A criterion of warpage about center-anchored deformable focusing micromirrors

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Abstract: - A criterion to determine the warpage condition of centered anchored deformable focusing mirrors is derived. With the material properties, structure size, and fabricating process temperature, a nondimensional number can be used to determine the deformable focusing mirror is warpage or not. The result shows when the thickness of depositing layer increasing, the warpage temperature decreases. However, as the thickness of structure plate increasing, the warpage temperature increases nonlinearly. Under some conditions, even the temperature increases over the melting temperature of metal, the focusing mirror would not become warpage. The effect of outer radius on warpage temperature is also discussed. It shows as the outer radius increasing, the warpage temperature decreases fast and reaches a limit temperature.

Key-Words: warpage, center-anchored, deformable focusing mirror, MEMOS, MEMS, stress gradient, residual stress

1 Introduction

Micro-Electro-Mecha-Optical System (MEMOS) is widely used for the advantages of lightweight, small inertial, low heat capacity, smooth surface, low power, compatibility with microelectronics, batch fabrication, and low cost. In MEMOS, one of the most important microstructures in optics applications is the micromachined deformable mirrors with different types actuated by electrostatic forces [1-9]. They are often used in adaptive optics (AO) [10], which could be used in optic system with dynamical application. Its applications include projection display, light modulation, etc [11]. For MEMOS, the metal is using as reflecting layer to reflect light. However, the mismatch of thermal expansion coefficients between the metal layer and the structure layer will induce residual stress by stress gradient after release, and thus bend the structure layer. But, the center-anchored deformable focusing micromirror [9] is fabricated by surface micromachining and has advantage of converting the undesirable structure deformation caused by residual stress during fabricating process to the profile of focusing the coming light to focus point. However, as the residual stress is large enough to make the strain become nonlinear and unassymetric, the bifucation of curvature happens and is called warpage. It would damage the micromirrors and decrease the performance. Therefore, how to prevent the warpage is important. The criteria of warpage is obtained in the work. Theory of plates is used to model the behavior of structure plate depositing a metal layer. To examine the happening of warpage of material compositing thin layer, some literature based on curvature concept and using analytical or numerical methods [12-18] are expressed. Therefore, the warpage criteria of center-anchored focussing micromirrors is derivedfrom the concept in this work. Including the material properties, structure size, and fabricating process temperature, a nondimensional number can be used to judge whether the deformable focusing mirror is warpage or not. It shows as the thickness of depositing layer increasing, the warpage temperature decreases. And as the thickness of structure plate increasing, the warpage temperature increases nonlinearly. Under some conditions, it is found that even the temperature is above the melting temperature of metal, the focusing mirror would still not become warpage. The effect of outer radius on warpage temperature is also expressed. It shows as the outer radius increasing, the warpage temperature decreases fast and reaches a limit temperature.

2 Model of thermal stress in plate

The structure of center-anchored sector plate with metal deposition atop is shown in Figure 1. By theory of plates-and-shells, the governing equation is [19,20]:

$$D\nabla^4 w = -\frac{1}{1-\nu}\nabla^2 M^*$$

$$M^* = \alpha E\int_{-t/2}^{t/2}(\Delta T)\,zdz$$

$$D = \frac{Et^3}{12(1-\nu^3)} \qquad (1)$$

where, E is the Young's modulus, ν is the Poisson's ratio, D is the flexural rigidity of the plate, t is the thickness of plateα is the coefficient of thermal expansion, z is the direction of heat flux (i.e. the direction normal to thickness), and M* is the moment caused by thermal stress.

Assuming one-dimensional steady-state conduction, the thickness of structure layer and metal layer are t_1 and t_2, respectively. Therefore, the temperature difference for metal layer is and shown in Figure 2:

$$\Delta T = \frac{1}{2}(T_1 + T_0) + \frac{1}{2}(T_1 - T_0)\frac{z}{t_2/2} \qquad (2)$$

The moment M^* induced by the thermal stress of metal can be expressed as:

$$M^* = \frac{\alpha_2 E_2 (T_1 - T_m)\left(t_2 + \frac{t_1}{4}\right)^2}{12} \qquad (3)$$

The boundary conditions is:

$$\begin{aligned} &r = r_i, \quad w = 0, \quad \frac{dw}{dr} = 0 \\ &r = r_l, \quad M_r = 0, \quad V_r = 0 \end{aligned} \qquad (4)$$

where

$$M_r = -D\left[\frac{\partial^2 w}{\partial r^2} + \mu\left(\frac{1}{r}\frac{\partial w}{\partial r} + \frac{1}{r^2}\frac{\partial^2 w}{\partial \theta^2}\right)\right] - \frac{M^*}{1-\mu}$$

For a center-anchored circular plate with the boundary conditions above, the deformation is obtained:

$$w = cm_1 \ln r + cm_2 r^2 \ln r + cm_3 r^2 + cm_4 \qquad (5)$$

where

$$cm_1 = -2cm_3 r_i^2$$

$$cm_2 = 0$$

$$cm_3 = -\frac{M^*}{2D(1-\mu)\left[(1+\mu) + (1-\mu)\frac{r_i^2}{r_o^2}\right]}$$

$$cm_4 = -cm_1 \ln r_i - cm_3 r_i^2$$

To determine the warpage is to find the bifurcation of curvature beginning. Therefore, when the curvatures in r-direction and θ -direction are different, the warpage is happening. The curvatures in r-direction and θ -direction are:

$$\kappa_r = \frac{\frac{d^2 w}{dr^2}}{\left[1 + \left(\frac{dw}{dr}\right)^2\right]^{3/2}} \qquad (6)$$

$$\kappa_\theta = \frac{1}{\sqrt{w^2 + r^2}} \qquad (7)$$

As the curvature of r-direction is larger than the θ -direction, the bifurcation begins. Therefore, a nondimensional number $N_{warpage}$ is difined by:

$$N_{warpage} = \frac{\kappa_r}{\kappa_\theta} \qquad (8)$$

With Equations (5) to (8), the $N_{warpage}$ is expressed as:

$$N_{warpage} = \frac{2cm_3\left(\frac{r_i^2}{r^2} + 1\right)\sqrt{f(r)}}{\left[1 + 4cm_3^2\left(r^2 - 2r_i^2 + \frac{r_i^4}{r^2}\right)\right]^{3/2}}$$

$$f(r) = cm_3^2 r^4 + cm_1^2(\ln r)^2 + cm_4^2 + 2cm_1 cm_3 r^2 \ln r + 2cm_1 cm_4 \ln r + (2cm_3 cm_4 + 1)r^2 \qquad (9)$$

When $N_{warpage} > 1$, the warpage happened. While $N_{warpage} < 1$, the center-anchored forcusing micromirro is symmetric and without warpage.

3 Result and Discussion

Consider the focussing mirror with inner radius r_i is 50 μm and outer radius r_o is 250 μm. The thickness of structure layer is 2 μm. Different depositing metal thickness and the critical sputtering temperature causing warpage is shown in Figure 3. It shows when the thickness of depositing metal layer thickness increasing, the warpage decreases. When the metal thickness reaches 0.5 μm, the temperature even less than 100 ℃. The dufferent structure thickness Figure 4 shows the relationship between warpage temperature and metal thikness under different structure thikness t_1 . It is obvious the thicker structure layer would need larger warpage temperature with the same metal thickness. If the metal thickness is 0.5 μm, the relation between structure thkness t_1 and warpage temperature is shown in Figure 5. It is found that as the t_1 increasing, the warpage temperature increases nonlinearly. When the structure thickness t_1 reaches 5 μm, the warpage temperature is above 2000 ℃ . This temperature is larger than the melting temperature of chronuium. That is, under the condition, the structure would not warpage during fabricating process. Figure 6 shows the relationship between warpage temperature and structure plate thikness under different metal thikness t_2. It is found that as the metal layer increasing, the warpge temperature decreases under the same structure plate thickness. The relationship of outer radius and warpage temperature is shown in Figure 7. Where, the thicknesses of structure plate, metal layer, and inner radius are 2, 0.1, and 50 μm. It shows as the outer radius increasing, the warpage temperature decreases fast and reaches to a limit values.

4 Conclusion

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The warpage condition of centered anchored deformable focusing mirrors is determined by a criterion derived in this work. A nondimensional number can be used as a criterion to determine the deformable focusing mirror is warpage or not. This non dimensional number is composed by the material properties, structure size, and fabricating process temperature. The result shows the thicker depositing layers need lower warpage temperature. However, as the thicker structure plate needs the higher warpage temperature. Even the temperature being over the melting temperature of metal, the focusing mirror would still not become warpage. As the increasing of outer radius, the warpage temperature decreases fast and reaches a limit temperature.

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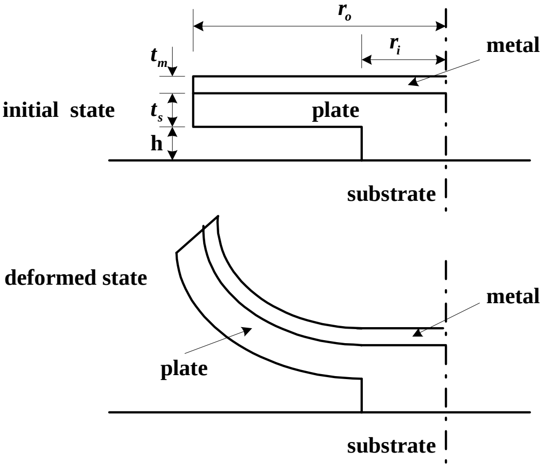

Figure 1 Half cross-section of a center-anchored circular and their underlying substrate.

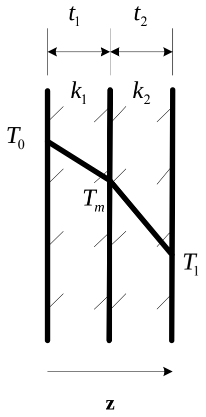

Figure 2 Temperature profile of metal and structure layer.

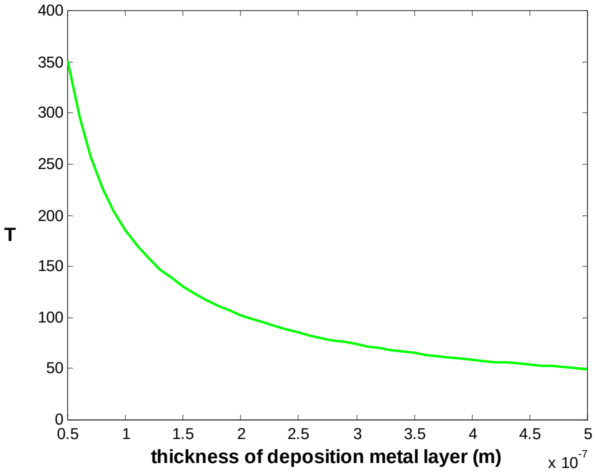

Figure 3 The relationship between metal thickness and warpage temperature

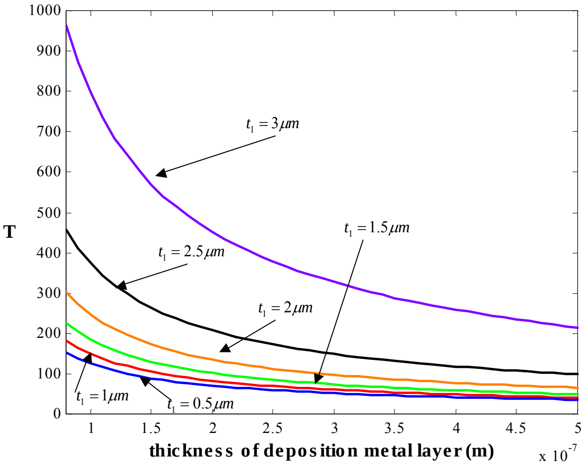

Figure 4 The relatioship between warpage temperature and metal thickness under different t_1

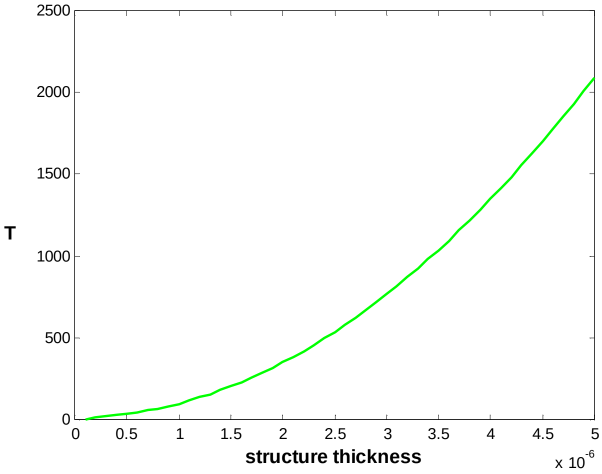

Figure 5 The relationship between the structure thickness and warpage temperature.

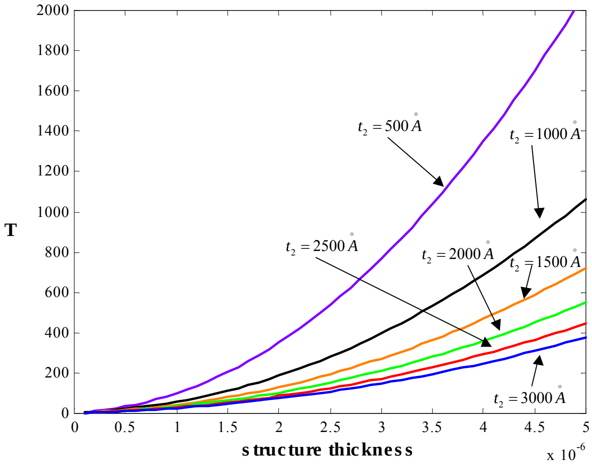

Figure 6 The relationship between warpage temperature and structure plate thickness under different t_2

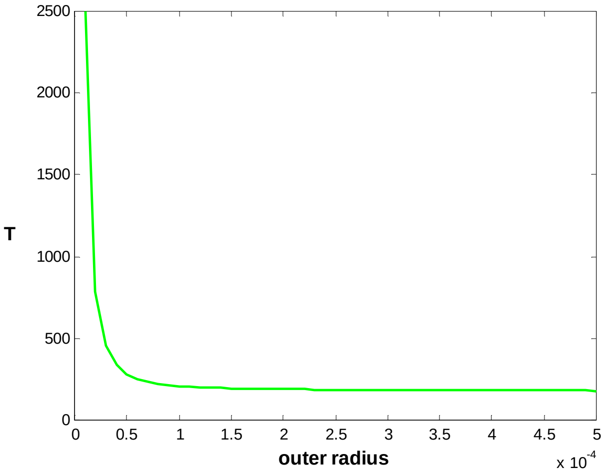

Figure 7 The relationship between the outer radius and warpage temperature.