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2D MEMS scanner integrating a position feedback

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Abstract. An integrated position sensor for a dual-axis electromagnetic tilting mirror is presented. This tilting mirror is composed of a silicon based mirror directly assembled on a silicon membrane supported by flexible beams. The position sensors are constituted by 4 Wheatstone bridges of piezoresistors which are fabricated by doping locally the flexible beams. A permanent magnet is attached to the membrane and the scanner is mounted above planar coils deposited on a ceramic substrate to achieve electromagnetic actuation. The performances of the piezoresistive sensors are evaluated by measuring the output signal of the piezoresistors as a function of the tilt of the mirror and the temperature. White light interferometry was performed for all measurement to measure the exact tilt angle. The minimum detectable angle with such sensors was 30µrad (around 13bits) in the range of the minimum resolution of the interferometer. The tilt reproducibility was 0.0186%, obtained by measuring the tilt after repeated actuations with a coil current of 50mA during 30 min and the stability over time was 0.05% in 1h without actuation. The maximum measured tilt angle was 6° (mechanical) limited by nonlinearity of the MEMS system.

1 Introduction

Since years and years MEMS micro mirrors devices are continuing to be the subject of new development for applications like displays, LIDAR and endoscopes. Compared to bulk scanners, MEMS scanners present the advantages of low volume and mass, which are important features particularly for portable devices (pico projectors, smartphones), space applications (inter satellite communication, LIDAR), or endoscopy. An area of much interest is the single mirror raster scanner, consisting of a small mirror (<1.5mm) with a very fast scanning speed (one fast and one slow axis for 2 D tilting scanners) achieved by actuating the device at its resonant frequency and often under a vacuum environment. Another possibility consists of driving a scanner in DC mode (off the resonant peak) to use it as a pointing scanner. For this case, the scanning speed is slower and reachable tilt angle is lower than the resonant scanner at identical power consumption and geometry. For both kinds of devices, it is necessary to control the mirror position with a sensing device to stabilize the scanning speed for resonant devices or the tilt position for a pointing scanner. This can be achieved optically [1] with a PSD or a 4 quadrant diode, electrostatically [2] or with an integrated piezoresistive sensor [3]. In previous work [4], we had reported the fabrication and testing of a biaxial electromagnetically actuated moving-magnet scanning mirror achieving a tilt of 8.6° with a squared shape mirror of 4mm width. This system worked in open loop mode and was composed of a mirror surface coated on both sides, a silicon compliant membrane acting as the MEMS deformable part, a magnet glued to the center of the membrane and a ceramic based coil for the actuation (Figure 1). All parts are assembled at chip level.

In this work, the system was improved to achieve higher scanning speed using a position feedback control, achieved with doped silicon piezoresistors configure as 4 Wheatstone bridges around the MEMS deformable part. To investigate the sensor performances, the signal output was measured as a function of tilt angle as well as noise level.

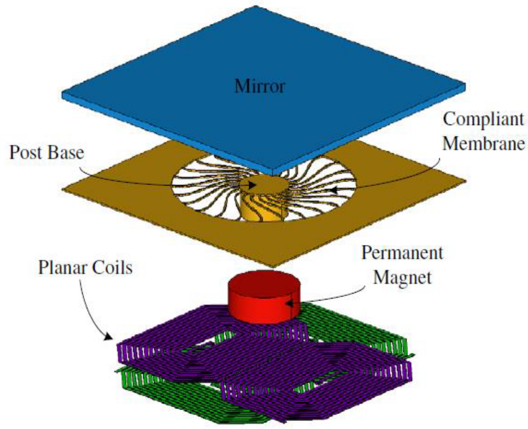

Figure 1. Exploded view of the electromagnetic system concept [4]

2 Concept

Piezoresistive sensors are acting as stress/strain sensors and to obtain a maximized signal output, i.e. a maximum of resistance change; they should be placed where the

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maximum stress of the compliant membrane is located. The piezoresistive sensor is composed of 2 doped P-type regions (Boron). One is acting as the stress sensitive part and is low doped (p+) and the second highly doped (p++) act as interface between the p+ region and the aluminum electrical interconnections. Each stress sensor is composed of 4 piezoresistors mounted in a Wheatstone bridge for compensating the resistance variation as a function of temperature and orientated in the <110> direction and at each 90° positions. With this method, only 2 perpendicular sensors should be enough to measure the tilt angle but the 2 others sensors can be used for redundant verification as the signal of 2 sensors at 180° should be opposite.
Mechanical tilt simulations of the springs have shown that the maximum stress/strain changes happen at the attachment of springs on the central pillar and have been selected as the most adequate position for the sensors. Figure 2 represents the layout at the membrane center with silicon shown in light grey, the electrical interconnections with dark grey, the p+ region with pink and the p++ region in green. For measuring the chip temperature, a Pt resistance is deposited on the chip frame to act as a temperature sensor which can be used to compensate the output signal variation of the piezoresistance with temperature.

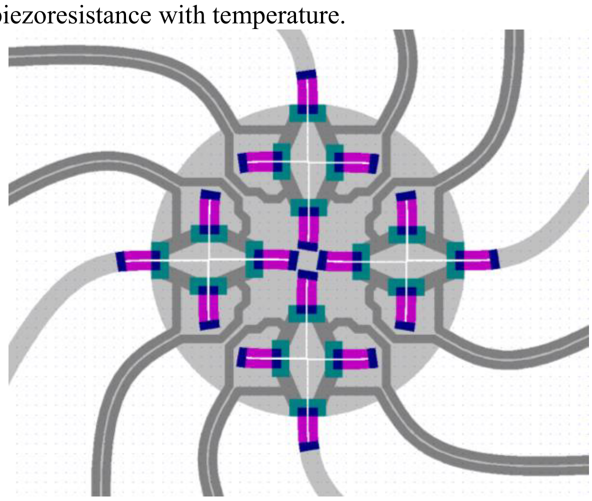

Figure 2. Piezoresistors positions on the MEMS membrane.

3 Fabrication

The fabrication of the mirror and the compliant membrane is based on SOI wafers to obtain well controlled geometries. The mirror fabrication consists of a double side DRIE etching and double side gold or aluminium coating to obtain good reflectivity. The double side coating gives the advantage to obtain a very flat mirror and a low temperature curvature dependency.
For the compliant membrane, the fabrication consists of:
- Definition of the p++ and p+ regions by localized boron implantation.
- Deposition and patterning of the passivation layer
- Deposition and patterning of the aluminium electrical interconnections
- Double side DRIE to form the flexible beams
- Release of the structures

The result of the fabrication of the compliant membrane is represented in Figure 3 and a closed view of the piezoresistive sensors on the Figure 4. Sensor 1 and 2 represents the 2 bridges used further during testing and dashed lines corresponds to the tilt directions when applying current in the 2 pairs of micro coils.

The assembly of the mirror and the permanent magnet to the compliant membrane is achieved by using a dedicated alignment system equipped with a microscope. Epoxy glue is used as joining material. The device is then attached to a PCB and wire bonded to connect piezoresistive sensors and the 2 temperature sensors to external connectors. The planar micro coils were fabricated by Cu electroplating on ceramic. The 2 layers of coils were insulated with a thin polyimide sheet. The final mounted system is presented in Figure 5.

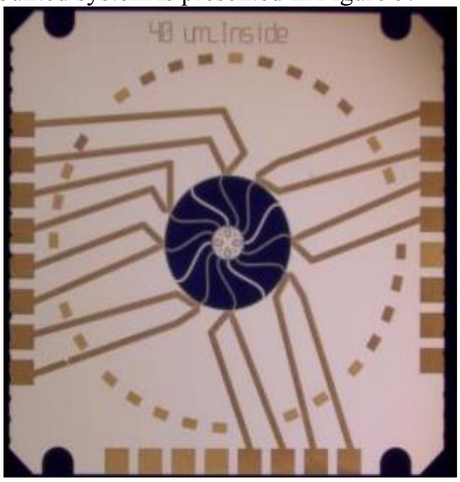

Figure 3. Fabricated compliant membrane.

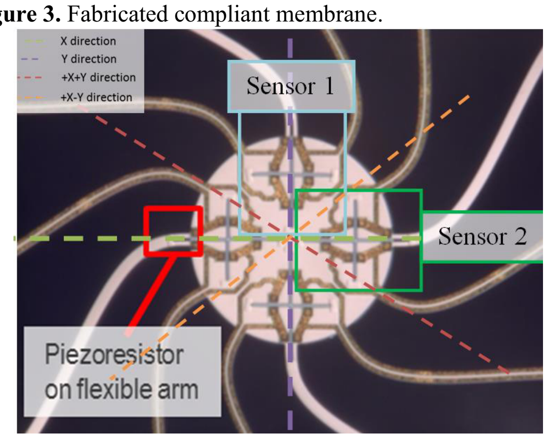

Figure 4. Positons of the sensors layout with tilt axes.

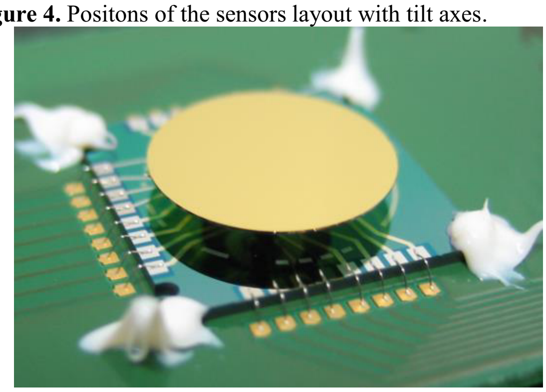

Figure 5. Assembled scanner system on PCB.

4 Characterization

For the characterization of the fabricated micro mirrors with integrated position sensors, the tilt angle is measured with a Wyko optical profilometer. Power supply is realized with Keithley 2400 sourcemeters (coil current supply, Wheatstone bridge current supply). Output signals are measured with a Keithley 2000 multimeter (voltage measurement, 4 points resistance measurement) with a precision of 10μV.

4.1 Electrical noise

Electrical noise measurements were performed on the MEMS device with a probe station, an x1000 homemade signal amplifier and an HP3562a dynamic signal analyzer. To control the amplifier level, a standard resistance of 5.6kΩ was measured to calibrate the measurement system.
A typical noise figure is depicted in Figure 6, giving a noise close to a standard resistance (5nV/√Hz). Accordingly at the targeted sampling frequency for position control, the noise level is below 1μV.

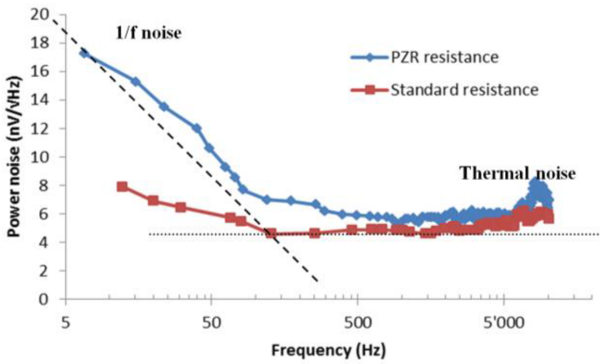

Figure 6. Noise figure for a piezoresistive bridge.

4.2 Minimum detectable tilt angle

The minimum detectable tilt angle measured by optical profilometry corresponds to the lowest output signal of the piezoresistive sensors that can be measured from the multimeter. Only stable digits were evaluated. The minimum detectable angle by this method was 30µrad (13bits) which corresponds to an output signal variation of 50μV. This value is much higher than the electrical noise measured and can be explained by a non-optimized electrical interconnections system; particularly the wires were not shielded.

4.3 Tilt angle as a function of coil current

The tilt angle was measured for a coil current up to 1A (Figure 7). Lower tilt angles were obtained compared to previous worked due to a strong nonlinearity of the system. The tilt direction is given in Figure 8. The tilt direction is not constant. This can be explained by a misalignment of the different parts of the assembly and/or by the nonlinearity of the system. This device was presenting a pretilt of 1° in the direction 30°.

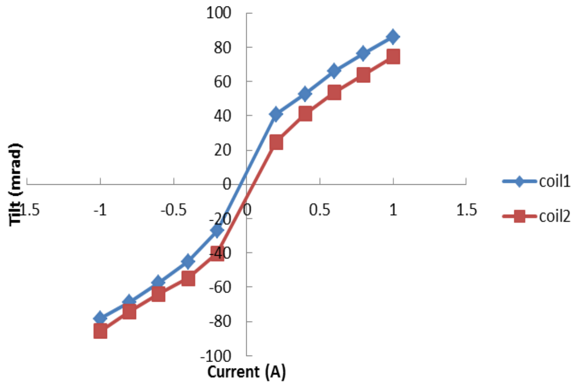

Figure 7. Tilt angle in function of the coil current.

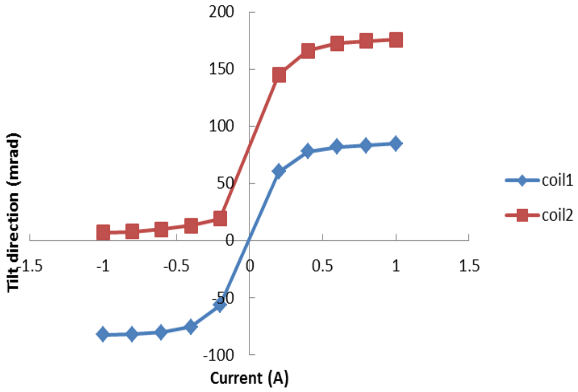

Figure 8. Tilt direction in function of the coil current.

4.4 Position sensors response

The coil's current was varied from -1A to 1A in steps of 0.5A for both axis and the output signals of the position sensors were measured as well as the tilt angle and tilt direction. The tilt dependency of the piezoresistive sensors is depicted in Figure 9 and 10 where a negative sign was attributed to tilt angle values between 0 and -180°. The dashed lines correspond to tilt directions obtained by actuating the system with 1 coil or 2 coils. Their corresponding direction is shown in Figure 4.
As predicted, each sensor is sensitive to tilt direction and amplitude. The signal output of 2 sensors appears to be sufficient to determine the position of the mirror. Figure 11 represents the mapping of the mirror position according to the output signal of 2 perpendicular sensors. The position mapping with the piezoresistive sensors was compared with the results from an optical position sensor (optical profilometer); a fitting was realized by using the curve fitting toolbox from Matlab®. The most adapted fitting function is poly33 presented in eq. (1) which had given an average fit value better than 99%. Linear fitting would give correlation coefficient of 95%. The result of the fit is presented in Figure 12, including the results from the optical position sensor. The sensitivity of the piezoresistive sensors is about 0.5mV/mrad without signal amplification.

f(x,y) = p00 + p10*x + p01*y + p20*x2 + p11*x*y+ p02*y2 + p30*x3 + p21*x2*y+ p12*x*y2 + p03*y3

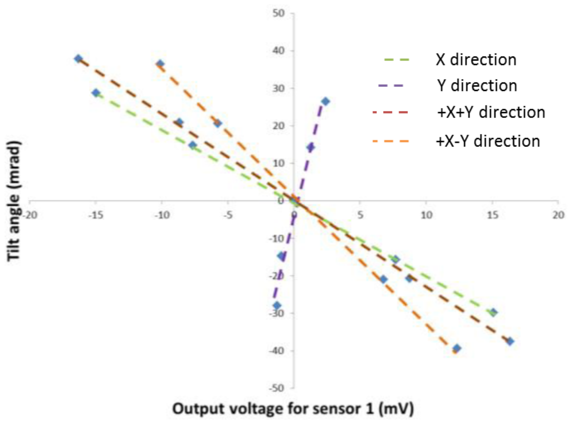

Figure 9. Tilt angle and output signal variation for sensor 1.

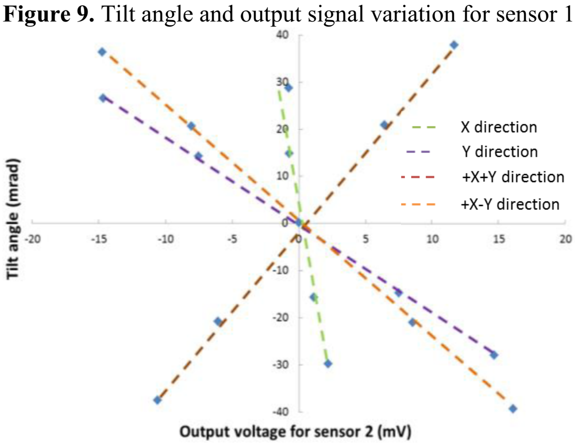

Figure 10. Tilt angle and output signal variation for sensor 2.

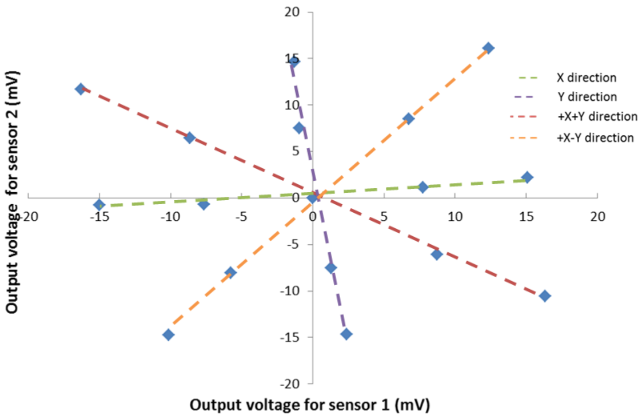

Figure 11. Position mapping as a function of the output voltage variation for sensor 1 and 2.

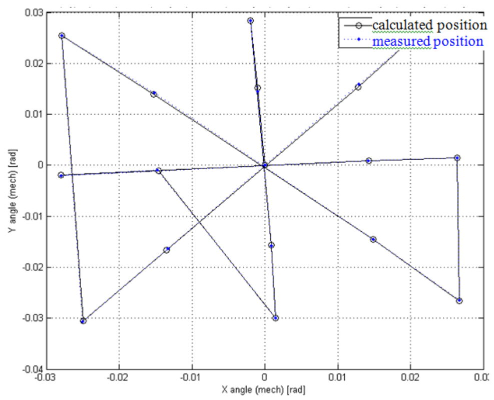

Figure 12. Optical position compared to piezoresistive sensor positioning.

4.5 Temporal stability

To investigate the variation of the sensors over time, the drift from a fixed tilt was measured by following the sensors signal output during a period of 1.5h. The standard deviation was about 9µV (0.037% of the output signal) corresponding to a tilt variation of 18µrad, so below the resolution of the measurement system resolution.

4.6 Tilt accuracy

This measurement consists of measuring the tilt angle for a specific coil current of 50mA during 30 minutes. In total, 7 measurements were performed and a standard deviation of 5µV (0.0186% of the output signal) corresponding to a tilt variation of 25 µrad (below the system measurement resolution). The stability of the position sensors is better in this experiment than the one in §4.5 which can be explained by a damping of the system by limiting position fluctuation in presence of the electromagnetic field. The tilt angle variation is in this case higher and can be attributed to the measurement system resolution in the range of 30 µrad.

5 Conclusion

A design and fabrication process was proposed to measure the position of a micro mirror scanner with a precision of at least 13 bits. Different testing experiments were performed to investigate the performance of the fabricated system. The piezoresistive sensor has a noise level lower than 1µV very close to a standard resistance giving the possibility to obtain a high accuracy position sensor which was measured to be < 30µrad without signal amplification or data treatment to obtain a resolution better than 13bits. By measuring at least 2 piezoresistors it was also possible to determine the mirror position in space with an accuracy equivalent of an optical profilometer (around 30µrad).

Acknowledgments
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