SUCCESSFUL FABRICATION OF POLYMER BASED LOW VOLTAGE ELECTROSTATIC ACTUATORS

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Abstract — In this work we present the successful fabrication of a polymer based zipper actuator to achieve a high stroke electrostatic actuation. The whole process is completely wafer level compatible and allows the integration of optical elements, e.g. mirrors or microlenses, without further assembly steps. Instead of the commonly used silicon \cite{1} we use the UV-curable OrmoComp to build the actuator. OrmoComp has a significantly lower elastic modulus (about 1 GPa), only a fraction of actuation voltage is necessary for a similar deflection. The major drawbacks of the polymer based approach are a challenging fabrication process, which is described in this paper, and, due to the stiffness, a low resonance frequency. All process steps are realized as a lithographic structuring of positive tone, respectively negative tone resists, allowing the full wafer level fabrication of polymer based electrostatic actuators. A specific development process makes it possible to induce stress in the OrmoComp layer, creating an out-of-plane actuator based on common two dimensional lithography process steps. We present the results on the first completely wafer level fabricated zipper actuator, creating an out-of-plane motion up to 470 \(\mu\text{m}\) at an actuation voltage of 374 V.

Keywords: Actuator, electrostatic, polymer, zipper actuator, wafer level, OrmoComp, lithography, optics

I - Introduction

Actuator technology for micro-electromechanical systems (MEMS) is an extensive field with a lot of variety in the utilized physical principles and fabrication technologies. Both differ significantly from the macroscopic equivalents. The main reason for that is, for one, a completely different approach in the fabrication technology and on the other hand the scaling laws for physical effects.

The electrostatic principle is based on the Coulomb attraction between two different point charges. Therefore electrostatic actuation is a surface effect and because of that independent of the volume. The resulting forces increase with decreasing gap size between the electrodes. Electrostatic actuation is a preferred principle in MEMS because of the compliance to the required miniaturization \cite{2}.

The fabrication becomes more challenging when aiming for an increased miniaturization because smaller parts need to be assembled with a higher absolute accuracy to maintain the relative accuracy at the target feature size. The intention of the presented work is a fabrication without a piecewise assembly of the components which can be achieved by a wafer level based fabrication approach.

Electrostatic actuators are often based on silicon providing a high resonance frequency due to their stiffness and the inherent conducting capabilities, both are necessary in high frequency tip-tilt mirrors \cite{3}. As a drawback the fabrication is limiting the design to two dimensional structures for the individual layers.

UV-curable polymers on the other hand are soft and non-conducting. They can be imprinted, thus allowing the realization of complex three dimensional freeforms \cite{4}. With the high transparency such polymers are a worthwhile material for MEMS and micro-opto-electromechanical systems (MOEMS).

In this paper we describe a sample design to build a high stroke electrostatic actuator which can be used to position e.g. microlenses or –mirrors. Utilizing the synergies between the material, the fabrication process and the actuation principle it is possible to lift one of the most typical MEMS actuator principles in a microactuator suitable mm scale, opening a whole new field of applications and varieties for electrostatic actuators.

II - Design and Principle

The zipper actuator is designed as a system of two electrodes, one at the bottom of a curved and flexible cantilever beam (OrmoComp in this case), the second planar and rigid on a substrate. In the ideal case there is no gap, only the electrical insulator between the electrodes at the clamped end. Due to the fabrication process and the sacrificial layer to create a free standing beam, a minor gap up to 14 \(\mu\text{m}\) is necessary. When a potential difference is applied, the resulting large force in this area pulls the flexible electrode towards the rigid. The region with the small gap moves along the electrode (see Figure 1), combining a large stroke and a large force in a single electrostatic actuator. Depending on the overall design of the actuator and the restoring force it is relatively easy, in contrast to classic electrostatic gap-closing actuators, to achieve a stable behavior over the whole displacement.
The design (see Figure 2) is based on the idea to position a microlens or a mirror in a microoptical system, suitable for wafer level fabrication and low voltage applications. Each beam acts as the above explained zipper actuator, the circle in the middle is the area for a possible microlens or mirror. Those parts are connected by smaller arms which act as spring elements to provide a restoring force.

The individual values are listed in Figure 3. Actuator A and B are based on the same design but fabricated with different heights for the individual layers.

### III - Fabrication Process

Conventional UV-lithography is used for the fabrication process, performed on a 4” borofloat glass wafer as substrate. Negative tone hybrid polymer OrmoComp is used for the main parts of the actuator and SiO2 for insulation (2 µm thickness). The sacrificial layers, creating a free standing beam and structuring the functional layers, are made of different positive tone photoresists. Electrodes are sputtered metallization films with a thickness of 150 nm structured via etching or lift-off. The entire fabrication process is explained step by step in Figure 4.

1. Thin film metallization (150 nm Ti) on a 4” glass substrate, structured with an etching or lift-off process.
2. Disposal of 2 µm SiO2 as insulator.
3. Spin coating of a positive photoresist A as sacrificial layer with a thickness of 7 to 14 µm, depending on probe and target design.
4. Development of the sacrificial layer after UV exposure through a photomask.
5. Uniform metallization of the whole substrate with 150 nm Ti.
6. Spin coating of a positive photoresist B as mask for etching process.
7. UV exposure and development of the second positive Tone resist layer. Then etching the underlying Ti layer with the structured second positive tone resist layer.
8. Removal of the last layer of photoresist B
9. Dispensing and imprinting OrmoComp with various thicknesses between different samples.
10. UV exposure through a photomask to structure the OrmoComp. Creating parts with a smaller lateral dimension working as soft links respectively springs.
11. Specific development process, inducing intrinsic stress in the OrmoComp layer. The magnitude of the stress also depends on the exposure time.
12. Removal of the uncured OrmoComp and the whole sacrificial layer of photoresist A to create a free standing cantilever beam. Intrinsic stresses bending the beam upward, creating the out-of-plane zipper actuator.

It is notable that all metallization layers were structured without a mechanical deposition shadowmask. Instead a lift-off respectively an etching process based on conventional UV-lithography was used. This makes it possible to use the positioning and feature size accuracy and resolution of the lithography photomasks. Additionally, and quite important for complex actuator designs, it is possible to mask isolated areas without the necessity of supporting bars.

The result of the whole process is shown in Figure 5, a small upward bending of the beam is visible. Figure 6 shows an example of several actuators with increasing intrinsic stresses, resulting in a higher upward bending and therefore a higher stroke when actuated.

IV - Results

The deflection-voltage dependency was measured using a laser displacement sensor at the centre of the circle. The electrostatic force developed between the electrodes above 500 V at pull-in exceeds the adhesive strength of the metallization, damaging the upper electrode. Therefore a maximum voltage of 450 V was applied. For all measurements we used an identical voltage regime: In 4.5 V steps with a 500 ms interval between each other the voltage is ramped up to 450 V and back down to zero. This ramp is repeated four times with different top voltages (112.5 V, 225 V, 337.5 V, 450 V).

We present the deflection results for two actuators of the same design with different geometry values (see Figure 3 for details). In Figure 8 the complete deflection behaviour for the whole regime of actuator A is shown.

![Figure 5: One of the fabricated zipper actuators, a small upward bending of the beam is visible.](image)

![Figure 6: Example of actuators with increasing intrinsic stresses to alter the upward bending of the beam.](image)

![Figure 7: Measured deflection of the actuator variant A, a maximum deflection of 75 µm at 450 V is achieved.](image)

The deflection curve measured for an applied voltage of up to 450 V for actuator A is shown in Figure 7. A deflection of 75 µm was achieved. Up to this point no instability, which is typical for electrostatic actuators, occurs. A small hysteresis in the magnitude of 20 V can still be observed.
The deflection of the whole voltage regime for actuator A is shown in Figure 8. A repeated ramping of the voltage only has a diminishing effect on subsequent actuations. If no pull-in effect occurs no residual charges, stresses or deformations remain.

Actuator B shows a distinctive pull-in effect at 374 V, resulting in the maximum deflection of 470 µm. In this case the restoring force is not sufficient to cause a lift-off from the insulator when reducing the applied voltage. With a 200 µm smaller bending height the pull-in voltage of actuator B is lower than the pull-in voltage of actuator A, even with an increased beam thickness of 83 µm instead of 52 µm.

V - Conclusion and Outlook

A successful realization of polymer based electrostatic actuators on wafer level could be achieved. The design of the actuators allows the implementation of microlenses or mirrors.

The structuring of the metallization layers was completely based on lithography photomasks, no mechanical shadowmask was used. This leads to an increased accuracy of the alignment of the layers and the lateral resolution within the layers.

One of the presented actuators shows a stable deflection with a discreet voltage-deflection dependency up to 75 µm at 450 V. The actuator with the bistable pull-in effect achieved a deflection of 470 µm at only 374 V, although the restoring force of the spring element is too weak for a lift-off and will be increased in future design iterations.

In comparison to a past publication [5] we could obtain a continuous metallization with good adhesion and developed a process to manipulate the intrinsic stresses in the UV-cured polymer. We could increase the deflection about 420 µm while decreasing the voltage about 125 V.

Future works on this whole topic will be concentrated on the better understanding of the manipulation of the intrinsic stresses in the polymer and the general reduction of the necessary voltage and overall size, respectively increasing the possible deflection. This can be achieved by improving the geometry of the actuator and reducing thickness of the different layers, especially of the sacrificial layer and with it the initial gap between the electrodes.

The geometry greatly affects the pull-in behavior of an electrostatic actuator, we are confident to be able to push the pull-in effect to higher voltages or even completely avoiding it with the appropriate customized actuator design.

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References