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Stress-modulated tilt actuator for tunable optical prisms

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ABSTRACT

A tunable optical prism MOEMS based on the deformation of a liquid droplet is presented. An aluminum-nitride membrane is tilted by a novel type of thermo-mechanical actuator. The actuation principle is based on a thermo-mechanical modulation of the intrinsic stress in aluminum-nitride beams. Based on an analytical model, the key parameters of the actuator are optimized. Furthermore, the influence of the intrinsic stress on the actuator properties is investigated. These dependencies and the model are verified by mechanical characterization of samples. Operation in air and with ambient fluid has been confirmed. An image shift of 30 mm is found in a microscopic setup which corresponds to 19 % of the field of view.

1. Introduction

A large number of tunable micro-optical components have already been investigated in the past. They offer advantages such as compact design, low weight and thus highly dynamic operation as well as low energy consumption. In contrast to lenses [1–4] and mirrors [5], which have intensively been investigated, there are only a few approaches for tunable prisms.

With respect to the authors' knowledge, all use electro-wetting on dielectrics (EWOD), a technique which is already strongly investigated for liquid lenses [6]. Generally, the advantages of such systems are a low power consumption and fast actuation. These systems often manipulate the interface of two liquids. During the selection of the used liquids their refractive index, density and electric properties have to be considered. Furthermore, the utilization of multiple, laterally separated electrodes enable the combination of lens and prism functionality with a 2D tilt [7,8]. In order to get a flat interface and a pure prism characteristic, rather complex three-dimensional electrode structures [9–11] are necessary and often a passive plate is introduced, which floats between the two phases [12].

In this contribution we present an approach, where two planar plates confine a droplet. Thermo-mechanical actuators tilt one of these surfaces as shown in Fig. 1. The liquid droplet is located between a glass chip and a transparent thin film membrane that is suspended in a silicon frame (Si-frame). If the frame rotates, the liquid droplet forms a wedge with an angle θ_m. For the setup shown in Fig. 1 and in case of small wedge angles, the optical deflection angle θ_o is given by:

$$\theta_o = (n - 1) \cdot \theta_m \tag{1}$$

where n is the refractive index of the liquid used.

Hence our approach utilizes an actively tilt-able plate, which is flat and offers pure prism characteristics. The stack of MEMS-chip, spacer and glass-chip is rather easy to integrate. The liquid wedge is confined by MEMS- and glass chip. Here we use one liquid only, which translates the mechanical tilt effectively in an optical deflection angle. Compared to EWOD approaches, the liquids can be chosen more freely and hence liquids with a very high refractive index can be used. During liquid selection its surface tension should be dominant compared to its weight. This relation is described with the Bond number, which should be smaller than one. Furthermore the liquid droplet should wet the surfaces of the MEMS- and glass-chip.

Surface tension gains in importance when scaling down liquids in micro-optical components. Therefore, the actuator setup should be rather stiff and offer a high driving force. Simultaneously, a high deformation during actuation is required for a large beam deflection. Thus, the actuation principle should provide sufficiently high power. Hence, for the presented approach, the thermo-mechanical actuation is chosen.

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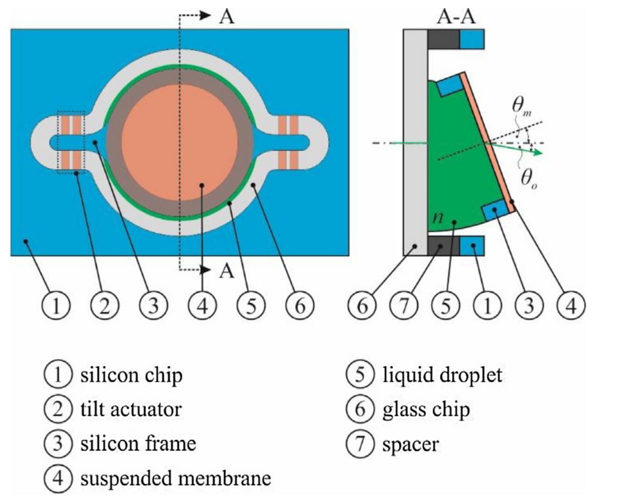

Fig. 1. Scheme of the tunable prism based on droplet deformation due to thermo-mechanical actuation.

2. Actuator design

2.1. Selection of actuator material

In terms of a simple fabrication it is favorable that both the actuator and the membrane are made of the same material. Therefore, the chosen thin film material should be transparent and offer a high energy density during thermo-mechanical actuation. Table 1 summarizes the essential thermo-mechanical properties of Si_3N_4, SiO_2, polydimethylsiloxane (PDMS), nano-crystalline diamond (NCD) and nano-crystalline aluminum-nitride (AlN). Based on the Youngís modulus E and the coefficient of thermal expansion α, the energy density W_{th} during thermo-mechanical actuation is calculated:

$$W_{th} = \frac{1}{2} \cdot E \cdot \alpha^2 \tag{2}$$

The thermal diffusivity α_{th} of a material relates its thermal conductivity λ, specific heat c and its density ρ. Thus the thermal diffusivity describes the dynamic thermal properties, where high values of α_{th} allow a highly dynamic actuation:

$$\alpha_{th} = \frac{\lambda}{\rho \cdot c} \tag{3}$$

The comparison of the energy densities of in principle suitable materials shows, that AlN offers the highest value during thermo-mechanical actuation. With an adequate actuator design, the energy density of $2.66 J m^{-3} K^{-2}$ can be transduced in high force/high deformation. PDMS on the other hand offers a high thermal expansion but lags of a sufficient Youngís modulus. Furthermore, AlN offers a very high thermal diffusivity. AlN is chosen as a material for both, thermo-mechanical actuator and transparent membrane.

Table 1
Comparison of the thermo-mechanical properties of common transparent materials in tunable optical components.

material	energy-density in $J m^{-3} K^{-2}$	thermal diffusivity in $10^{-6} m^2 s^{-1}$	references
SiO_2	0.006	1.06	[13–15]
Si_3N_4	1.35	9.18	[14–16]
NCD	0.52	759	[17–20]
PDMS	0.58	0.18	[21,22]
AlN	2.66	146	[23–26]

2.2. Actuation principle

In general, there are two types on thermo-mechanical actuators. The first one utilizes two materials with different thermal expansion and Youngís-Modulus. Their deflection is based on the mismatch in thermal expansion. The major drawback of this type is the parasitic deflection during any change in ambient temperature. In order to overcome this disadvantage, thermomechanical actuators make use of a monolithic layout. This approach is based on one material, only, whereas the deflection is caused either by an asymmetrically mechanical layout [27] or by a temperature gradient [28]. Our approach uses the thermo-mechanical modulation of the intrinsic stress in thin AlN beams. Similar to monolithic actuators, this approach is almost immune to changes in ambient temperature.

For the rotation of the Si-frame with the optical membrane in Fig. 1, this frame is located between two similar actuators. One actuator is built up of four AlN-beams, which are arranged in a symmetrical setup. Fig. 2 a) shows a cross-sectional view of on actuator. The four AlN beams connect the Si-frame with the basic silicon chip. Two of these beams are located at an upper level, whereas the other two are at a lower level. All beams have initially the same tensile intrinsic stress due to the fabrication process for AlN, and thus there is no overall torque on the Si-frame. For the actuation, resistive heaters allow the individual heating of the AlN beams. If two diagonally arranged beams are heated (e.g. upper left and lower right in Fig. 2 b)), the AlN locally expands, the tensile stress and thus the force at these beams are reduced. Now the force setup becomes unsymmetrical and a torque is generated, which causes the Si-frame rotation (clockwise in Fig. 2 b)). Heating the other two beams (upper right and lower left in Fig. 2) allows bi-directional tilt (counter-clockwise).

2.3. Model

Fig. 3 shows a detailed model of the actuator geometry. Each of the four beams has a length of L, and their vertical separation is $2H$. The Si-frame has a width $2B$. The location of the AlN-beam j is given by its end-points P_{j1} and P_{j2}. The beam is fixed to the Si-frame at P_{j1} and to the chip at P_{j2}. For the un-actuated case the location of these eight points is given in Fig. 3 a).

Three parameters have to be considered for the design of the actuator: The first and most important one is the silicon frame geometry. The maximum tilt is achieved if P_{11} and P_{31} form a straight line together with P_{32}, O and P_{12}. Hence the maximum wedge angle φ_{geo} is given by:

$$\phi_{geo} = \arctan\left(\frac{H}{B}\right) - \arctan\left(\frac{H}{B+L}\right) \tag{4}$$

Eq. (4) shows the dependence of the wedge angle on the beam length L, their vertical separation $2H$ and Si-frame width $2B$. For $L \gg H$, the second term becomes neglectable.

The second and third parameter result from the strain of the AlN beams during rotation. The unheated beams have to contract during rotation. Their stress should be tensile, unless the maximum wedge angle is achieved. Hence, the second parameter is the necessary intrinsic stress.

The heated beams expand during actuation. In order to achieve rotation, the heated beams should be unstressed for $\varphi = \varphi_{geo}$. This can be achieved by an appropriate heating of the beams.