MONOLITHIC INTEGRATION OF MOEMS ON CMOS BACKPLANES USING SURFACE MICROMACHINING TECHNIQUES

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***Abstract* — A new generation of spatial light modulators (SLM) is being developed based on SiO2 sacrificial layer technology and multilevel actuator designs. In this paper, we will present general requirements of monolithic integration of MOEMS structures on CMOS backplanes, advantages of used SiO2 sacrificial layer process and new structural MEMS material used to achieve long-term stable operation of high reflective mirrors.**

This sophisticated micromachining technology will be demonstrated presenting actual spatial light modulator developments and key parameters of these devices.

***Keywords :* MOEMS, monolithic integration, micro mirror array, spatial light modulator**

I - Introduction

As a kind of optical MEMS (micro electro mechanical systems also called MOEMS) spatial light modulators (SLM) are based on arrays of individually deflectable micro-mirrors. Depending on their field of application mirror deflection can be realized as torsional, piston type or a combination of both. Such SLM are used as high speed pattern generators in DUV lithography, for mask inspection, for wave front correction in adaptive optics, structured illumination and for projection systems. Using a CMOS compatible surface micromachining process micro-mirror arrays are fabricated on customized CMOS backplanes with various mirror sizes that can be as low as 8µm. The underlying ASIC supplies each mirrors with one or more individual voltages that are needed for the mirror actuation. Drift free mirror deflection and a superior mirror planarity are major challenges for these optical MEMS devices.

Corresponding to their application micro-mirror's deflection range varies from a few nanometers up several micrometers. Furthermore an analog deflection scheme is often essential for many applications. Actuation principle is based on attraction forces between two plates of an air gap capacitor where one movable plate is supported by a micromachined spring structure to provide the restoring force. Figure 1 illustrates this principle showing a layout of tilt micro-mirror that is intended for torsional movement only. If a voltage is applied between mirror and one of the driving electrodes then the mirror will tilt around the springs towards that driving electrode.

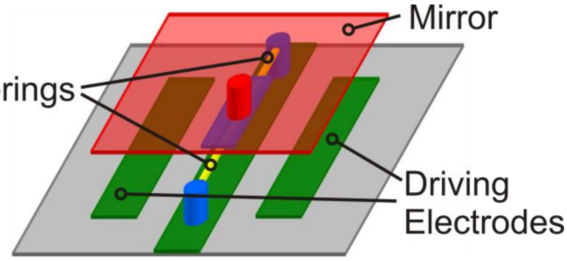

Figure 1: Sketch of a tilt micro-mirror

As a simple example the deflection characteristics of a linear suspended piston type MEMS drive will be derived. The corresponding simplified schematic is shown in Figure 2.

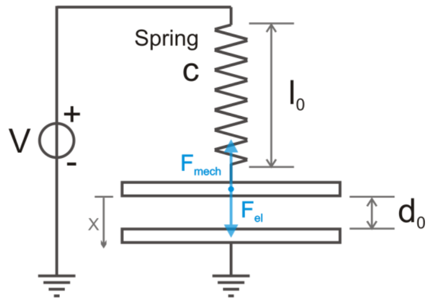

Figure 2: Schematic drawing of a simple parallel plate MEMS actuator

The force that is generated by the electric field inside the air gap is given by equation (1) where A is the capacitor area, d the distance between the two plates and V the applied voltage respectively.

$$F_{el} = \frac{1}{2}\varepsilon_0 A\left(\frac{V}{d}\right)^2 \;\; with \;\; d = d_0 - \Delta x \;\; (1)$$

One of the capacitor plates is movable and suspended by a spring. This spring provides a restoring force if that plate is dislocated by Δx from its zero position given at a capacitor plate distance d_0. This mechanical force is given by equation (2) where c is the spring constant.

$$F_{mech} = c\Delta x \;\; (2)$$

If equation (1) and (2) are combined and solved for the driving voltage V, deflection characteristics is given by equation (3).

$$V = \sqrt{\frac{2c\Delta x}{\varepsilon_0 A}}\,(d_0 - \Delta x) \qquad (3)$$

Looking at the normalized deflection characteristics plotted in Figure 3, it can be seen that the equilibrium of electrical and mechanical force becomes unstable if the plate is moved by more than 1/3 of the zero position plate distance d_0. This is the so called pull-in point that is caused by the strong nonlinearity of the electrostatic force in dependency of the plate distance d given by equation (1). Once this point is exceeded the electrostatic force grows faster than the mechanical restoring force of the spring resulting in an immediate touchdown of the movable plate.

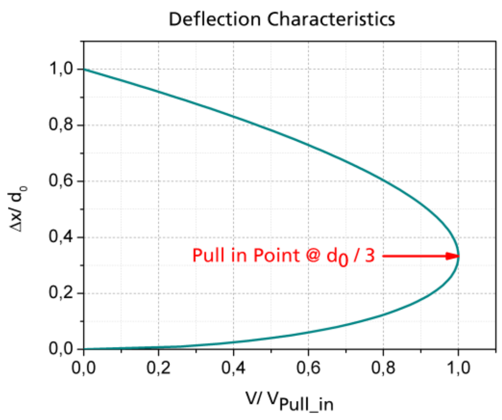

Figure 3: normalized deflection characteristics of a parallel plate actuator with a linear spring

Other types of actuator movement like tilt or a combined tilt piston movement are possible by an appropriate design of the restoring springs and an asymmetrical spring placement with respect to the air gap capacitor.

II – Surface Micromachining Process

Spatial light modulators (SLM) may contain up to millions of individually deflectable mirrors. Figure 4 shows basic schematics of such a SLM device.

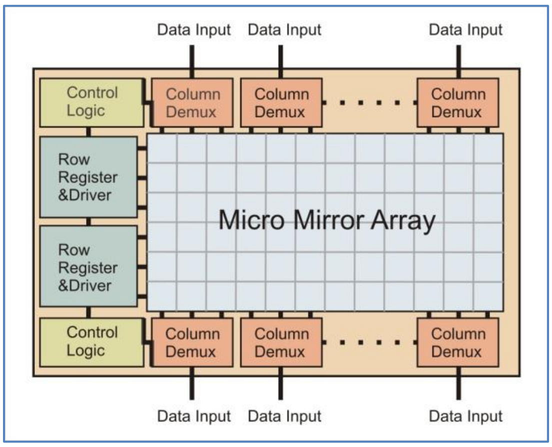

Figure 4: Schematic drawing of SLM chip

The high level of integration that is needed to manufacture these devices is achieved by the monolithic integration of MOEMS with a high voltage CMOS backplane. To supply every single mirror with one or more individual voltage the mirror array is driven by a circuit that is similar to a DRAM capable of storing analog voltages. The micro-mirrors translate the analog voltages that are stored in simple DRAM cells underneath the mirrors into an analog deflection state.
A schematic cross section of an entire micro-mirror cell is drawn in Figure 5. The CMOS backplane is a robust LOCOS poly silicon gate process with up to three metal layers that can supply the micro-mirrors with voltages up to 35 volts.

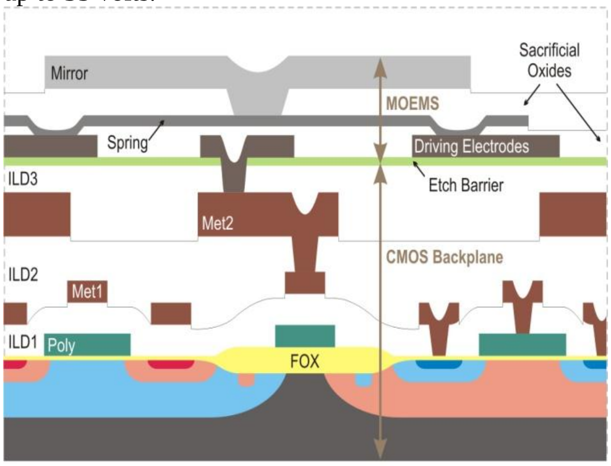

Figure 5: *Schematic cross section of a IPMS MOEMS structure on a CMOS backplane*

One key element of surface micromachining processes is the sacrificial layer process. These sacrificial layers are defining the air gaps necessary for the movement of the MEMS structures and fixing all fragile MOEMS structures, i.e. springs, stoppers and mirrors throughout wafer processing. As one of the last process steps the sacrificial layers are removed by an isotropic etch in order to create a free moving structure.

The IPMS MOEMS process uses PECVD SiO_2 as sacrificial layer material that is finally removed by a gas phase hydrogen fluoride etch [1]. Using SiO_2 has the advantage that standard CMP processes from BEOL with low defect levels and excellent planarization results can be used to smooth out the sacrificial layers. It is essential for micro-mirror arrays to include several CMP steps throughout the CMOS and MOEMS processing in order to maintain the high surface quality, especially surface planarity needed for optical systems. A minor drawback of SiO_2 sacrificial layers is the need for a separate etch barrier to protect the underlying SiO2 based ILDs during the release etch. Since the etch barrier layer needs to be a dielectric that is chemically inert to the hydrogen fluoride gas phase etch Al_2O_3 was chosen over a few other materials [2], [3].

The second important component for such MOEMS structures is the choice of materials to create structural elements. As different MEMS layers serve different purposes the materials must be chosen with respect to their function (Young's modulus, creep, and reflectivity) to ensure a stable and outstanding MEMS performance. Therefore a multi-level MOEMS process is used where each level is representing a different function by using an appropriate material. Typically MOEMS setup contains up to three structural layers.

For a precise analog operation the spring layer needs to be perfectly elastic to avoid instabilities caused by material creep. Therefore an amorphous TiAl alloy is used as spring material [4]. The example depicted in Figure 6 shows a tilt mirror with a TiAl spring that has been continuously deflected for 30 min by approx. 80 nm. For a target deflection of 78 nm measured drift was less than 2nm per hour (2%).

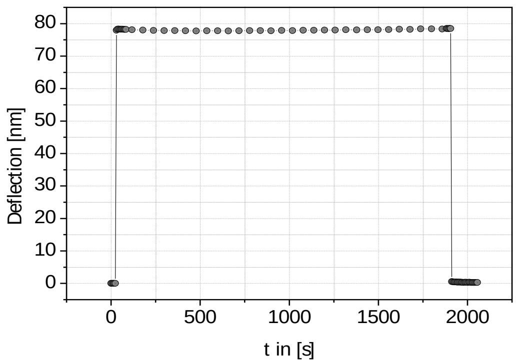

Figure 6: *Long term static deflection of a tilt micro mirror*

This multilevel setup allows the usage of a different material as mirror layer. Aluminum based alloys are CMOS compatible, providing good planarity and high reflectivity over a wide wavelength range. For applications where higher reflectivity is necessary dielectric layers can be used in addition [5]. A white light interferometer height profile of 4 mirrors (pixel pitch is 16µm) based on aluminum alloys is shown in figure 7 and shows a superior planarity in nm range.

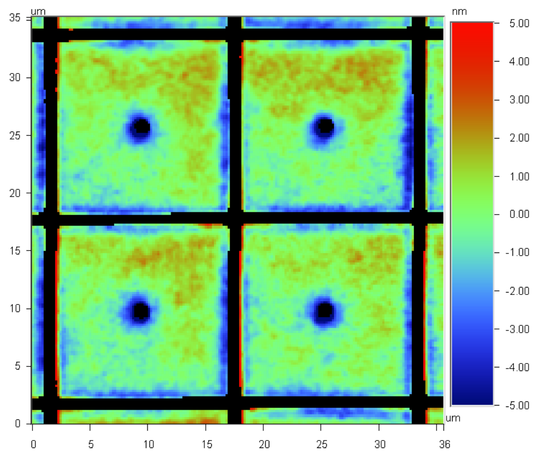

Figure 7: *WLI height profile of 4 micro-mirrors*

The overall thermal budget of the IPMS MOEMS process on CMOS backplanes stays well below 440°C to avoid any damage of the CMOS interconnects.

III – Application Examples

A. 1 Megapixel SLM

One application of micro-mirror arrays is the use as pattern generator in DUV excimer laser based micro lithography systems like mask writers [6]. The 1 Megapixel SLM depicted in figure 8 contains 2048 x 512 individually deflectable tilt mirrors. Such a high count of mirrors is needed to maximize the throughput. The 1 MegaPixel SLM has an image frame rate of 2 kHz resulting in a writing speed of 2 GPixels/s.

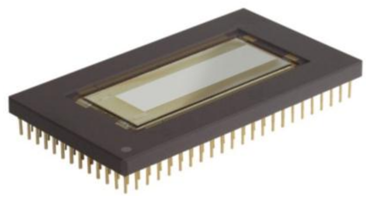

Figure 8: *1 MPixel SLM chip*

The imaging principle is based on Fourier optics and spatial filtering. It enables a sub-grid addressing by the true gray scaling feature of these analog SLM devices [7]. The operation wavelength is 248nm. Not deflected mirrors will result in white pixels and black pixels are created if the mirrors are tilted by 62nm. The micromirrors of the 1 Megapixel SLM have a size of 16 µm x 16 µm.

Figure 9 shows a SEM image of the two-level tilt mirrors consisting of an Al based mirror plate and torsional TiAl springs that are hidden underneath the mirror (mirrors are removed in lower part of this picture).

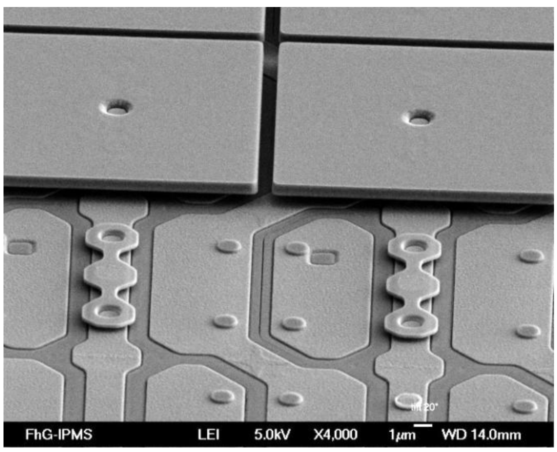

Figure 9: *SEM image of micro mirrors on the 1MPixel SLM*

B. 64kPixel MMA

A more versatile SLM device capable of operating at wavelengths from 240- 800 nm is shown in figure 10. The operation at higher wavelength requires a larger deflection of its tilt mirrors to achieve reasonable contrast values [8]. The SLM chip has an image frame rate of 1 kHz and contains 256 x 256 individually deflectable mirrors with a size of 16 µm x 16 µm.

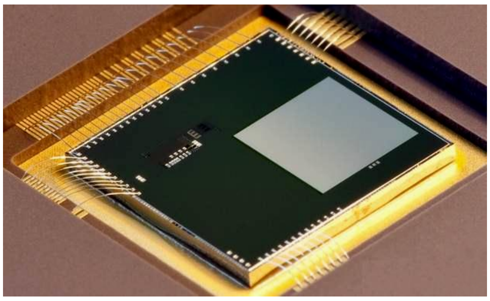

Figure 10: *64k Pixel MMA Chip*

Air gap height (d_0) needs to be increased for larger deflections according to the pull-in criterion. On the other hand the electrostatic force is decreased if the air gap is made larger. To counteract the weaker electrostatic drive the spring must be made very soft. Micromirrors with very soft TiAl springs for an extended range of deflection are fabricated using a three-level MOEMS process [8] with an additional reinforcement layer. The cross section in figure 11 is showing the vertical construction of a three-level micro mirror setup. Compared to a typical two-level actuator an additional hinge reinforcement layer is essential to maintain the entire structure (i.e. posts) due to very thin hinge layers (down to 70 nm).

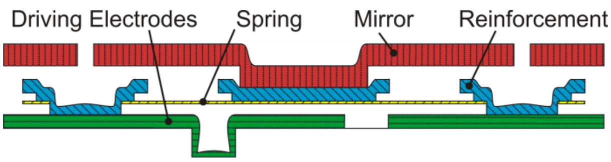

Figure 11: *Schematic cross section of 3- level actuator*

A SEM image of SLM chip which was fabricated using a three-level actuator process is shown in figure 12.

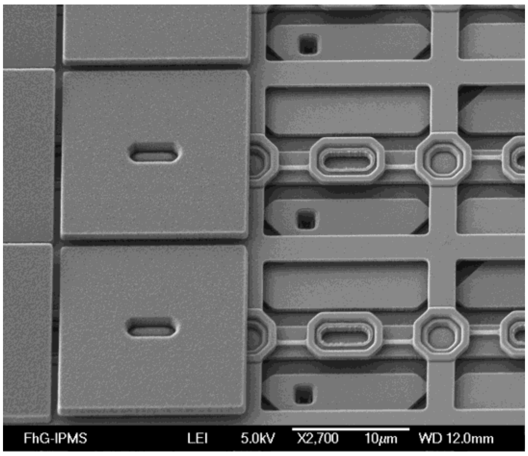

Figure 12: *Mirror and hinge structure in of a 64k Pixel SLM chip*

IV - Conclusions

A new process of monolithic integration of MOEMS structure using micromachining was successfully developed. One feature of this micromachining process is the SiO2 sacrificial layer technology to achieve defect free oxide layers with sophisticated surface planarity using standard CMP processes. Through a separation of hinge and mirror levels and in this sense also the material it is now possible to optimize layers properties independently. A three-level actuator design allows a complete tuning of deflection characteristics which lead to new applications for SLM devices.

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