New Designs for MEMS-Micromirrors and Micromirror Packaging with Electrostatic and Piezoelectric Drive

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ABSTRACT

Developments for miniaturized, MEMS based micro-mirrors are an active area of ongoing research due to the promising perspectives for cost efficient and precise pico-projectors and scanners for e.g. LIDAR applications. In this article we report several devices of 1-dim and 2-dim micro-mirrors based on new designs and new process capabilities using piezoelectric actuators. For micro-mirrors an 8'' wafer-level packaging process was developed using pre-processed borosilicate glass wafers. An optimized design of an optical package is presented that avoids any stray reflexes and ghost images in laser projection applications. For 1dim piezoelectric micro-mirrors, diameter 1.2 mm and 1 mm, scan angles in resonance mode of 40° and 73.2° at frequencies of 60 kHz and 27 kHz in ambient air have been achieved in various designs with driving voltages between 10 V and 15 V. Devices for 2-dim microscanners with electro-static and piezo-electric actuation are presented.

Keywords: MEMS, micro-mirror, vacuum packaging, laser scanning

1 INTRODUCTION

In recent years MEMS (Micro-Electro-Mechanical-System) based micro-mirrors, which are used for modulation of light in microscanner systems, are used in various application fields. Robust pico-projectors using high-efficiency laser-diodes are of interest for consumer products and in the automotive industry for high contrast head-up displays and automotive dashboard displays. Microscanners are also of interest for automotive light detection and ranging (LIDAR) systems and for intensity modulation in laser based automobile front lights [1].

The main actuating principles for MEMS micro-mirrors are -electro-static, -electro-magnetic, -electro-thermal and -piezo-electric. Advantages and disadvantages of these driving principles have been discussed in Ref. [2]. For a thermal drive the mechanical deflection frequency is limited to below 1 kHz. For an electro-magnetic drive miniaturization is limited by the necessary torque that has to be generated by an external electro-magnet. In the following examples are discussed for electro-static and piezo-electric driven micro-mirror designs. The piezo-electric drive shows the highest driving efficiency of all actuating principles with a power dissipation that is up to one order of magnitude lower that the other principles. Electro-static drives typically provide a small force only since the electro-static force decreases with electrode distance. Therefore micro-mirrors with electro-static actuation are most often operated in resonance mode where they show the highest deflection angles and highest frequencies. By vacuum encapsulation the resonance frequency and deflection angles of MEMS micro-mirrors can be increased further, drastically increasing the Q-factor of these micro-mechanical oscillators. Q-factors of up to 145,000 have been determined experimentally for vacuum packaged micro-mirrors [3].

For a laser video projection system a large tilt angle, the operating frequency and aperture size of micro-mirrors are the most important parameters. Also the frequency ratio of the two scan directions is of importance for a two-dimensional projection. Standard video signals are configured for one slow scanning frequency of 60 Hz and a fast line scan from 24 kHz up to 54 kHz depending on the resolution of the projected picture. A low micromechanical resonance frequency of 60 Hz corresponds to a suspension spring of very low stiffness leading to a fragile MEMS device. A more stable system should therefore use two unequal higher resonance frequencies. For such a projector a Lissajous scanning system has to be used instead of two separated line-scans. Principles of Lissajous projection with micro-mirrors and the optical resolution that can be achieved have been discussed in detail in refs. [3], [4].

A slow scan frequency can be realized by operation below the mechanical resonance frequency. In this non resonance mode a piezo-electric actuation can lead to higher scan angles due to the relative high bending force that a bimorph piezo-electric actuator can apply. Compared to electro-static driven micro-mirrors the piezo-electric actuated systems demand a production process of higher complexity due to the additional layers and materials that have to be deposited. In the following recent examples of MEMS micro-mirror demonstrators are described. A wafer-level packaging process is described with optical packages that are optimized for optical projection systems.

2 PIEZO-ELECTRIC MICRO-MIRRORS

Several designs of 1 D micro-mirrors have been produced. The various designs were characterized by FEM simulations and by testing finished components [5]. The mirrors are actuated by using a bimorph of silicon and a layer of PZT as piezoelectric material. Voltage induced bending of the actuator is transmitted to the micro-mirror by two connection bars. The connection bars are acting as levers and amplify the mechanical displacement of the actuators [5]. The mechanical displacement is coupled into the torsion bars that are fixing the micro-mirrors. Two design examples are shown in Fig. 1. For design A meandering connection bars are applied to reduce the mechanical stress within the bars during torsion motion of the micro-mirror to allow high scanning angles. In design B the torsion bar of the microscanner is realized as a double bar. This increases the stiffness of the torsion spring resulting in an increased eigenfrequency.

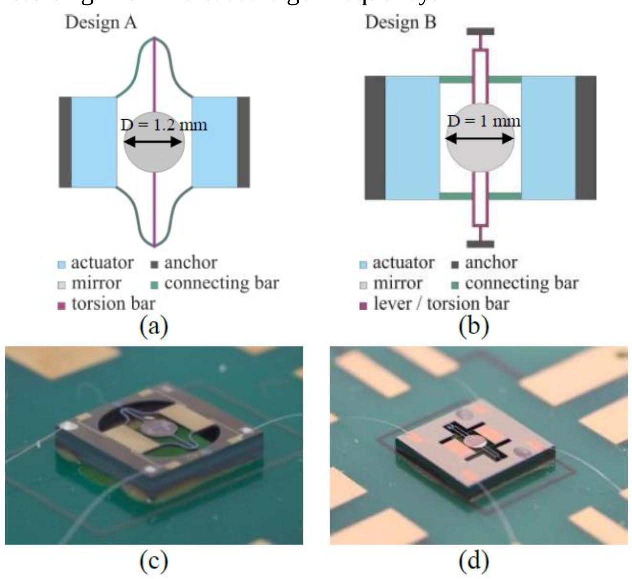

Fig.1.: Design schematics and wire bonded micro-mirrors. (a) and (b) Design A and B; (c) and (d) micro-mirror with design A and B.

From FEM simulations of the various designs the maximum material stress can be estimated. For design A a maximum shear stress of 1.3GPa at a deflection angle of 15° is calculated. For design B a maximum shear stress within the double torsion bars of 3.7GPa at a deflection angle of 15° is calculated. Resonance frequencies are 27kHz and 60kHz for designs A and B. This value is in accordance with the results of FEM simulations. For design A a $\theta_{opt}\cdot$D-product of 73.2°·mm at 27 kHz is experimentally determined driven by a 15V unipolar rectangular pulse signal. For design B a $\theta_{opt}\cdot$D-product of 40°·mm is observed at 60 kHz at 10V driving voltage. For the fabricated devices Q-factors of 1800 have been derived from the measured oscillating decay times at ambient pressure. For another micro-mirror design with an optical aperture of 1.4mm x 4mm fabricated by the same process technology a value of 60.2°·mm at 16.7 kHz was determined at 8V driving voltage [5].

2.1 Design for a 2D Micro-Mirror

A design for a two-dimensional scanning micro-mirror with piezo-electric actuation was realized. For one of the two perpendicular scanning directions a low micro-mechanical resonance frequency was realized by using elongated actuators. For the other axis the resonance frequency was increased by using short actuators of thicker material thereby increasing spring stiffness. The intention was to allow a two-dimensional optical raster-scan by operating one fast scanning frequency and one slow frequency. The slow axis can also be operated in non-resonant mode to reduce the scanning frequency further. Mirror design and FEM simulations are shown in Fig. 2.

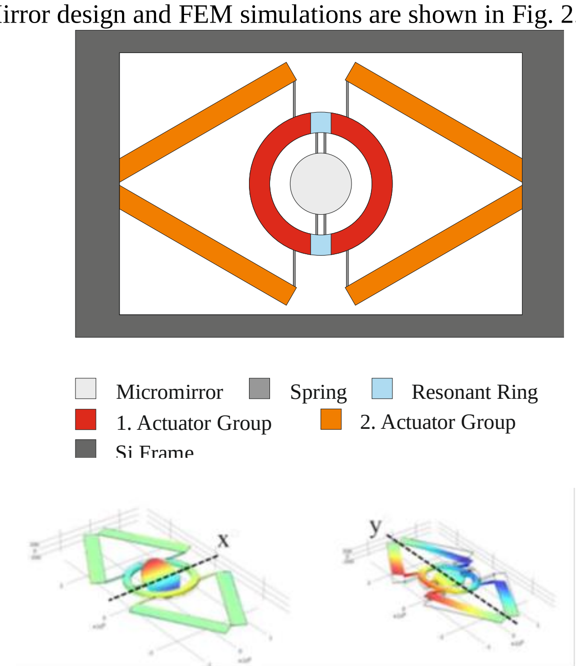

Fig. 2: Design of a 2D micro-mirror and FEM simulation of two resonant scan modes [6].

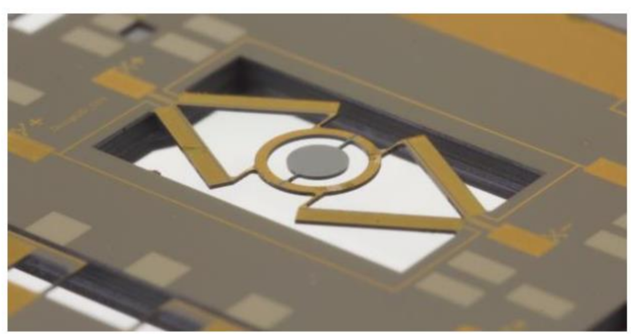

Fig. 3.: 2D micro-mirror. Device dimensions are 7mm x 9.4mm.

For fabrication of the device above with actuators of two different thicknesses 8’’ silicon wafers are used on which two layers of poly-silicon are deposited separated by two buried SiO_2 layers. On top of the poly-silicon Ti/Pt is deposited as bottom electrode below the active PZT layer and Cr/Au as top electrode. The manufacturing process is shown in Fig. 4. Actuators of 13µm thickness and actuators of 75µm thickness with higher stiffness are fabricated. The micro-mirror reflective layer is realized by a 100nm Al layer on top of the thicker poly-silicon layers. This thickness of the micro-mirror increases the mirror stability against any deformation of the mirror surface.

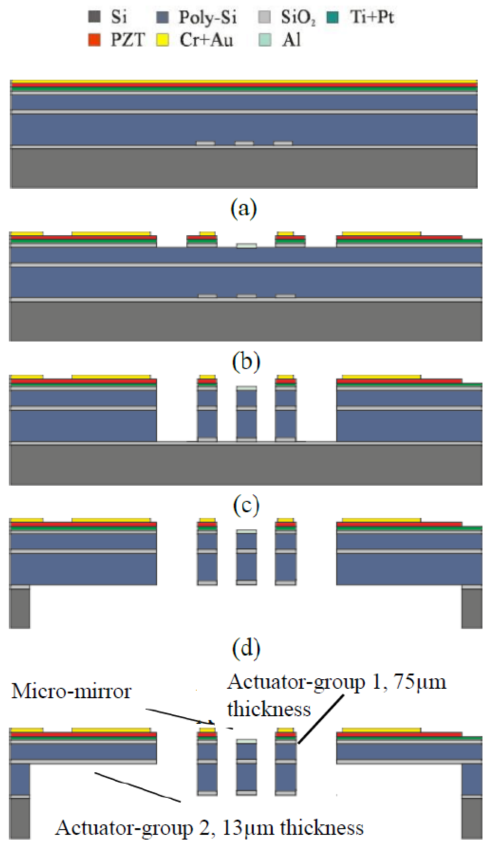

Fig. 4.: Process-flow for 2 D micro-mirrors.

All functional layers are deposited on an oxidized 8'' silicon wafer [6]. Two layers of poly-silicon of different thicknesses are used as active micro-mechanical material (a). Mirror surface and piezo-electric material and electrodes are structured by wet- and dry-etching processes (b). Actuators and mirrors are defined by a front-side DRIE etching (c). The mirror and the 75µm thick actuators are released by back-side DRIE etching (d). Actuators of 13µm thickness are than released by a second DRIE etch process (e).

Mechanical properties of the fabricated 2D microscanner have been determined. Resonance frequencies of 23.9 kHz and 1.5 kHz have been measured for the fast and slow axis. In resonance scan angles of 21.4° for the fast and 31.3° for the slow axis are obtained applying a driving voltage of 20V for both axes. With a non-resonant, quasi-static drive at a voltage of 25V a scan angle of 13.7° for the slow axis is realized. Additional design variations will be fabricated and evaluated to further improve the micro-mechanical parameters. For larger deflection angles thicker layers of the piezo-electric material will be applied and combined with poly-silicon beams of different thickness. To apply the micro-scanners as small laser pico-projectors the angular position of the mirror has to be monitored. First tests for position monitoring of resonant driven micro-mirrors with integrated piezo-electric or capacitive sensors have demonstrated an excellent sensitivity and resolution for position control [2].

3. ELECTRO-STATIC 2D MICRO-MIRROR

Several designs of MEMS microscanners for projection application have been realized using electro-static actuation. A force is generated between capacitor electrodes by an external voltage. The electrodes are fabricated as interlacing comb electrodes. Thereby the area of the capacitor electrodes is enlarged increasing the electrostatic force between the electrodes. The micro-mirror-plate and comb electrodes can be produced in poly-silicon using established MEMS surface micro-machining processes. Large scan angles and high scan frequencies can be achieved by vacuum packaging of the micro-mirrors. Vacuum packaged MEMS scanning mirrors with activated thin film getters inside the package may exhibit Q-factors up to 145.000 [3]. This packaging process can be performed as a wafer level packaging process leading to low manufacturing costs. An example of a vacuum packaged 2D scanning MEMS mirror for laser display application is shown in Fig. 5 [3]. Mirror diameter of the device in Fig. 5 is 1mm. Resonance frequencies of the two axes are 18 kHz and 600 Hz leading to scan angles of ± 15° with 60V driving voltage for both axes. Application of this microscanner in laser projection has been discussed in ref. [3]. Other designs of MEMS mirrors have been fabricated and tested. To reduce the resonance frequency of the slow axis further the mass of the external gimbal structure has been increased increasing the inertia. With this process variant resonance frequencies of 35.8 kHz and 230 Hz have been realized.

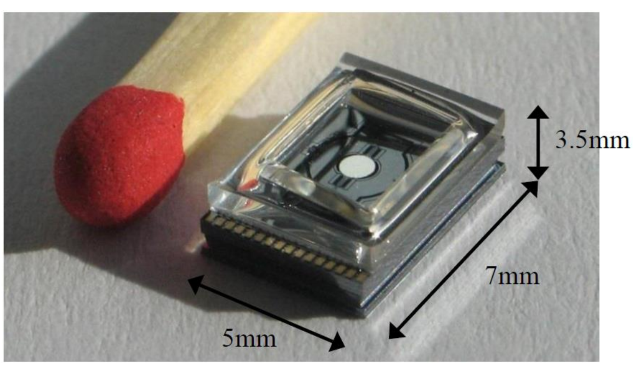

Fig. 5.: Biaxial vacuum packaged MEMS mirror for laser display application.

4. PACKAGING FOR 2 D MICRO-MIRRORS

Advantages of vacuum packaging of resonant driven micro-mirrors have been discussed above. Hermetic sealing of a MEMS device ensures additionally protection against particle contamination or contamination by chemical reactants. Optical packages that can use wafer scale bonding processes offer a cost effective way for vacuum encapsulation. A simple process would be wafer bonding between a MEMS and a glass wafer. By packaging with a parallel glass window a partial reflection of the laser beam on the surface of the glass wafer creates a bright spot in the center of a projected image. To a certain extend intensity of this unwanted spot can be reduced by an anti-reflective coating. However a complete reflex elimination in the image can be only obtained using an inclined optical window with respect to the mirror surface [7], see Fig. 6.

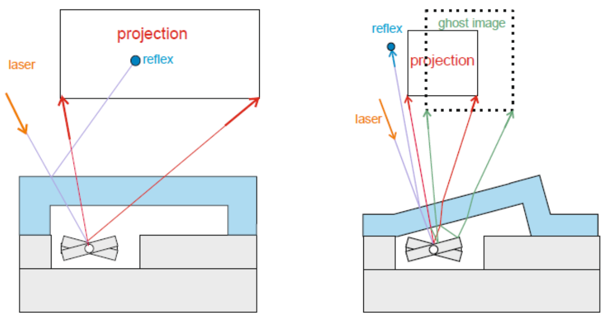

Fig. 6.: Left (Flat cover): A first order reflex results in a bright laser spot in the image; Right (Inclined window): The reflex is located outside of the projetion.

In addition to the suppression of the primary reflex, it is important to avoid disturbing superimposed images caused by higher order reflections. The most relevant of these image artifacts, the secondary reflection arises by reflections of the projected image at the glass surface on the micro-mirror. This produces an enlarged and weakened version of the original image, which superimposes the projected picture and becomes clearly observable in the picture contrast, see Fig. 6, right picture. For optimized glass covers a specific glass forming technology has been developed that allows fabrication of glass cap wafers with tilted 3D-shaped glass windows. This glass forming technology has been described in Refs. [8], [9], [10]. If the tilt angle of the window is larger than the maximum mechanical tilt angle amplitude of the MEMS mirror then the reflected spot is shifted outside the projected image.

Requirements on the optical quality of a glass cover for projection displays have been estimated by optical simulations with the software package Zemax®. Conditions for an optimized optical package of a 2D micro-mirror have been evaluated. A complete suppression of the first order reflex and secondary image can be achieved in 2D microscanners by an improved cover design and a slight acentric positioning of the micro-mirror under the lid. By an adjustment of the micro-mirror on the chip and an increase of the distance between mirror and glass cover to 1.3mm an operation of the 2D micro-mirror between ± 15° in the X-axis and ± 9° in the Y-axis can be achieved without the appearance of first and second order stray reflexes. For this set-up the glass lid has to be adapted to 4mm x 4mm inner dimensions and 5mmx5mm outer dimensions [7].

5. SUMMARY

New devices of MEMS micro-mirrors and optical packages have been fabricated and evaluated for application in miniaturized laser video projectors. For an integrated 2D raster scanner with minimum dimensions a novel gimbal-mounted, piezoelectrically driven 2D micro-mirror was developed. The micro-mirror has two torsion modes with perpendicular axes, the respective resonant frequencies are 23.9 kHz and 1.5 kHz. Both axis can be excited in resonance mode, the slow axis can also be driven quasi-statically. A novel fabrication technology has been developed for realizing an optimized 2D micro-mirror which uses different thicknesses for the spring suspensions for the two axes. In this way spring stiffness can be enhanced which increases the resonance frequency while supporting a compact design configuration. For the x-axis a total optical scan angle of 22° was achieved, while the y-axis scan angle constitutes a value of 31° in resonant driving and 13.7° by quasi-statically driving.

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