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Abstract—A bimorph varifocal micromirror actuated thermoelectrically by a Peltier element is reported. The single crystal silicon micromirror is 1.2 mm in diameter with a centered 1 mm diameter gold coating for broadband reflection. The actuation principle is capable of varying the micromirror temperature above and below the ambient temperature, which contributed to a 57% improvement in the addressable curvature range in comparison to previously reported electrothermal and optothermal actuation techniques for the device. Altering the device temperature from 10°C to 100°C provided a mirror surface radius of curvature variation from 19.2 mm to 30.9 mm respectively. The experimental characterization of the micromirror was used as a basis for accurate finite element modeling of the device and its actuation. Negligible optical aberations are observed over the operating range, enabling effectively aberration-free imaging. Demonstration in an optical imaging system illustrated sharp imaging of objects over a focal plane variation of 212 mm.

Index Terms—Varifocal micromirror (VFM), Silicon-on-insulator multi-user MEMS processes (SOIMUMPs), Imaging, Thermal actuation, Finite element analysis, Optical MEMS.

I. INTRODUCTION

MEMS with varifocal properties have been demonstrated to be beneficial in biomedical imaging applications, particularly where spatial limitations are incurred. Varifocal micromirrors (VFM) provide the necessary requirements to produce compact, high quality imaging systems. This was highlighted by Dickensheets [1] with focus on confocal microscopy and optical coherence tomography (OCT). In confocal microscopy the use of a VFM [2], [3] or a tunable microens for focal adjustments has been reported [4]. A confocal laser scanning endoscope was demonstrated using a VFM with scanning capability [5]. OCT [6] and multiphoton scanning microscopy [7] have also been achieved using VFMs.

Typically VFM actuation mechanisms can be separated into four main categories: electrostatic [8]-[13], piezoelectric [14]-[16], pneumatic [17] and electrothermal [18], [19]. Optothermal actuation via a laser was also reported [19]. A combination of electrostatic and pneumatic actuation was recently demonstrated to achieve convex and concave VFM surfaces [20]. An electrostatically-actuated VFM with simultaneous scanning capability has been reported by Sasaki et al. [21], achieving a focal plane tuning range from -128 mm to +98 mm. The focal power of their micromirror was demonstrated to fluctuate by less than 1% while simultaneous scanning was performed. Lukes and Dickensheets [12] reported a SU-8 deformable membrane mirror which was capable of 137 µm of focal tuning range through electrostatic actuation in an optical microscope with 42x magnification.

In our previous work [19], a 1.2 mm diameter single crystal silicon micromirror with a 1 mm diameter gold coating, forming a bimorph VFM, was characterized using two actuation techniques. These were electrothermal actuation, by applying a current through the serpentine suspension beams as current-flow increased, whilst the stability of both electrothermal and optothermal actuation was sensitive to ambient temperature fluctuations and can provide stable temperatures above and below the ambient temperature level. Furthermore, these types of actuation could only achieve a temperature increase from the ambient temperature level.

In this paper we report a new actuation technique for VFMs using a thermoelectric (Peltier) element, which improves the focal plane variation of the imaging system by over 50% compared to [19] and does not exhibit the mentioned limitations. This actuation technique is independent of ambient temperature fluctuations and can provide stable temperatures above and below the ambient temperature level. A finite element analysis (FEA) of the device behavior is described in section II, where consideration of thin-film material properties allowed an overlap of simulated results and experimental characteristics. Analysis of the thermoelectric actuation through evaluation of the Zernike coefficients for varying mirror actuation is described in section III, while the...
mirror implementation in an optical imaging system is described in section IV. These illustrate that the VFM manifests near-aberration-free imaging using this actuation principle. Demonstration of this Peltier based actuation technique for VFMs also shows the potential for using thin-film thermoelectric coatings, such as \( \text{Sb}_2\text{Te}_3 \) [22] or \( \text{Bi}_2\text{Te}_3 \) [23]. This technology has been reported for power generation [24], cooling and temperature sensing [25] but has not yet been investigated for MEMS-scale imaging applications. An actuation technique of this nature would allow direct control of the device temperature with a considerable reduction in the size of the system.

II. DEVICE CHARACTERIZATION

A. Fabrication and Design

The VFM was fabricated using the silicon-on-insulator multi-user MEMS process (SOIMUMPs) from MEMSCAP Inc., details of which can be found in [26]. The VFM comprises a 10 \( \mu \)m thick device layer of phosphorus-doped single crystal silicon and a 0.65 \( \mu \)m thick layer of gold. The silicon micromirror has a diameter of 1.2 mm, with the 1 mm diameter gold coating deposited concentrically on its surface using electron-beam deposition. This produces a bimorph micromirror with a broadband reflection coating. Eight radially distributed serpentine suspension beams connect the VFM to the 400 \( \mu \)m thick silicon substrate. The beams have a width of 8 \( \mu \)m and a thickness of 10 \( \mu \)m. Gold pads for electrical connection were used in [19] and are retained in this design, however they are not used for this actuation technique. A scanning electron microscope (SEM) image of the fabricated device can be seen in Fig. 1.

B. Stress Analysis

To create an accurate FEA of the devices, their exhibited stresses after fabrication required characterization due to discrepancies between initially measured material properties and those described by Miller et al [27], who used the same fabrication process for their 10 \( \mu \)m thick single crystal silicon devices. The single crystal silicon layer of the VFM is subject to a through-thickness stress gradient due to polishing and doping processes during fabrication. This gradient, together with a compressive residual stress, leads to an initial concave curvature of the mirror surface prior to deposition of the gold layer. The stress gradient can be directly related to the curvature through analysis of the bending moment \( M \). The bending moment due to a stress gradient can be evaluated using [28]:

\[
M = \Delta \sigma I ,
\]

where \( \Delta \sigma \) is the stress gradient and \( I \) is the moment of inertia. The bending moment is also directly related to the curvature \( \kappa \) using [29]:

\[
\kappa = \frac{1}{\text{ROC}} = \frac{M}{EI} ,
\]

where ROC is the radius of curvature and \( E \) is the Young’s modulus. Using (1) and (2), one can obtain an equation for the stress gradient \( \Delta \sigma \) relative to the curvature of a deflected beam in the form of:

\[
\Delta \sigma = E \kappa
\]

TABLE I

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Beam Length (( \mu )m)</th>
<th>( \kappa ) (( \text{m}^{-1} ))</th>
<th>( \Delta \sigma ) (MPa/( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>700</td>
<td>13.4</td>
<td>2.26</td>
</tr>
<tr>
<td>2</td>
<td>800</td>
<td>13.1</td>
<td>2.21</td>
</tr>
<tr>
<td>3</td>
<td>600</td>
<td>14.7</td>
<td>2.48</td>
</tr>
<tr>
<td>4</td>
<td>700</td>
<td>14.4</td>
<td>2.43</td>
</tr>
<tr>
<td>5</td>
<td>800</td>
<td>13.7</td>
<td>2.32</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
<td>15.4</td>
<td>2.60</td>
</tr>
<tr>
<td>7</td>
<td>700</td>
<td>14.8</td>
<td>2.50</td>
</tr>
<tr>
<td>8</td>
<td>800</td>
<td>13.7</td>
<td>2.55</td>
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<tr>
<td>9</td>
<td>600</td>
<td>15.1</td>
<td>2.43</td>
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<tr>
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<td>700</td>
<td>14.4</td>
<td>2.26</td>
</tr>
<tr>
<td>11</td>
<td>800</td>
<td>13.4</td>
<td>2.55</td>
</tr>
<tr>
<td>12</td>
<td>600</td>
<td>14.6</td>
<td>2.47</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>14.2</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Fig. 1: SEM image of the VFM, showing the 1.2 mm diameter single crystal silicon micromirror and the 1 mm diameter concentric layer of gold deposited on the micromirror surface.

Fig. 2: VEECO optical profiler image showing the cantilever beams. Samples 1 to 12 from Table I range from left to right.
To evaluate the stress gradient of our device, 10 µm thick, 50 µm wide cantilever beams of lengths 600 µm, 700 µm and 800 µm were fabricated using the same SOIMUMPs fabrication without the deposition of the gold layer. This cantilever test structure can be seen in Fig. 2. The ROCs of the test beams were measured using a VEECO NT1100 optical profiler, and hence the curvature was obtained by taking the reciprocal of these values. These values, together with calculated values for the stress gradient using (3), are shown in Table I. A value of 169 GPa was used for the Young’s modulus of single crystal silicon [30], accounting for the anisotropy of single crystal silicon. The average value for the stress gradient of the cantilever beams was calculated to be 2.40 MPa/µm.

The deposition of the gold layer on the VFM resulted in an additional tensile residual stress, providing a measured ROC of 20 mm (κ=50 m⁻¹) at a temperature of 20 °C. The residual stress in the gold layer, σ₉, can be calculated using the Stoney equation modified to consider the anisotropy of the single crystal silicon layer and symmetrical radii of curvature of the major axes [31]:

\[
\sigma_{\text{st}} = \frac{E_{\text{si}}(\kappa_{\text{si}} - \kappa_{\text{au}})h_{\text{si}}^2}{6t_{\text{si}}(1 - \nu_{\text{si}})},
\]

where \( \nu \) is the Poisson ratio and \( t \) is the thickness, with the notations ‘si’ and ‘au’ representing silicon and gold respectively. Assuming \( \nu = 0.28 \) [30], the residual stress in the gold layer was calculated to be 200.4 MPa.

C. Finite Element Modeling

FEA results are highly dependent on the material parameters used. For this reason, simulations of the cantilever test beams and the VFM were compared to experimental measurements. The simulations were performed using the FEA software COMSOL Multiphysics, with the material parameters shown in Table II. A value of 57 GPa was used for the Young’s modulus of the gold layer, similar to that calculated from cantilever mechanical deflection measurement techniques for thin-film gold [32],[33].

The cantilever test beams were modeled considering only the single crystal silicon material and applying the through-thickness stress gradient in the x-direction. A fixed constraint on one end face was implemented. Separate simulations for cantilever lengths of 600 µm, 700 µm and 800 µm were performed, resulting in an initial curvature of 14.2 m⁻¹ for each model. This matches the average curvature value in Table I. The stress gradient was then applied to the full single crystal silicon micromirror model, shown in Fig. 3(a), in the x- and y-directions. Fixed constraints were placed at the outer end faces of the serpentine suspension beams. This resulted in a curvature of 13.2 m⁻¹; slightly lower than the measured curvature of the cantilever test beams. Finally the application of the 0.65 µm thick gold layer was implemented, resulting in a mirror surface profile shown in Fig. 3(b) using the parameters from Table II. At a VFM temperature of 20 °C, the

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**Table II: Material Parameters of the Simulated VFM**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Single crystal silicon</th>
<th>Gold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>GPa</td>
<td>( E_{\text{si}}=169 )</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( E_{\text{au}}=130 )</td>
<td></td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>-</td>
<td>( \nu_{\text{si}}=0.36 )</td>
<td>0.44</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>GPa</td>
<td>( G_{\text{si}}=79.6 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>( G_{\text{au}}=50.9 )</td>
<td></td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>ppm/K</td>
<td>2.53 at 290 K</td>
<td>13.7 at 200 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.62 at 300 K</td>
<td>14.2 at 293 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.84 at 330 K</td>
<td>15.4 at 500 K</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>2330</td>
<td>14300</td>
</tr>
<tr>
<td>Residual stress</td>
<td>MPa</td>
<td>-3.9</td>
<td>200.4</td>
</tr>
<tr>
<td>Stress gradient</td>
<td>MPa/µm</td>
<td>2.40</td>
<td></td>
</tr>
</tbody>
</table>
Actuation of the VFM was performed using a thermoelectric device (Peltier element) integrated in a closed-loop temperature feedback system, as shown in Fig. 5. The MEMS chip, on which the VFM is fabricated, was secured on an aluminum block using thermal paste to enhance heat transfer to the device. Measurement of the temperature of the aluminum block, using a thermistor, allowed closed-loop control of the VFM temperature. The temperature of the VFM was varied from 10 °C to 100 °C in intermediate steps of 10 °C, allowing sufficient time at each step for the device to reach thermal equilibrium. The ROC of the device, measured using a VEECO NT1100 optical profiler, varied from 19.2 mm to 30.9 mm over the respective temperature range.

Using the parameters from Table II, actuation of the VFM was simulated using COMSOL Multiphysics by altering the temperature of the device. A parametric temperature sweep matching the experimental settings was performed. As observed in Fig. 6, a strong overlap between simulated and experimental ROC values is present. The simulated ROC values were measured on the [100], [010] and [110] axes and varied by less than 0.1 mm, indicating the anisotropy of the single crystal silicon layer had negligible effects on the simulated VFM performance.

The optical aberrations present in the VFM were quantified using Zernike polynomials [34], where a MATLAB program was used to calculate the Zernike coefficients from the measured surface profiles [35]. Fig. 7 shows the first 15 Zernike coefficients at VFM temperatures of 10 °C, 60 °C and 100 °C. The piston term, $Z_1$, and the tilt terms, $Z_2$ and $Z_3$, quantify the alignment of the measurement process and...
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\[ L_{o,\text{min}} = \frac{D \times \text{ROC}_{\text{min}}}{2D - \text{ROC}_{\text{min}}} \]  

\[ L_{o,\text{max}} = \frac{D \times \text{ROC}_{\text{max}}}{2D - \text{ROC}_{\text{max}}} \]

where \( \text{ROC}_{\text{min}} \) and \( \text{ROC}_{\text{max}} \) are the ROCs of the VFM at 10 °C and 100 °C respectively.

Fig. 9: Optical imaging system configuration, showing two objects located at total distances of \( L+L_{o1} \) and \( L+L_{o2} \) from the VFM. Reflected light from the objects is focused onto a CMOS sensor via a 50/50 beam splitter and the VFM, located at a distance D from the sensor.

Fig. 10: Images recorded by the CMOS sensor in the optical imaging system with objects placed at (a) \( L_{o,\text{min}}=23 \) mm and (b) \( L_{o,\text{max}}=235 \) mm from the sensor. The circled areas represent the position of the respective focal planes.

The previous actuation principles for this VFM device were limited by current-induced heat in the suspension springs (which can lead to thermal damaging without current limitation) and the sensitivity to ambient temperature. Furthermore, laser illumination effects would be dependent on the size, shape and location of the beam on the VFM surface. The use of a Peltier element does not exhibit any of these limitations. The limiting factors of using this technique are the effectiveness of the heat conduction to the VFM and the operating range, stability and size of the Peltier device.

V. DISCUSSION

To further assess the performance of the VFM it was implemented in an optical imaging system, shown in Fig. 9. Light from the objects was reflected towards the VFM using a 50/50 beam splitter, and then focused by the VFM onto a CMOS sensor located at a distance D from the VFM. The minimum and maximum object distances, \( L_{o,\text{min}} \) and \( L_{o,\text{max}} \), can be calculated using:
variation over the actuation range would be observed compared to the thin-film gold parameters used in this work, conveying the sensitivity of the models to this parameter. A significant increase (>10%) in each respective ROC value would also be observed.

VI. CONCLUSION

A bimorph, varifocal micromirror actuated using a Peltier element was experimentally characterized and modeled by FEA. Actuation of the VFM over a temperature range from 10 °C to 100 °C resulted in a ROC range of 11.7 mm (19.2 mm to 30.9 mm). Simulated mirror surface curvatures are in excellent agreement with these results, yielding a strong match between FEA and experimental measurements. Zernike VFMs in the future.

REFERENCES


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