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MONOLITHIC VERTICAL COMBDRIVE ACTUATORS FOR ADAPTIVE OPTICS

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High aspect ratio vertical combdrive actuators are demonstrated which advance the capabilities and applications of SOI-MEMS by adding additional independent degrees of freedom of operation: both upward and downward vertical pistoning motion as well as bi-directional pure rotation. The methodology for the first time enables monolithic fabrication of isolated vertical combdrive sets in the SOI device layer, with combfinger self-alignment and pre-engagement (initial overlap.) This is demonstrated in a micromirror device shown in Fig. 1a, which exhibits four modes of actuation outlined in Fig. 1b: bi-directional static optical deflection from –20° to +19°, and independent bi-directional pistoning motion from –7.5 μm to +8.25 μm. Lowest resonant frequency of the device is 1491 Hz in tilting mode and 2619 Hz in pistoning mode.

Silicon on insulator (SOI) based MEMS have become increasingly interesting recently as a platform for a variety of optical applications [1]-[5]. A variety of methodologies are investigated to provide the needed additional degrees of freedom (DoF) to the basic SOI-MEMS in-plane motion. Particularly of interest is providing 1DoF and 2DoF rotation of micromirrors. There is also demand for micromirrors with independently controlled rotation and pistoning motion [6] for phased array applications and adaptive optics. We previously demonstrated laterally actuated micromirror structures with large static optical rotation of ±20° - achieved by fabricating vertically displaced beams [3]. However, to address the need for pure pistoning, as well as the combination of pistoning with rotation, our previous fabrication methodology required improvements.

Of interest was to add vertical combdrives. Vertically staggered SOI combdrives perform well for single-sided rotation applications [1]. Recently, that process was improved to provide self-alignment of upper and lower combfingers [4]. However, in previous processes, no isolation is available between combdrive fingers in either upper or lower sets, so one-sided rotation was demonstrated. The support beams are stiff full thickness device layer beams, also inadequate for pistoning. The upper and lower combfinger sets are separated by the thickness of insulating oxide, requiring biasing (pre-tilting) of devices which is undesirable [7]. Pre-engaged vertical combfingers were demonstrated recently [8], though in a process that includes metal alloys and eutectic bonding with difficult alignment of the combfingers.

Our 4-mask process alleviates these limitations: **1)** all combfingers are monolithically fabricated in the device layer allowing isolated independently powered vertical combdrive sets. This enables independent up- or down- pistoning and bi-directional rotation. **2)** comb-fingers are timed etched such that there is 10 μm of overlap allowing linear force operation from 0V. **3)** support beams can be of desired thickness, not confined to full thickness of device layer as in previous work - as demonstrated here in 30 μm *upper* beams (of a 50 μm thick device layer). **4)** comb-fingers are self-aligned by the same wafer-stepper mask. **5)** all electrodes are isolated in the device layer and easily routed to pads accessible from the wafer's top side.

The process is shown in Figs. 2 and 3, and described in detail elsewhere [9]. It requires selective, high aspect ratio multilevel etching of SOI wafers, using DRIE. The timed, multi-level DRIE from front and back of the device layer results in the various types of beams. The critical improvement in this methodology over [3] is the novel use of the *BACKUP mask* (Fig. 2) which enables the *Upper* beams shown in Figs. 1 and 2. The *BACKUP mask* is now *embedded* in the insulating oxide before SOI bonding, such that tight dimensional control is possible, and alignment to top device layer is very accurate. Our self-alignment technique described in Fig. 3 aligns both top-side oxide *masks* with a single *mask* before DRIE, not requiring repeated DRIE steps as in previous technique [4].

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[3] V. Milanović, M. Last, K. S. J. Pister, "Monolithic Silicon Micromirrors with Large Scanning Angle," *2001 IEEE/LEOS International Conference on Optical MEMS*, Okinawa, Japan, Sep. 2001.

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[6] Krishnamoorthy, U., Li, K.., Yu, K., Lee, D., Heritage, J.P and Solgaard, O. "Dual-Mode micromirrors for Optical Phased Array Applications", *Transducers'01*, Munich, Germany, June 2001.

[7] J.-L. A. Yeh, *et al*, "Electrostatic Model for an Asymmetric Vertical Combdrive", *Journal of MEMS*, Vol. 9(1), Mar. 2000.

[8] J.-M. Kim, *et al*, "Fabrication of silicon optical scanner for laser display," Optical MEMS'00, Kauai, HI, 21-24 Aug. 2000, p.13-14.

[9] V. Milanović, "Multilevel Beam SOI-MEMS Fabrication and Applications," *submitted to IEEE/ASME J. of MEMS*, May 2002.

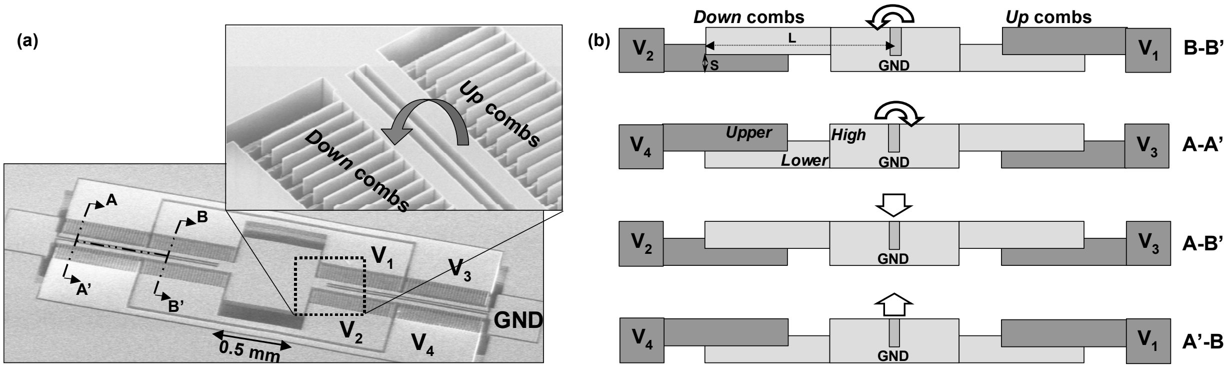

Figure 1. One-axis micromirror with 4 isolated vertical combdrive sets for up *and* down *piston actuation and independent bi-directional rotation. (a) Pistoning* down *uses electrodes V2&V3, pistoning* up *uses V1&V4, positive rotation V1&V2 and opposite rotation V3&V4. (b) schematic of 4 different cross-sections in the device showing the use of both upward and downward actuating combdrives for pure rotation.*

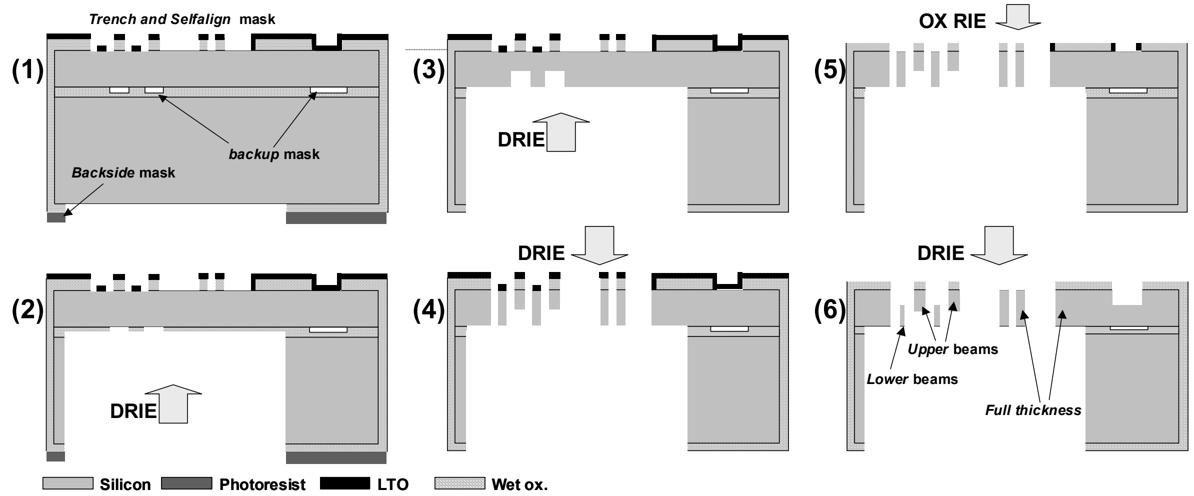

Figure 2. Schematic of the etching steps of the advanced Multilevel Beam SOI MEMS *[9], which allows close spacing of Upper and Lower beams and hence vertical comb-drive actuators. Note in step 1),* Backup *mask is pre-etched into the insulating oxide before SOI bonding, giving tight dimensional control. Step (1) already has all 4 masks applied to the wafer with topside masks aligned to buried* Backup mask.

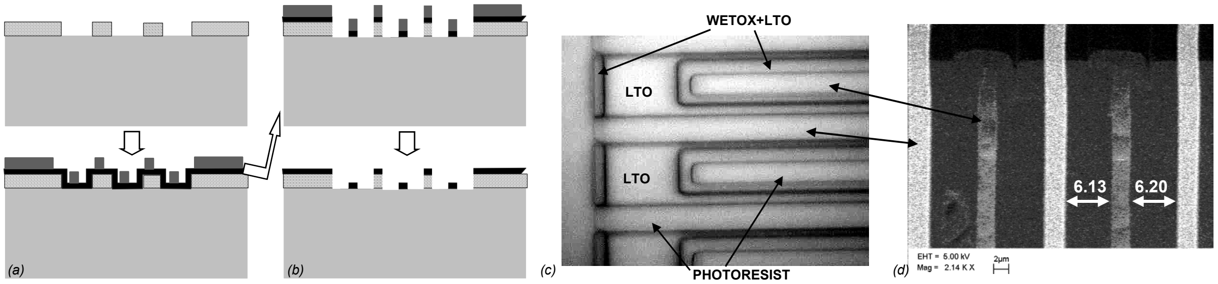

Figure 3. Novel mask self-alignment methodology: (a) since top side multilevel etching requires oxide masks of 2 different thicknesses, those masks are self-aligned by growing the first mask by 2 µm, and then (b) cutting it back with the 2^{nd} mask such that Upper and Lower fingers are both in the same (2^{nd} mask). This is the Selfalign *mask is in depiction of Fig. 2. (c) microphotograph shows some mis-alignment which is then corrected by etching both oxides with the photoresist mask, and (d) SEM demonstrates comb-finger symmetry.*

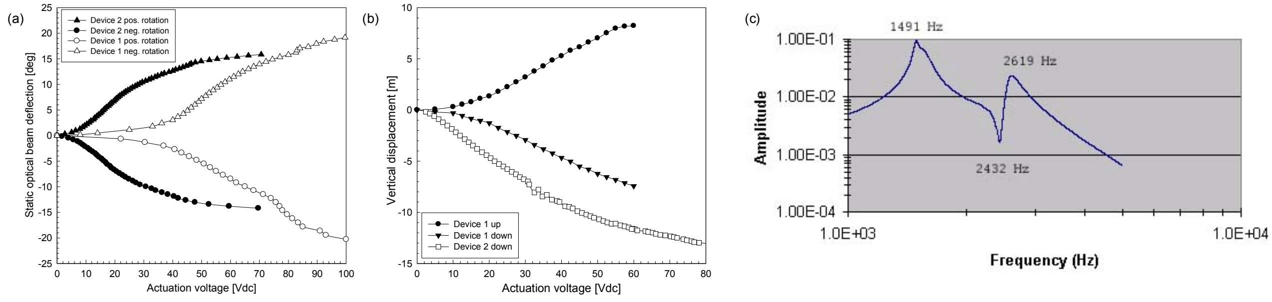

Figure 4. Characterization of two devices: (a) static bi-directional rotation - electrodes 1&2 to achieve positive angle rotation, electrodes 3&4 to achieve negative angle pure rotation, (b) static pistoning - electrodes 2&3 give piston motion down, electrodes 1&4 give piston motion up, and (c) dynamic characteristics of Device 1 – first peak is tilting mode and second peak is pistoning (independently confirmed.)