An electrothermally actuated Membrane as oscillating Pinhole for the high-frequent Modulation of Light

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Differential Confocal Microscopy (DCM) can provide nanometer depth sensitivity for optical profilometry. We investigate a new approach for the creation of a differential depth signal through an oscillating pinhole, thereby reducing overall size, yet enhancing speed of the detection.

1 Introduction

DCM had been developed over two decades ago to enhance the depth-sensitivity of confocal microscopy. While originally used within its small linear depth-range, it is of major interest for closing the control-loop towards the specimen in positioning systems for the accurate measurement and fabrication. Recently, a principle had been shown, that reduces noise in DCM by applying Lock-In filtering through an tuneable acousto-optical gradient index lens (TAG lens) [1]. While applying an alternating driving signal, the probing confocal spot of the objective will oscillate axially. When scanning axially over the specimen in order to probe its surface, multiplication with the driving signal of the TAG-lens followed by low-passing will create a differential curve towards the specimen's surface. Speed of the oscillation is a key for preventing vibration enter as well as raising throughput. The tuneable lens however has only limited speed, because of its overall size. In conjunction with the used objective there may be only one focal plane where aberrations are minimized. Therefore, we presented an approach [2] to shift the oscillation to the detecting pinhole itself. Thereby the optical systems remains at its constant best adjustment, while the pinhole is only required to be small for best lateral and axial resolution. This mechanical constrain enables high oscillation frequencies. The formerly used pinhole in a cantilever only provided insufficient shadowing of stray-light entering the actual detector as well as low deflection for high frequencies. Here we present our attempt on an oscillating pinhole membrane to expell stray-light and enhance deflection at high frequencies.

2 Design

Key design-goals are to reach an oscillation frequency of $f_{0n} \geq 100$ kHz. High deflection is desired to achieve a high contrast oscillating over the detection point-spread function. A diverging goal hereby is to keep the pinhole-layer as thin as possible to prevent axial shadowing. Therefore the function of mechanical carrying and pinhole are separated from another into two individual layers. A third layer forms the actuator for the deflection. Thereby, the design for an electro-thermally driven membrane of previous work has been adapted [3].

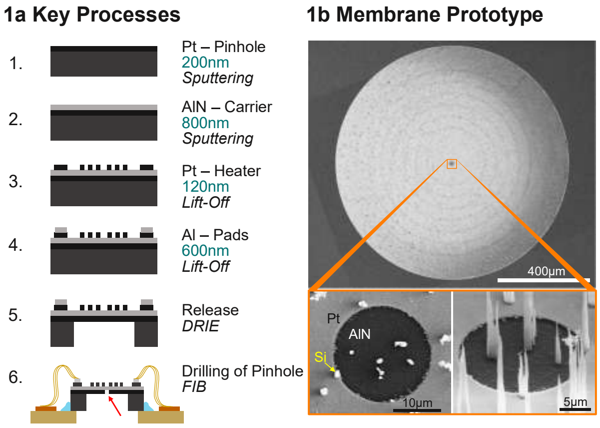

Fig. 1 *Key Processing Steps for the manufacturing of electrothermally actuated pinholes.*

As it is the major design goal, dynamical properties shall be estimated. Overall, such a multilayer membrane can be described by a lumped stiffness $D = \sum_i E_i \cdot t_i^3/(12(1-\nu_i^2))$ and residual tension $T = \sum_i \sigma_{0i} \cdot t_i$. Both parameters are part of a biharmonic partial differential equation as shown in [4]. There the relationship $\lambda_2^2 = \lambda_1^2 + Ta^2/D$ was derived. For the clamped membrane, the eigenvalues λ_1, λ_2 must fulfil further: $\lambda_2 I_1(\lambda_2 a)/I_0(\lambda_2 a) = -\lambda_1 J_1(\lambda_1 a)/J_0(\lambda_1 a)$. With this relationship n eigenvalues λ_{1n} for radial symmetric modes can be found numerically and used for the calculation of the eigen-

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frequencies f_{0n}:

$$f_{0n} = \frac{\lambda_{1n}}{2\pi}\sqrt{\frac{D}{\varrho a^4}\left(\lambda_{1n}^2 + \frac{Ta^2}{D}\right)} \qquad (1)$$

Where $\varrho = \sum_i \rho_i \cdot t_i$ is the density per unit area. Inserting tabulated material data and estimating a residual stress of $\sigma_0 = 150$ mW [3], the first eigenmode should be at $f_{00} = 105.45$ kHz, reaching the target speed.

3 Prototype

The key steps of processing are shown in Fig. 1a. To achieve smallest pinhole diameters as well as preventing another high load on the filigree membrane, the platinum is etched by focused gallium-ions. This etching was stopped directly after reaching the aluminium-nitride carrier to maintain high membrane stability. An example of a manufactured membrane of radius $a = 500$ µm is shown in Fig. 1b as indicated by the red arrow in Fig. 1a. The pinhole has a diameter of $d_{PH} = 20.3$ µm. The residual stress had been monitored after the deposition steps as $\sigma_0 \approx 350$ N/mm². Influence of the following DRIE step and pinhole milling are neglected. As Fig. 1b (detail) shows, a significant density of silicon-needles of varying tens of micrometers height are left on the membrane as a result of the DRIE.

The deflection amplitude at different excitation voltages and frequencies has been measured first with a laserinteferometric vibrometer by SIOS GmbH. Fig. 2 shows an example excitation of $V_{pp} = 20$ V and $V_0 = 30$ V at $f_{01} = 187$ kHz. The radial symmetric modes are alternating with higher modes. At f_{01}, the deflection reaches $\hat{z}_{01} = 177$ nm. Two decades attenuation to the other modes proof a sufficient clean oscillation of the pinhole. The orange lines indicate fitted eigenfrequencies following the introduced model. The fit implies, that due to the approximate heating of $P_{el} \approx 288$ mW the residual stress reduces to $\sigma_0^{Osc} \approx 60$ MPa. The residual deviation of the modelled f_{0n}^{fit} in Fig. 2 arises from the actual mechanical properties of the produced thin-films, the influence of the complex heater structure ,that has been simplified to an equivalent homogeneous layer, and the silcon needles.

The membrane has been tested for the modulation of the PSF in a single-pass system. An optical fiber is imaged through a tube lens and a microscope objective of $NA = 0.80$ onto the pinhole. The platinum pinhole layer blocks $(1 - T)_{Mem} \approx 99.2\%$ of the employed helium-neon laser, while the transmittance through the pinhole maintains $T_{PH} \approx 71.3\%$. Transmittance could be even higher, if silicon-needles would not have partially obstructed the pinhole as seen in Fig. 1b.

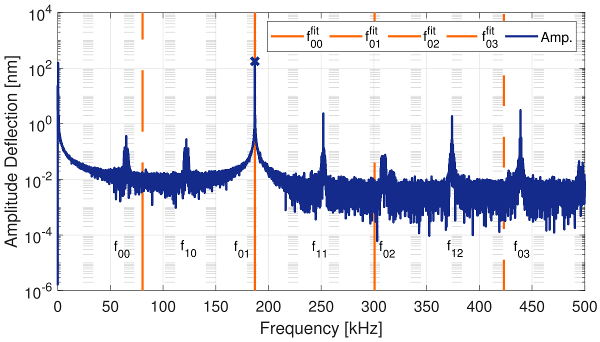

Fig. 2 *At f_{01} excited oscillating pinhole measured by an interferometric vibrometer.*

4 Conclusion

We have shown a on MEMS processing based approach for an actively oscillating pinhole. The DRIE process needs to be tuned so, that the density of silicon needles deminishes. Alternatively, wet etching maybe could be easier to implement, although the membrane shape would change. For the given knowledge of the input parameters, the model achieves a good prediction on the eigenfrequencies. The transition from higher to lower residual tension during heating corresponds to a change from thin membrane to thin plate. Further integration of thermal expansion is required to estimate the deflection of such multilayers. The currently achieved highest deflection of an $a = 500$ µm membrane is of about $\hat{z} \approx 500$ nm and therewith already suitable for the lock-in detection. Higher deflection would allow lower *NA* to still produce contrast which would be favorable to achieve higher magnification. A smaller pinhole improves that, too. Besides another optimization of the electrothermally actuated multilayer, the inverse piezo-effect as used in ultrasonic transducers could be a promising alternative. However, the next step ist the implementation of the introduced oscillating pinhole into the setup of a DCM.

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