Research Article

Design, Simulation, and Analysis of Micro/Nanoelectromechanical System Rotational Devices

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1. Introduction

MEMS technology is a representation of microscopic implementations of sensors and actuators which are fabricated using microfabrication techniques. MEMS/NEMS devices generally fall in the range between 1 and 1000 nanometers in size. MEMS/NEMS technologies are developed for the fabrication of integrated circuits (IC). MEMS/NEMS devices can be categorized into sensors and actuators in μ scale, which can be further used in macroworld. They have wide applications in the fields as diverse as microsatellites, automotive, aerospace, telecommunication, biomedical, wind tunnel instrumentation etc. MEMS/NEMS has strong multidisciplinary character. MEMS/NEMS devices have the following advantages like less power consumption, small size, improved performance, increasing reliability, lesser weight, and less cost than devices which are working on similar fundamental principle in macrosize. MEMS/NEMS-based devices are fabricated using IC fabrication techniques along with special techniques to fabricate three dimensional (3D) structures. It has high precision and high aspect ratio. It scales the size of the device without changing the property of the materials.

MEMS-based thermal actuator is an electromechanically actuated device which works based on Joules’ law of electrothermal heating. Amplification of thermal force may be done in design of thermal actuator. Electrothermal actuator fabricated using single crystal silicon or polysilicon as a compliance structure. Atre and Boedo [1] analyzed the variation of tip deflection of actuator with respect to the applied

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voltage. The thermal behavior of the polysilicon material and its relationship in the calculation of deflection by analytical methods are studied. The experimental and simulation results of six different actuator designs are compared. At high voltages, the finite element model overestimates experimentally determined values. Thermal conductivity of polysilicon plays an important role in predicting actuator deflection. Geisberger et al. [2] discussed about the influence of dopant concentration in electrical and thermal conductivity. Investigating the static and transient response of the thermal actuator at different excitation frequency and voltage, the simulated and measured data are compared. Relatively poor fit of simulation data using constant conductivities explains the importance of thermal properties of the material. Heo and Kim [3, 4] designed a robust to maximize the actuator deflection with respect to applied voltage and baseline design by the topology optimization method. Optimize the thermal actuator design, which is robust to noise factors.

Heo and Kim [5] described the optimal design to maximize the rotation angle of the actuator for fixed input power. Element connectivity parameterization formulation method is used to eradicate numerical instabilities. Haefner et al. [6] evaluated the lifetime evaluation of microgears, which depend on the geometry shape deviations (tooth deformation) and finite element model-based prognostic method. Islam and Islam [7] analyzed the finite element method of stress, contact stress, and bending stress for spur gears, used in the hybrid vehicle power transmission system. Arefin et al. [8] implemented both PV module and wind turbine in internal combustion engine-based vehicle. Wind turbine blade design was simulated using ANSYS CFD. Jin et al. [9] designed impact of upstream deflector parameters (rotor distance influence, width influence, distance influence, and height influence) in vertical axis wind turbines. Compare with the simulated and experimental results with and without deflector, Deflector reduces negative torque and increases efficiency of wind turbine.

Arefin and Islam [10] studied about noise characteristics and emission characteristics of micro gas turbine, which is used as range extender for electric truck. Suitable temperature of operating the micro gas turbine for maximum power is studied. Noise reduction methods are proposed at higher speed, output power is increased, and vibration (noise) and CO emission are reduced. Karbosi et al. [11] compared the properties of two micro actuators such as distribution of temperature, power consumed, and actuation of two micro actuators. Analysis of two designs is like design a—different beam lengths and design B—different beam sections and flexure part, to produce maximum deflection. GA Optimal design produces 70% increase in tip deflection. Lo et al. [12] modeled the electrothermal-mechanical system into a combination of electrical, thermal, and mechanical model using the lumped model technique. Deflection and frequency bandwidth are analyzed to attain and determine static gain.

Dhinakaran et al. [13] demonstrated the combination of electrothermal and electrostatic actuation mechanisms. It gives pull-in behavior at low voltage and makes hybrid actuator and hybrid bidirectional actuator perfect for switching applications. Chiorean et al. [14] analyzed the effect of geometrical parameters on the output force of Chevron actuators. The authors also considered the effect of thermal expansion of substrate. It studies about the impact of substrate silicon deformation due to forces in anchors and thermal expansion of substrate silicon or effect of central shaft expansion in actuator displacement. Suocheng et al. [15] studied bimetal film thermal expansion-based microthermal actuator variation of actuator displacement at
different voltage values and temperature ranges. Time taken to achieve maximum displacement (response time) at different voltage levels is also investigated. Potekhina and Wang [16] designed hot and cold arm type actuators where differential thermal expansion is achieved by various geometrical shapes like changing beam shape, modifying electrical parameters like selective doping, modified resistance, or topological parameter changes like multimode or bidirectional operation. Sun et al. [17] explained about the single walled carbon nanotube (SWCNT) electrothermal actuators thermal expansion that is based on the following parameters such as amount of joule heating and coefficient of thermal expansion, induced stress relaxation mechanism and post-secondary curing. Li et al. [18] studied the application of series of V-beam thermal actuator amplification for MEMS applications in specific areas like safety and arming. Yogeshwaran et al. [19] discussed about the temperature distribution dynamics and displacement and its impact on the device dimensions and properties of material and applied

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Coefficient of thermal expansion of polysilicon ($\alpha$)</td>
<td>$2.7 \times 10^{-6}$ K$^{-1}$</td>
</tr>
<tr>
<td>2.</td>
<td>Electrical specific resistance of polysilicon at room temperature ($\rho_0$)</td>
<td>$2 \times 10^{-3}$ $\Omega$ - cm</td>
</tr>
<tr>
<td>3.</td>
<td>Thermal conductivity of polysilicon ($k_p$)</td>
<td>32 W-m$^{-1}$-K$^{-1}$</td>
</tr>
<tr>
<td>4.</td>
<td>Thermal conductivity of air ($k_a$)</td>
<td>0.006 W-m$^{-1}$-K$^{-1}$</td>
</tr>
<tr>
<td>5.</td>
<td>Thermal conductivity of silicon($k_n$)</td>
<td>2.25 W-m$^{-1}$-K$^{-1}$</td>
</tr>
<tr>
<td>6.</td>
<td>Thickness of polysilicon ($t_p$)</td>
<td>2000 nm</td>
</tr>
<tr>
<td>7.</td>
<td>Thickness of air ($t_a$)</td>
<td>2000 nm</td>
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<tr>
<td>8.</td>
<td>Thickness ($t_{p0}$)</td>
<td>2000 nm</td>
</tr>
<tr>
<td>9.</td>
<td>Thickness of silicon ($t_n$)</td>
<td>2000 nm</td>
</tr>
</tbody>
</table>

Figure 5: Temperature analysis of silicon (circular disc 5 $\mu$m).

Figure 6: Temperature analysis of silicon (square arm 10 $\mu$m).
Kim et al. [20] designed and fabricated the multilayered structure with platinum heater. Ni-Co-based flexible substrate as thermal bimorph actuators and thermal insulation (isolation) layers are also employed. Ulkir [21] designed bidirectional electrothermal actuator which displaces in two directions. Authors compared the fabrication process of 2-photon polymerization (2PP) and digital light processing (DLP) methods, which are 3D printing techniques. Steiner et al. [22] studied the relation between actuator area and deflection distance based on V-shaped Chevron type beams. Duzng [23] modeled the V-shaped thermal actuator using ordinary differential equations. Author studied about the thermal inertia of the system, if the applied voltage is in the form of square pulse, the output is in form of concave trapezium. Li et al. [24] discussed the application of thermal actuator in testing the fracture strength of thin films. Voltage is applied to thermal actuator, which creates the thermal expansion; due to thermal expansion force that is created which is used to fracture the test structure. Suryanarayanan et al. [25] compared experimental results, and simulation results are correlated using back propagation neural network. Simulation results fitted with neural network provide a cost-effective model for V-shaped thermal actuator. The author proposes that the length of flexure would not increase the stress on the arm length, and it also increases the lifetime of actuator. López-Walle et al. [27] discussed heat transfer characteristics that are important in improving the performance of thermal actuator. Kim et al. [28] discussed the application of bimorph thermal actuators in rotation control of micromirrors. Two bimorph actuators produce vertical displacement of 25 μm at 10 V, which rotates micromirror by 20°.
2. Importance of Microthermal Rotary Actuator

Electrostatic actuation and thermal actuation are methods to obtain actuation in MEMS. This method of actuations is very popular since this actuation provides simplicity, fast actuation rates, and low power consumption, and it uses silicon as its material. This type of actuation method is a common method of driving MEMS devices because it is compatible with microfabrication.

Thermal microactuators have the following advantages like higher force, lesser operating voltages, and less susceptibility to adhesion failures compared to electrostatic actuators. Microthermal actuators do require more power, and their switching speeds are limited by cooling times. It produces higher displacement and higher force than electrostatic actuators.

3. Types of Microthermal Rotary Actuator

3.1. A-Symmetric (Bimorph). A bimorph is a microcantilever based thermal actuator used as an actuator or sensor which consists of two metal layers. In some applications, it also has a passive layer between the two active layers. The term bimorph is most commonly used with thermal bimorphs. The first theory about the bending of thermally actuated bimorph was given by Stoney. In Figure 1, schematic diagram of A-symmetric (bimorph) is shown. It has generally a single material. The deflection is produced here due to asymmetry in the shape. This type of thermal actuator is also called as hot-cold beam actuator.

3.2. Symmetric (Bent Beam, Chevron). Chevron-shaped actuators are one of the most popular actuators in the MEMS...
community (also called V-beam thermal actuator). Its principle is based on the thermal expansion of a single material to generate the motion, which is amplified using different geometric constraints. The V-beam thermal actuators are capable of producing high output force for low operating voltage. The output force (displacement) depends on the inclination of the beam. In Figure 2, Chevron beam actuator is shown.

3.3. Designing of Microthermal Rotary Actuator. Designing of microthermal rotary actuator is done using structural mechanics. For designing the microthermal rotary actuator, the important parameters used are materials and dimensions. Finite element method (FEM) software used to design the thermal actuator. Here, COMSOL is used for simulation. The actuator’s operation involves three coupled physics phenomena: electric current conduction, heat conduction with heat generation, and structural stresses and strains due to thermal expansion. In COMSOL, the joule heating model uses the heat equation given in equation as the mathematical model for heat transfer in solids.

3.3.1. Dimensions. Microthermal rotary actuator is done using structural differ from varying its length and shape of the cold disc. Length of the hot arm is varies from 500 nm to 2500 nm. Height of the cold beam is 500 nm, and the diameter of the cold beam is 200 nm. Figure 3 shows the microthermal rotary actuator structure.

3.3.2. Materials. Materials used for designing of microthermal rotary actuator are silicon and poly silicon. Each material has a unique property which makes them to use in designing the microthermal rotary actuator.
3.4. Theoretical Analysis

3.4.1. Electrothermal Analysis. The above Figure 4 shows the 1D actuator. According to joule's heating, rate of heat input = rate of heat going out

\[ Q_{\text{in}} + Q_{\text{joule}} = Q_{\text{out,arm}} + Q_{\text{out,sub}} \]  

Since

\[ Q_{\text{in}} = -k_p w t_p \left( \frac{dT}{dx} \right)_x ; \quad Q_{\text{joule}} = J^2 \rho w t_p dx, \]

\[ Q_{\text{out,arm}} = -k_p w t_p \left( \frac{dT}{dx} \right)_{x+dx} ; \quad Q_{\text{out,sub}} = S dx w \frac{T - T_{\text{sub}}}{R_T}, \]

where \( T \) is the temperature at any given location of the actuator, \( T_{\text{sub}} \) is the substrate temperature, \( \rho \) is the resistivity of material, \( k_p \) is the thermal conductivity of material, \( J \) is the current density of hot arm or cold disc, \( S \) is the shape factor, \( R_T \) is the thermal resistance between the device and the substrate.

Substitute above values in Equation (1), and we get

\[ -k_p w t_p \left( \frac{dT}{dx} \right)_x + J^2 \rho w t_p dx = -k_p w t_p \left( \frac{dT}{dx} \right)_{x+dx} + S dx w \frac{T - T_{\text{sub}}}{R_T} \]

(3)

Thermal resistance between the device and the substrate is given by

\[ R_T = \frac{t_a}{k_a} + \frac{t_{p0}}{k_{p0}} + \frac{t_n}{k_n}, \]

(4)

where \( t_a, t_{p0}, \) and \( t_n \) are the thickness of the element above the polysilicon layer, thickness of polysilayer, and thickness of silicon layer. \( k_a, k_{p0}, \) and \( k_n \) are the thermal conductivity values of air, polysilicon and silicon, respectively.

Substitute the needed values to Equation (4) from Table 1. After calculating thermal resistance obtained, it is \( R_T = 7.7205 \times 10^{-5} \).

Current density is the amount of current by unit area. The current density of hot arm and cold disc is calculated from

\[ J_h = \frac{I}{w_p t_p}, \]

(5)

\[ J_c = . \]

Using the above equation, the calculated current density value is \( J_h = 7.5 \times 10^{11} \) and \( J_c = 15 \times 10^{11} \). The calculated values almost match with the values obtained from simulation; so, the device can be able to fabricate.

Shape factor of the hot arm is given by

\[ S = \frac{t_p}{w_p} \left[ \frac{2 t_a}{t_p} + 1 \right] + 1. \]

(6)

The obtained shape factor is \( S = 1.6 \mu \text{m} \).

Resistivity is calculated by using the Van der paw method:

\[ \rho = (2.971 \times 10^{-2}) T + 20.858. \]

(7)

At room temperature, the resistivity is \( \rho = 21.5 \mu \Omega \).

Simplifying the Equation (3), we get

\[ \frac{d^2 T(x)}{dx^2} = \frac{S(T(x) - T_{\text{sub}})}{k_p t_p R_T} - \frac{J^2 \rho}{k_p}. \]

(8)

3.4.2. Rotational Analysis.

\[ \Delta L_h = R \delta. \]

(9)
where $R$ is the radius of the disc. $\Delta Lh$ is the total expansion of the free end. $\delta$ is the angle of rotation.

Here, taking $R$ as 10 and the angle of rotation as 3.90, then $\Delta Lh = 3900$ nm.

4. Results and Discussion

4.1. Stress Analysis. Stress analysis is conducted to find the deformation of microthermal rotary actuator for the given pressure. Normal pressure for the stress analysis is about 7 GPa which is the yield strength of the silicon material and 8.4 GPa for poly silicon.

4.2. Von Mises Stress Analysis. This analysis is used in microthermal rotary actuator. So, when the stress is given, the material starts to yield after the critical value of yield strength which depends on von Mises stress.

4.3. Current Density Analysis. Current density is defined as the amount of charge per unit time that flows through a unit area of a chosen cross-section. Here, expected current density of a MEMS/NEMS thermal rotary actuator should be less than the electric field for fabrication.

4.4. Temperature Analysis. Temperature is a physical property of matter that quantitatively defines hot and cold. It is the indication of thermal energy present in all matter, which is the source of occurrence of heat, which is a flow of energy, when a body is in contact with another one which is cooler. The obtained temperature plot should be less than melting point of the material used there, and the devices is simulated under room temperature 298 K.
4.4.1. Temperature Analysis. Figure 5 shows the temperature plot of silicon actuator at room temperature. Here, center arm experiences high heat because the current value is high. Figure 6 shows the temperature of silicon actuator at room temperature. If the area of the centre arm is increased, temperature is high but less compared to previous square arm of 10 $\mu$m. Figure 7 shows the temperature of silicon actuator. The obtained value is 298 K. Polysilicon and silicon are behaving similar in temperature analysis. If the square arm size is 5 $\mu$m, temperature developed is so high. Figure 8 shows the temperature of polysilicon actuator. The obtained value varies from 297.98 K to 4893.6 K. As discussed in silicon-based rotary actuator, here, also, if size of arm is increase, then temperature rise is reduced.

Figure 9 shows the temperature of polysilicon actuator. The obtained value varies from 273 K to $2.2305 \times 10^7$. Figure 10 shows the temperature of polysilicon actuator. Here, the thickness is increased; hence, heat developed is decreased. The obtained value varies from 298 K to 350.51 K.

4.4.2. Current Density Analysis. Figure 11 shows the current density of silicon actuator. The obtained value is 298. Figure 12 shows the current density of silicon actuator. The value of bending is 298. Figure 13 shows the current density of silicon actuator. The value of bending varies from 298 to 350.51. Figure 14 shows the current density of poly Si actuator. The value of bending varies from 297.98 to 4893.6. Figure 15 shows the current density of poly silicon actuator.
The value of bending varies from 272 to $2.2307 \times 10^7$. Figure 16 shows the current density of poly silicon actuator. The value of bending varies from 272 to 350.

4.4.3. Stress Analysis. Figure 17 shows the von Mises stress of silicon-based actuator. Its range varies from 0 to $7.9144 \times 10^{-9}$. Figure 18 shows the von Mises stress of silicon-based actuator. Its range varies from 0 to $8.403 \times 10^{-9}$. Figure 19 shows the von Mises stress of silicon-based actuator. Its range varies from 0 to $8.4303 \times 10^{-8}$. Figure 20 shows the von Mises stress of polysilicon actuator. The value of bending varies from 0 to 4.709. Figure 21 shows the von Mises stress of silicon-based actuator. Its range varies from 0 to $8.636 \times 10^{-8}$. Figure 22 shows the von Mises stress of silicon-based actuator. Its range varies from $8.4303 \times 10^{-3}$ to $4.709 \times 10^{-7}$. Thermal rotary microactuators are a favorable solution to the need for large displacement, low-power MEMS actuators. It is confirmed to be a robust actuation method in surface micromachined devices. Such devices have been used in a variety of different applications like

(i) Micromechanical switches
(ii) Micromotors
(iii) Microscale tensile testing

4.4.4. Micro/Nanogear. A micro/NEMS gear is a part of a rotating machine which has cut teeth or, in the case of a cog wheel, it has inserted teeth (called cogs), which wire with another toothed part which is used to transmit...
torque. Geared devices can change the speed, torque, and direction of a power source. Gears always used to change torque, through their gear ratio, and they are considered as a simple machine. The teeth on the two interlocked gears have the same shape. Two or more meshing gears, working in a sequence, are called a gear train or a transmission. A gear can mesh with a linear toothed part, called a rack, producing translation instead of rotation.

4.5. Dimension. Microgear design has been done in Figure 23 using the parameters such as inner dimension that is 171 μm and outer dimensions that are 40 μm. The number of teeth is
This work presents the out of plane microthermal rotary actuator with different structures and different dimensions. Stress analysis of microthermal rotary actuator shows its stress bearing capacity for different structures that are different. Current density and temperature analysis show that the safer limit and melting point of the actuator are the same at the every point in the actuator. Also, in microgear eigen frequency analysis is done, it shows that the total displacement of the microgear is same as every point of the design.

### Data Availability

The data used to support the findings of this study are included in the article. Should further data or information be required, these are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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