Design and Simulation of Electrothermally Actuated Silicon Microgripper

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ABSTRACT
Microgrippers find their importance in the field of micro assembly and nano assembly in semiconductor electronics. The crucial features to be examined throughout the design of the microgrippers are large displacement, low temperature and low power. By increasing the length of cold arm, extended arm and the flexure, the displacement of the device can be surpassed. A microgripper based on Electro-Thermal Actuators (ETA) that can produce larger displacement is presented. This microgripper is of open type in which arms have an initial open gap of 14µm. The maximum displacement of each arm is 64µm for the applied voltage of 24V. COMSOL MULTIPHYSICS v4.3b Software is used as a simulation tool. This design of microgripper is utilized for the movement of optical components and for driving gears of motors.

Keywords-- ETA, Microgrippers, COMSOL MULTIPHYSICS, Stress, Displacement, Temperature

I. INTRODUCTION
The evolution of miniaturization technology has pronounced the development of compact micro tools. The three major considerations for making microtools are:
(1) Design the device in shape and size
(2) The device material and mechanical properties
(3) Actuation mechanisms of the device

The microgrippers are utilized for a variety of applications, such as in security and defense, medicine, remote surveillance, and distributed networks [1]. Microgrippers with a controlled grasping force and accuracy are in demand[10]. Also, the microgripper be obliged for large opening displacement at low temperature and low-power consumption.

The microgripper can be governed by either electro-static or electro-thermal actuation. Thermal actuator provides larger forces and is also easier to control in contrast to the electro-static actuator. Electro-thermal microactuators are a promising solution for large and linear displacement, lowpowerMEMS actuators. Hence, ETA is the best driving mechanism for micro grippers. Due to the presence of temperature at the gripper points, it is not suitable to use electro-thermal actuator for the biological applications. The electro-thermal actuator is also called as a “Heatuator” [3]. ETA takes an advantage of its shape to create “bi-metallic” effect by the use of a single material.

The electro-static actuation based microgrippers, that can pick and place nano wires are demonstrated[5]. Microgrippers are made with different materials, such as polymer[7, 9] ceramic[11], nickel[4] and with different geometries. Microgrippers with chevron-type structures using nickel material have been reported[4]. The closed microcages, with highly compressively stressed diamond such as carbon and an electroplated Ni bimorph structure have been reported[4, 11]. The actuation range and piezoresistive sensitivity of an ETA microgripper established on a three-beam actuator/sensor structure using gold have been reported[8].

The electro thermally actuated silicon microgripper have not been reported much. In this paper, we proposed a microgripper based on electro-thermal actuators with silicon as a material that is highly reliable at elevated temperatures. The proposed microgripper achieves the maximum displacement of 64µm when the applied voltage is 24V. We discuss, the performances of ETA-based silicon microgripper, which is extremely well grounded at higher/elevated temperatures (>1414°C).

The clue to obtain higher deflection is to increase the length of extended arms and cold arms. The basic structure of an ETA is shown in Figure 1(a). The ETA consists of a thin long arm (called a hot arm) and a broad short arm (called a cold arm), the two arms are connected by a folded connector structure. When a DC voltage source is applied at the two electrodes, the current passes through the device. The current flows...
from one electrode to the other. The thin arm gets hotter quickly (higher current density), as the resistance of the thin arm is greater than the resistance of the broad arm. Therefore, the thin arm will bend towards the broad arm to achieve thermo-elastic equilibrium as shown in Figure 1(a). The device with the two arms connected in parallel is shown in Figure 1(b). When the device is connected in parallel, the broad arm will bend towards the narrow arm as the resistance of the broad arm, in this case is smaller and draws more current.

II. PROPOSED SYSEM

2.1 Device Design

We can achieve maximum displacement of the basic ETA by extending the arms, with lateral movement and the structure as shown in Figure 2. The total length of the device is taken as 1020μm from the anchors. When the device is connected in series, the resistance of the broad arm is in a series with resistance of the thin arm (the resistance of the thin arm is more than the resistance of the broad arm). Hence, the current in the structure is decided by the resistance of the thin arm. Consequently, a thinner hot arm leads to lower current and, hence, requires lower power for the same applied voltage. Also, the deflection force will be lower if the gap between the two arms i.e. the hot and cold arm is larger. Therefore, smaller the gap and narrower beams are, deflection force will be larger [9]. Hence, in our design, we have selected the values as follows: the widths of the flexures and hot arms are 10μm, and the gap between the arms, i.e. hot and cold arm is 12μm. Total length of the device is 1020μm from the anchors, the widths of the flexures and hot arms are 10μm. The device is designed with a hot arm length of 420μm, a cold arm length of 420μm, and the flexure of 100μm, spacing between the hot arms (extended arms) is 14μm and the length of the extended arm is 600μm.

Figure 1 (a) Series arrangement of basic electro-thermal actuator; (b) parallel arrangement

Figure 2: Structure of the proposed ETA microgripper with dimensions

Table 1 Material Properties of Silicon

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>VALUE</th>
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<tbody>
<tr>
<td>Young’s modulus</td>
<td>170 Gpa</td>
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<tr>
<td>Thermal conductivity</td>
<td>130 W/MK</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.28</td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>1.82 × 10−4 Ωm</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>700 J/kgK</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>2.6 × 10−6K</td>
</tr>
</tbody>
</table>

2.2 Finite Element Simulation

The performance of the ETA-based microgrippers has been studied and simulated using COMSOL Multiphysics version 4.3b. The material properties of silicon used in simulation are alluded in Table 1. Generally, in ETAs, failure of the structure occur either due to excess temperature, i.e. when the temperature exceeds the melting temperature of silicon (1414°C) or failure due to excessive thermal stress present at the flexures. Hence, for victorious operation of the device, it is mandatory to study the temperature
profiles on the hot arm and the stress at the flexures and connectors for various voltages.

The boundary conditions are utilized such that the ends of the actuators at the anchors are mechanically fixed, and all other boundaries are free to move for the lateral movement. The DC voltage is selectively applied at the ends of the arm of the actuator. Resistivity of the material is temperature dependent and is given by the following equation:

\[ \rho = \rho_0 [1 + \alpha (T - T_0)] \]  

where

- \( \rho_0 \) is the resistivity at a reference temperature,
- \( \alpha \) is the temperature coefficient of resistivity,
- \( T_0 \) is the reference temperature.

The heat diffusion equation is given by

\[ \nabla^2 T + q/k = 1/\alpha (\partial T/ \partial t) \]  

where

- \( \alpha \) is the thermal diffusivity
- \( T \) is the temperature distribution
- \( k \) is the thermal conductivity of the material
- \( \rho \) is the density
- \( c \) is the specific heat capacity
- \( q \) is the volumetric heat loss

The heat transfer due to convection (and/or conduction) as a function of temperature is given by

\[ q(t) = h (T - T_0) \]  

where

- \( h \) is the heat transfer coefficient of the material
- \( T \) is the temperature distribution
- \( T_0 \) is the reference temperature.

2.3 Performance Measures

In order to analyze the behavior of the above structure using COMSOL MULTIPHYSICS, we have applied the parametric sweep for the voltage varying from 0V to 24.5V. Some of the performance measures that are used to evaluate the performance of the device are:

Temperature – For the various applied voltage, we check the corresponding temperature distribution in the device.

Current density - The current density distribution in the device is noted down for the corresponding various applied voltage. The current density profile should be uniformly distributed.

Stress and displacement of the arms - The stress distribution in the device is determined for the various applied voltage. The occurrence of maximum stress allocation in the device is noted. Hence, the simulation has been carried out for the voltage of up to 24V. The results are discussed in the next successive subsections.

III. RESULTS AND DISCUSSION

3.1 Current Density

Figure 3 exhibits the snapshot of the maximum current density of the device for an applied voltage of 24V. This shows that, the current flow is maximum in the narrow arm and moderately less in wide arm. The maximum current density of the structure for 24V is 9.9725 \( \times 10^7 \) A/m². For the voltage range of 0-24V, maximum current density of the device is marked against the applied voltage as demonstrated in the Figure 4. Current density increases linearly with the applied voltage.

![Figure 3 Current Density Distribution of the device for an applied voltage of 24V](image)

![Figure 4 Current Density Vs Applied Voltage](image)

3.2 Temperature

Similarly, the Figure 5 demonstrates the temperature distribution across the structure. In our structure, we observed the maximum temperature at the center of the hot arms reaches 1327°C at 24 V, which is less than the melting temperature of silicon (1414°C). When the applied voltage is increased to 24.5V, we have observed the maximum temperature of the devices reaches 1427°C. Hence, the maximum value of the applied voltage has to be limited to 24 V for our device, beyond which the device may get damaged. The maximum temperature of the device is plotted against the applied voltage as illustrated in the Figure 6. The maximum temperature increases exponentially with the applied voltage.
Figure 5 Temperature across the device for an applied voltage of 24V

Figure 6 Applied Voltage Vs Temperature

3.3 Stress and Displacement

The stress distribution on the device for an applied voltage of 24V is illustrated in Figure 7. The stress is low and uniform in the most parts of the device and the maximum stress occurs at the flexure. As the applied voltage increases, the stress and the displacement of the arm increase. For the applied voltage of 24V, the maximum stress at the connectors is 60MPa, which is low compared with the yield stress of silicon.

Figure 7 Stress distribution of device for an applied voltage of 24V

Figure 8 exhibits the increase in the displacement of the upper arm measured with respect to its original position corresponding to the increase in applied voltage. We observe that the device shows maximum displacement of 64μm at 24V. The profile is well matching with the parabolic fit.

Figure 8 Applied Voltage Vs Displacement

IV. CONCLUSION

A novel model of electro-thermal based silicon microgripper is designed and simulated using COMSOL. The microgripper capable of producing a large displacement at a reasonably low applied voltage is presented. This design of microgripper is used for movement of optical components and for driving gears of motors. The design of a silicon microgripper has been analyzed, and the simulation results, using COMSOL MULTIPHYSICS software v4.3b was conferred. Simulation results show that the temperature shows up 1470 K (1327°C) at 24 V, and this temperature is less than the melting point of silicon. The experimental results show the fidelity of the devices at high temperatures. Hence, the design of silicon microgripper presented in this article has the advantage of low-power dissipation, and large displacement.

REFERENCES


