



Design and Simulation of Bidirectional In-Plane Chevron Beam Microtweezer

Neha Jain^[1], Anurekha Sharma^[2], Sandeep Kumar^[3]

^{[1], [3]} Department of Electronics and Communication Engineering, SDDIET, Panchkula, India

^[2] Department of Electronic Science, Kurukshetra University, Kurukshetra, India.

Abstract: This paper presents the modified design of a bidirectional electrothermal chevron beam microtweezer proposed by J. K. Luo [1]. The original design has been modified to include inward in-plane motion. Thus, the modified design is capable of bidirectional motion. The structures are designed and simulated using COMSOL Multiphysics 4.2a. The bidirectional chevron beam microtweezer shows an in-plane displacement of $2.192\mu\text{m}$ outward and $0.6178\mu\text{m}$ inward and an out-of-plane displacement of $2.1594 \times 10^{-8}\text{m}$ for an applied voltage of 4V. The effect of number of beams, length of beams and residual stress on the deflection of the chevron beam microtweezer has also been studied. A comparison between calculated and simulated results has been shown for the displacement of the actuator and both of them are in agreement with each other.

Keywords: MEMS, Actuators, Electrothermal, Chevron, Bidirectional, Microtweezer.

I. Introduction

MEMS refers to the term Micro Electro Mechanical System. MEMS consists of mechanical structures, microsensors, microactuators and microelectronics. Microactuators convert electrical input to mechanical form [2]. Application of MEMS exist in biomedical and biological fields, diagnostics, drug delivery, tissue engineering, microassembly of microelectronics, information technology etc [1]. Popular drive mechanisms for actuation are piezoelectric, electrostatic, shape memory and electrothermal. Electrostatic materials have the disadvantage that they cannot produce large displacement and force. Piezoelectric actuators require high voltages of upto hundreds of volts, hence unsuitable for biological applications. SM (shape memory) based actuators are inefficient in their working [1]. Electrothermal actuators have the advantage that they can produce large displacement and forces but at the cost of higher power consumption [3]. Electrothermal actuators are based on Joule heating. An electrothermal actuator can be U-beam or V-beam actuator. U-beam actuator is based on non-uniform joule heating while a V-beam actuator is based on uniform heating and expansion of the beams. A bent beam thermal actuator uses its shape to enhance the thermal expansion of its beams. Heat required for actuation is generated by electrical resistive heating [4]. A bent chevron beam actuator provides a scalable force along with displacement confined in one dimension [5]. The performance of a conventional chevron actuator is limited by high temperature expansion of the beams that is confined near the shuttle. It is degraded by the thermal expansion of the long shuttle that connects the apexes of the beam [5]. Applications of actuators are optical modulators, RF and optical switches, micromanipulators etc.

Many authors have done in the field of chevron beam actuators viz-a-viz Alex Man Ho Kwan et.al [5] proposed two design approaches to improve the performance of electrothermal in-plane micro actuator with chevron beams. They tried to improve the performance of actuator by improving Figure of Merit which is defined as the product of actuation displacement and force. Ehab Rawashdeh et.al [4] discussed the design and performance of a kink actuator which is a modified form of the bent-beam actuator. The main difference between kink and chevron actuators is that chevron actuators consist mainly of a straight arm which has a small portion of length that is bent. M.S. Suen et.al [6] proposed a method to optimize the stress concentration and fillet radius of the electrothermal V-beam microactuators. The main objective of this study was to get a relationship between aspect ratio and fillet radius to improve stress concentration. J. K. Luo et.al [1] discussed thermal actuator based micro tweezers with three different driving configurations. Out of three designs, type2 has the highest tip opening outwards which is based on chevron beam structure. This work presents a modified design of type 2 structure with an objective of providing bidirectional displacement.

II. Design concepts

Consider a conductor with a potential difference V applied across its ends causing a current I to flow through it, then its resistance and potential V are related as

$$V = IR \quad (2.1)$$

The power loss (rate of energy loss per unit time) in a resistor appears in the form of thermal energy and is given by

$$P = VI = I^2 R \quad (2.2)$$

This power is also known as ohmic heating or Joule heating. Power results in heating of the structure which causes thermal expansion according to the equation 2.3.

$$\Delta L = \alpha_E L \Delta T \quad (2.3)$$

where, α_E = Thermal expansion coefficient

ΔT = Temperature difference

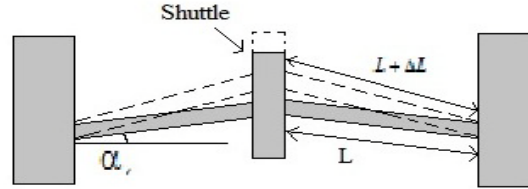


Figure 2.1: Chevron beam actuator

This elongation in the beam produces deflection of chevron beam actuator is given by equation 2.4 [7]:

$$Def_{chev} = [L^2 + 2L(\Delta L) - L^2 \cos^2(\alpha)]^{1/2} - L \sin(\alpha) \quad \text{where,} \quad (2.4)$$

L = Length of single beam

α = Pre-bending angle

ΔL = Elongation of the beam due to thermal expansion [3], where ΔL is given by equation 2.3

Stiffness of the shuttle with N number of beams is given by the following equation [8]:

$$k_{CHV} = N192EI / (2L)^2 \quad (2.5)$$

where,

N = Number of beams

E = Young's modulus

L = Length of beam

I = Moment of Inertia, which is given by [9]

$$I = tw^3 / 12 \quad \text{where,} \quad (2.6)$$

t = Thickness of beam in μm

w = Width of the beam in μm

III. Design and Simulation

The original structure [1] given in figure 3.1 shows an outward deflection. This structure consists of chevron beam and inverted chevron beam design. The motion of the shuttle pushes the inverted chevron structure upward and deflects the arms of the microtweezer outwards.

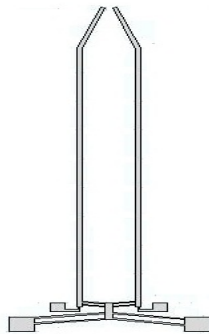


Figure 3.1: Original design

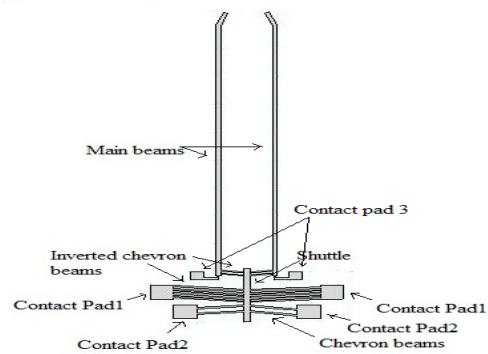


Figure 3.2: Proposed design for bidirectional motion

The design in fig. 3.1 is modified as shown in fig. 3.2 to provide bidirectional motion of microtweezer. This structure consists of two inward chevron beam structures and one chevron beam structure which shows an inward deflection when voltage is applied across contact pad 1 and it shows an outward deflection when voltage is applied across contact pad 2. Contact pad 3 is provided with the potential in both the cases.

A. Simulation results

The structure given in figure 3.2 was designed and simulated in COMSOL 4.2a. The main beam and chevron beam structures are made of polysilicon while the contact pads are made of copper. The material properties of both the materials are given in table 3.1.

Table 3.1: Material properties

Property	Polysilicon	Copper
Electrical conductivity(σ) in S/m	0.25×10^5	58.1×10^6
Coefficient of thermal expansion(α) in 1/K	2.61×10^{-6}	16.5×10^{-6}
Heat capacity at constant pressure(C_p) in J/ kg*K	678	384
Density(ρ) in kg/m ³	2320	8960
Thermal conductivity(k) in W/m*K	34	401
Relative permittivity (ϵ_r)	4.5	4.5
Young's Modulus(E) in GPa	160	120
Poisson's ratio(μ)	0.22	0.34

Geometrical dimensions of proposed design are shown in table 3.2

Table 3.2 Geometrical dimensions of proposed design

Parameter	Dimensions
Length of anchors	50 μ m
Width of anchors	50 μ m
Length of chevron beam	150 μ m
Width of chevron beam	5 μ m
Length of inverted chevron	50 μ m
Width of inverted chevron	4 μ m
Length of main beam	900 μ m
Width of main beam	10 μ m
Tilt angles	5.71°
Length of the shuttle	190 μ m
Gap between chevron beams	25 μ m
Gap between inverted chevron beams	10 μ m

Figure 3.3 and 3.4 shows displacement distributions for a bidirectional microtweezer which shows both inward and outward displacement in a single structure. This is because this structure consists of both chevron beams and inverted chevron beams in its design which can displace the tweezer in either direction based on to which contact pads the voltage is applied. When a potential of 4V is applied across contact pad1 it shows an inward displacement and when this voltage is applied across contact pad2 it shows an outward displacement.

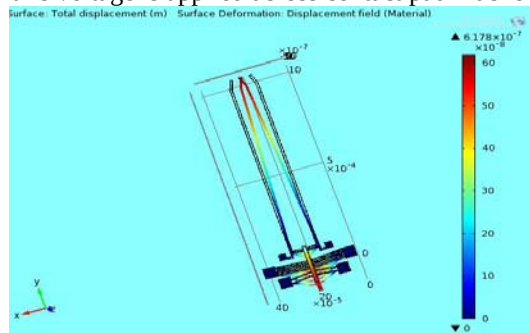


Figure 3.3: Bidirectional microtweezer with inward displacement

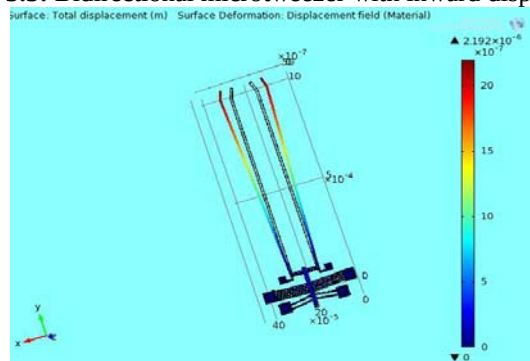


Figure 3.4: Bidirectional microtweezer with outward displacement

Figure 3.5 and 3.6 shows the temperature distribution for bidirectional microtweezer. In this figure structure reaches maximum temperature of 881K at an applied voltage of 4V while temperature at tips is approximately at room temperature.

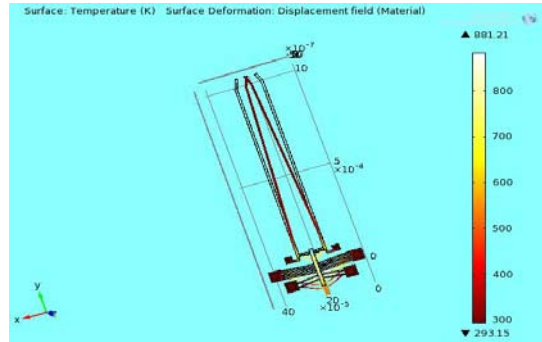


Figure 3.5: Temperature distribution for inward deflection

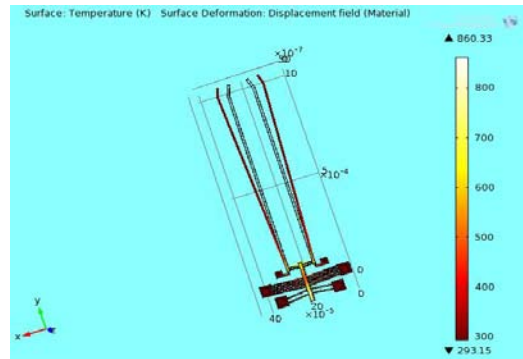


Figure 3.6: Temperature distribution for outward deflection

Figure 3.7 shows variation of displacement with applied voltage for inward and outward deflection.

Voltage Vs Displacement

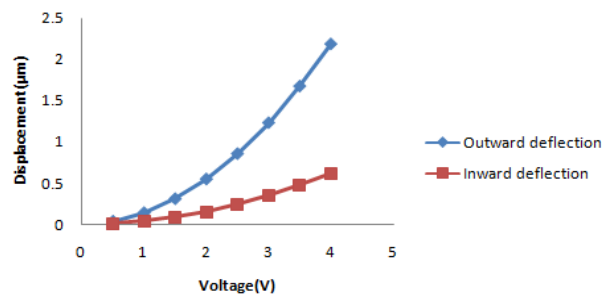


Figure 3.7: Voltage Vs displacement

Figure 3.8 shows variation in temperature on shuttle with applied voltage.

Voltage Vs Temperature

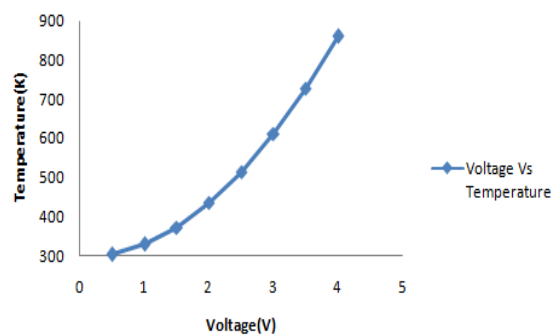


Figure 3.8: Voltage Vs temperature

Variation of displacement with number of beams

Figure 3.9 shows that as the number of beams increases displacement also increases up to five beams. After that it almost saturates. This trend follows irrespective of change in length.

Number of beams Vs displacement

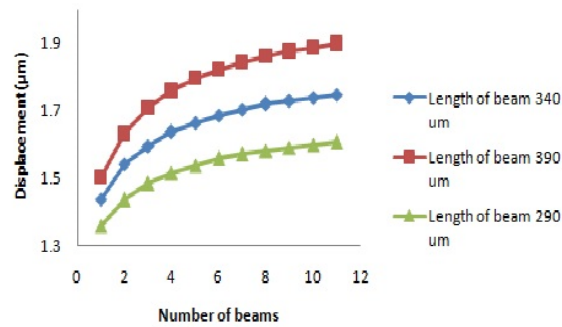


Figure 3.9: Number of beams Vs Displacement

Figure 3.10 shows the variation in stiffness with number of beams.

Number of beams Vs Stiffness

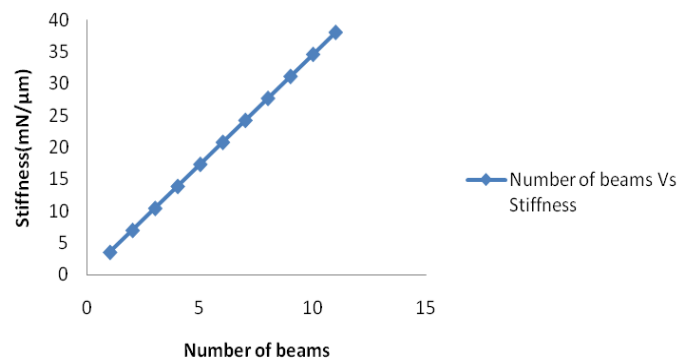


Figure 3.10: Number of beams Vs stiffness

Figure 3.10 shows that upon increasing the number of beams for a chevron beam actuator, stiffness of the beam also increases. This stiffness accounts for the limitation in increase in displacement with the increase in number of beams. Residual stresses are introduced in the structures when thin films are deposited at an elevated temperature. This can be compressive stress or tensile stress. In the present design we are using polysilicon as the material, therefore stress induced here is compressive stress. As the compressive stress increases structure becomes flexible. Hence displacement increases on increasing compressive stress. Figure 3.11 shows effect of compressive residual stress on displacement.

Residual stress Vs Displacement

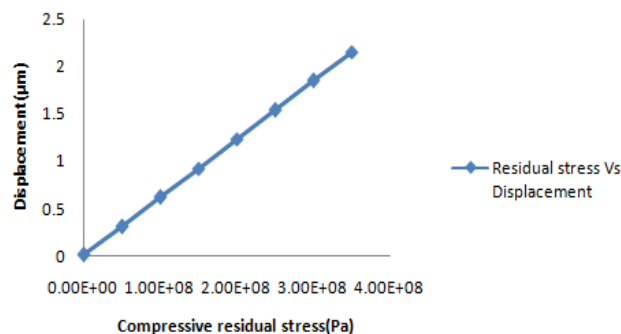


Figure 3.11: Residual stress Vs displacement

Figure 3.11 shows that as the compressive residual stress increases, the displacement of the microtweezer also increases. In this work, for a compressive stress in the range 150MPa to 350MPa displacement is increased from 0.3067μm to 2.156μm.

IV. Results and Discussions

Simulated versus calculated results for chevron beam actuator are shown in figure 4.1. It can be observed that both the results are in agreement with each other.

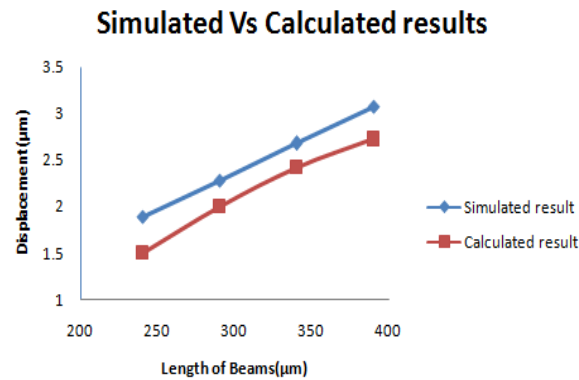


Figure 4.1: Simulated Vs calculated results

For fixed voltage, height and material properties, the displacement is proportional to the square of the beam length. This is given by equation 4.1 [10]:

$$\mu = \beta \alpha L^2 V^2 / 3kpd \quad (4.1)$$

where,

μ is the displacement, β represents difference in displacement for different actuators and its value is unity for chevron beam actuator, α is thermal expansion coefficient, L is the length of the beam and V is the applied potential.

Hence increasing the beam length is the effective way to achieve a larger displacement. But there is a limitation on the beam length due to buckling and stiction problems, and the maximum displacement of a chevron actuator is therefore limited [10]. The inward displacement and outward displacement for same applied voltage is different due to the different lengths of the two chevron beams. Therefore, the bidirectional behaviour can be easily tailored by optimising the lengths. Chevron is modelled as a doubly supported beam with rigid ends. Effect of stiffness with number of beams has been studied and it is observed that as the number of beams increases stiffness also increases. This is evident from figure 3.10. Hence in the modified design number of chevron beams is limited to five, as beyond this there is no substantial increase in displacement. Effect of compressive residual stress on displacement has also been studied. As the compressive stress is induced in the structure flexibility of the beams increases, hence displacement of the actuator also increases. This is evident in figure 3.11.

V. Conclusion

This paper presents the design and simulation of a bidirectional chevron beam microtweezer. The presented design shows an out-of-plane displacement of 2.1594×10^{-8} m which is very less as compared to in-plane inward and outward displacement of $2.192 \mu\text{m}$ and $0.6178 \mu\text{m}$ respectively for applied voltage of 4V. Effect of compressive residual stress is also studied on displacement and it is found that as the compressive residual stress increases displacement also increases. Effect of stiffness is studied which indicates that number of beams of the actuator is limited to five in this case.

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