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Self-assembly technique for MEMS vertical comb electrostatic actuator

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Abstract: We report a very simple and reliable method for making Self-Assembled Vertical Comb (SAVC) drive actuators by using the standard SOI bulk micro-machining processes. The initial angular offset of the movable combs is prepared by using the process stiction which occurs during drying process after sacrificial release. The optical scanner integrated with SAVC has shown good electrostatic scanning performance of over 1.0-degree static-rotation angle with a typical drive voltage of 20 V without any in-use electromechanical failure.

Keywords: vertical comb, process stiction, self-assembly, self alignment

Classification: Micro- or nano-electromechanical systems

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1 Introduction

Electrostatic comb drive actuator is a powerful micro mechanism compared with other type of electrostatic micro actuators of given device footprint [1], and is commonly used for practical applications in the field of micro electro mechanical systems (MEMS) [2]. Vertical comb (VC) drive mechanism is a similar structure but is designed to produce large out-of-plane motion with relatively low voltage, which is also widely used for optical MEMS scanners [3, 4]. The key technique to develop VC is to make the height difference (offset) between the stationary and movable combs, which is inevitable to create vertical electrostatic force.

For this reason, the structure and fabrication process of VC are rather complicated compared with those of parallel plate actuators, and two different approaches of fabrication have been proposed. The first example is usually referred to as staggered-combs, in which one of the comb pair is made taller than the other [3]. The fabrication process of this model is relatively straight forward because of the compatibility with bulk micro-machining process of SOI wafer. However, the staggered combs frequently suffer from electrostatic in-plane instability due to the misalignment of photolithography steps to define the comb pair. The second example of VC is so-called "lifted-up"-combs, in which one of the paired combs is lifted-up from the wafer surface to make the height offset after sacrificial release [5]. The internal stress of molten polymer, for instance, is used for post-release self-assembly. The risk of in-plane instability is lower than that of the staggered-comb model thanks to the self-alignment process using a single photomask. However, the yield of self-assembly is poor in general, and the use of such organic material leads to degradation of the long-term reliability of the device.

In this paper, we propose a new fabrication process of Self-Assembled Vertical Comb (SAVC) drive actuators. An initial angular offset of the movable vertical comb is self-assembled by using in-process stiction during drying process after sacrificial etching. Fabrication process of out-of-plane-motion actuators can be greatly simplified with the SAVC mechanism, because the whole vertical combs are patterned in the active layer of SOI with only one photomask, and that the out-of-plane offset is made without extra process.

2 Design and Fabrication of Self-Assembled Vertical Comb

Fig. 1 shows the schematic illustration and the self-assemble process of the electrostatic mirror with SAVC, in which a mirror is suspended with a pair of torsion bars, and combs are located on the mirror edges. On each supporting torsion bar, we set an additional H-shaped hinge and a stiction pad with release holes. By using the surface tension force during drying process after hydrofluoric acid releasing, the stiction pads are pulled down to the substrate and create a vertical displacement. The H-shaped hinges are designed to cause angular shift of the torsion bars when the stiction pads are fixed downward. The angular shift creates the vertical offset of the comb teeth located on the edge of the mirror as shown in Fig. 1 (b). After assembly, the

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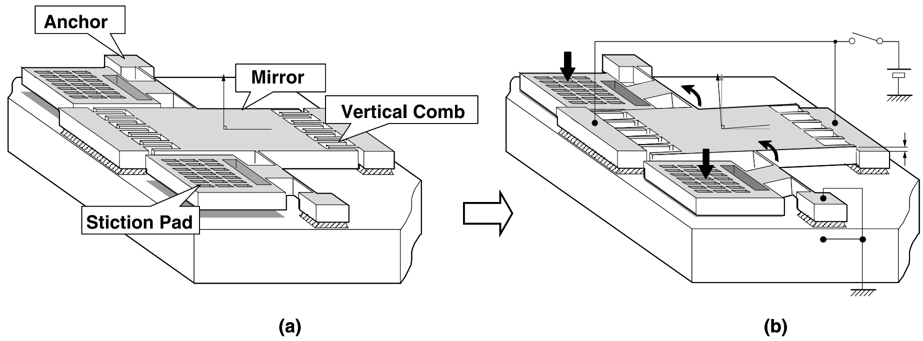

Fig. 1. Schematic illustration of self-assembled vertical comb drive actuator. (a) before stiction, (b) after stiction

stiction pads and H-shaped hinges work as a part of the anchor. The mirror can be now driven clockwise when voltages are applied to the fixed-comb electrodes.

The fabrication process of SAVC can be performed by using the standard SOI bulk micromachining. The active layer of an SOI wafer (30-μm-thick silicon / 2-μm-thick oxide / 400-μm-thick silicon substrate) is first patterned into the mirror shape by using the deep reactive-ion etching (DRIE). The movable and the static combs are made by the self-alignment process with one photo mask. A part of the substrate behind the mirror is etched into a cavity to the buried oxide (BOX) to make a room for the mirror to tilt. The mirror is released by selectively removing the BOX in a hydrofluoric acid, followed by rinse in de-ionized water and natural dry in the air. At this moment, the stiction pads are pulled downward by the surface tension of water and permanently bonded to the substrate for VC assembly. The mirror and the contact pad metals are deposited by vacuum evaporation of 5-nm-thick chromium and 50-nm-thick gold through a stencil mask.

3 Operation of SAVC Scanner

Fig. 2 shows an SEM micrograph of a fabricated SAVC scanning mirror. A square mirror (700 μm $\times$ 800 μm) is supported with a pair of suspensions; the inner suspensions are for electrostatic operation (2 μm wide and 70 μm long) and the outer bars on the H-shaped hinge are for self-assembly (4 μm wide and 30 μm long with a 40 μm distance $L_{\rm h}$ between axes). The initial angular offset of the assembled mirror is almost 3.0 degrees, which is given by the BOX thickness and the hinge space L_h. Large initial offset of comb height (15 μm out of plane) can be seen in Fig. 2.

The yield of self-assembly was found to be more than 90%. No mechanical failures could be seen through an ultrasonic-wire-bonding process in which the device temperature rose up to 170°C. Judging from the experimental results, the main force of bonding is thought to be the Van-der-Waals force because stiction pads and substrate were firmly bounded without aid of annealing. Fig. 2 also shows a movie of the SAVC operation observed in the SEM vacuum with a driving voltage of triangle wave between the movable

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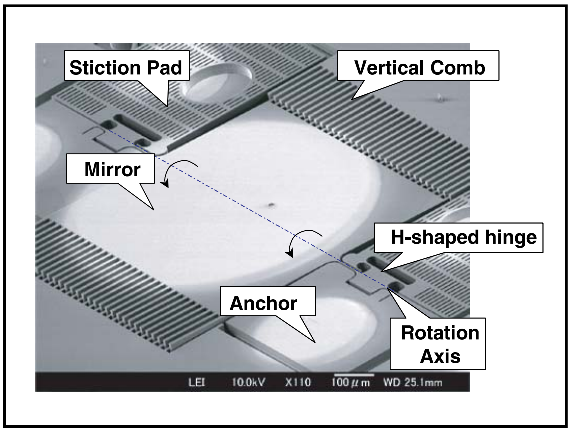

Fig. 2. SEM micrographs of SAVC scanner made of a 30-μm-thick SOI. A motion picture of SAVC scanner in operation has been attached.

and the static combs. Thanks to the highly accurate self-alignment of the combs and the large suspension-rigidity, no in-plane instability was found during the operation, even when the scanner was over-driven with an excess voltage of up to 40 V. Fig. 3 shows the curve of tilt angle as a function of drive voltage. The mirror rotated over 1.0 degree with a 20 Vdc, which was sufficient to realize optical components such as VOA of our previous report [6].

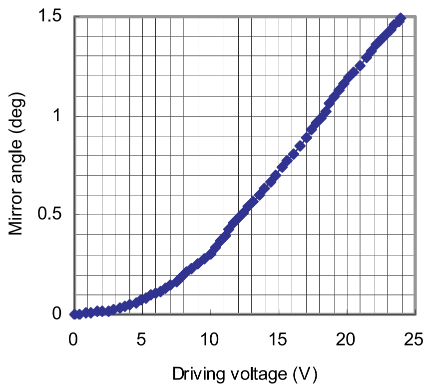

Fig. 3. Experimentally confirmed mirror angle versus drive voltage.

We also investigated shock tolerance (5000 m/s^2 in the ±X, Y, and Z directions) and vibration robustness (20-2000 Hz at 50 m/s^2 for three different axes) test to confirm the reliability of the stiction pads. There was no mechanical damage of the mirror or delaminations of the stiction pads through the harsh tests. These experimental results have shown that the bonding of stiction pads is strong and reliable to hold the assembled microstructures.

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4 Conclusion

We have developed a very simple and reliable self-assembly method for MEMS electrostatic vertical–comb drive actuators by using the surface stiction. For demonstration, we used the Self-Assembled Vertical Comb (SAVC) structure for a MEMS electrostatic optical scanner that could be used for fiber optic variable optical attenuators [6]. Surface stiction has been thought to be a weak point in the MEMS fabrication technology, and great efforts have been made to get rid of it. However, we have discovered the benefit of using the surface stiction in terms of fairly good repeatability and firm bonding force when used as a tool for self-assembly for, such as, making the height offset of the vertical comb drive actuators.

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