.1 The cross section of thermal multimorph actuator

The mask layout is depending on PolyMUMPs design rules [3]. PolyMUMPs is a three-layer polysilicon surface micromachining process. This process has the general features of a standard surface micromachining process as follow; polysilicon is used as the structural material, deposited silicon oxide is used as the sacrificial layer, silicon nitride is used as electrical isolation between the polysilicon and the substrate, Metal is the top layer of the device and can be used as conductive layer. All dimension and thickness of each layer is shown in table 1.

Table1 All dimension and thickness of thermal actuators [4]

Material layer	Wide (μm)	Long (μm)	Thickness (μm)
Nitride	15	100	0.6
Polysilicon	3	200	0.5
Silicon dioxide	15	100	2.75
Gold	15	100	0.5

Figure 2 shows the mask layout of each layer designed by Tanner L-edit

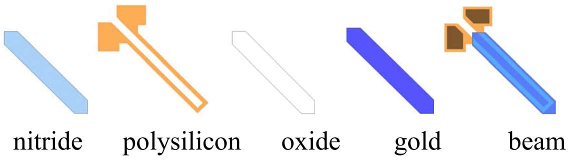


Fig.2 Thermal multimorph actuator mask layout designed by Tanner L-edit

3. DESIGN MODELING

The actuators utilize the thermal expansion properties of materials to produce bending motion. When a current is applied across the actuators, they heat up, causing expansion. A heat source is an electric current pass through an ohmic conductor (polysilicon wire). Parameters such as geometry, size, and overall configuration can be varied to achieve optimal deflection.

The actuator is bent by the difference of coefficients of thermal expansion (CTE) of two-kind of different layer. The tip deflection is govern by this equation [4].

$$d = \frac{1}{2} kL^2 = \frac{3}{4} L^2 \frac{\Delta T}{t_1 + t_2} \frac{\alpha_2 - \alpha_1}{1 + \frac{(E_1 t_1^2 - E_2 t_2^2)^2}{4E_1 t_1 E_2 t_2 (t_1 + t_2)^2}}$$

Where d is a beam deflection, r is radius of curvature = $1/k$, k is the beam curvature, L is the beam length, α_1 and α_2 are the CTE of two material layers, E_1 and E_2 are their Young's modulus, t_1 and t_2 are their thickness, and ΔT is the temperature difference between the operation and initial temperatures.

4. 3-D MODELING AND SIMULATION

The actuator's model was created using the process simulator and CIF mask was imported to CoventorWare, a commercial simulation software from Coventor Inc. Table 2 shows the thin film material properties used in this modeling and numerical simulation. Based on this information, a solid model was created as shown in figure 3. The multi-layers of the device are 3-D modeled and meshed with 27-node extruded brick elements, and transferred for analysis. The meshed model was show in figure 4.

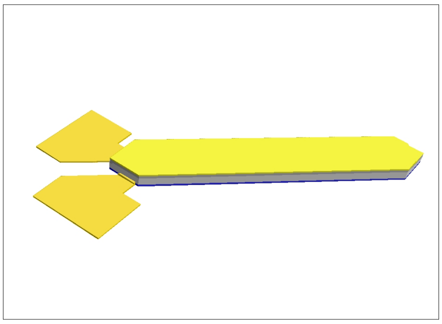


Fig.3 Thermal multimorph actuator 3-D model using CoventorWare

4.1 3-D Modeling

Firstly, a thermal-electric simulation is performed followed by Electro-thermal solver. The 2-D layout and process information of thermal multimorph actuator is used to build a solid model. When the 3-D model is created, the next step is the mesh generation throughout the beam as shown in figure 4. The beam is meshed with 27-node extruded brick elements. The finite elements and boundary elements techniques are used to solve the differential equations of each physical domain in this case. The differential equations are solved by discretizing the 3-D model into a mesh that consists of a number of elements with a specified number of nodes. When the mesh model is generated, this information is transferred to the solver for additional conversion such as boundary conditions. The DC drive voltage is applied to the end node of polysilicon wire and the joule heating is calculated. The resulted temperatures are then applied as loads to the thermal-structural part of the simulation. The deforming part with temperature distribution was generated and shown in figure 5.

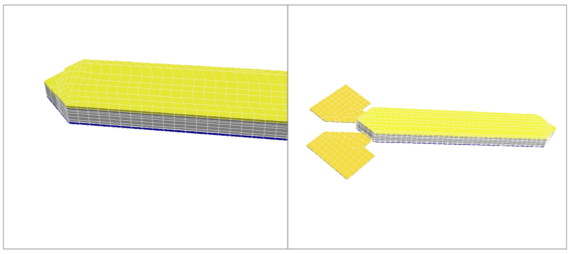
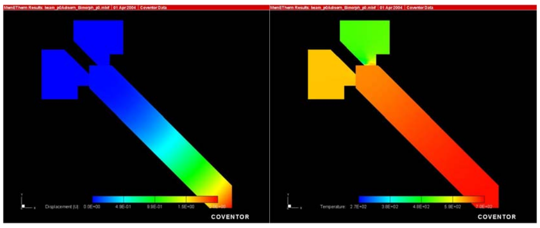


Fig.4 Meshed solid model for FEA using CoventorWare

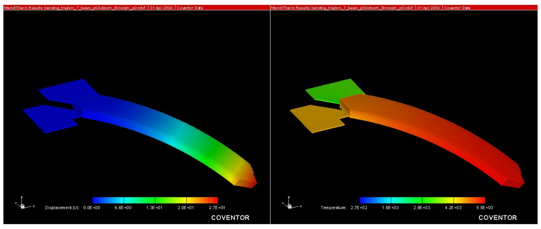
4.2 Simulation results

These are two type simulations; the first simulation is using only one input voltage applied (5 volt) to solver and secondly simulation is parametric study with variable voltage input. Figure 6 shows bending and thermal behavior of the thermal multimorph beam with varied input voltages.



(a) (b)

Fig.5 Bending and thermal behavior of the thermal multimorph beam with fixed input voltage of 5 volt. (a) Showing the beam displacement. (b) Showing the beam temperature distribution



(a) (b)

Fig.6 Bending and thermal behavior of the thermal multimorph beam with varied voltage from 0 to10 volt.(a) Showing the beam displacement. (b) Showing the beam temperature distribution

The simulation results show that the beam deflection of 1.9 µm with input power of 40 mW. These results compared with the beam deflection measured from experiments were shown in figure 7. The beam deflection experiments are measured using white-light interferometer. When the beam is actuated, the tip of actuator bends down. Because of the coefficient of thermal expansion mismatch between silicon dioxide and gold layer of 40:1, the maximum deflection of 2.5 µm with input power of 40 mW is achieved experimentally.

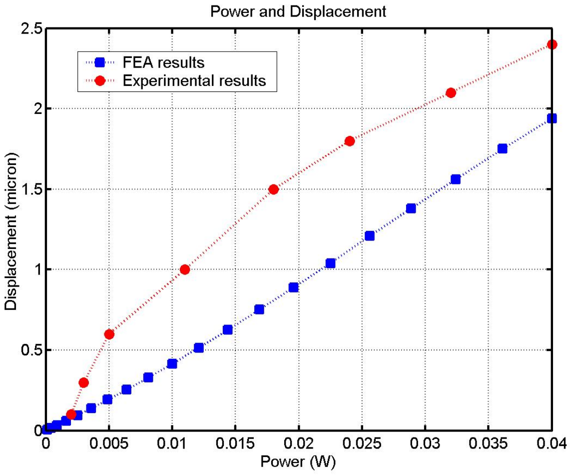


Fig.7 Beam bending versus applied power

The result comparison was shows an averaged error of 20% between FEA simulations and experimental results. This error might be caused by the different values of boundary condition, real dimension device and material properties.

The first, boundary conditions in FEA simulation are different from exact condition of the experiment such as initial temperature.

The second, the dimensions of fabricated device can be different from original dimensions in 2-D layout design that caused from the fabrication process.

And lastly, the material properties of fabricated beam might be different from the material database information be using in CoventorWare.

Table 2 The Thin film properties used for simulation

Property	Unit	Poly Silicon	Oxide	Gold
Elastic Constants	MPa	1.65e05	7.0e04	7.72e04
	Poisson ratio	2.3e-01	1.7e-1	4.2e-01
Density	kg/µm^3	2.23e-15	2.1e-15	1.9e-14
CTE	1/k	3.5e-06	0.35e-6	1.42e-5
Thermal Conductivity	pW/µm.K	5.0e007	1.42e06	3.0e08
Specific Heat	pJ/kg.K	1.0e14	7.1e-14	1.28e14
Electrical Conductivity	pS/µm	7.0e010	-	3.4e13

5. CONCLUSION

In summary, the 3-D thermal multimorph actuator simulation using CoventorWare are suitable to understand the device behavior as this paper reported. A design modeling allows us to use many types of materials as a multi-layer structure to determine the maximum actuator performance. The achieved maximum deflection is 1.9 µm with input power of 40 mW. Thermal multimorph actuator can be used to actuate small elements in many applications such as micromanipulator, microscope and microrobotics.

ACKNOWLEDGMENTS

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