Optical Properties of Surface Micromachined Mirrors with Etch Holes

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Abstract—We have investigated the optical properties of surface-micromachined polycrystalline silicon reflectors within the visible spectral range at five different wavelengths. The measurement results of the reflectivity of various microreflectors at four different incident angles (20°, 30°, 45°, and 60°) are presented. Optical properties of microreflectors realized using the multiuser MEMS process (MUMPS) have been investigated. Our studies have found that etch holes, widely used in the surface micromachining process to reduce the time for releasing structures by sacrificial undercutting, have a great influence on the optical properties of micromachined mirrors. Diffraction patterns created by two-dimensional etch-hole arrays on micromachined mirrors have been investigated. The diffraction by etch holes obeys the Fraunhofer diffraction theory when a collimated light source (e.g., a laser beam) is incident. We have shown that when the dimension of etch holes increases, an increasing portion of the incident power will be diffracted and transmitted due to etch holes, leading to decreasing reflectivity of surface micromachined mirrors. [408]

Index Terms—Etch hole, optical property, surface micromachining.

I. INTRODUCTION

In recent years, the microfabrication technology has been applied to enable microoptical systems with applications such as communication and display [1], [2]. Many novel microoptical devices have been reported, such as optical modulators, mirrors, diffraction gratings, and tunable Fabry–Perot filters, to name a few. These devices can be further integrated with sensors, actuators, and integrated circuits (IC's) to form microoptoelectromechanical systems (MOEMS) such as the digital micromirror display (DMD) [3]. Many microoptical devices have been fabricated using polycrystalline surface micromachining techniques, with the polycrystalline thin film grown by low pressure chemical vapor deposition (LPCVD) as the structural layer and the silicon oxide thin film as the sacrificial material. One such process, the multiuser MEMS process (MUMPS) [4], has been widely used for the purpose of fast and low-cost development of MOEMS.

As the polycrystalline material is finding increasingly wide use in integrated optoelectronics and MOEMS, its optical properties have received attention [5]–[9]. Investigation of surface properties such as roughness, scattering, absorption, and reflection has been conducted. For example, the refractive index of thin films has been studied extensively to reveal the effect of temperature, light intensity, and microstructure [10]–[12]. It has been observed that surface roughness and grain size influence optical properties [9]. However, optical measurements in these above-mentioned studies have all focused on LPCVD thin films that have been grown in the laboratory of individual groups. The optical properties of materials involved in common MEMS processes have not been examined systematically.

Our current study has been conducted with two major focuses. First, we have conducted a comprehensive investigation on the reflectivity of a polysilicon micromachined mirror developed through the common MUMPS along with other single crystal silicon (SCS) and polysilicon mirror surfaces. At five discrete wavelengths within the visible spectral range (632.8 nm, 611.4 nm, 604.0 nm, 594.1 nm, and 543.5 nm), the effects of metal coating on the reflectivity are characterized. Secondly, effects of etch holes on optical properties have been identified. In many microoptics applications, the surface area of structures (e.g., mirrors) must be relatively large (e.g., several mm²) as dictated by optical functionality. One such example is a free-space optical reflector as shown in Fig. 1, where etch holes are spaced by 30 μm in a two-dimensional array [13]. A close view of a typical etch hole (5 × 5 μm²) is shown in Fig. 2. Etch holes are inevitable for these applications under current surface micromachining technologies. However, these holes can potentially cause optical diffraction, which is undesirable to free-space optical systems by generating noise and erroneous crosstalk signals. In this paper, we have investigated the effects of etch holes on optical diffraction and on reflectivity.

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II. THEORIES

A. Reflectivity at the Interface of Air and Silicon

Suppose a plane wave is incident on the interface of two homogenous and nondispersive media at a given incident angle—$\theta_i$. If the magnetic permeabilities of these two media, $\mu_1$ and $\mu_2$, are equal, the reflection coefficient of power ($r$) for incident light polarized normal to the plane of incidence (TE) is determined by

$$r_{\perp} = \frac{\cos \theta_i - \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \sqrt{1 - \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2 \sin^2 \theta_i}}{\cos \theta_i + \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \sqrt{1 - \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2 \sin^2 \theta_i}}, \quad (1a)$$

For incident light polarized parallel to the plane of incidence (TM), $r$ is determined by

$$r_{\parallel} = \frac{\cos \theta_i - \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \sqrt{1 - \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2 \sin^2 \theta_i}}{\cos \theta_i + \sqrt{\frac{\varepsilon_2}{\varepsilon_1}} \sqrt{1 - \left(\frac{\varepsilon_1}{\varepsilon_2}\right)^2 \sin^2 \theta_i}}. \quad (1b)$$

The terms $\varepsilon_1$ and $\varepsilon_2$ are the electric permittivities of the two media at the interface [14]. When the two media are lossless, $\varepsilon_1$ and $\varepsilon_2$ are real. And $\varepsilon_1$ and $\varepsilon_2$ will be complex when the two media are lossy. The estimation of $r$ by (1a) and (1b) is only valid for ideal, smooth material interface. Many factors can affect the value of $r$. For example, roughness of actual polysilicon surface as influenced by conditions of film growth and treatment can cause scattering of light at the interface, which makes the actual value of $r$ lower than the theoretical value predicted by (1a) and (1b).

B. Diffraction by Etch Holes

The diffraction by two-dimensionally arrayed etch holes can be estimated by using the Fraunhofer diffraction theory when a collimated light beam is incident. It is analogous to the case in which a uniform plane wave is diffracted by crossed gratings. Fig. 3(a) and (b) illustrates the pertinent geometric parameters in the diffraction grating and the diffraction pattern of the normal incidence case. As shown in Fig. 3(a), $d_1$, $d_2$ and $l_1$, $l_2$ are the spacings and the dimensions of the etch holes in the $x$ and $y$ directions, respectively. The terms $N_1$ and $N_2$ are the number of etch holes in the $x$ and $y$ directions, respectively.

Fig. 3(a) and (b) illustrates the pertinent geometric parameters of (a) the etching holes and (b) the diffraction pattern. $\theta$ and $\psi$ are the diffraction angles in the $x$ and $y$ direction, [Fig. 3(b)]. The diffraction pattern can be determined by [15]

$$I(\theta, \psi) = I_0 \left[ \frac{\sin \left(\frac{\lambda}{2} N_1 k d_1 \sin \theta \sin \left(\frac{\lambda}{2} N_2 k d_2 \sin \psi\right) \right)}{\sin \left(\frac{\lambda}{2} k d_1 \sin \theta \right) \sin \left(\frac{\lambda}{2} k d_2 \sin \psi\right)} \right]^2 \frac{\sin^2 \left(\frac{\lambda}{2} k d_1 \sin \theta \sin \psi\right)}{\left(\frac{\lambda}{2} k d_1 \sin \theta \sin \psi\right)}, \quad k = \frac{2\pi}{\lambda} \quad (2)$$

in which $I_0$ is a coefficient. When $z$ is much greater compared with $x'$ and $y'$, the position of the main maxima of the power intensity of diffraction can be approximated using the following equations (at $\theta_i = 0^\circ$):

$$\sin \theta = \frac{m \lambda}{d_1} \approx \frac{x'}{z} \quad (3)$$

$$\sin \psi = \frac{n \lambda}{d_2} \approx \frac{y'}{z} \quad (4)$$

with $m$ and $n$ being the order of diffraction.

Although square-shaped etch holes appear frequently in designs, the actual shape of etch holes after plasma etching tends to be a circle due to imperfect lithography and etching (Fig. 4). In this case, (5) should be used to calculate the distribution of the intensity in the diffraction pattern in order to obtain a more accurate estimation.

$$I(\theta, \psi) = I_0 \left[ \sin \left(\frac{\lambda}{2} N_1 k d_1 \sin \theta \sin \left(\frac{\lambda}{2} N_2 k d_2 \sin \psi\right) \right) \right]^2 \left[ \frac{\sin \left(\frac{\lambda}{2} k d_1 \sin \theta \sin \psi\right)}{\left(\frac{\lambda}{2} k d_1 \sin \theta \sin \psi\right)} \right] \frac{2 I_0 (k s w)^2}{k s w} \quad (5)$$

In this equation, $w$ is equal to $\sqrt{x'^2 + y'^2}$ and $s$ is the radius of the etch holes.

For a typical micromachined mirror developed through MUMPS, $d_1 = d_2 = 30 \mu m$, and $l_1 = l_2 = 3 \mu m$. If a laser beam with the beam diameter of 1 mm is used, $N_1$ and $N_2$ will be both equal to 33. The normalized intensity of the lowest few
The diffraction reduces the reflectivity of the mirror. Meanwhile, high-order diffraction beams can potentially cause crosstalks in free-space optical systems.

III. EXPERIMENTS

A. Optical Measurement Systems

Two optical measurement systems have been constructed (Fig. 5) to determine the reflectivity and to characterize the far-field diffraction pattern. In the system for the reflectivity measurement [Fig. 5(a)], a wavelength-tunable laser is used to generate laser beams of five different wavelengths. A spatial filter and a 10x reduction telescope are applied to remove noise and to scale the diameter of the laser beam down to 1 mm. An inline point power meter is placed in the path of the reference beam to monitor the fluctuation in the intensity of the light source during the measurement. A second power meter is used to measure the intensities of the incident beam and the reflected beam alternatively. Fig. 5(b) illustrates the system for characterizing the diffraction patterns. It consists of a charge-coupled device (CCD) camera for capturing the diffraction pattern projected 30 cm from the micromirror. The recording and analysis of diffraction patterns are performed on a personal computer.

B. Preparation of Samples

Three basic types of mirror surfaces are prepared. The first one is a highly polished single crystal silicon wafer surface. The second one consists of a layer of 2-μm LPCVD polysilicon thin film (deposited at a process temperature of 600 °C) on top of a layer of 2-μm silicon oxide film. The third one is a micromirror developed through MUMPS. It contains etch holes with dimension and spacing compatible with MUMPS design rules (A detailed description of MUMPS can be found in [4]). The polysilicon surface of interest is the poly layer, produced by the LPCVD process and later treated with annealing and phosphorus doping. Since the main goal is to study the reflectivity of flat surfaces, the MUMPS mirror is not released from the substrate.

Each type of mirror surface mentioned above is accompanied by a reference mirror surface, which has an additional layer of 200-nm-thick thermally evaporated gold film on top of the silicon or polysilicon surfaces. The three mirror surfaces without gold film coating are designated as SCS, Poly, and MUMPS, respectively. The three surfaces with gold film coating, on the other hand, are designated as SCS-Au, Poly-Au, and MUMPS-Au, respectively.

The surface roughness of each mirror surface is measured by using a Dimension 3000 Atomic Force Microscope (AFM) (Digital Instruments, Inc.). The measurement results for the SCS, Poly, and MUMPS surfaces are shown in Fig. 6. The area of the scanning window used in surface characterization is 10 × 10 μm². The characterization is done across the entire surface of each sample, which shows that the roughness is quite uniform. The RMS roughness values for SCS, Poly, and MUMPS are 1.26, 43.3, and 7.1 nm, respectively. AFM measurements also show that gold coating does not change the surface roughness.
C. Reflectivity

We obtained measurement data of reflectivity for six surfaces under different incident angles and wavelengths while the polarization of the incident light was perpendicular to the plane of incidence (TE). As an example, the measured reflectivity values of the SCS, the Poly (without gold coating), and the SCS-Au surfaces at different incidence angles (at 632.8 nm) are plotted in Fig. 7. In Fig. 7(a), the theoretical curve for the SCS mirror surface is calculated by using Eqn. (1a). The reflectivity data of single crystal mirror surface closely matches the theoretical curve. The SCS mirror closely resembles an ideal reflector surface due to tight control of curvature and roughness. For TM polarized light, similar measurements should follow (1b) in exactly the same way.

The plot for the polysilicon mirror (Poly) is shown in Fig. 7(b). Since the Poly surface has a larger roughness than that of SCS, more power loss occurs due to the scattering, which leads to a smaller reflectivity. The scattering due
to surface roughness can be estimated by using the scalar scattering theory [16]
\[
\frac{R_s}{R_o} = 1 - e^{-(\pi \delta \cos \theta_i / \lambda)^2}
\]  
(6)

where \( R_s \) is the reflectivity due to scattering of surface roughness and \( R_o \) is the total reflectivity from the surface. The wavelength of the incident light \( \lambda \) is 632.8 nm, and \( \delta \) the RMS roughness is 43.3 nm for the polysilicon mirror. The theoretical curve for the polysilicon mirror in Fig. 7(b) is obtained by subtracting the scattering loss given by (6) from that of SCS given by (1a).

The reflectivity of the gold mirror (SCS-Au) at different angles is plotted in Fig. 7(c). The reflectivity is close to 1 since the thickness of the gold film, 200 nm, greatly exceeds the skin depth (8 nm at \( \lambda = 632.8 \) nm).

The measurement data of reflectivity at four different incidence angles (20°, 30°, 45°, 60°) for the six mirror surfaces under five discrete wavelengths (632.8, 611.4, 604.0, 594.1, and 543.5 nm) are summarized in Figs. 8 and 9. The reflectivity of uncoated reflective surfaces (SCS, Poly, and MUMPS) is low (<50%). The Poly mirror surface has the lowest reflectivity. We believe the reflectivity is low for Poly reflective surfaces due to increased surface scattering. The reflectivity of surfaces with gold coating increases by almost 100% compared with uncoated counterparts. The reflectivity of SCS and Poly mirrors with gold coating at 543.5 nm is smaller than those at other wavelengths. This generally agrees with reported optical characteristics of gold. For example, one report shows that the reflectivity of gold decreases as the wavelength becomes shorter than 560 nm [17].

D. Diffraction by Etch Holes

We have designed two groups of polysilicon mirror surfaces with etch holes to study the effect of etch holes on optical
properties of reflective surfaces. One group (Group 1) contains mirror surfaces with etch holes of the same spacing (30 μm), but of various dimensions: 6 × 6, 8 × 8, 10 × 10, 14 × 14, 15 × 15, 16 × 16, 18 × 18, 21 × 21, and 23 × 23 μm². Another group (Group 2) contains etch holes of identical dimension (5 × 5 μm²), but of different spacing (10 μm, 15 μm, and 20 μm). The effects of etch hole dimension and spacing on the diffraction pattern thus can be identified.

A laser beam is directed onto the sample with the incidence angle of θ in the y plane, shown in Fig. 10. From the Fraunhofer diffraction theory, the position of the intensity maxima in the diffraction pattern is determined by (7) and (8).

\[
d_t \left( \sin(\theta_t + \theta) - \sin(\theta_t) \right) = m\lambda, \quad \text{for } x' \text{ direction} \tag{7}
\]

\[
d_0 \sin \psi = n\lambda, \quad \text{for } y' \text{ direction} \tag{8}
\]

with θ and ψ being the diffraction angle in x' and y' directions, respectively [15]. The diffraction pattern of the MUMPS sample at \( \lambda = 632.8 \text{ nm} \), captured by a CCD camera, is illustrated in Fig. 11. The measured intensity distribution of the diffraction pattern of the MUMPS mirror at \( \lambda = 632.8 \text{ nm} \) is shown in Fig. 12. A good match between the measured result and theoretical value [determined by (7) and (8)] of the spacing of two main intensity maxima \( \Delta \) is found.

The dimension of etch holes will control the intensity distribution of the diffraction pattern, affecting both the power reflected from the mirror and the angular spread of the diffracted beams. Fig. 13 presents the normalized intensity of the reflected beam obtained with Group 1 surfaces at \( \lambda = 632.8 \text{ nm} \). The normalization was performed by dividing the intensity of the zeroth-order beam reflected from a polysilicon surface with etch holes by the intensity reflected from an area of the same wafer that does not have etch holes. Thus, all the surface and material factors affecting the reflectivity described
in Section III-C are accounted for. As shown in Fig. 13, the reflectivity decreases as the etch hole dimension increases. This results from the fact that more light is transmitted through the etch holes, and more light is diffracted by etch holes as they get larger.

The spacing of etch holes will also affect the reflectivity of micromachined mirrors. Fig. 14 shows the measurement result of the reflectivity of the mirror surfaces in Group 2 at λ = 632.8 nm. As the spacing between etch holes increases, the reflectivity of the mirror surface increases mainly due to the decrease in filling factor.

The theoretical curves of reflectivity in Figs. 13 and 14 were calculated using the procedure described in the following. The loss due to the light transmitted through the etch holes corresponds to the ratio between the total area of etch holes and the area of the entire reflector surface, which is denoted as the filling factor of etch holes. From Fig. 3, we find that the filling factor is $f$. Secondly, (5) is used to calculate the intensity of the (1,0) and (1,1) diffraction orders. The sum of light intensity of these two orders provides an estimate of the diffraction loss. The loss factor due the scattering of surface roughness is calculated by (6), using $\lambda = 632.8$ nm, and $\delta = 43.3$ nm. The various theoretical loss components for the two cases above are listed in Tables I and II, respectively.

Most of the power diffracted by the etch holes lies in the main lobe of the $\sin^2(p)$ function (where $p = k\lambda/2d$) or the
first-order Bessel function for a circular hole. According to (2) or (5), the smaller the dimension of the etch holes, the wider the main lobe of the diffraction pattern. The reflected beam is composed of more diffraction modes as the dimension of the etch holes decreases; hence, the angular spread of the reflected beams is greater. However the spacing of the diffracted orders (Δ) does not depend on the dimension of the etch holes, only on the spacing between them.

IV. DISCUSSIONS AND CONCLUSIONS

We have investigated the effects of etch holes on the optical properties of micromachined mirrors within the visible spectrum. Etch holes exert two major effects on the optical properties of micromachined mirrors, namely, diffraction and reduction of reflectivity. The reflectivity is decreased as the filling factor of etch holes increases, caused by either an increase of etch-hole dimension or a decrease of etch-hole spacing. An increase in the etch-hole spacing will result in greater reflectivity, at the potential expense of increased etching time to completely release a surface-micromachined structure.

REFERENCES


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