MEMS SPATIAL LIGHT MODULATOR FOR OPTICAL MASKLESS LITHOGRAPHY

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ABSTRACT

128x512 arrays of electrostatically actuated piston micromirrors with 3 μm and 5 μm individual pixels and 90% optical fill factor are realized using a polysilicon surface micromachining process with 5 structural layers and 130nm minimum features. To modulate Deep Ultraviolet (DUV) radiation for Optical Maskless Lithography application, continuously controlled vertical motion of 80nm is achieved at less than 4V. The micromirror response time is less than 10 microseconds. A wiring layer is used to actuate subarrays of up to 128x128 mirrors at the same time in linear gratings, checkerboards and other patterns.

INTRODUCTION

One of the critical technical barriers in the area of Optical Maskless Lithography (OML) for IC fabrication[1,2] is development and implementation of the appropriate beam modulation technology. A MEMS Spatial Light Modulator (SLM) can provide a solution for this challenge, and enable systems to achieve sub 50nm critical dimensions (CD) with throughput of at least one 300mm wafer level per hour.

MEMS SLMs for OML with larger, tilt pixels (16 μm x 16 μm) and up to 1M-pixel size have been previously developed[2] and have found successful commercial application in mask writing. Such devices are built out of Aluminum on top of electronic circuitry supplying ~25V drive signals. However, SLMs with pixels smaller than 5 μm are needed to build the next generation maskless lithography tools capable of 50nm CD[3]. High frame rates (10kHz) and pixel counts (10 Million pixels) are needed to achieve high throughput. Compared to tilt micromirrors, piston micromirrors are easier to reduce in size while maintaining low actuation voltage, and piston-type SLM provides additional capabilities for OML, such as strong phase shifting[4]. Pixels characteristics need to be stable over long times, many cycles of operation and under exposure to UV light. Polysilicon often provides better mechanical performance and stability compared to Aluminum, which may be subject to creep and fatigue. We have built and tested a standalone polysilicon MEMS

technology building block, demonstrating performance consistent with these application requirements and scalable to very large pixel counts.

To achieve large pixel counts, electronic drive circuits have to be provided for each mirror. Low voltage operation is absolutely critical, since we have to use high density, low voltage CMOS drivers to fit within the extremely small footprint of our pixels. While the ultimate goal is to hybridly integrate the polysilicon MEMS with drive electronics to address each mirror individually(to be reported elsewhere), to test the MEMS technology we have incorporated a wiring layer to deliver the electrical drive signal without integrated drivers. We have pre-wired our micromirrors and tested them in lines, gratings, checkerboards and other patterns actuated by only a few distinct signals with up to 8192 mirrors connected in parallel to a single wire.

FIGURE 1. Conceptual drawing of the MEMS mirror array and the single mirror. Yellow – reflector, gray – spring, green – movable electrode, blue – fixed electrode and ground.

MICROMIRROR ARRAY DESIGN

Figure 1 shows a conceptual drawing of our MEMS array. Each pixel is actuated electrostatically by applying voltage to a lower fixed electrode, with ground lines in between pixels. The mirror is supported at its center by an elastic, doubly-clamped spring. This spring provides the mechanical restoring force as well as the electrical contact to the ground lines. Even for springs as thin as 100nm, their length has to span over several pixels to provide the required compliance for low voltage operation. Each spring is electrically and mechanically connected to an upper electrode underneath it, which maximizes the force achieved by the actuator by bringing the electrodes closer and increasing the area. It also shields the spring from the electric fields of neighboring electrodes by completely surrounding them with structures at the ground potential. Springs of neighboring pixels are interdigitated in between the upper electrodes and the

mirrors; by design there is enough room for the required vertical motion without any of the parts coming in contact. With this approach we achieve the compliant structure needed for very small mirrors without resorting to extremely thin layers or very soft, unconventional materials. Not shown, under the fixed electrodes, a polysilicon wiring layer insulated by the silicon nitride dielectric is used to bring the electrical signals to the lower electrodes from the probe pads on the periphery of the array.

To build the MEMS mirrors we use a fabrication process with 3 moving and 2 fixed polysilicon structural layers and 3 sacrificial Silicon dioxide layers. Layer thicknesses are 100 to 500nm for structural layers, and 400 to 700nm for sacrificial layers. Each layer is patterned using a 193nm scanner, achieving CDs of less than 130nm and interlayer alignment better than 50nm. The reflectors are planarized by chemical mechanical polishing (CMP) to produce a smooth, flat top surface. The structures are then freed by etching the sacrificial material (wet etch in 49% HF), and dried using a supercritical point CO₂ dryer. Coating the top surface of the mirrors with 300Å Aluminum reflective layer completes the device (Figure 2).

FIGURE 2. Scanning electron micrograph of the (A) 3 μm pitch and (B) 5 μm pitch MEMS mirrors in arrays. One mirror is snapped down for illustration. The top surface is planarized by CMP and coated with evaporated Al for high reflectivity.

FIGURE 3. Undulating springs (top) reduce sensitivity to residual or induced stress, as illustrated by the FEA analysis (bottom). The pixel size is 5 μm and "n" is the undulation frequency.

The lateral undulations (“wiggle”) in the springs are designed to provide effective strain relief. In a linear elastic regime, the piston resonance frequency $f_{PISTON} \propto \sqrt{K}$, where K is the linear stiffness of the spring. Figure 3 shows finite element analysis of the f_{PISTON} as a function of the compressive residual stress for a case of a 5 μm mirror with different spring undulations. The springs, 300nm wide, 100nm thick, 20 μm long, are clamped at both ends, with the mirror attached in the middle. For straight beams ($\delta = 0$) the frequency shows a strong stress dependence and the buckling instability appears at $\sigma = 23\text{MPa}$ as evident by the frequency going to 0. As the in-plane undulation δ is increased, the effect of the residual stress is reduced and the buckling instability is pushed to larger stress values. For $\delta > w$ the number of periods n of the undulation within the spring length does not significantly affect the stress dependence of the frequency.

Using the same mask set, three lots with different layer thicknesses were fabricated – the spring thickness t and the electrode gap g were (t, g) : (100nm, 460nm), (180nm, 690nm), and (110nm, 420nm). Each lot contained 36 design variations, 18 each for 3 μm and 5 μm pitch. The spring length for 3 μm mirrors varied from 12 to 30 μm , the spring length for 5 μm mirrors varied from 20 to 50 μm . Nominal spring widths were between 130nm and 460nm. Only small variations of the spring width for each particular length were made, since each spring footprint has to be equal to the mirror area. The longest springs were the narrowest. Other layout variables, such as spring undulation and mirror fill factor, were generally found not to have any significant effect.

All devices were successfully released and dried with all mirrors intact. The deliberate almost 3-decade variation of spring stiffness had a profound effect on actuation voltage and initial mirror height variation, as described below. In particular, the devices in the lowest decade typically showed signs of lateral stiction or had too much height variation after the release to be useful. On the remaining devices we have observed high moving mirror yields with few stuck mirrors, as verified by actuating subarrays of up to 128x128 mirrors. For the devices on the stiff end on the spring design, less than 10 visibly bad mirrors out of 65,000 were typical.

MICROMIRROR ARRAY PERFORMANCE

The piston motion induced by applying a voltage to the lower electrodes was measured by a Wyco NT3300 optical profiler operating in phase shifting

FIGURE 4. Piston motion as a function of applied voltage. Lower inset shows an optical profile of a pattern with 32 actuated mirrors. Top inset shows the fitting residual errors.

interferometry mode, producing height profiles such as shown in the inset in Figure 4. In this case, a device designated A2 with 21 μm long, 110nm thick and 150nm wide springs was activated at 3.9 V. The pre-wired pattern was a group of 32 mirrors that form an 8 mirror by 8 mirror alternating line and space array. After baseline removal, vertical position data is extracted from the center of each mirror for a series of voltages. The current at each applied voltage was much less than 1 nA, indicating that essentially no voltage drop should occur except at the electrodes themselves.

To calibrate the mirrors, each position (z) versus voltage (V) data set is fit by a non-linear least squares method to the equation:

$$V = \sqrt{\frac{-z_0 K - z g^2}{K}}$$

where K is a constant that includes the spring stiffness, g is the initial electrode-electrode gap, and z_0 is the measured mirror piston position at 0 V. The parameters K and g are allowed to vary for each mirror. This equation is based on a simple 1-dimensional spring and an idealized parallel plate capacitor models, yet it fits the trends remarkably well; Figure 4 shows a plot of the measured piston motion versus voltage for 10 mirrors from the device A2 and curves representing the data fit. The second inset in Figure 4 is a plot of the difference between the data and the fit position versus piston position for over 300 points taken from device A2. For the majority of data, the difference is less than 1 nm. We went up and down in voltage several times, taking separate measurements, thus low residuals demonstrate high accuracy and repeatability of the mirror motion.

FIGURE 5. Initial mirror position variation as a function of design spring stiffness. Results from $3\mu\text{m}$ and $5\mu\text{m}$ mirror pitch designs from 78 die across three lots shown. The line for visual reference shows a square-root relationship. The inset shows an example of optical profiler data.

As evident from the Figure 4, a significant variation in mirror positions exists, affecting their calibration curves and reducing the overall dynamic range of the SLM. This 0V spread was found to have a near-normal distribution for the majority of the devices, except the ones with stuck mirrors. It can be characterized by a single number, the RMS position variation, and was found to vary systematically with the nominal design spring stiffness, Figure 5. Further study is under way to understand and reduce the variation.

Although no detailed quantitative analysis has yet been performed, the piston range and actuation voltage scaled qualitatively in an expected way across multiple designs. The piston range was roughly proportional to the electrode gap, and the voltage increased with both the gap and the spring stiffness, resulting in a large variation, from less than 1V to over 60V, as expected.

In order to study the dynamic response, 405nm laser light was projected onto SLM devices that were actuated with a square wave voltage source. These devices were pre-wired so that 64 alternating rows, each with 128 mirrors moved with the voltage source. The resulting diffraction pattern consisted of a square array of spots with additional spots that formed only when the alternating mirror pattern was activated. A fast Si photodetector was placed in the beam path of such a modulated first diffraction order spot and the photocurrent was recorded. Figure 6 shows the dynamic response of the same A2 mirror devices. The 0-95% ON time, measured at the applied voltage step up from 0 to 3.0 V is less than $10\mu\text{s}$, and the 100-5%

FIGURE 6. Dynamic response. “Off” time $2\mu\text{s}$ (upper panel), “On” time $10\mu\text{s}$ (lower panel).

OFF time, is even shorter at about $2\mu\text{s}$. The experiment was performed in air at atmospheric pressure and room temperature. Small oscillations of the curve suggest the piston mode resonance frequency around 300KHz.

CONCLUSION

We have built and tested a standalone polysilicon MEMS technology building block consistent with OML requirements: arrays of 128×512 pixels with 3 and $5\mu\text{m}$ pitch, 90% optical fill factor, Al coating for high reflectivity, accurate and repeatable 80nm stroke at 4V applied voltage, acceptable uniformity, response time of $10\mu\text{s}$. Our fabrication process is based on optical lithography and we can scale up to a 10M-pixel array within the tool capability. Future work will focus on improving uniformity and producing a device suitable for hybrid integration with IC drivers. More broadly, while smaller, individual MEMS devices have been built using E-beam lithography, this work demonstrates order-of-magnitude improvement in density for large arrays of multi-layer devices enabled by high-resolution optical lithography.

ACKNOWLEDGEMENTS

This material is based upon work supported by DARPA under SSC SAN DIEGO Contract No. N66001-04-C-8028

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