Sensors and Actuators A 172 (2011) 516–522

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Initial deflection of silicon-on-insulator thin membrane micro-mirror and fabrication of varifocal mirror

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ARTICLE INFO

Article history:
Received 7 September 2010
Received in revised form 12 August 2011
Accepted 30 September 2011
Available online 6 October 2011

Keywords:
Micro-mirror
Deformable mirror
Silicon-on-insulator wafer
Residual stress

ABSTRACT

Thin membranes fabricated from silicon-on-insulator (SOI) wafer are valuable for deformable mirrors. The mirror is controlled to generate a specific wave-front with precision smaller than a wavelength. Here, we investigate quantitatively the initial deflection of the thin membrane mirrors fabricated from SOI wafer, which are often used in micro-electro-mechanical systems. A 1-μm-thick and 450-μm-diameter mirror fabricated from SOI wafer deflects upward around the circumference at an angle of 0.12°. The maximum deflection of the mirror is 320 nm at the center. The stress conditions of the mirrors are analyzed on the basis of material strength theory. The deflection is explained by the residual stress of the buried oxide layer of SOI wafer. The in-plane stresses of the micro-mirrors of diameters from 450 μm to 860 μm range from compressive stress of 1.2 MPa to tensile stress of 2.1 MPa. Furthermore, based on the above experimental and theoretical analyses, a 1-μm-thick varifocal micro-mirror of the diameter of 400 μm is fabricated. The focus of the mirror is varied from −28 mm to 21 mm with the deviation smaller than 4 nm from parabola in the mirror central region.

1. Introduction

Micro-mirror is a key component of optical micro-electro-mechanical systems (MEMS). Micro-mirrors are intensively studied for various applications [1]. Rigid flat micro-mirror is easily fabricated from a polished bulk silicon substrate having a radius of curvature larger than 1 m [2]. On the other hand, thin membrane mirror has an advantage of the small inertia suitable for fast scanning mirror. Polycrystalline silicon micro-mirror fabricated by low pressure chemical vapor deposition in surface micromachining is compact and light [1]. However, the polysilicon micro-mirror often suffers deflection due to residual stress. More recently, a flat polysilicon micro-mirror with a bulk silicon frame is also reported using the tension by crystallization of amorphous silicon layer [3]. Silicon nitride micro-mirror is also flat due to strong tension [4].

Varifocal mirrors have been used for several applications such as range finder and confocal microscope [5]. In the recent reports, the varifocal mirrors are shown to be useful for coherence tomography to change the laser spot position along optical axis, and thus, the depth and lateral resolutions are improved [6,7]. Moreover, the varifocal mirror is studied for conventional imaging optics, in which the study is focused on parabolic surface to remove spherical aberration [8,10].

Recently, silicon-on-insulator (SOI) wafer has been widely used for the fabrication of many kinds of MEMS. In the case of the thick micro-mirror fabricated from SOI wafer, due to the bulk crystal property, the crystalline flatness is obtained. On the other hand, thin crystalline silicon membrane fabricated from SOI wafer is often utilized to obtain a flexible surface at low actuation voltage for the mirrors of adaptive optics [9]. Mescheder et al. reported a varifocal mirror consisting of an electrostatically driven membrane-mirror with nearly parabolic surface over a large area using a ring shaped counter electrode, which is a part of a chip package [10]. The mirrors were fabricated from a 5-μm-thick top silicon layer of SOI wafer. Hokari et al. proposed a convex varifocal mirror on the basis of materials strength theory, and the deformation of a plate was purely spherical if only a bending moment was applied to the circumference [8]. The spherical surface was well approximated to be a parabola if deflection was small. The proposed mirror was fabricated from a 10-μm-thick top silicon layer of SOI wafer and a glass plate, which were connected by anodic bonding. In these reports, the residual stresses of SOI wafer such as in-plane stress were not taken into account for designing the varifocal mirrors because the thickness of the mirror was relatively thick (>5 μm) [8,10]. Kurczynski et al. fabricated a low-stress membrane from a SOI wafer for a deformable mirror in adaptive optics [9]. The mirror was fabricated from a 1 μm thick top silicon layer of SOI wafer and suffered

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doi:10.1016/j.sna.2011.09.042

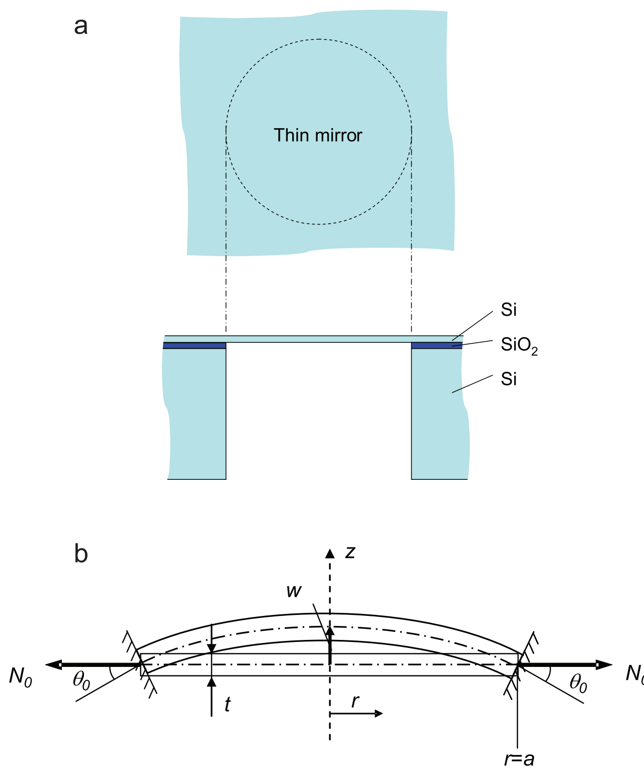

Fig. 1. (a) Schematic diagram of thin mirror fabricated by etching Si substrate and SiO_2 layer of SOI wafer. The edge of the thin mirror is supported by the Si substrate through the SiO_2 layer. (b) Circular plate model with an initial in-plane force N_0 clamped at angle θ_0. This model is used for the evaluation of the thin mirror deflection.

an initial deflection. In the case of the thin mirror, the residual stress of SOI wafer affects the mirror shape.

To control the wave-front of reflected light, the mirror profile is controlled with the precision better than a fourth of wavelength [11]. For the more precise system such as astrophysical deformable mirror, the wave-front is needed to be controlled with the deviation less than a tenth of wavelength (~10 nm) in the entire mirror region. In the case of varifocal mirror, the focal length is ideally varied without aberration by applying electrostatic force on the micro-mirror. However, there are few reports on the quantitative investigation of the initial deflection of the thin micro-mirrors fabricated from SOI wafer although SOI wafer suffers the residual stress of silicon dioxide (SiO_2) layer.

In this paper, we investigate the initial deflection of thin micro-mirrors fabricated from SOI wafer with the precision better than 1 nm. The deflection is also analytically investigated on the basis of the material strength theory. Moreover, the electrostatic varifocal micro-mirrors are fabricated and the deflections are measured. The varifocal mirror is studied for future incorporation in confocal microscope to improve the depth resolution as described in Ref. [5].

2. Theoretical approach

We consider here a common simple structure of thin micro-mirror fabricated from SOI wafer as shown schematically in Fig. 1. A circular mirror is supported by a SiO_2 layer and a silicon substrate. The silicon substrate and the SiO_2 layer of SOI wafer are removed below the mirror by deep reactive ion etching (RIE) and hydrofluoric acid etching, respectively. Here, we assume that the top silicon layer and silicon substrate are tensile, and the SiO_2 layer is compressive before etching. After the etching of the substrate, the top silicon layer becomes compressive or tensile depending on the stress conditions of the layers. Usually the remained SiO_2 layer is still compressive. In the recent report, a thin film supported by a substrate deflected at the edge by the residual stress after etching partially the substrate [12,13]. Therefore, the top silicon layer can deflect by the residual stress around the circumference of mirror. Here, we assume that the mirror has a uniform in-plane force and a uniform bending moment. These conditions are expressed in the model of Fig. 1(b). The circular mirror is clamped at an angle θ_0 by the circumferential bending and has an in-plane force N_0. The radius from the center axis is expressed by r, the vertical axis is denoted by z, the mirror radius is a, and the thickness is t. The deflection of mirror from the neutral plane is expressed by w. If the deflection of the mirror is small, the deflection can be governed by the differential equations [14]:

$$\begin{cases} \xi^2 \dfrac{d^2\theta}{dr^2} + \xi \dfrac{d\theta}{dr} - (1 + k^2\xi^2)\theta = 0\,(N_0 > 0) \\ \xi^2 \dfrac{d^2\theta}{dr^2} + \xi \dfrac{d\theta}{dr} - (1 - k^2\xi^2)\theta = 0\,(N_0 < 0) \end{cases} \tag{1}$$

where

$$\xi = \frac{r}{a}, \theta = \frac{a}{t}\frac{dw}{dr}, D = \frac{Et^3}{12(1-\nu^2)},$$

$$k = \begin{cases} \sqrt{\dfrac{N_0 a^2}{D}} & (N_0 > 0) \\ \sqrt{\dfrac{-N_0 a^2}{D}} & (N_0 < 0) \end{cases}$$

and E is Young's modulus and ν is Poisson's ratio.

In the case of in-plane tensile force N_0 ($N_0 > 0$), the general solution is expressed as:

$$\theta(\xi) = C_1 I_1(k\xi) + C_2 K_1(k\xi) \tag{2}$$

where C_1 and C_2 are arbitrary constants, $I_n(\xi)$ is the nth order modified Bessel function of the first kind, and $K_n(\xi)$ is the nth order modified Bessel function of the second kind. From the boundary condition, the deflection slope at the center of mirror is zero, thus $\theta = 0$ at $\xi = 0$, therefore,

$$C_2 = 0 \tag{3}$$

The mirror edge is clamped at angle θ_0, then,

$$C_1 = \frac{a\theta_0}{tI_1(k)} \tag{4}$$

Substituting Eqs. (3) and (4) into Eq. (2), we obtain:

$$\theta(\xi) = \frac{a\theta_0}{tI_1(k)} I_1(k\xi) \tag{5}$$

The corresponding deflection is obtained by integrating Eq. (5):

$$w(r) = \frac{\theta_0 a}{kI_1(k)} I_0\left(\frac{k}{a}r\right) + C_3 \tag{6}$$

Since the deflection at the mirror edge is zero:

$$C_3 = -\frac{\theta_0 a}{kI_1(k)} I_0(k) \tag{7}$$

Substituting Eq. (7) into Eq. (6), we obtain the deflection curve of the mirror as a function of r:

$$w(r) = \frac{\theta_0 a}{kI_1(k)} \left(I_0\left(\frac{k}{a}r\right) + I_0(k) \right) \tag{8}$$

In the case of in-plane compressive force N_0 ($N_0 < 0$), the general solution is expressed as:

$$\theta(\xi) = C_4 J_1(k\xi) + C_5 Y_1(k\xi) \tag{9}$$