Design and Simulation of Cascaded Kink Beam Actuator

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Abstract— This paper describes the design, simulation and fabrication of a Cascaded Kink Beam MEMS Thermal actuator. Thermal actuators based on Micro Electro Mechanical System (MEMS) are highly advantageous because of their ability to deliver the actuation with great displacement and force. The basic principle of working is ohmic heating effect resulting in thermal expansion of the beams, thereby providing displacement in the actuators. The Cascaded kink Beam Thermal Actuator geometrically amplifies the thermal expansion of the beams. The proposed is a cascaded kink beam actuator including a bent beam structure to provide increased displacement. The design provides static displacement greater than 35um for an applied potential of 6 volts, requiring an area of 2mm x 2mm square meter. This performance is achieved at lower drive voltages necessary for the actuation, without effecting the elastic nature of the structure, also the variation in temperature is not exceeding the temperature point with stress lesser than the maximum limit of silicon material.

Keyword- MEMS, Kink Actuator, Cascaded Actuators.

INTRODUCTION

MEMS (Microelectromechanical systems), it's a pioneering field that adapts for new use in technology to accomplish a specific set of objectives. MEMS sensors is widely used in the aerospace and defence sector. A swift advancement has been seen in the MEMs research and development specially in the field of actuators. Currently five major types of actuators are used in MEMS [1]. Electro thermal, electro static, piezo electric, electromagnetic and shape memory alloys-based actuators. Electro thermal actuation is based on a balance between thermal energy generated by an electrical current and the heat dissipation through the environment of the substance. The kink beam actuators use the total thermal expansion which is constrained in one direction [2]. The kink actuator consists of straight and slanted parts as shown in figure 1(a) and figure 1(b). The main thermal elongation occurs in the straight path, and the central kink guides deformation in the chosen direction. The critical design parameters are arm length(L1), Bent Length(L2), and bending angle (θ1). The kink actuators have higher amplification factor than the V Actuators, thus it has a potential for application that requires a large output displacement. The cascaded arrangements of the basic kink beam structure can significantly increase the output displacement. It is observed that the simple kink beam actuator provides twice the displacement when compared to the bent beam for similar geometrical dimension without exceeding the temperature and stress limitations.

In the design presented here the primary units are anchored to the substrate and the secondary unit is relatively thinner beams acting as bent beam structure to provide better displacement than regular cascaded bent beam actuator. The device has a kink beam actuator as the primary units with a bent beam structure at the centre. The actuation current is applied either across the primary stage, where the current and the secondary, thereby providing good mechanical amplification. Therefore, the total displacement produced by cascades design is much larger than a single kink beam actuator [3]. The drawback of a cascaded structure is an increased risk of out of plane buckling which is prevented by limiting the operational temperature. This paper presents a novel structure based on cascaded kink beam actuator as shown in figure 2.

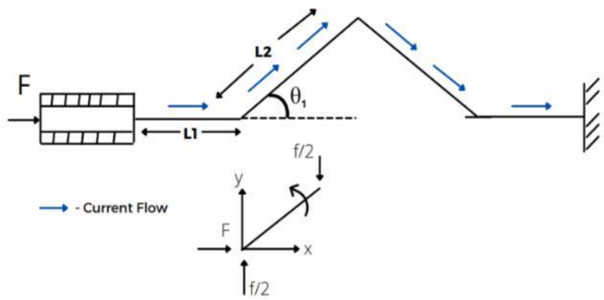


Figure 1. Structure of simple kink beam actuator

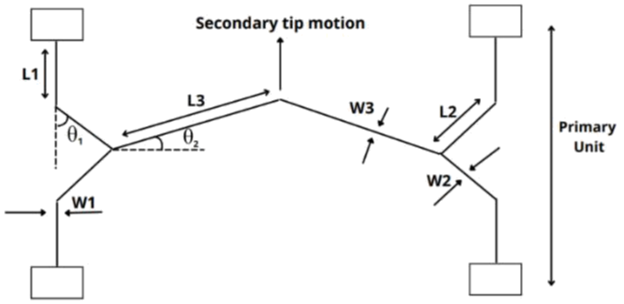


Figure 2: Structure of cascaded kink bent beam actuator

INNOVATION IN DESIGN

Design:

The proposed work includes the primary unit as kink beam cascaded with the bent beam structure results in attainment of greater displacement of about 35um for an applied 6V potential at a lesser area requirement. However, the simulated cascaded kink beam structure which includes simple kink beam as primary and secondary units to form a cascaded system resulted in buckling of the primary units leading to the failure of the system. Hence, the design proves to be better than cascaded bent beam and fully cascaded kink beam actuators. Also, the maximum temperature and stress is lesser than the maximum limit of elastic deformation.

Architectural details and dimensions:

The dimensional measurements and the material properties of the design cascaded kink beam actuator is given in table 1 and 2.

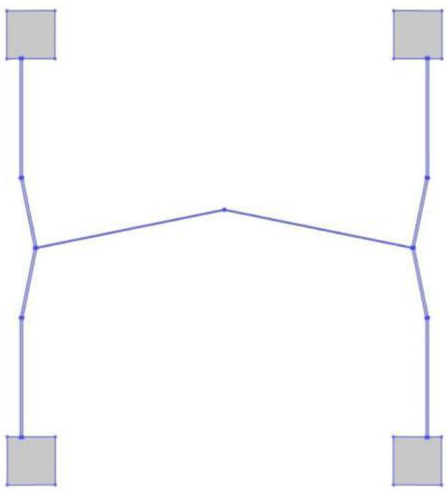


Figure 3. Kink Beam structure

Table1: Device dimensions

Geometry dimensions	Values
Size of anchor	200um X 200um
Length, L1	500um
Width, W1	10um
Θ1 and θ2	0.2 radians
Length, L2, L3	300 and 800um
Width, W2	10um
Width, W3	5um
Total area of the device	2000um x 2000um

THEROETICAL ANALYSIS AND SIMULATION RESULTS

Actuator's performance is easily tailored by altering the bending angle, for the fabrication of geometrically well-defined mechanical structures mechanical structures [4].

Theoretical calculation:

The basic principle of working is based on Joule heating, where the heat generated per unit volume per unit time due to joule heating is given by,

$$H = i^2rt$$

Where 'i' is the current, 'R' is the resistance, which varies due to temperature and time 't'.

The maximum deflection of electrothermal actuator is given by,

$$D_{max} = 2\frac{tan\theta 1}{k} * \tan\left(\frac{kL1}{4}\right) - (L1\tan\theta 1)\frac{1}{2}$$

where, L1 is the length of the thermal actuator beam

θ1 is the angle made by the thermal actuator beam with respect to the horizontal, k is unknown eigen value

$$k = \sqrt{F/IE}$$

where, F is the reaction force, E is the young's modulus of Si, is the second moment inertia of actuator beams

$$I = bd^3/12$$

Electrothermal analysis:

In the proposed structure of the cascaded kink beam the actuator beam lengths are found to be longer than the height and widths. As we fabricate using the SOI wafer configuration, the height of the beam equals the active layer thickness and the gap 'g' between the beams and the substrate equals the oxide layer thickness. In the case of very small gap under a suspended silicon beam, convention and radiation can be considered to be negligible and conduction through air to the substrate dominates. But, conduction from sides of the beam to the surrounding air to the substrate cannot be ignored and must be accounted for the shape conduction factor 'S'. This geometric factor represents the heat loss from the sides and the bottom of the beam to expected heat loss from the bottom of the beam only.[5] An empirical equation has been developed for 2um to 50um. This shape factor is given by,

$$S = \frac{4}{w}(10^{-6} + g) + 1$$

Where w is the width of the element and ‘g’ is the gap between the actuator beam and the substrate. Further the heat loss due to the air gap is given as,

$$Q = SK_a wdx\frac{dt}{g}$$

Table2: Material properties

Description	Value
Density	2330 kg/m^3
Coefficient of thermal expansion	2.6e-6/K
Poisson’s Ratio	0.28
Heat capacity at constant pressure	700J/(kg-K)
Thermal conductivity	131 W/(m-K)
Electrical conductivity	2000 S/m
Young’s modulus	166GPa

Simulation results:

The simulation results of stationary study for plotting the temperature and displacement graph is shown in Fig. 6 and 7. The comparison results of the simulation of cascaded bent beam and present design along with their transient analysis is shown in Table 2. The results indicate that the cascaded bent beam is able to achieve a displacement of 30 µm at 30 ms whereas the prepared design could reach the displacement of 35 µm at 26 ms without much difference in the stress and temperature variation.

The simulation is performed in COMSOL Multiphysics software. The device structure is shown in Figure 3. The temperature and displacement variation are as shown in Figure 4,5. The potential level above 8.5v will tend to elastic deformation as the temperature exceeds 1000K, which is closer to the MP of Silicon.

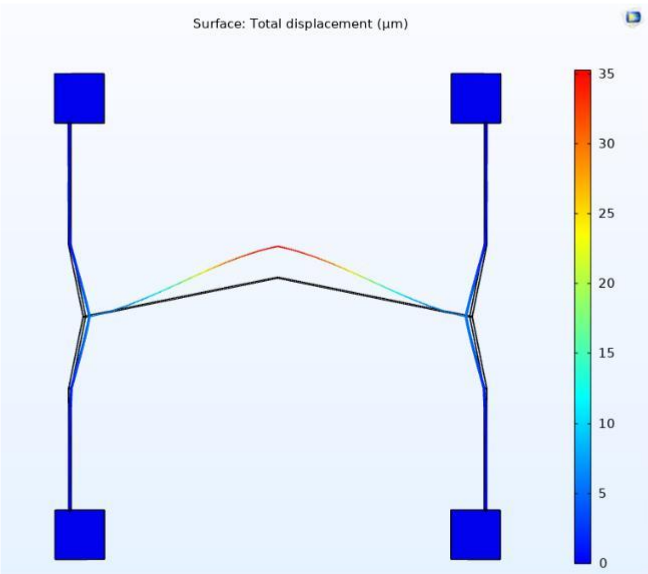


Figure 4. Displacement variation for a applied potential of 6v

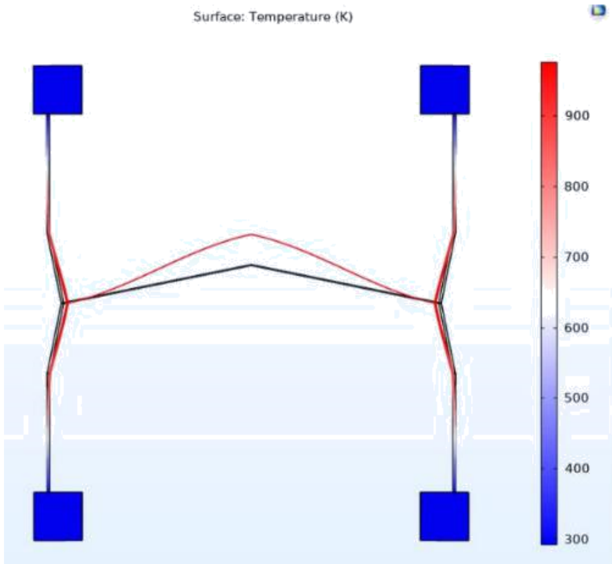


Figure 5: Surface temperature variation for an applied voltage of 6V

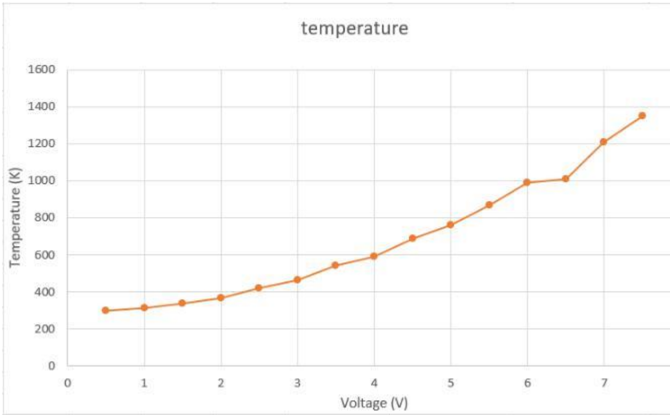


Figure 6: Voltage vs Temperature

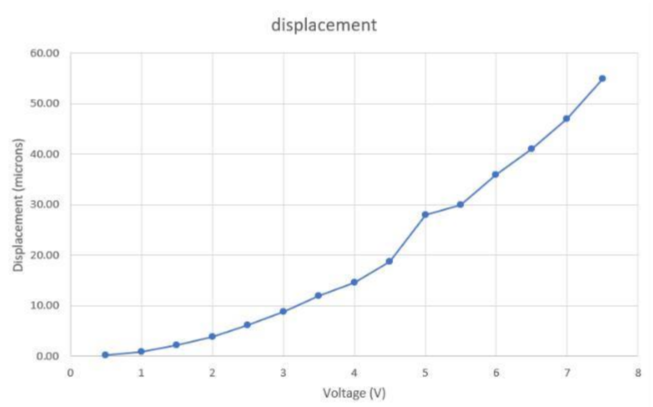


Figure 7: Voltage vs Displacement

Comparative analysis of Cascaded chevron actuator and Cascaded kink actuator:

As we have incorporated kink beam as the primary units in our design, and not cascading of the kinked beam as the secondary beam has led to failure of the structure the below simulation shows the result,

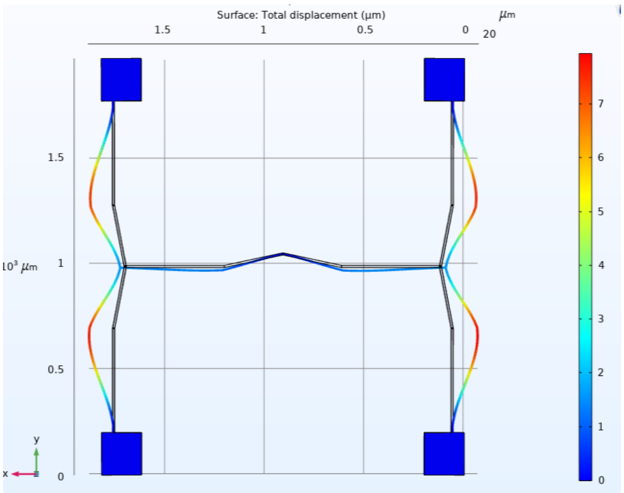


Figure 8. Simulation for setting the secondary beam as kink beam

The structure cascaded kink beam was therefore simulated by using a compliant secondary unit for the amplification of displacement from the primary unit.

This structure also has shown better results than the traditional cascaded chevron actuator, the following results and simulation shows the benefit of using the kink actuator over the chevron actuator, this comparative analysis is done mainly considering three factors,

- Displacement
- Temperature
- Stress

Displacement results:

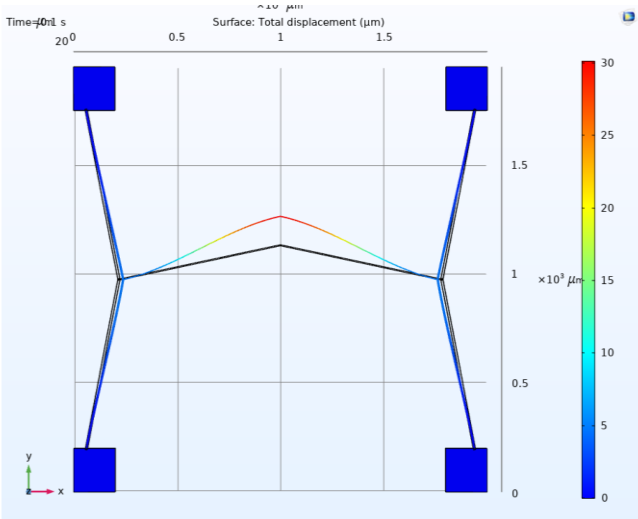


Figure 9. Displacement for cascaded chevron actuator for voltage of 6V The max displacement is found to be 30um.

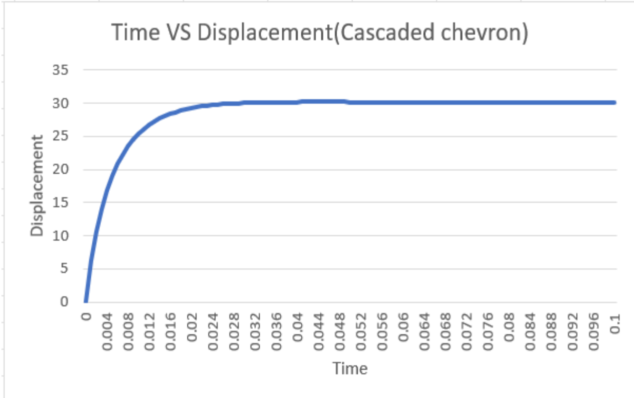


Figure 10. Transient analysis for displacement for cascaded chevron actuator for voltage of 6V. The max displacement is found to be 30um at 30ms.

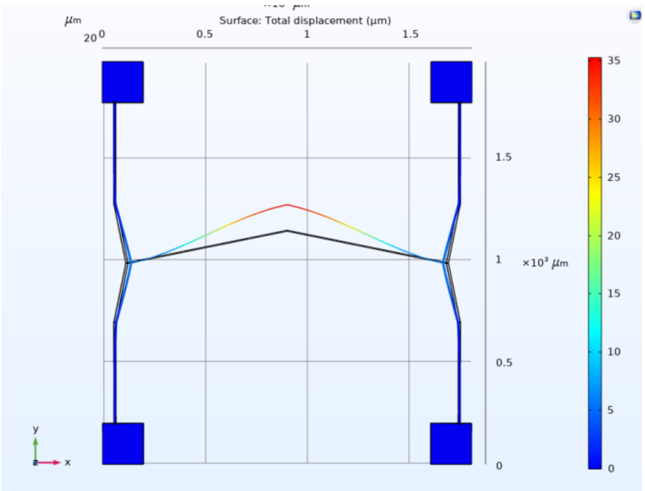


Figure 11. Displacement for cascaded kink actuator for voltage of 6V The max displacement is found to be 35um.

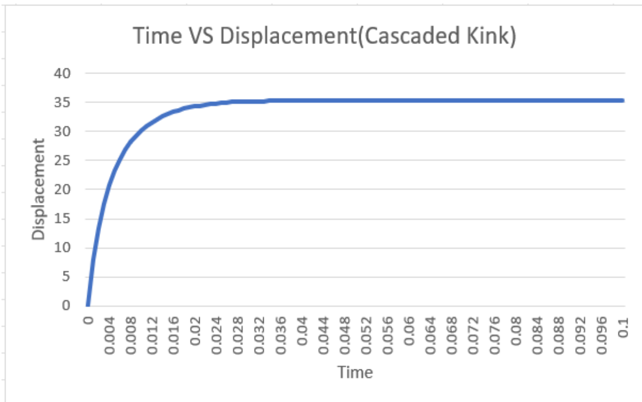


Figure 12. Transient analysis for displacement for cascaded kink actuator for voltage of 6V. The max displacement is found to be 35um at 26ms.

This result of the displacement has shown that two structures of the same material and dimensions of beam length, it has resulted in two very different result with a difference of 5um i.e., 16% gain in the displacement. The transient analysis shows that the Cascaded kink actuator reaches its maximum displacement more than and faster than cascaded chevron by 4ms.

Temperature results:

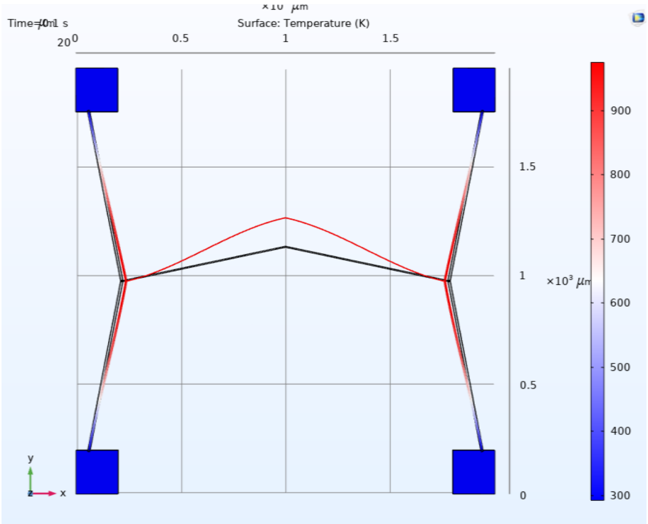


Figure 13. Temperature for cascaded chevron actuator for voltage of 6V
The max temperature is found to be 975K.

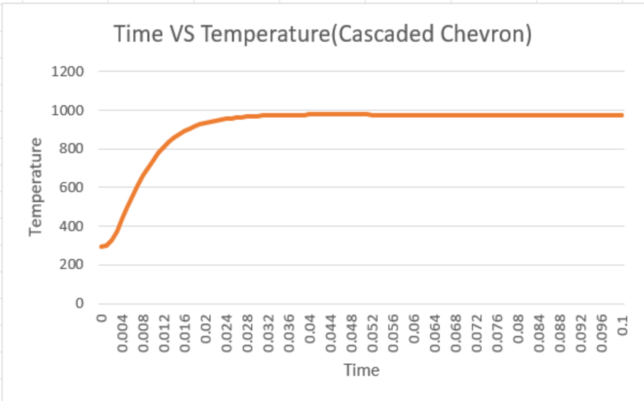


Figure 14. Transient analysis for temperature of cascaded chevron actuator for voltage of 6V.

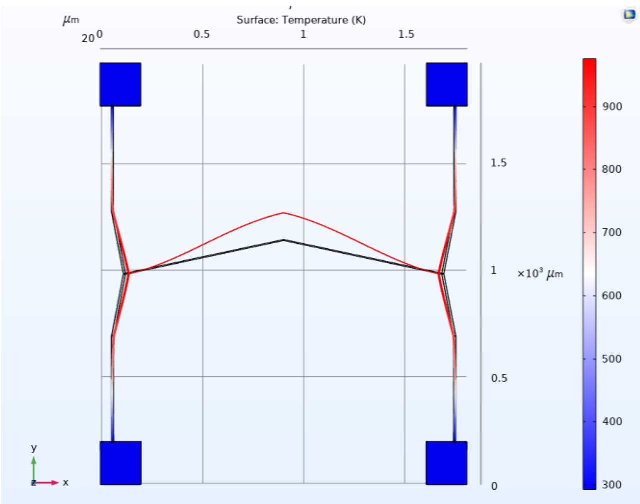


Figure 15. Temperature for cascaded kink actuator for voltage of 6V
The max temperature is found to be 975K.

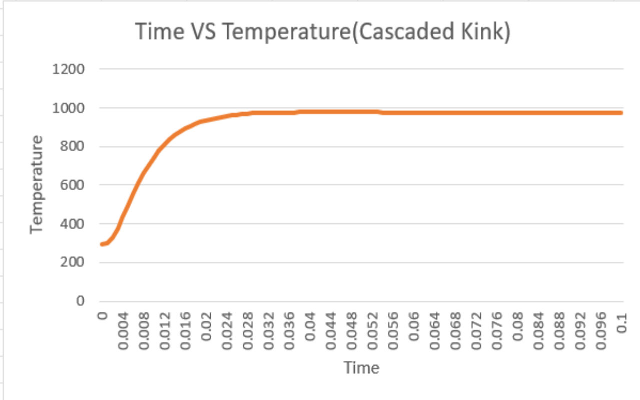


Figure 16. Transient analysis for temperature of cascaded kink actuator for voltage of 6V.

The results for temperature have been same for both the Cascaded Chevron actuator and Cascaded Kink actuator.

Stress results:

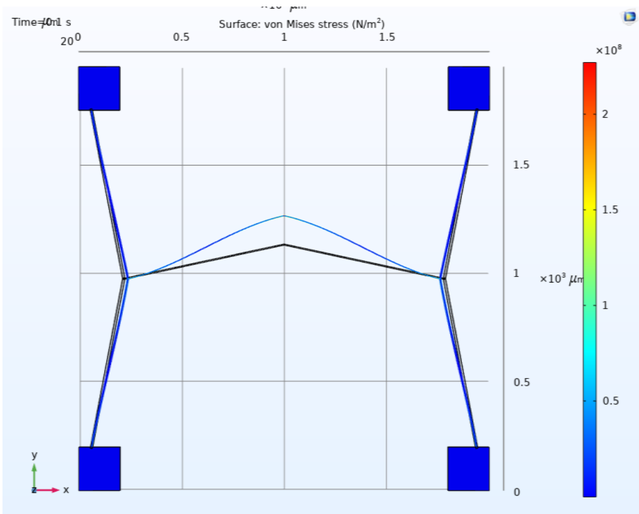


Figure 17. Stress analysis for cascaded chevron actuator for voltage of 6V

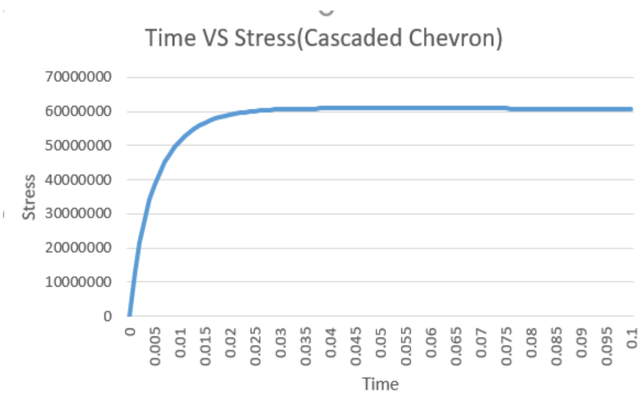


Figure 18. Transient stress analysis for cascaded chevron actuator for voltage of 6V at the point of displacement observed.

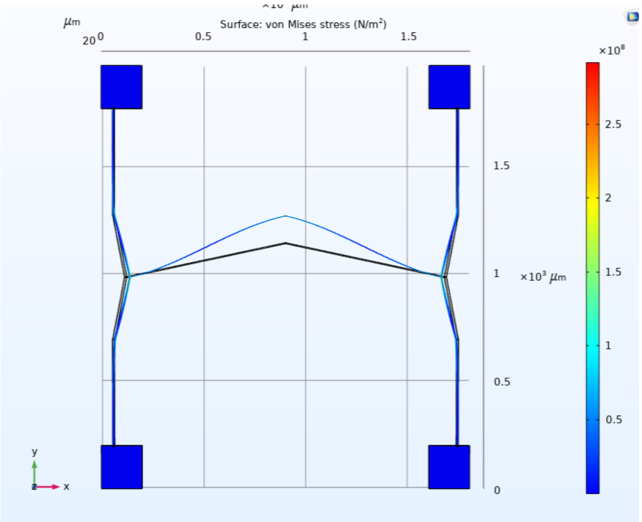


Figure 19. Stress analysis for cascaded kink actuator for voltage of 6V

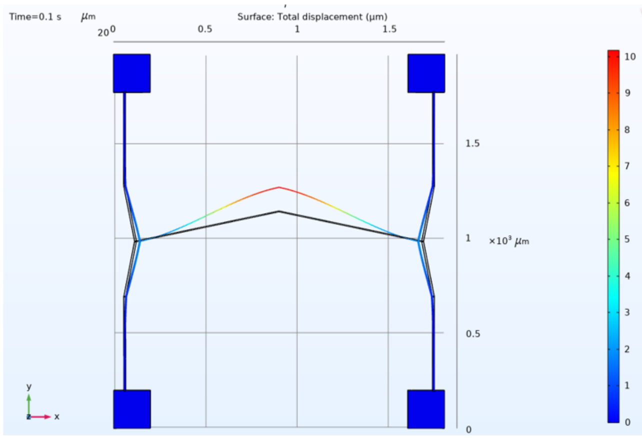


Figure 21. ET analysis displacement for cascaded kink actuator for voltage of 6V

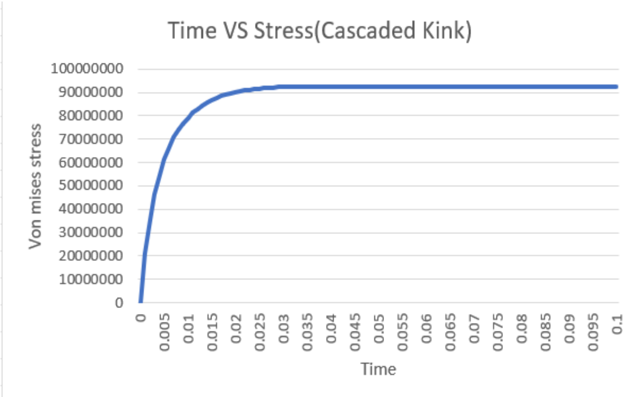


Figure 20. Transient stress analysis for cascaded chevron actuator for voltage of 6V at the point of displacement observed.

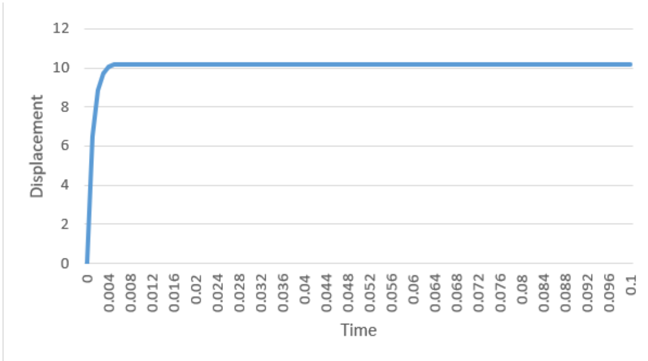


Figure 22. Transient ET analysis displacement for cascaded kink actuator for voltage of 6V

The stress analysis plot shows that the stress for cascaded kink actuator has a stress of 1×10^8 N/m^2 more than that of the cascaded chevron actuator, but well under the stress constraint.

Electrothermal analysis results:

The following results are shown when considering the electrothermal conditions, where we consider the heat loss due to air gap and shape factor.
The results have been simulated considering displacement,

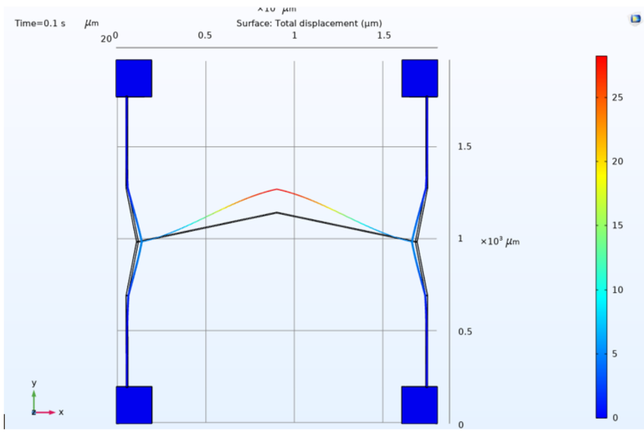


Figure 23. ET analysis displacement for cascaded kink actuator for voltage of 10V

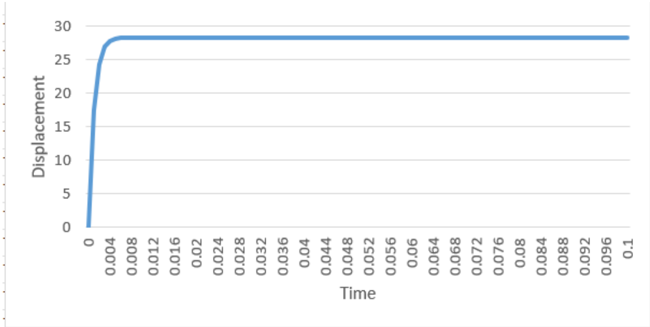
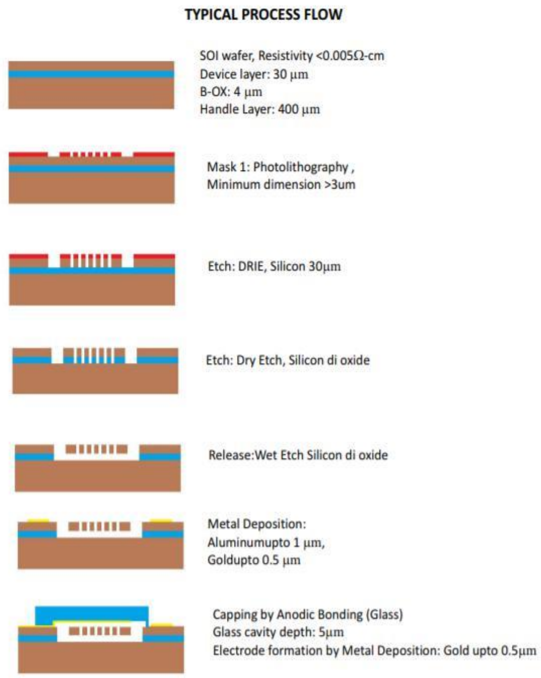


Figure 24. Transient ET analysis displacement for cascaded kink actuator for voltage of 10V

The results above clearly show that for a voltage of 6v the displacement obtained is 10um and at a voltage of 10v the displacement obtained is 28um.

FABRICATION FEASIBILITY

The device fabrication process is summarized in Figure 6. The fabrication process begins with silicon wafer of a relatively high resistivity. First a diffusion mask thermal oxide is grown and patterned. Diffusion is then carried out to make the exposed regions much more conductive than the rest of the wafer. The minimum dimension size of the designed actuator is found to be 5um.



CONCLUSION

The work gives brief description of cascaded kink beam actuator to achieve higher displacement in a lesser area. The simulation has been carried out using COMSOL Multiphysics tool. From the simulation results it is evident that the design presented here is able to perform better than a cascaded kink beam actuator by overcoming the buckling effect, also a higher displacement of 35 um is achieved at 26ms when compared with the cascaded bent beam actuator. Electrothermal analysis shows that the minimum displacement value no longer reaches the minimum limit of the displacement after including the conduction losses through air, hence proving it to be an Indigenous design. The device response is in linear to the applied potential in terms temperature and displacement.

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