Analysis of a Comb Type Microactuator Used in Micro Thermal Switches

P. K. Patowari, J. Saikia, P.S. Chatterjee, A. Ramachandran, Ashwin P.G. and S. Baishya

Abstract— **This paper deals with the analysis of a micron scale thermal actuator which can be used in micro thermal switches. This actuator works on the principle of expansion due to joule heating effect which is obtained by passing electric current through applying a potential difference of 1.5V across the base of the actuator. It has the shape of a comb and is made of annealed copper. The teeth of the comb expand linearly on passage of current through the base. As the cut-off voltage is reached, the teeth expand (linearly) and touch a grounded plate causing the current to flow through the shorter path of the circuit and thereby preventing the flow of excess current further into the circuit. Prevention of flow of current causes the teeth to shrink back to its original configuration and again the flow of current through the comb is restored. This analysis includes voltage distribution, stress distribution and temperature distribution of the micro thermal actuator in Comsol Multiphysics 3.5a software platform. There is a MEMS module incorporated in this software which is especially used for design and simulation of MEMS systems. The switch is found to be extremely sensitive because it is observed that this device achieved the desired results at a very low voltage i.e. 1.5V. This device can be used to protect MEMS systems from overloading.**

Index Terms— **microactuator; micro thermal switch; MEMS; Comsol Multiphysics**

I. Introduction

MICRO-Electro-Mechanical-Systems (MEMS) is one of the aspects of modern technology that consists of miniaturized electro-mechanical elements which are made using the techniques of micro fabrication. The critical physical dimensions of MEMS device vary from well below one micron on the lower end of the dimensional spectrum and all the way to several millimeters. The greatest promise of MEMS lies in the ability to produce mechanical motion on a small scale [1]. While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable and interesting elements are the microsensors and microactuators.

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Microsensors and microactuators are appropriately categorized as "transducers", which are defined as devices that convert energy from one form to another. There are many types of actuators viz. thermal actuators, electrostatic actuators etc. Thermal actuators use the thermal expansion of materials to achieve mechanical actuation. The characteristic parameter of thermal expansion of a solid material is the coefficient of thermal expansion. The coefficient of thermal expansion of a material is a function of temperature, which generally increases with rise in temperature. Mechanical strain of a material is directly proportional to the temperature change. This mechanical strain is responsible for the realization of the actuation obtained in the MEMS devices. Microswitches are a type of miniaturized device that is actuated by very little physical force. The defining feature of microswitches is that a relatively small change of physical quantity at the electrical contacts produces a relatively large movement at the free end of the actuator. The electro-thermal microactuators deflect or expand on the generation of heat due to passage of current through it. The amount of expansion or deflection is a function of the current passed. So this property of the microactuator can be used in controlling the flow of electric current in case of electro-thermal microswitches.

Much research has been going in the field of comb-drive actuators. Jeong et al. characterized the nonlinear behavior of a resonant comb-drive microactuator and compared it with the numerical results and experimental data [2]. Schonhardta et al. presented the electromagnetic comb drive actuator which allows over 100µm of linear actuator motion at large air gap widths of 25µm at 300 coil windings, at a structural height of 400µm and for an applied current of 8mA [3]. Chen et al. proposed new comb drives using high stiffness ratio springs designed and modeled to provide capabilities of large static displacement and continuous motion for applications, such as micro XY stage, two dimensional lens scanner, variable optical attenuator, optical switch etc. [4]. Harouche et al. used finite element analysis to simulate electrostatically actuated shaped comb drives operating under dc conditions (zero actuating frequency) [5]. Patowari et al. presented finite element analysis of a horizontal monometallic thermal actuator for MEMS application with three different materials namely single crystal silicon, poly-silicon and titanium [6]. Bharali et al. designed and analyzed a multilayered electrothermal actuator for MEMS [7].

In this paper, a comb type microactuator, which can be used as a part of micro-thermal switch, has been designed and analyzed. This type of switch prevents the flow of excess current into a micromechanical device.

II. Principle And Design

The first and foremost criterion of a MEMS device is that the member should have some sort of mechanical functionality whether or not the element can move. The comb type microactuator which has been designed and analyzed in this work is shown in Fig. 1. This type of actuator can be used in microthermal switches. The teeth in the comb depicted in the design satisfy the aforementioned criterion. Though one end of each of the teeth is fixed, the linear expansion of each of the teeth due to electro-thermal effect leads to actuation, and thus satisfies the very criteria of making it a MEMS device. The physical dimension of the actuator is in the scale of micrometers, which makes it a component of a miniaturized switching system. This is the general outlook towards MEMS application. The actuator designed here is the simplest of all micromechanical systems having elongation along the length of the actuator teeth.

The basic principle on which the actuator has been made is a cantilever with a uniformly distributed load on it. A cantilever is a mechanical structure whose one end is fixed while the other end is free to translate. As can be seen in Fig.1, the model of this comb drive consists of an array of cantilevers which have been connected to a fixed unit at the end. The actuator is made of annealed copper. The base is constrained in all the directions and the teeth are free to translate linearly. The two ends of the base of the comb are at different electric potentials causing a flow of current through it. Due to the flow of electric current the base gets heated up due to Joule heating. As the material of the comb is thermally conducting heat flows throughout the comb. It tends to expand but it is restricted in all directions except longitudinally along the length of the teeth.

Now as the cut-off voltage is reached the teeth expand by the requisite amount. Subsequently these come in contact with a grounded plate which is kept at a predefined distance from the teeth of the comb. The teeth being made of conducting material, causes the current to be diverted through it. This prevents the flow of excess current further into the micromechanical device(s). When the flow of current is stabilized the teeth shrink back and the contact is broken causing the current to flow through the original circuit again. The small size of the switch ensures high sensitivity and better performance.

The analysis of this model has been done in Comsol Multiphysics 3.5a. A range of potential differences were applied across the base of the comb. Then analysis was done for various displacements of the comb teeth and for various maximum temperatures. The analysis has been carried out for deflection of the actuator, the maximum temperature generated in the actuator and the stress developed for different applied voltages. The range of voltages producing the maximum deflection at temperatures lower than recrystallization temperature was found out. The following four cases have been dealt with in the analysis.

a) Variation of Electric Potential.
b) Variation of Temperature.
c) Variation of Total Displacement.
d) Variation of Von Mises Stress.

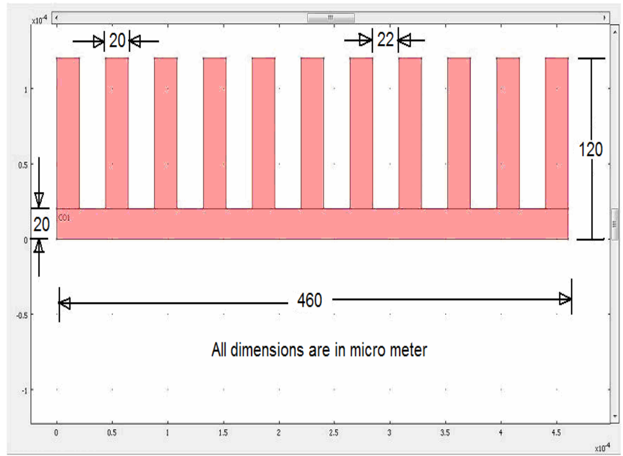

Fig. 1. Basic design of the model

III. Analysis

A. *Variation of Electric Poltential*

A positive potential is applied at one end of the comb base and the equal amount of negative potential is applied at the other end of the base of the comb. Thus the total potential difference or applied voltage will be equal to the sum of the potentials applied. The effect of different set of voltages has been tested for the amount of elongation. It has been found that 1.5V is the maximum potential difference that can be applied without exceeding the recrystallization temperature of the material i.e. annealed copper. Figure 2 shows the deformation displacement with variation of electric potential in the order of +0.75V in one end and -0.75V in the other end. Thus the total potential difference applied across the comb is 1.5V.

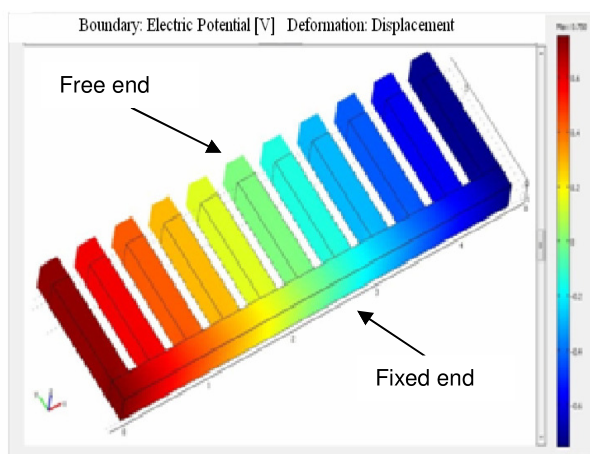

Fig. 2. Variation of electric potential

B. *Variation of Temperature*

Figure 3 shows the variation of temperature with displacement. The temperature varies from a minimum of 298K to a maximum of 520.3K that is within the recrystallization temperature of annealed copper, which is nearly 573K for annealed copper. The temperature distribution is uniform along the length of the teeth of the comb as they are of uniform length and cross sectional area.

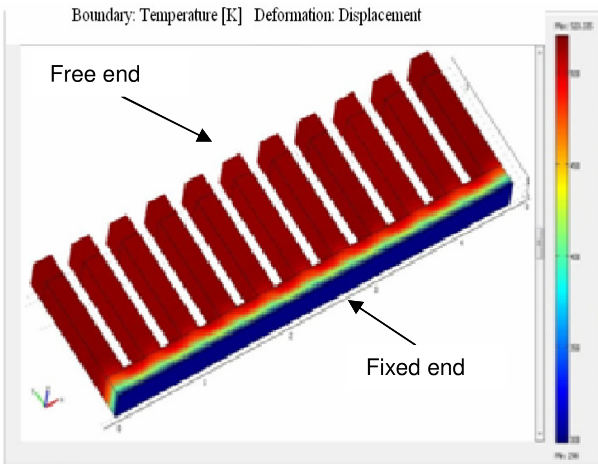

Fig. 3. Variation of temperature

C. *Variation of Total Displacement*

Import Figure 4 shows the variation of total displacement in the deformed position. As can be seen, the deformation is restricted to one direction with a maximum value of 0.8µm which is exactly equal to the distance between the grounded plate and the tip of the comb teeth. The maximum total displacement is occurring at the tip of the teeth. The minimum value of total displacement occurs at the base of the comb as it is fixed to the wall.

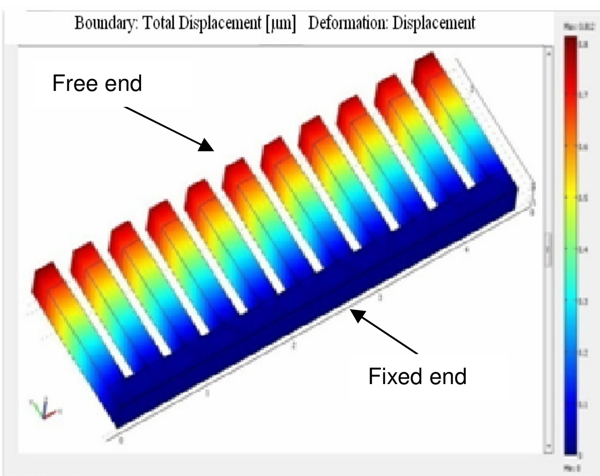

Fig. 4. Variation of total displacement

D. *Variation of Von Mises Stress*

Figure 5 clearly shows the variation of von Mises stress with voltage. The stress reaches a maximum value of 1.229MPa and is within the yield strength of annealed copper, i.e. approximately 70MPa. The maximum stress is occurring at the base edge of the teeth due to the phenomenon of stress concentration. The minimum value of stress occurs at the wall due to dissipation of the stress at the support i.e. the wall in which the comb is fixed.

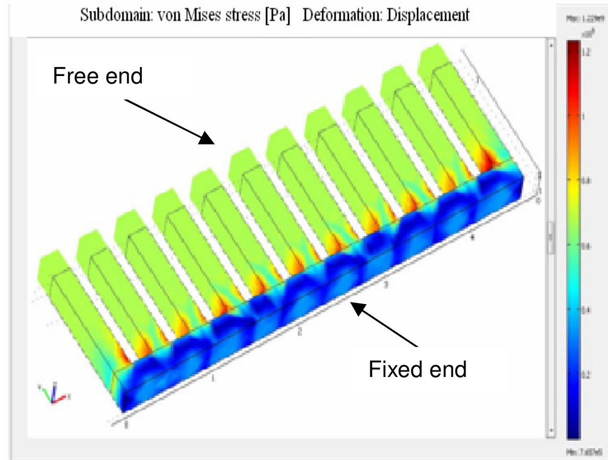

Fig. 5. Variation of von Mises stress

IV. Results and Discussions

A. *Temperature V/S Actuation Voltage*

Figure 6 clearly shows that the temperature varies almost linearly with voltage. The maximum temperature of 500K was found to be reached at an input voltage of 0.75V in each end. The variation of temperature with applied voltage is found to be gradual till 0.08V. After 0.08V till 0.75V the variation becomes abrupt.

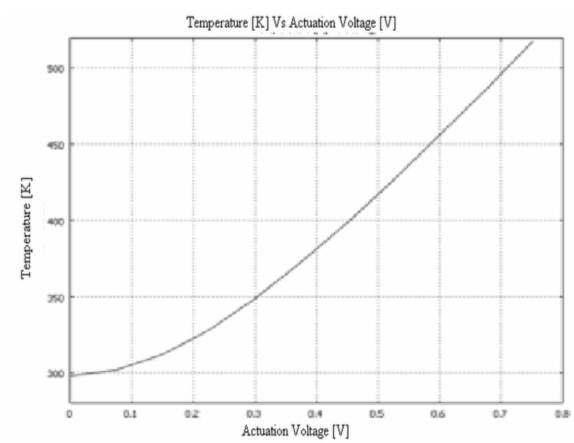

Fig. 6. The variation of temperature with voltage

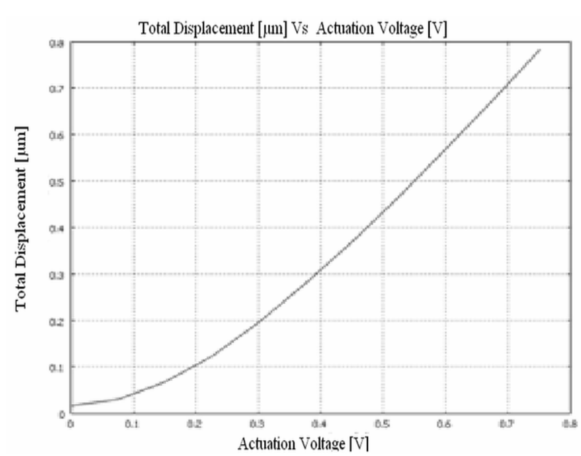

Fig. 7. Variation of displacement with voltages

B. *Total Displacement V/S Actuation Voltage*

Figure 7 clearly shows the variation of displacement with voltage. The slope of the curve varies at different ranges of voltages. The maximum total displacement is found to be approximately 0.8µm which occurs at an applied voltage of 0.75V in each end. From the plot, it is found that the total displacement increases steadily till about 0.08V. After 0.08V till 0.75V the variation is abrupt in nature.

V. Working and Application of the Switch

A. *Working of the Switch*

When the current is passed through the base of the comb, the teeth of the comb keep on elongating in one direction due to joule heating. The elongations in other directions have been restricted.

- A ground plate is kept at a distance of 0.8µm from the tip of the teeth of the comb.
- As the voltage increases beyond 1.5V the teeth elongate and touch the ground plate. Thus, the teeth act as a short circuit and the current starts flowing through the teeth rather than the base of the comb. Thus the system for which the trip switch is designed is saved from overloading of voltage beyond the cut-off voltage.
- As soon as the current is stopped, the teeth shrink back to its original shape due to its elasticity.
- Thus, these switches can be used to prevent the flow of excess current into a circuit or system beyond a cut-off voltage.

B. *Application of the Switch*

This switch can be used as a trip switch to protect a device from excessive voltage. This remains 'ON' till the operating voltage remains within the safe limits. As the voltage exceeds the safe limit the switch trips ensuring the safety of the device and the circuit. As the voltage stabilizes, the switch turns 'ON' ensuring automatic operation of the device.

VI. Conclusions

1) Annealed copper was used as the actuator material as it has high yield strength and recrystallization temperature.
2) The maximum potential difference that can be applied across the actuator is 1.5V without exceeding the recrystallization temperature i.e. nearly 573K for annealed copper.
3) The maximum temperature reached in the comb is through out the entire length of the teeth and its value is 520K which is below the recrystallization temperature of annealed copper.
4) The maximum total displacement is found to be approximately 0.8µm which occurs at an applied voltage of 0.75V.
5) The von-Mises stress or equivalent tensile stress is the maximum at the corners of the base of the teeth which results in stress concentration there at that zone. This maximum stress is found to be equal to 1.229MPa well below the yield stress value of annealed copper i.e. approximately 70MPa.
6) The elasticity of annealed copper will be retained and the teeth will spring back to its initial position as soon as the circuit breaks.

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