STATIC LARGE-ANGLE MICROMIRROR WITH ALUMINUM NITRIDE SPRINGS

S. Weinberger, Y. Cheriguen, M. Hoffmann

Ilmenau University of Technology, IMN MacroNano®, Department Micromechanical Systems, Max-Planck-Ring 12, 98693 Ilmenau, Germany

Abstract — In many applications, especially in measurement systems (e.g. optical tracking systems) mirrors with enlarged static, but dynamically adjustable deflection are required. The core problem for large angle deflections is the required torsional spring. In most devices, this spring is made of silicon due to its excellent elastic properties. Unfortunately, the spring is relatively stiff resulting in large forces for static deflection. Here, aluminum nitride is used for the spring. It is fabricated by CMOS-compatible reactive sputtering resulting in a nanocrystalline structure of well-oriented needle-like AlN crystals. AlN has a high mechanical strength and a linear elastic behavior. These material properties enable the fabrication of thin and compliant springs. Beside the geometric parameters the spring stiffness is tunable by the mechanical film stress. For highly dynamic mirror deflection, an electrostatic actuation is used. Planar-plate electrodes enable high static rotation angles (more than 10°).

Keywords: micromirror, torsional spring, aluminum nitride

I - Introduction

Resonant micromirrors are well-known for scanning applications, but also statically adjustable mirrors have many applications. For example, optical target tracking requires mirrors with large static deflection but also high dynamic [1], [2].

Although micromirrors are already well-investigated optical MEMS [3], there is still a lack of mirror devices with a large static deflection range. Usually, the torsion spring is made of silicon due to its excellent elastic properties. Silicon springs are relatively stiff resulting in large restoring forces. The solution proposed here is the use of aluminum nitride (AlN) as spring material deposited by CMOS-compatible reactive sputtering and leading to a nanocrystalline structure. Because of this, the sputtered aluminum nitride has excellent mechanical properties [4]. Hence it is possible to fabricate 400-nm thin AlN/Al-torsion springs with low polar moment of inertia and therefore static rotation angles with more than 10° at moderate operating voltages. For highly dynamic mirror deflection, an electrostatic actuation by planar-plate electrodes is used (Figure 1).

II – Design and Simulation

The simulation was done with FEA under ANSYS and COMSOL. The torsion springs are optimized according to stability and stiffness. An optimized electrode position is important for a maximized tilt angle. Large electrode areas reduce the operating voltage but lead to an early pull-in.

A. Spring Design

The torsion springs consist of a 300 nm AlN film for the mechanical stability and a 100 nm Al film for the electrical mirror surface contact. The intrinsic stress in the spring’s thin film has a great influence to the spring stiffness (Figure 2).

Figure 1: Sketch of the gimbal mounted micromirror with planar-plate electrodes

Figure 2: Calculated spring stiffness vs. AlN film stress (300 nm AlN and 100 nm Al with zero stress)

Too high intrinsic stress destroys the torsion springs and must be avoided. The stress in the fixing points is usually much higher than the global film stress.
To beware these stress maxima, clamping radii are used. With the help of the radii optimization shown in Figure 3, a stress reduction close to the global stress can be achieved.

Figure 3: Calculated maximal intrinsic film stress vs. clamping radius (500 nm AlN with 300 MPa film stress; 100 nm Al with 60 MPa film stress)

B. Electrode Design

The maximum rotation angle is limited by the pull-in effect which describes the system instability caused by a faster increasing electrostatic torque than the mechanical restoring torque of the spring (non-linear effect).

For a large static rotation angle, the electrode position and distance have to be optimized (Figure 4). By changing the bottom electrode position, the pull-in angle \( \theta_{\text{pull-in}} \) can be tuned. A small bottom electrode close to the rotation axis maximizes the possible angle but increases the operating voltage, too. An optimal electrode distance \( z_0 \) is reached by limiting the angle \( \theta \) with a mechanical stop close to the pull-in angle \( \theta_{\text{pull-in}} \). For extended angles and large mirror surfaces, a long distance \( z_0 \) is necessary. To avoid a high operating voltage and therefore risk of electrical breakthrough between the planar-plate electrodes, the polar moment of inertia must be minimized.

Figure 4: Sketch of a planar-plate actuated mirror; the electrode areas are black-colored

To avoid charging effects, isolation layers are not used [5] and every part of the mirror has a defined electrical potential. There are metal areas around the bottom electrode with the same electric potential as the mirror to avoid charging of the glass substrate. These metal areas are also used as landing electrodes [6].

Figure 5 shows exemplarily simulated electrical torque curves for different electrode positions with the maximal voltage and mechanical torque curves for different spring designs. The criterion by the choice of the electrode position is a maximal tilt angle; therefore the electrical torque must always be higher than the mechanical. The operating voltage is limited by the electrical breakthrough between the bottom electrodes. Measurements show that 300 V for a 10 µm and 400 V for a 25 µm gap are safe values.

Figure 5: Calculated characteristic curves of the maximal electrical and the mechanical torques

An exemplarily angle vs. voltage curve is shown in Figure 6. The simulation is done for the favored stiffness \( K = 1 \times 10^{-9} \text{Nm.rad} \) with optimized electrodes, till the reach of the pull-in.

Figure 6: FE-analysis of an exemplarily angle vs. voltage curve for a 1-D mirror

C. Mirror Shape

Intrinsic stress of AlN or of Al film warps the gimbal and mirror and could even destroy them. In the case of measurement applications, the warping leads to errors and must be minimized. The mirror structure itself is made of stress free bulk-silicon. A thick silicon structure reduces the warping (Figure 7), but increases its weight. The results in Figure 7 are extreme values for the case, where the AlN film is all over the mirror surface. To reduce intrinsic stress and to avoid charging, just AlN anchors are on the mirror surface (Figure 1). Figure 8 shows the decrease of the 1st natural frequency.
by the increase of the silicon thickness. A low natural frequency supports oscillations due to ambient vibrations or fast movements and hinders a defined mirror positioning. A trade-off between mirror surface flatness and dynamic behavior must be performed. We used 60 µm silicon-bulk for our first samples.

- Figure 7: Exemplarily FE-analysis of the mirror surface deflection for different silicon thicknesses (mirror size: 1000 µm x 1000 µm; AlN film stress: 300 MPa; Al film stress: 300 MPa)

- Figure 8: Simulation of the natural frequency vs. silicon thickness (mirror size: 1000 µm x 1000 µm; AlN film stress: 300 MPa; Al film stress: 300 MPa; spring length: 200 µm; spring width: 40 µm)

### III - Technology

#### A. First Samples

Figure 9 and Figure 10 show first realized samples of the mirrors with the very thin torsion springs.

#### B. Fabrication Steps

A short overview of the fabrication is given in Figure 11. The mirror is fabricated in a stacked-wafer process of 300-µm thick silicon and a 500-µm thick glass wafer. LPCVD-Si₃N₄ is used as KOH etch mask on the silicon wafer back side. On the front side, the LPCVD-Si₃N₄ is removed by RIE. The deposition of the aluminum nitride functional layer follows using reactive sputtering. The AlN-springs are patterned by ICP-RIE with chlorine chemistry [7] and the KOH-mask is etched by RIE with fluorine chemistry. As electrode material and reflective film, 100 nm Al is deposited. The Al film is etched with phosphoric acid. An 800 nm thick Al contact pad is deposited through a shadow mask. The wafer is mounted in a single-side etching box and a membrane is etched by KOH from the back side to define the silicon mirror structure. The KOH-mask is removed by RIE and channels for the conducting patches are etched between the KOH-pits by the help of spray coating and DRIE.

The bottom electrodes are fabricated on the glass substrate by depositing and patterning AlCu.

The silicon and glass wafers are aligned and bonded with glue. After that, the wafer stack is separated by dicing. Now the chips are etched by isotropic dry etching to release the torsion springs. Finally the chips are mounted on a PCB and the electrical contacts are realized by wire bonding.
The challenge of high rotation angles in non-resonant mode at moderate operation voltage for micromirrors is described. Therefore, a new technological concept based on aluminum nitride torsion springs with planar-plate electrodes is presented. The key to this novel concept is the use of aluminum nitride because of its excellent mechanical behavior. First samples of this novel mirror type are fabricated and measurements are planned as the next step. The scope of application for these static mirrors with large deflection are measurement systems e.g. an optical microtracker system that allows measuring the 3-D position of a tool center point (TCP) by tracking a retroreflector by laser beams. Thus the mirrors must be able to provide a large static deflection as well as a fast dynamic actuation.

This project is funded by the Federal Ministry of Education and Research (BMBF) within the project “Spitzenforschung und Innovation in den Neuen Ländern - Kompetenzdreieck Optische Mikrosysteme”, Grant No. 16SV5473

References