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Wobbling Mode AlN-Piezo-MEMS Mirror Enabling 360-Degree Field of View LIDAR for Automotive Applications

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***Abstract*—Aluminum nitride piezo MEMS mirror for laser beam scanning in automotive LIDAR applications was developed. The mirror has an optical aperture of 4 mm, chip size of 6.75x6.75x2mm^3, and scanning frequency of 1.6 kHz. A tilt angle of +/- 15 degrees corresponding to 30-degree optical scan angle is achieved with a low drive voltage of ~ 2 V_{pp}.**

Keywords—MEMS, mirror, LIDAR, AlN, SOI, automotive

I. Introduction

Advanced driver-assistance systems (ADAS) and self-driving vehicles are and will be using several systems for mapping their surroundings and to provide the data for decision-making: satellite & inertial navigation, cameras, radar, ultrasound, 5G and vehicle-to-everything communication (V2X), and laser range finding (LIDAR).

Camera-based perception is progressing rapidly, but it lacks the accurate 3D information. Radar operates in poor conditions but cannot provide good angular resolution. Ultrasound is very sensitive to small obstacles but is limited to short distances. LIDAR, due to its superior beam shape, offers an advantage by providing high angular resolution 3D-data of the surroundings to a high distance.

The common understanding is that ADAS and self-driving cars will incorporate several or all of the abovementioned systems. The sensors systems need to be compact, e.g. matchbox sized, affordable (~100 €), and robust enough for the automotive environment, requiring long lifetime and maintenance free operation.

For LIDAR, pressing down the size and the cost of the system, while maintaining the high performance (long range, high angular resolution, and high scan rate) up presents a significant challenge. These goals are being pursued by several approaches at present [1].

Several types of LIDARs are being developed for the automotive applications: round scanning (this work), and xy-scanning as main scan types. Typical commercial LIDARs use electric motor operated mirrors to scan the beam, which results in large and/or non-robust systems. Another interesting approach is to use an optical phased array for beam forming and steering (see e.g. [2]) which, however, is of lower technological readiness level at the moment.

Scanning or switching mirrors are a well-known family of MEMS actuators. There is a variety of products using either built-in electrostatic actuation or external magnetic or galvanic actuators. The latter allows large scan angles but makes the system rather large. Two single-axis mirrors may be used to provide 2D scanning.

In order to facilitate development of a compact, low-cost, round scanning LIDAR operating in the near-IR, we have developed a high-amplitude wobbling mode scanning MEMS mirror operating with low voltage and power based on piezo MEMS.

II. Requirements

The 360-degree laser scanning system building on the approach of the MiniFaros–project and mirror of Hoffman et al. [3] is shown in Fig. 1. Laser enters the system orthogonally to the plane of scanning through special omnidirectional lens; it is deflected from the circular mirror, which is operated in a wobbling mode, where the direction of tilt orbits around the optical axis, and with the omnidirectional lens, directs the laser horizontally to the direction of tilt. The system sets the requirements presented in Table 1 for the mirror.

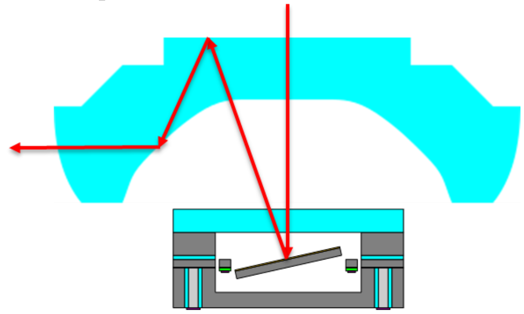

Fig. 1. 360 degree round scanning system based on wobbling mode mirror and an omnidirectional lens.

The tilt angle of +/- 15 degrees and the mirror diameter of 4 mm can immediately be detected as rather extreme values for a MEMS device.

TABLE 1: REQUIREMENTS FOR THE SCANNING MIRROR

Max. Optical scan angle (deg.)	30
Max. tilt angle (deg.)	15
Resonance frequency (kHz)	1.6
Q-value	~4000
Tilt angle/voltage (deg./V)	4.5
Mirror diameter (mm)	4
Die size (mm^3)	6.75 x 6.75 x 2
Reflectance (at 900-1000 nm)	>95 %

III. METHODS

A. PiezoMEMS platform

The piezoMEMS platform, where AlN-based actuators are monolithically integrated on the silicon MEMS structures was chosen as it allows high force generation with low voltage and extremely small area actuators. While the static motion generated with AlN-based actuators is very small, with high *Q*-value resonant amplification one can reach large amplitude motion. The cross section of piezo actuators is illustrated in

Fig. 2 where they can be seen as the on both sides of the Au-coated reflector plate.

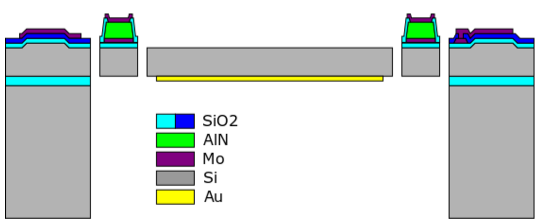

Fig. 2: Cross section of the MEMS mirror structure with piezo actuators.

B. Mirror design

The scanning mirrors were designed to have a tripod-configuration (Fig. 3), where three actuator-springs are attached to the 4 mm diameter circular mirror with 120-degree spacing. On each of the springs, 250 µm in width, there are Mo-AlN-Mo actuators that are driven with AC voltages in 120-degree phase difference. The springs also have piezoelectric sensors for position feedback. The silicon in both the mirror and the springs is 50 µm thick, while the actuator stack is Mo 0.15 µm / AlN 1.5 µm / Mo 0.5 µm. Insulator layers of SiO_2 are applied between the bottom and to electrodes.

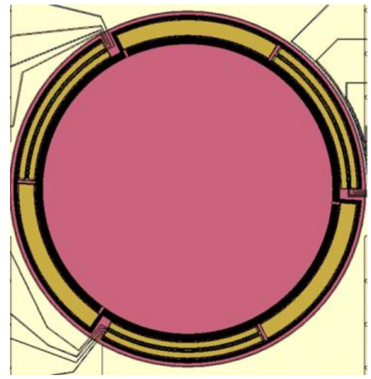

Fig. 3: Design of a tripod-mirror.

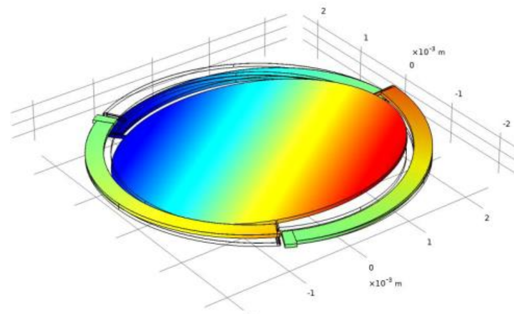

Fig. 4: Simulated tilting mode of the mirror. There are two such orthogonal modes the superposition of which results in the round-scanning wobbling mode.

C. Mirror fabrication

The MEMS was manufactured on SOI wafers with <111>-oriented 50 µm thick device layer from Okmetic Oyj.

The fabrication started by creation of packaging related recesses in to the device layer. This was followed by oxidation, deposition and patterning of the Mo-AlN-Mo actuator, and the SiO_2 insulator layers. Next, the mirror was defined into the device layer by a DRIE trench etch. Processing was then continued from the backside of the wafer with mirror release by DRIE removal of the handle wafer below the mirror. Finally, the surface of the mirror was coated with a reflecting metal (Au+diffusion barrier) by evaporation though a shadow mask by Murata Electronics.

D. Mirror packaging

The packaging was carried out by Murata Electronics using glass-Si technology and anodic bonding. Electric connections were provided by Si vias with thick glass insulator. The optical side was sealed with a glass wafer. The three-wafer stack was bonded together in a single step. A getter was applied in order to achieve low pressure in the package. Dicing to chips finalized the device manufacturing.

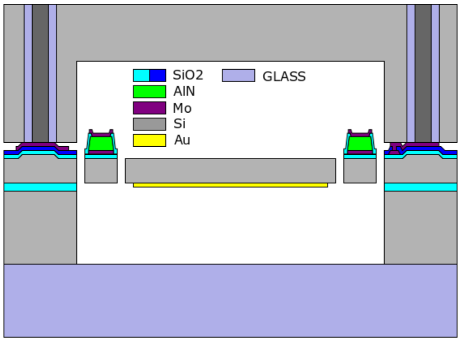

Fig. 5: Cross section of the packaged mirror. Actuators and electrical connections are on top, the reflecting surface and glass window at the bottom.

E. *Mirror characterization*

The assembled mirror package was characterized electrically by measuring impedance to individual actuator legs with an impedance analyzer, determining the frequency and *Q*-value. For optical performance, the mirror was driven into the wobbling mode with a specific driver electronics board while the vibration mode and tilt angle were observed by reflecting a laser beam from the mirror to a projection screen.

F. *Drive electronics*

Driving electronics for the mirror was built on PCB level. The wobbling mirror needs three drive signals with 120-degree phase difference with amplitude control and three readouts for position feedback. The electronics was designed to be able to provide up to four drive signal and analog feedback signal pairs (Fig. 6). As the tilt angle is very high and in the nonlinear regime, careful attention to the startup of the mirror was required from the driving system, which can be programmed to scan the frequencies and perform a specific startup sequence.

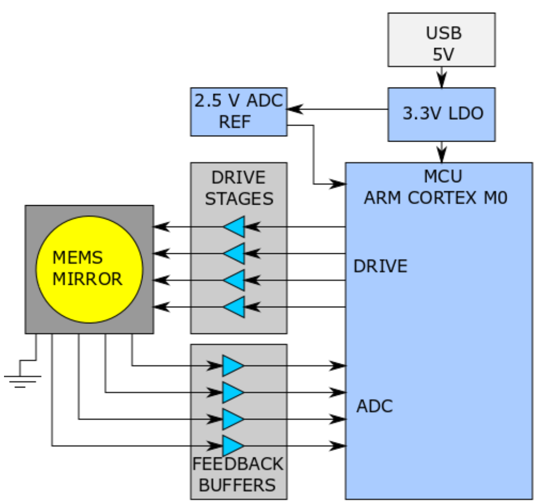

Fig. 6: Block diagram for the mirror drive electronics.

IV. Results

A. *Fabrication*

A photograph of a mirror from the actuator side is shown in Fig. 7. After initial loops for fine-tuning the process steps and some layout details, the yield of functioning mirrors is good. A packaged mirror assembled on a ceramic substrate and installed on the driver board is shown in Fig. 8.

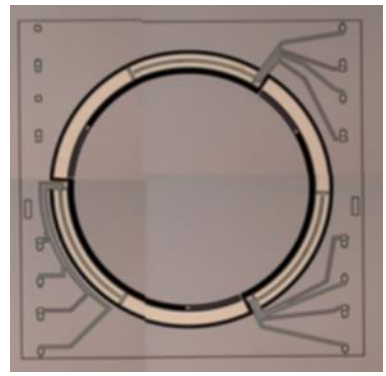

Fig. 7: Photograph of a released MEMS mirror from the actuator side with the piezo actuators and their electrodes visible on the springs as lighter regions.

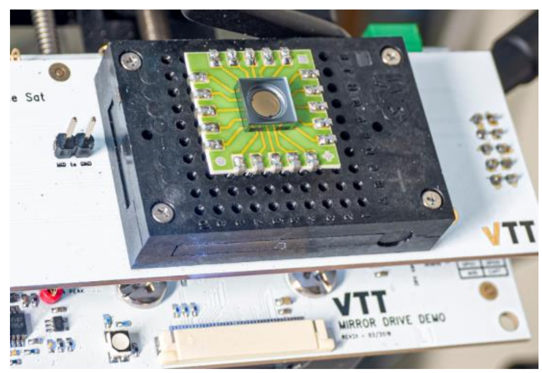

Fig. 8: Mirror assembled on the drive electronics board (bottom-most board).

B. *Mirror performance*

Electrical characterization of the mirrors showed resonance frequencies to be 1.6 kHz as designed and indicated a *Q*-value in the tens of thousands, which is well over the specification allowing lower than specified drive voltage. Optical testing showed that the +/-15 degree tilt is achieved already with 2 V drive voltage, indicating 7.5 degree/V tilt response. Some initial designs broke before the desired amplitude but with careful re-design of the anchor and spring details that was avoided.

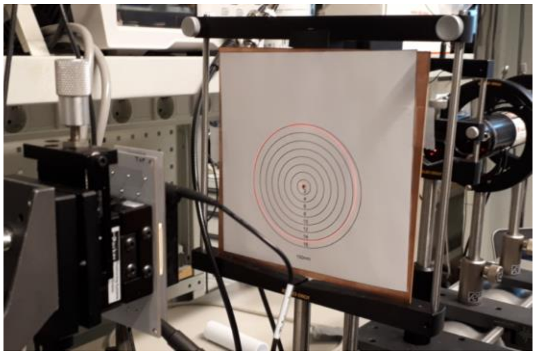

Fig. 9: +/-15 degree scanning achieved with 2 V drive in optical bench test. Drive electronics and mirror on the left, laser on the right, and projection screen for angle measurement in the middle.

The mirror surface was found to be slightly curved at rest – a bow of ~5 µm was measured on one tested device. Another challenge in the mirrors is dynamic deformation, i.e. how the mirror surface shape deviates from perfect plane or rest shape during a cycle of vibration. This was assessed by FEM simulation, which indicated variation from 1 to 3 µm (amplitude of deviation from planar shape) at 16 degree tilt amplitude, depending on anchor design. Interferometric measurements gave an estimate of ~5 µm deformation amplitude when driven in high amplitude piston mode.

V. Discussion

The AlN based piezo MEMS platform, previously having been applied to timing resonators and gyroscopes, proved to scale well to much larger high amplitude mirrors. Resonant amplification with a high *Q*-value is the key to reaching the large scan angle with a very low voltage drive. In addition to the wobbling mode, single-axis, xy-, Lissajous and piston mode scanners can be realized similarly - with the limitation to resonant operation. AlN does not provide means to meaningful static or non-resonant scanning, other ways of actuation need to be resorted to for such functionality.

The stresses induced by the large motion need to be addressed by careful design of springs and anchoring as was indicated by the breaking of some early designs. The large device with high amplitude also needs a lot of room – this requires for example using thicker than standard wafers and a wafer level package with very large cavity height. The cavity height is in fact a limiting factor to the tilt angle.

The observed static deformation of the mirrors - most likely due to stress from the reflecting metal layer - needs to be addressed, as well as the dynamic deformation. Specifications for these from the system level are an important design guideline (wavelength of laser, beam quality requirements, etc.). The static deformation can be reduced mainly by process optimization, while the dynamic can be addressed by design.

The x- and y- tilt modes, superposition of which the wobbling mode is, were found not to have full degeneracy. The high driving amplitude and duffing-behavior however enabled to merge them into the wobbling mode. The startup of the mirror needs a special routine to lock into the wobbling mode.

In further work, a new package based on metal bonding will be developed, the deformation issues will be addressed. The mirror drive electronics capabilities will be extended to attitude control of the mirror.

VI. Conclusions

A piezo MEMS wobbling mode mirror with 4 mm aperture and 6.75x6.75x2 mm^3 chip size package enabling round-scanning LIDAR was developed. The device was able to meet the requirements for +/-15-degree scanning angle (30-degree optical) with a low AC drive voltage of ~2 V_{pp}. The piezo actuators were monolithically integrated on the mirror springs, requiring no additional area nor external actuation mechanisms.

Challenges to be addressed in further work are static and dynamic deformation of the mirror.

The capabilities of the presented piezo MEMS mirror are not limited to the wobbling mode and circular geometry. One and two axis linear scanning and Lissajous-scanning can be realized as well, limiting to resonant operation.

Acknolewdgement

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