Surface micromachined MEMS deformable mirror based on hexagonal parallel-plate electrostatic actuator

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Abstract. Deformable mirrors (DM) based on microelectromechanical system (MEMS) technology are being applied in adaptive optics (AO) system for astronomical telescopes and human eyes more and more. In this paper a MEMS DM with hexagonal actuator is proposed and designed. The relationship between structural design and performance parameters, mainly actuator coupling, is analyzed carefully and calculated. The optimum value of actuator coupling is obtained. A 7-element DM prototype is fabricated using a commercial available standard three-layer polysilicon surface multi-user-MEMS-processes (PolyMUMPs). Some key performances, including surface figure and voltage-displacement curve, are measured through a 3D white light profiler. The measured performances are very consistent with the theoretical values. The proposed DM will benefit the miniaturization of AO systems and lower their cost.

1. Introduction
Deformable mirrors (DM) are the most important device of adaptive optics (AO) technology [1,2]. They can compensate wavefront distortions which are induced by atmospheric turbulence, ocular aberration, etc. Miniature DMs based on microelectromechanical system (MEMS) technology, or MEMS DMs, have many advantages compared to conventional DMs, such as low cost, low energy consumption and high actuator count [3,4].

The most conventional structure of DMs is a continuous facesheet supported by a periodic arrangement of actuators, whose deformation will deform the continuous facesheet and correct the phase of incident light. The arrangement of actuators mainly has two geometries, hexagon and square. Hexagonal geometry has less actuator count and smaller fitting error when the two geometries have the same period [5]. Unlike conventional DMs, MEMS DMs adopt square geometry more universally.

Surface micromachining and bulk micromachining fabrication processes are two main MEMS processes. Surface micromachining has the higher integration, better IC compatibility and reliability. In this paper, we proposed a surface micromachined MEMS DM based on hexagonal electrostatic actuator. The remaining sections of the paper are organized as follow: Section 2 is the structural design and analysis of the DM. The fabrication and test are described in Section 3 and a conclusion is detailed in Section 4.
2. Design and analysis

The hexagonal and square geometry arrangements for DM are shown in Figure 1 and \( d \) is the pitch. Three parameters, stroke, bandwidth, and actuator coupling, mainly determine the performance of MEMS DMs. Among them, the stroke is determined by the fabrication processes for an electrostatic actuator. Thus the stroke is not need to be considered in the structural design. The displacement of facesheet under different voltages can be solved through the balance between electrostatic force and elastic restoring force. These two forces can be expressed as [6]

\[
F_{\text{elec}} = \frac{\varepsilon_0 S V^2}{2(g-x)^2}, \quad (1)
\]
\[
F_{\text{elas}} = k_a x, \quad (2)
\]

where \( \varepsilon_0, S, V, g, k_a \) and \( x \) are permittivity of vacuum, area of actuator electrode, driving voltage, gap between actuator electrodes, spring constant of actuator, and displacement of facesheet, respectively.

Another parameter, bandwidth, is also not need to be considered because that a bandwidth of several hundred or one thousand Hz is totally enough for most AO systems. On the contrary, the optimum value of actuator coupling is 5%~12% [7]. Therefore the actuator coupling should be analyzed and designed carefully. The actuator couplings for square and hexagonal geometries can be expressed as

\[
C_{\text{Rect}} = \frac{1}{1 + 4k_a/k_m}, \quad (3)
\]
\[
C_{\text{Hex}} = \frac{1}{1 + 6k_a/k_m}, \quad (4)
\]

where \( k_m \) is spring constants of facesheet. Obviously, hexagonal geometry has a lower actuator coupling compared with square geometry when they have the same spring constants of actuator and facesheet. The spring constant of facesheet can be expressed as [8]

\[
k_m = \frac{24EI}{d^3}, \quad (5)
\]

where \( I \) and \( E \) are moment of inertia of the section of facesheet and Young’s modulus, respectively. When there is a residual tensile stress \( \sigma \) in the facesheet, the spring constant should be modified to [9]
where $u = \frac{d}{2} \sqrt{\frac{N}{EI}}$, $N = \sigma (1 - \nu) dt$, and $\nu$ are the Poisson’s ratio of the facesheet. Thus it can be seen that the residual stress produces an extra term in the equation. Moreover, generally facesheet is a multilayer membrane (silicon + metal) to increase the surface finishment and reflectivity. So an effective $EI_{\text{eff}}$ product should be used to replace the one in above equations. $N$ also should be replaced by the sum of residual stress of every layer. Based on the design and process parameters [10,11] listed in Table 1, the spring constant of facesheet can be computed as $k_m = 19.74 \text{N/m}$.

### Table 1. Designed parameters of the facesheet.

| Symbol | Quantity                        | Value   |
|--------|---------------------------------|---------|
| $d$    | actuator period                 | 408\(\mu\)m |
| $E$    | Young’s modulus of material silicon | 158GPa |
| $\nu$  | Poisson’s ratio of material silicon | 0.22 |
| $t$    | thickness of silicon            | 1.5\(\mu\)m |
| $\sigma$ | residual stress of silicon    | -10MPa |
| $E_{\text{metal}}$ | Young’s modulus of material metal | 78GPa |
| $\nu_{\text{metal}}$ | Poisson’s ratio of material metal | 0.42 |
| $t_{\text{metal}}$ | thickness of metal              | 0.52\(\mu\)m |
| $\sigma_{\text{metal}}$ | residual stress of metal        | 50MPa |

Based on $k_m$ and the optimum value of $C_{\text{hex}}$, we can compute $k_a$ using equation (4) and the result shows that it should be located in $24.13 \text{N/m}$–$62.52 \text{N/m}$. For tuning $k_a$ accurately, the supporting beam of the actuator is designed as Figure 2(a). Here $b$ is a tunable parameter and $b=0$ represents the conventional fixed-fixed beam.

Figure 2. (a) Sketch map of the hexagonal actuator; (b) Layout of the DM.

As Figure 2 shows, the actuator is supported by twelve fixed-guided beams. So the spring constant of actuator is [12]
\[ k_a = \frac{12kP}{2\tan\frac{kl}{2} - kl}, \quad (7) \]

where \( P = \sigma_{\text{act}} (1 - \nu_{\text{act}}) w_{\text{act}} \), \( k = \sqrt{\frac{P}{E_{\text{act}} I_{\text{act}}}} \), and \( l = \sqrt{x^2 + y^2} \). \( E_{\text{act}}, \nu_{\text{act}}, I_{\text{act}}, t_{\text{act}} \) and \( \sigma_{\text{act}} \) are Young’s modulus, Poisson’s ratio, moment of inertia, thickness and residual stress of actuator. All these parameters are listed in Table 2.

**Table 2.** Designed parameters of the hexagonal actuator.

| Symbol | Quantity | Value |
|--------|----------|-------|
| \( E_{\text{act}} \) | Young’s modulus of the hexagonal actuator, silicon | 158GPa |
| \( \nu_{\text{act}} \) | Poisson’s ratio of the hexagonal actuator, silicon | 0.22 |
| \( t_{\text{act}} \) | thickness of actuator | 2μm |
| \( \sigma_{\text{act}} \) | residual stress of actuator | -10MPa |
| \( w_{\text{act}} \) | width of beam | 3μm |
| \( a \) | horizontal length of the skew beam | 111.5μm |
| \( b \) | vertical length of the skew beam | 12.25μm |
| \( g \) | initial gap between actuator electrodes | 2μm |
| \( L_{\text{upper}} \) | side length of the upper electrode of actuator | 210μm |
| \( L_{\text{lower}} \) | side length of the lower electrode of actuator | 200μm |

Based on the parameters listed in above table, we can obtain that \( k_a = 26.22 \text{N/m} \), and satisfy the optimum range.

Considering actuator coupling, the elastic restoring force should be modified to

\[ F_{\text{el}} = k_a x + k_m (x - C_{\text{Hex}} x). \quad (8) \]

### 3. Fabrication and Characterization

#### 3.1. Fabrication

A DM prototype including 7 element is fabricated by a commercial MEMS surface process PolyMUMPs [10] in Run 90. The SEM picture and micrograph of the DM are shown in Figure 3.
Figure 3. SEM picture (a) and micrograph (b) of the prototype.
Due to the uncertainty of the process, some fabrication parameters are different from the reported ones listed in above tables. Table 3 list these different parameters provided by the foundry [10], except for the last row, which is measured by us.

Table 3. Different structural parameters compared to above two tables.

| Symbol | Quantity                  | Value         |
|--------|---------------------------|---------------|
| \( t \) | thickness of silicon      | 1.52\( \mu \)m |
| \( \sigma \) | residual stress of silicon | -6MPa        |
| \( t_{\text{metal}} \) | thickness of metal        | 0.49\( \mu \)m |
| \( \sigma_{\text{metal}} \) | residual stress of metal  | 28MPa        |
| \( \sigma_{\text{act}} \) | residual stress of actuator | -6MPa     |
| \( g \) | initial gap between the two actuator electrodes | 4.53\( \mu \)m |

3.2. Characterization

3.2.1. Surface profile. The characterization of the prototype is measured by a white light 3D profiler (Zygo NewView 7300). Figure 4(a) shows the surface figure of the DM prototype. As the figure shows, except the central element, all elements are bending upwards due to the residual stress. Thus the initial gap between the two actuator electrodes is increased to 4.53\( \mu \)m, as shown in Table 3. In the succeeding work we should avoid this phenomena.

Figure 4. (a) Measured surface profile of the DM; (b) Theoretical and experimental results (displacement of the driven actuator versus driving voltage) of the DM.

3.2.2. Device performance. Through measuring the surface of the prototype under different voltages, the displacement of the prototype is measured and plotted in Figure 4(b). At the same time the displacement is calculated through above equations and plotted in Figure 4(b), too. The theoretical performances are consistent with the measured values. A stroke, i.e., maximum displacement, of 0.68\( \mu \)m is obtained under a driving voltage of 30V.

4. Conclusions
A novel DM based on hexagonal parallel-plate electrostatic actuator is proposed. The actuator coupling of the device is analyzed and computed. A prototype of the DM is fabricated and measured. The computed and measured results of the displacement are consistent very much. In the future the surface figure of the presented DM should be improved to promote its application.
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