Effect of Thermophysical Property Variations on Surface Micromachined Polysilicon Beam Flexure Actuators

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ABSTRACT

Electrically heated, thermally driven, surface micromachined polysilicon beam flexure thermal actuators have been investigated using analytical methods that employ constant material properties either taken at room temperature or based on a set of averaged temperatures over the device operational range. In this paper, we present a comprehensive finite element analysis approach to examine the relative importance of temperature dependent material properties of heavily doped polysilicon on the static response of thermal actuator systems in air and vacuum environments. The results of the comprehensive analysis, which includes conduction, convection and radiation, are validated by comparing the predicted actuator deflection to that obtained experimentally.

Keywords: thermal microactuators, finite element analysis, thermal conductivity, ANSYS.

1 INTRODUCTION

The basic electro-thermal beam flexure actuator uses the principle of Joule heating for thermal expansion and movement. As shown in Figure 1, the beam flexure actuator design consists of a thin arm, wide arm, and flexure arm connected together at one end and constrained elastically at the anchors. The anchors are rigidly attached to the substrate. Application of a potential difference at the anchors generates a non-uniform electric field. The larger current density in the thin arm causes a greater thermal expansion than that in the wide arm, leading to motion of the actuator tip towards the wide arm.

These actuators are typically fabricated by a MUMPs surface micromachining process that utilizes heavily doped polysilicon as the structural layer [1]. An array of such actuators has been widely employed in optical MEMS applications [2,3]. Efficient MEMS development not only requires reliable fabrication processes, but it also requires flexible design and analysis tools. Recently, these actuators have been analyzed using analytical [4,5] or finite element methods that use constant material properties based either on room temperature or averaged over a range of temperatures [6,7,8]. Typically, these actuators have been characterized for their force, deflection and current characteristics.

In this paper, the response of a thermal microactuator is analyzed with a comprehensive finite element model that includes full temperature dependencies of material properties and the means to impose all heat transfer modes. Actuator deflection characteristics are examined in air and vacuum environments, and the importance of thermophysical property variations that affect the analysis are investigated. The model is partially validated by comparing computed actuator tip deflection with experimental data [2,3,5,6,8]. This comparison will provide insight to the material properties that influence the behavior of the actuator and whether more research is warranted on temperature dependent parameters of heavily doped polysilicon.

2 ANALYSIS

The analysis of the actuator requires the solution of a generally nonlinearly coupled electro-thermal-elastic boundary value problem.

2.1 Boundary Conditions

Figure 2 shows a 3-D view of the actuator suspended above the substrate after release. The actuator arms are separated from the substrate by a 2 µm air gap, while the anchors remain attached to the substrate which acts as a heat sink at an assumed ambient temperature [1]. A thin nitride layer separates the substrate from the air gap. The substrate, nitride layer, and the surrounding air are not modeled directly but their effects are included indirectly through various boundary conditions. An electrical potential difference V is applied across the anchors, which causes non-uniform Joule heating. The deflection of the actuator due to this heating is parallel to the substrate.
Under normal modes of operation, the actuator will transfer heat to the surroundings and substrate by all three basic modes of heat transfer (conduction, convection and radiation), though some modes will likely dominate over the others under different conditions.

The conductive heat loss to the substrate through the air gap is modeled as an effective conductive heat transfer coefficient $h$ defined as

$$h = \frac{1}{(t_a/k_a + t_n/k_n + t_{Si}/k_{Si})}$$  \hspace{1cm} (1)

Here $t_a, t_n, t_{Si}$ represent the thickness of the air gap, nitride layer, and silicon substrate, respectively, and $k_a, k_n, k_{Si}$ represent thermal conductivities of air, nitride layer, and silicon, respectively. A conductive shape factor $S$ is used to account for the heat loss from the vertical faces of the actuator to the substrate, where $S$ is expressed as [9]

$$S = (t/w)[2t/t + 1] + 1$$  \hspace{1cm} (2)

where $t$ is the thickness of the element vertical face, $t_v$ is the height of the air gap between the element and the substrate, and $w$ is the width of the element vertical face.

Convection
Radiation
Intra-device conduction
Conduction to substrate through air gap

The convective heat loss from the top horizontal faces of the actuator to the (upward) ambient surroundings is represented by heat transfer coefficients taken from correlations developed for a heated horizontal face facing upwards [10].

The effects of radiation heat transfer are included as the device operates at high temperatures and in vacuum environments.

Table 1 lists available constant and temperature-dependent material property parameters taken from the literature and used in this analysis. Note that the constant value for each material property does not necessarily coincide with that computed at room temperature using the corresponding equation.

### Table 1. Material property parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Constant Value</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus of polysilicon</td>
<td>169 GPa</td>
<td>16</td>
</tr>
<tr>
<td>Poisson’s ratio of polysilicon</td>
<td>0.22</td>
<td>16</td>
</tr>
<tr>
<td>Emmissivity</td>
<td>0.6</td>
<td>14</td>
</tr>
<tr>
<td>Stefan-Boltzmann constant</td>
<td>$5.67 \times 10^{-8}$ W-m$^{-2}$-°C$^{-4}$</td>
<td>14</td>
</tr>
<tr>
<td>Thermal cond. of air ($k_a$)</td>
<td>0.026 W-m$^{-1}$-°C$^{-1}$</td>
<td>9</td>
</tr>
<tr>
<td>Thermal cond. of nitride ($k_n$)</td>
<td>2.25 W-m$^{-1}$-°C$^{-1}$</td>
<td>9</td>
</tr>
<tr>
<td>Thermal cond. of silicon ($k_{Si}$)</td>
<td>150 W-m$^{-1}$-°C$^{-1}$</td>
<td>11</td>
</tr>
<tr>
<td>Thermal conductivity of polysilicon ($k_p$)</td>
<td>32 W-m$^{-1}$-°C$^{-1}$</td>
<td>12</td>
</tr>
<tr>
<td>Coeff. of thermal expansion of polysilicon ($\alpha$)</td>
<td>$2.7 \times 10^{-6}$ K$^{-1}$</td>
<td>14</td>
</tr>
<tr>
<td>Electrical resistivity of polysilicon ($\rho_0$)</td>
<td>$2 \times 10^3$ Ω-cm</td>
<td>14</td>
</tr>
<tr>
<td>Resistivity coefficient of polysilicon ($\alpha_0$)</td>
<td>$1.25 \times 10^{-3}$ °C$^{-1}$</td>
<td>14</td>
</tr>
<tr>
<td>$k_p(T) = \left((-2.2 \times 10^{-11})T^3 + (9.0 \times 10^{-8})T^2 + (-1.0 \times 10^{-5})T + 0.014\right)^{-1}$ W-m$^{-1}$-°C$^{-1}$</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>$\alpha(T) = \rho_0(1+\alpha_0(T-T_0))$</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>$\alpha(T) = \left(3.725{1-exp(-5.88\times 10^{-3}(T-125))} + 5.548\times 10^{-4}T\right)\times 10^{-6}$ K$^{-1}$</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>$k_a(T) = 3.9539 \times 10^{-4} + (9.886 \times 10^{-5})T - (4.367 \times 10^{-9})T^2 + (1.301 \times 10^{-11})T^3$ W-m$^{-1}$-°C$^{-1}$</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

The boundary conditions for the structure consist of constraining the displacement of the bottom faces of the anchors. For the results that follow, $l_t, l_f, w_t, w_f, w_w,$ and $g$ denote the length of thin arm, length of flexure arm, width of thin, flexure and wide arms, and gap between thin and wide arms, respectively, in microns.

### 2.2 Simulation

The coupled electro-thermal-elastic simulation is performed in ANSYS 5.6 using the direct method for analysis [17]. Thermal radiation is modeled using the radiosity solver method available in ANSYS [17]. As a baseline calculation, the finite element model employs constant material properties listed in Table 1 for the thermal conductivity of polysilicon and the thermal conductivity of the air gap. Temperature variations listed in Table 1 are then introduced. Simulation results are compared with measured data from six geometrically different thermal actuators operating in air and with measured data from a single thermal actuator operating in vacuum. Results from the air models also compared with results from an analytical model that assumes temperature averaged material property parameters. In vacuum, there is no conductive heat loss to the substrate and no free convection.
so the conduction and convection parameters are eliminated from the model.

3 RESULTS

Figure 3 compares the steady state tip deflection for one actuator from the finite element simulations with that obtained from experimental testing and with that obtained from a simplified analytical approach [2]. It is observed that constant material assumptions of $k_p$ and $k_a$ in the finite element model (“Constant $k_p,k_a$”) overestimates experimentally determined deflections at high voltages, while the analytical model predicts otherwise. At low voltages (and hence low temperatures), there is no significant difference among the model assumptions. Improved prediction of tip deflections at high voltage is observed by including either the temperature dependent thermal conductivity of polysilicon alone (“$k_p(T)$”) or that of the air gap alone (“$k_a(T)$”), but not both (“$k_p(T),k_a(T)$”). In all the finite element models employing air, full temperature dependency of thermal expansion and electrical resistivity are included.

At higher voltages, and hence higher temperatures, the thermal conductivity of air increases and more heat is transferred from the thin arm to the substrate that, in turn, limits deflection. Figure 4 shows that the performance of the second actuator agrees well with experiment using the same model assumptions employed with the previous actuator.

For the third actuator, Figure 5 shows that the “Constant $k_p,k_a$” model again overestimates experimental deflection predictions. However, in this case, both “$k_a(T)$” and “$k_p(T),k_a(T)$” models give acceptable agreement with measured data, while the “$k_p(T)$” model also overpredicts (to a lesser extent) the measured data at higher voltages.

For the remaining three actuators, it is difficult to choose one model that can be employed for accurate predictions due to the observed variations in agreement with the experimental data (Table 2). These variations might be caused by the use of the shape factor equation (2), which might be overestimating the heat loss, leading to errors in the actuator temperature profiles.

Figure 6 shows comparisons of the finite element results with experiments obtained in vacuum [6]. Constant material property assumptions (including thermal expansion and electrical resistivity) are observed to be completely insufficient in predicting actuator deflections. The thermal profiles in this case (not shown) also predict melting temperatures that are inconsistent with experimental evidence. These results indicate that, in the absence of an air layer, the thermal conductivity of polysilicon plays an
important role in predicting actuator deflection, and full
temperature dependency should be included for accurate
model predictions.

Figure 6. Deflection vs. power in vacuum, \( l_t = 200, l_f = 30, \)
w\(_l = w_f = 2, w_c = 14, g = 2 \)

4 CONCLUSIONS

A comprehensive finite element analysis of a beam
flexure thermal microactuator has been performed in air
and vacuum environments. Steady-state actuator tip
deflection data has been compared with available
experimental evidence, taking into account different
actuator designs and temperature-dependent material
property variations. In air at relatively large voltages, the
finite element model predicts significant differences in
deflection depending upon the thermophysical properties of
polysilicon. A unique finite element model that consistently
agrees with experiment could not be characterized. The
variation among the different formulations might arise from
the assumption of shape factors that approximate the heat
loss from the vertical sidewalls of the thermal actuator.
Another possibility for such variations might arise from the
material property variations of thin film polysilicon. The
thermal actuator behavior in vacuum was found to be
highly dependent on material property variations in
polysilicon, and full temperature dependencies must be
employed to accurately characterize actuator behavior.

REFERENCES

[1] Koester, D., Mahadevan, R., Hardy, B., Markus, K.,
“Multi-user MEMs processes (MUMPs) Design
Handbook,” Cronos Integrated Microsystems, JDS
“Thermal microactuators for surface-micromachining
[3] Butler, J.T., Bright, V.M., Reid, R.J., “Scanning and
rotating micromirrors using thermal actuators,” Proc.SPIE,
polysilicon thermal flexure actuator,” Journal of
modeling of polysilicon thermal actuators,” Proc. SPIE,
of polysilicon thermal micro-actuators,” International
Conference on Modeling and Simulation of Microsystems,
Boydston, N., “Thermally-actuated cantilever beam for
achieving large in-plane mechanical deflections,” Thin
55, 1996, pp.35-41.
Prentice Hall.
compliant mechanisms,” M.S. Thesis, University of
conductivity of heavily doped LPCVD polycrystalline
silicon films,” J. App. Physics, vol. 63, no.5, 1988,
pp.1442-1447.
combustible gas sensor,” Ph.D Thesis, University of New
Mexico, Albuquerque, NM, 1997.
[14] Lott, C.D., “Electrothermomechanical modeling of
surface-micromachined linear displacement microactuator,”
M.S. Thesis, Brigham Young University, Provo, Utah,
JDS Uniphase.
of temperature on mechanical properties of polysilicon,”

<table>
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<tr>
<th>Actuator</th>
<th>Expt.</th>
<th>Constant</th>
<th>( k_p(T) )</th>
<th>( k_a(T) )</th>
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