MONOLITHIC SILICON MICROMIRRORS WITH LARGE SCANNING ANGLE

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SUMMARY

We report on an implementation of laterally electrostatically actuated, torsionally suspended silicon-on-insulator (SOI) micromirrors with static scanning deflection of over 40° peak-to-peak optical angle. This, 5X increase from previously reported results for these types of devices is due to improved fabrication methodology as well as improved MEMS design, which are both described in this abstract. The micromirror structures are fully monolithic, micromachined from the front-side and back-side of an SOI wafer device layer, thereby theoretically providing utmost reliability and repeatability of operation. In-plane actuation is transformed into out-of-plane motion and rotation, enabling monolithic integration of a wide variety of SOI-MEMS sensors, actuators and micromirrors.

INTRODUCTION

A major obstacle in SOI MEMS is the lack of out-of-plane motion (including rotation) which would enable a variety of optical MEMS and other applications. We have previously reported on initial results and the basic methodology for achieving out-of-plane motion from lateral actuation [1]. In that work, we utilized lateral actuators and beams at different levels to produce torque on torsionally supported SOI micromirrors. Maximum static deflections of ~9° peak-to-peak optical angle were achieved. The methodology is very promising for many applications, as high aspect-ratio lateral actuators and position sensors can be combined with 2-axis rotation in the plane of the wafer in a relatively simple fabrication process. The design of the mirror is then be decoupled from the design and choice of the actuators.

The basic concept of lateral actuation is depicted in Fig. 1a. By applying a lateral pushing or pulling force in plane of the SOI wafer, the actuating arms apply load below the neutral axis of rotation of the mirror torsional suspensions. This results in torque/rotation, as well as some lateral displacement of the mirror. Such a structure can be designed in a variety of ways, e.g. utilizing *lowSCS* (low-level Single Crystal Silicon) beams as torsional suspensions, and *upperSCS* beams as actuating arms (as in Fig. 2c), actuating on a single suspension only, etc. We have experimented and report on a variety of designs, design improvements, and a new beam structure which decreases lateral movement while enabling rotation. Similarly, the micromirror itself can be either full device-layer thickness (Fig. 2b, 50 μm), or simply the 10 μm *upperSCS* layer (Fig. 2c) for ~2-3 times faster performance.

FABRICATION

Implementing the concept described above requires the capability of fabricating Si beams at different vertical levels in an SOI wafer. The basic methodology for creating Multilevel beam SOI MEMS is depicted in Fig. 1b. Namely, combination of front-side and back-side timed multilevel etches [2] of the same slab of single crystal Si results in Si beams at different vertical levels. The schematic in Fig. 1b gives an example where 3 masks are used. Two masks from front-side allow for 2 depths of etching, labeled in the arrows of Fig. 1b as “1” and “2,” through the full thickness, and to the lowSCS beam respectively. The 1 mask from the back-side allows etching up to upperSCS beam. The micromirrors demonstrated to date and reported in this work only utilize all 3 beams, i.e. *upperSCS*, *lowSCS* and *highSCS*, and only require 3 masks for beam fabrication + 1 one mask for removing handle wafer Si from backside of the shown device layer. Details of fabrication process were given previously [1]. The concept is easily extended by adding masks on front-side and back-side and fabricating beams at many more levels.

The sequential front- and back-side etching enables two distinct approaches at the fabrication with distinct advantages and disadvantages which will be discussed in detail: “front-side first” and “back-side first” approach. Such improvements in addition to the novel use of oxidation after etching to achieve smaller beam dimensions are responsible for significantly improved performance over previous structures [1].

IMPROVED DESIGN

Figure 2a shows a typical micromirror with *upperSCS* beams actuated in push-mode by *lowSCS* actuation arms. Actuation took place due to comb-drive charging (visible on the left) and the mirror is shown here at ~11° mechanical deflection (22° optical.) Previously, push-mode actuation achieved significant scanning angles (up to 8° optical), while pull-mode actuation rarely exceeded more than ~1° optical [1]. There are many reasons for this asymmetry, one of which is the significantly increased stiffness in actuating arms due to axial tension from pulling force, preventing actuating arm bending, and therefore rotation. There is also an effective decrease of torque radius with rotation which is highly detrimental. A design solution depicted in Fig. 2b resolves the problem and enables micromirrors to achieve equally significant scanning angles in pull-mode. Namely, the actuating arm can be attached to the torsional support beam at a point laterally displaced from the sheer axis of the torsion beam. The design with long displaced attachment of the actuating arm (340 μm forward from the axis), shown in Fig. 2b, provides for a significant increase of torque radius as the rotation, and therefore attachment lowering begins to take place.

While the full 40° peak-to-peak scanning angle can also be achieved by applying pull-mode actuators at both sides of the micromirror, in applications (such as 2DoF structures) where single side actuation is preferred (as depicted in Fig. 1a,) both push-mode and pull-mode are necessary for large peak-to-peak deflections. This solution has therefore solved this problem.

A novel torsional beam structure was also successfully tested, shown also in Fig. 2b. Namely, as mentioned before rotation is accompanied with lateral displacement of the mirror which can be detrimental in applications, but is also detrimental in actuator design, requiring more actuator stroke. The perforated beam shown in Fig. 2b has decreased lateral movement from typical 15-20 μm to about 5 μm, and still allows full 20° optical angle rotation.

NEW RESULTS

Several 1-axis micromirrors were successfully fabricated and tested, using both the “front-side first” and the “back-side first” approach. In all cases, mirrors were 700 μm in diameter,

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micromachined in n-type SOI wafers with device layer thickness of 50 μm, 2 μm of insulating oxide, and 300 μm thick handle wafers. In push mode, maximum deflection of +20.8º optical was demonstrated at 90V of actuation voltage. In pull mode, used to deflect the mirror in opposite direction, maximum deflection of –21.2º optical was demonstrated at 130V of actuation voltage. Mirrors have >1m radii of curvature, and <5nm surface roughness, though not coated with reflective metals. Most mirrors can be operated up to 2 kHz, while some were tested up to 4.6 kHz before resonating.

CONCLUSIONS

The combination of back- and front-side multilevel etches allows for a new genre of high aspect ratio MEMS with added degrees of freedom and added design freedom for MEMS designers. Most recent results shown here are very promising and verify the basic capabilities of this methodology.

[1] Milanovic, V., Last, M., Pister, KSJ, *Torsional Micromirrors with Lateral Actuators*, Transducers'01, Muenchen, Germany, Jun. 2001.
[2] Mita, Y.; Mita, M.; Tixier, A.; Gouy, J.-P.; Fujita, H. *Embedded-mask-methods for mm-scale multi-layer vertical/slanted Si structures*. Proceedings IEEE Thirteenth Annual International Conference on Micro Electro Mechanical Systems, Miyazaki, Japan, 23-27 Jan. 2000.

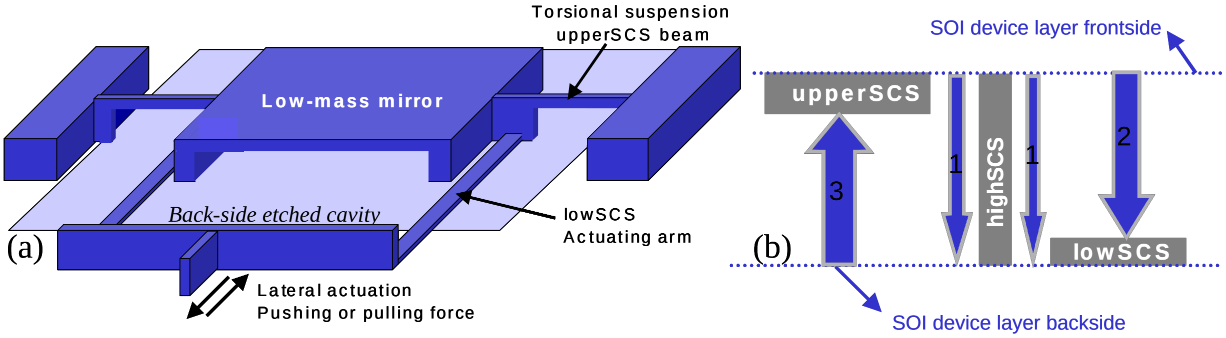

Figure 1. Schematic of Multilevel Beam SOI MEMS by front-side and back-side multilevel etching, which results in Si beams at different vertical levels providing out-of-plane capability for SOI MEMS. Conversion of in-plane actuation to rotation is achieved by multilevel deep reactive ion etching which allows application of force away from the mirror's axis of rotation.

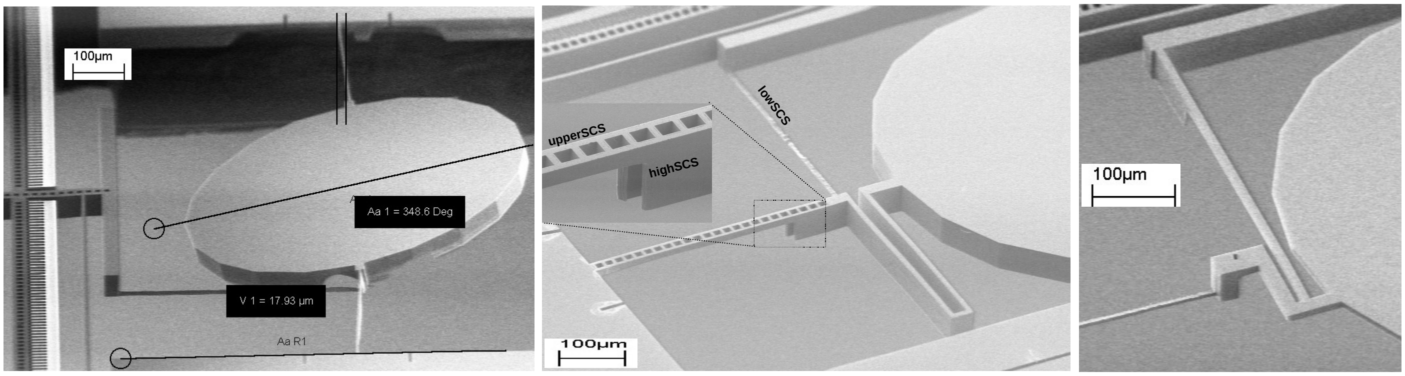

Figure 2. SEMs of SOI micromirrors: (a) Push-mode micromirror deflected 22° optical by comb-drive charging; actuation beams are connected to torsion beams on axis; (b) pull-mode structure, actuation arms are connected to torsion beams 340 µm forward from axis; (c) reversed beam utilization, lowSCS beam is used as torsional suport, and upperSCS as actuating arms and mirror itself.

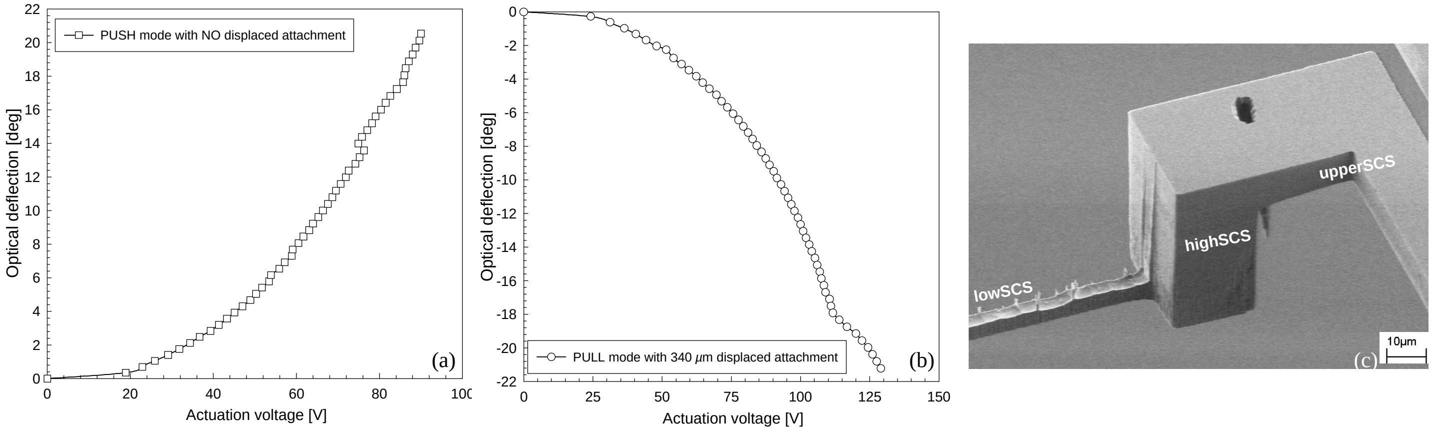

Figure 3. Measured static deflection of a single-axis micromirror both in (a) pushing mode, and in (b) pulling mode. Push-based actuation normally gives significantly more deflection but in this case the deflections are comparable because the pull-mode micromirror utilizes a 340 µm displaced attachment which significantly increases torque-radius on the torsion beams as the deflection increases.(c) Three types of beams utilized in design shown at higher magnification.

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