Assembly of Micro-3-D Components on SOI Wafers Using Novel SU-8 Locking Mechanisms and Vertical One-Push Operation

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***Abstract*—A novel out-of-plane assembly technique of 3-D microstructures is proposed and demonstrated by using simple vertical one-push operations. This one-push method has large probe positioning tolerance in both vertical and lateral directions to reduce the overall complexity of the assembly process. Micromirrors and corner cube reflectors are fabricated on silicon-on-insulator wafers using SU-8 photoresist as a second structure layer in a low-temperature process. Batch assembly of multiple mirrors assembled simultaneously is demonstrated.**

***Index Terms*—Assembly, hinge, microelectromechanical system (MEMS), one push, out of plane.**

I. Introduction

MICROASSEMBLED 3-D structures are used in many optical and RF microelectromechanical system (MEMS) applications [1]–[6]. Most of these components are fabricated in thin films by surface micromaching. They are then flipped out of plane to form the 3-D structures. Many techniques can be used to assemble the 3-D microcomponents. Aside from the manual assembly using microprobes, powered assembly processes have been demonstrated by using magnetic force [7], [8], electrostatic force [9], centrifugal force [10], ultrasonic triboelectricity [11], or on-chip actuators [2], [3], [12], [13]. Prestressed bimorph beams [14]–[16], surface tension [6], [17]–[19], and capillary force and fluidic transportation [20], [21] are also used for self-assembly. Recently, automated assembly was demonstrated using standard or specially designed equipment [22], [23]. The automated assembly is particularly attractive in microelectrooptical system-in-package (SIP) design such as the smart-dust module [24] or the miniaturized optical pickup head [25], [26], where multiple chips need to be assembled and wired. In this case, if the pick-and-place and wire bonding equipment in electronic packaging can be used, with or without modification, to assist the assembly of micromechanical and microoptical components, a more reliable, flexible, systematic, and economic assembly and packaging process can be designed and achieved.

In the traditional manual assembly or the recently developed automated assembly, microprobes or microgrippers are used to manipulate the orientation or the position of the microparts. The fragile microparts are fabricated on the surface of the wafer and only a narrow gap, formed by the removed sacrificial material, separates the two. Therefore, to insert a probe into the gap or pick a part with a microgripper requires very precise control of their vertical and lateral positions. The cost factors of assembly, including equipment, time, and yield, are thus difficult to be improved.

In this paper, we present a novel design and assembly of 3-D microcomponents on silicon-on-insulator (SOI) wafers using SU-8 locking mechanisms and simple vertical one-push operations. Compared to the existing techniques, the proposed assembly method has greatly reduced requirement on the probe positioning precision, and thus can help reduce the total assembly cost. The fabrication process employs SOI wafers, SU-8 photoresist, and dry etching. Such a low-temperature process makes it possible to integrate circuitry on the wafers directly. A new hinge locking mechanism is also introduced to eliminate both vertical and lateral play space, and thus improve the positioning accuracy of the hinge pins.

II. Device Concept and Design

A. Vertical One-Push Assembly Method

One of the major difficulties in manual or automated assembly of 3-D MEMS structures is the control and positioning of probes or pickup grippers. Since the thickness of the components and the gap spacing between the released components and the substrates are only a few micrometers, inserting the probes into the gap involves motion control in multiple degrees of freedom with high precision. In the new gripper design [22] or the single side-push method [23], the precision requirement on the contact head or the push probe is still high in the vertical and lateral directions in order not to destroy the fabricated grippers or microcomponents during the operation. Therefore, we propose a novel automated assembly with simple one-push operation in the vertical direction to relieve the precision requirement of the current techniques.

The schematic and layout of the proposed structure and assembly method are shown in Fig. 1, where a micromirror is used as an example. The fabrication process can be standard surface micromachining or SOI processes. The micromirror is fabricated in the first structure layer and hinged to the substrate. The hinges and side latches are fabricated in the second structure layer. As shown in Fig. 1(a), the mirror plate has an extended part, which is used as the push pad, on the other side of the

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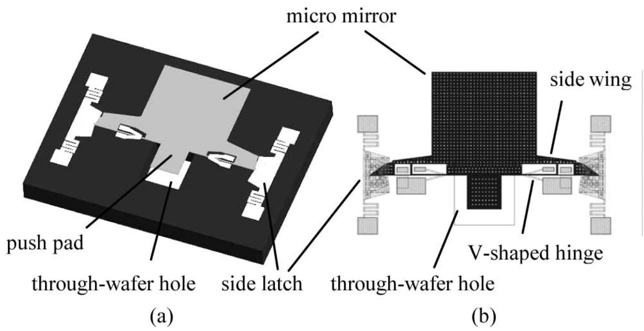

Fig. 1. Micro mirror. (a) Schematic. (b) Layout.

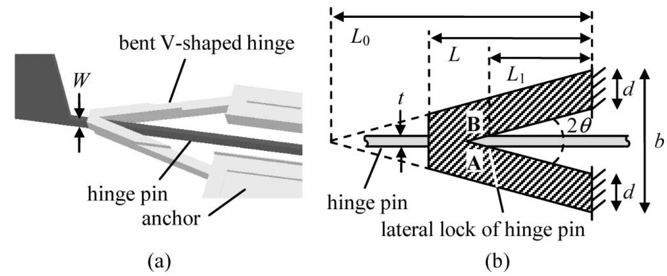

Fig. 2. Play-less V-shaped hinge after assembly. (a) Schematic. (b) Top view.

hinge pin. A through-wafer hole is etched under the push pad to provide the space for the vertical push operation. After the structure is released, a microprobe pushes the push pad. The mirror rotates about the hinge pin to the vertical position and is locked by the side latches. The push operation does not need to stop at a specific position as long as it is enough to rotate the mirror to the desired angle. Therefore, the tolerance of the vertical positioning is very large. Furthermore, since the alignment of the probes to the large pads, which are several hundred micrometers in dimension, is not critical, the lateral tolerance of operation is also large.

Multiple probes can be arranged as a push array so that multiple devices can be assembled simultaneously to achieve batch or wafer-level assembly. If the length of the probes in the array is different, sequential assembly of more complex structures is also possible in a single vertical push operation. Finally, the push probes and operations can be integrated as part of the pick-and-place or the bonding equipment so that the assembly and packaging of the microelectrooptical modules can be automated and simplified.

B. SU-8 Locking Mechanisms

When the push pad is pushed down, the hinged mirror plate rotates about the pin axis. As the mirror plate moves out of the plane, the side wings of the mirror plate contact the bottom of the side latches and rotate the spring-loaded latches. As the mirror plate reaches the upright position, it slides into the V-shaped notches in the side latches and is firmly locked in place. The final assembled mirror angle is determined by the locking latches and the hinge pin position. In conventional hinges [27], play space in the staple is needed for the pins to rotate. The play greatly affects the accuracy of the pin position and the flip-up mirror angle. Improved hinges were demonstrated by using a bent elastic cantilever beam to eliminate the vertical play [7], [28]. However, the lateral play still exists to allow unwanted offset of the pin position and the mirror angles. In Fig. 2, a novel V-shaped play-less hinge is proposed. As shown in Fig. 2(a), the width W of the hinge pin in the layout is larger than the gap g between the hinge and the substrate before assembly. Thus, when the pin is rotated out of plane, the anchored V-shaped hinge is pushed up and bent. The downward restoring force of the bent beams can eliminate the vertical play and fix the hinge pin on the substrate. Further more, the hinge pin is locked between the two legs of the V-shaped structure, and thus the lateral play is also eliminated. A typical design of the V-shaped hinge is shown in Fig. 2(b) with $d = 25$ μm, $b = 100$ μm, $L = 120$ μm, $L_1 = 84.5$ μm, $L_0 = 190$ μm, $\theta = 14.7^\circ$, $W = 11$ μm, $g = 10$ μm, and $t = 5$ μm = thickness of the SOI device layer. After assembly, the lateral lock points A and B are pushed up by $W - g = 1$ μm. The stiffness of the V-shaped structure in the vertical [29] and lateral [30] directions is, respectively,

$$k_{\mathrm{vertical}} = \frac{Eh^3 d\cos\theta}{2L_1^3}$$

$$k_{\mathrm{lateral}} = \frac{Eh(\theta - \sin\theta\cos\theta)}{\ln(L_0/(L_0 - L_1))}$$

where $h = 13$ μm is the thickness of the SU-8 hinge and $E = 4$ GPa is the Young's modulus of SU-8. From the aforementioned design parameters, it can be calculated that a downward restoring force of 176 μN is generated by the bent beams to hold the pin on the substrate, and the V-shaped structure has a lateral stiffness of $k_{\mathrm{lateral}} = 990$ μN/μm to constrain the pin from lateral shift.

C. Nonvertical Mirrors

Nonvertical mirrors are also used in many optical systems. For example, 45° mirrors are used in optical pickup heads to turn the light propagation from parallel to vertical directions with respect to the optical disk surface. To use the proposed assembly method for the 45° mirrors, a simpler structure and interlock mechanism are used. As shown in Fig. 3, the entire device is fabricated in the same structure layer. The spring latches in Fig. 1 are replaced by torsional beams. The positions of the angular interlocks on the mirror plate and the support frame determine the angle of the assembled mirrors. Two probes are needed for assembly, as shown in Fig. 3. After the mirror and the support are separately pushed up, probe 1 is removed from the support before probe 2 is removed from the mirror so that the two parts can be interlocked correctly. Even though two probes are illustrated in Fig. 3, they can be arranged as a probe array. As discussed before, the operation and timing of the two probes can be adjusted by their respective length in the array so that the assembly of two parts by a single push of array is still possible. Alternatively, more sophisticated side latches can be used to lock the mirror at nonvertical angles. More work on the design of the array and side latches is undergoing.

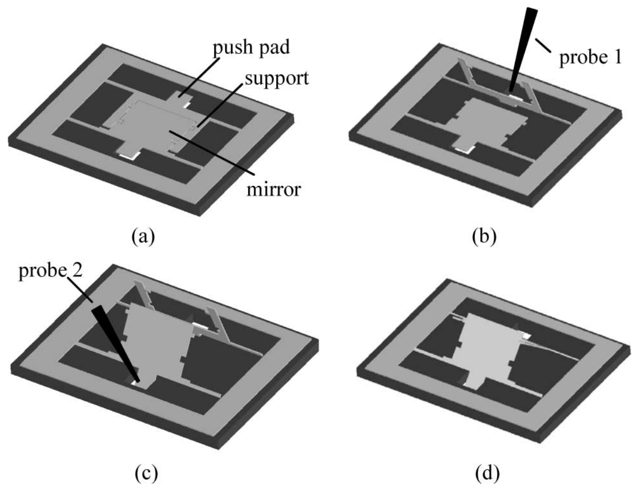

Fig. 3. 45° mirror schematic and assembly processes.

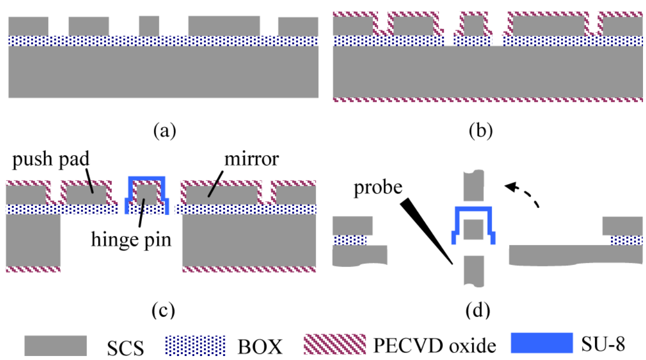

Fig. 4. Device fabrication process.

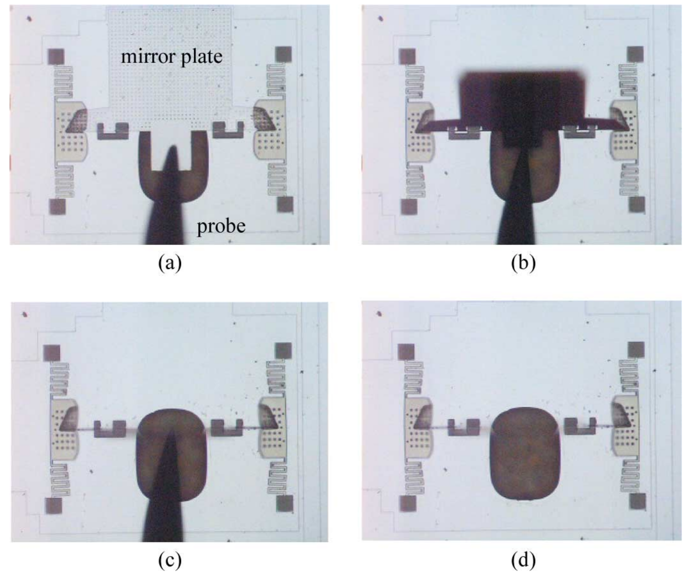

Fig. 5. Assembly of a fabricated micromirror. (a) Initial flat position. (b) Intermediate position. (c) Upright position. (d) Probe removed.

III. Device Fabrication

The fabrication of the proposed structure is similar to the standard multistructure-layer surface micromachining process. However, the commonly used polysilicon thin-film structure layer has residual stress and thus curvature issues so that it cannot be used for large mirror surfaces. Therefore, SOI wafers are used for the thick stress-free device layer. Since the device layer is single-crystalline silicon, it is also possible to fabricate optical detectors and integrated circuitry on the same wafer. To do so, high-temperature deposition processes of materials such as polysilicon should be avoided. Therefore, SU-8 photoresist is used as the second structure layer to fabricate the hinges and latches [26]. Since SU-8 is transparent to visible light, phase-type binary optical components can also be fabricated in this process.

Fig. 4 shows the fabrication process of the device in Fig. 1. The SOI wafer has a 5-μm-thick device layer, a 2-μm-thick buried oxide, and a 400-μm-thick handle layer. The micromirror is first patterned with FH6400 photoresist and etched by inductively coupled plasma (ICP) in the device layer [see Fig. 4(a)]. Three-micrometer-thick plasma-enhanced chemical vapor deposition (PECVD) oxide layers are then deposited on the front side of the wafer as a sacrificial layer and on the back side as the etching mask for the subsequent dry etching [see Fig. 4(b)]. The SU-8-to-substrate anchor window is opened in the oxide [see Fig. 4(b)]. A 13-μm-thick SU-8 photoresist is then coated on the wafer as the second structure layer. The side latches and hinges are patterned in the SU-8 layer [see Fig. 4(c)]. Subsequently, the through-wafer holes are etched in the handle wafer from the backside by ICP. Finally, the sacrificial and buried oxide is etched by HF vapor to release the structure; the mirror is then pushed up by a microprobe to the upright position [see Fig. 4(d)].

IV. Measurement and Discussion

A. 90° Mirrors

Fig. 5 shows the optical micrographs of a fabricated micromirror and its assembly sequence. The mirror size is 760 μm $\times$ 760 μm and the push pad is 250 μm $\times$ 250 μm. The mirror was manually assembled on a probe station under a microscope. The average assembly time of the mirror by the one-push method was about 30 s, whereas the assembly time of a conventional mirror without the through-wafer hole was about 80 s in our laboratory demonstration. The reduction of assembly time is significant. Fig. 6 shows the scanning electron micrographs of the devices. Fig. 6(a) is an array of assembled mirrors. In both Figs. 5(a) and 6(a), etching holes can be seen in the mirror plates for device release. If they are undesirable for the consideration of optical surface quality, the through-wafer hole can be extended to the mirror region so that the mirror can be released from the back. Thus, the released holes can be removed from the mirror, as shown in Fig. 6(b). Figs. 6(c) and (d) show the V-shaped hinge and side latch made of SU-8. The angle of the assembled mirrors is 89.8 $\pm$ 0.3°, which is good for most of the applications. To enhance the reflectivity, a 1000-Å-thick aluminum layer was coated with a measured compressive residual stress of about 70 MPa. It can be estimated that the mirror thickness needs to be increased to about 50 μm so that the center bowing of such a

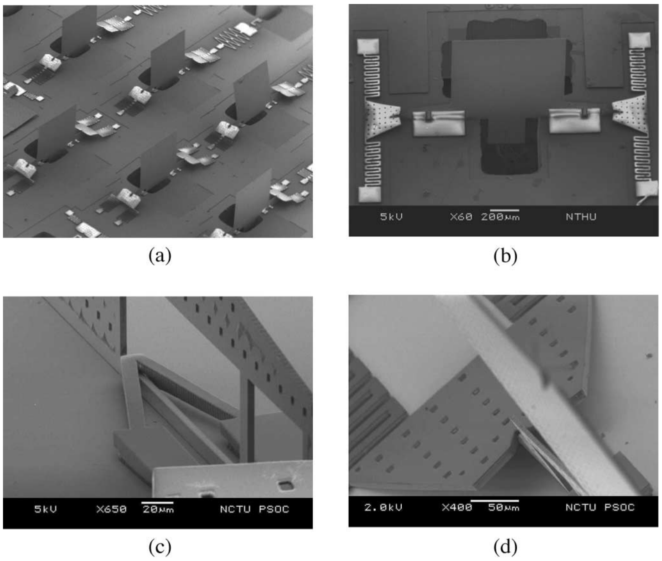

Fig. 6. Scanning electron micrographs of fabricated devices. (a) Mirror array. (b) Micromirror without etching holes. (c) V-shaped hinge. (d) Side latch.

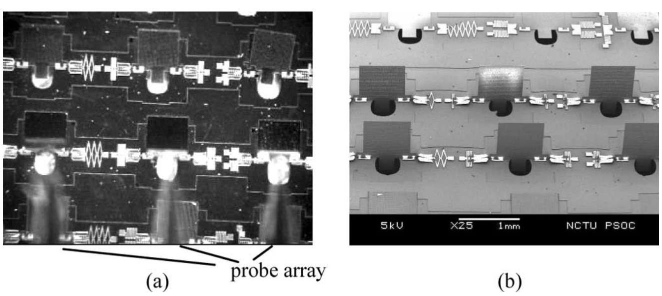

Fig. 7. (a) Optical and (b) scanning electron micrographs of rows of batch-assembled mirrors.

large mirror plate is smaller than λ/10 at $\lambda = 405$ nm. For such thickness, the PECVD oxide layer can no longer be used as the sacrificial layer. A different sacrificial material with enough thickness, a hingeless design (as in Fig. 3), or coating on both sides of the mirror plate must be adopted to solve the curvature issue caused by the metal coating.

B. Batch Assembly

Fig. 7 shows three mirrors assembled simultaneously by a row of three probes in a single-push operation. The mirrors are 760 μm $\times$ 760 μm and spaced by 2 mm from center to center. It should be noted that even though the lateral tolerance of probe positioning is large, the angular alignment of the row of probes to the row of mirrors becomes critical as the number of mirrors increases. For example, with 2 mm spacing between mirrors in Fig. 7, 1° misalignment between the two rows results in about 35 μm lateral offset of the probe position from one mirror to the next. If many mirrors are to be assembled simultaneously, the angular alignment should be controlled so that the probe is within the push pad for each mirror.

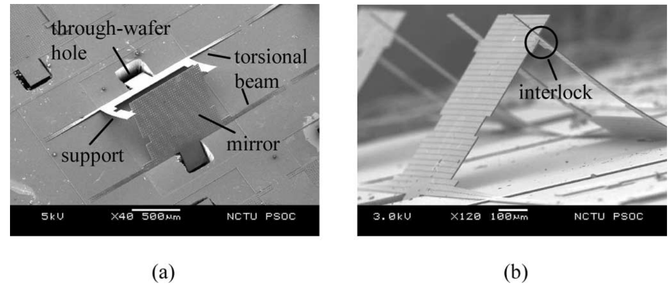

Fig. 8. Scanning electron micrographs of a 45° mirror.

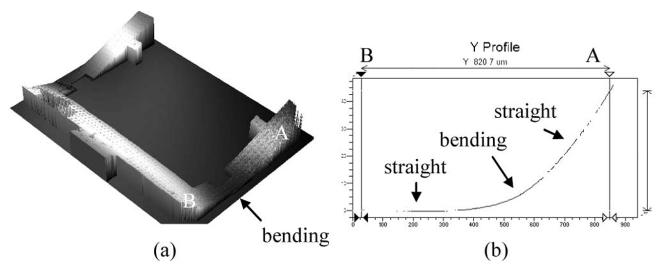

Fig. 9. Bending of the support in the 45° mirror. (a) 3-D profile. (b) AB cut.

C. 45° Mirrors

Fig. 8 shows the assembled 45° mirror by two probes and two pushes. The mirror plate is 800 μm $\times$ 640 μm. Latches are replaced by 45 μm $\times$ 720 μm torsional beams. The dimension of the beam should be designed so that the maximum stress at 45° torsion angle is smaller than the yield strength of silicon. The measured angle of the assembled mirrors is $45.9 \pm 0.2°$. Though the precision is satisfactory, the accuracy apparently needs to be improved. It was found from the WYKO interferometric measurement that the error was caused by the bending of the support near the thinnest part, as shown in Fig. 9. This problem can be solved by increasing the width, and thus its mechanical rigidity of the support. Mechanisms are also being developed to assemble the device using only one push, as discussed before.

D. Corner Cube Reflector

A corner cube reflector was designed and fabricated by using two 760 μm $\times$ 760 μm 90° mirrors, as shown in Fig. 10. The reflector is composed of the front surface of the mirror 1 plate, the back surface of the mirror 2 plate, and the substrate surface under mirror 2, as shown in Fig. 10(b). The two mirrors are assembled by the one-push method using the same through-wafer hole, as shown in Fig. 10(c). The angles of the assembled mirrors measured by an optical microscope were 89.9° between mirror 1 and substrate, 89.0° between mirror 2 and substrate, and 90.0° between mirror 1 and mirror 2 with a measurement resolution of 0.15°. The deviation of the reflected light from the incident light was measured optically for various orientations of the reflector with respect to the incident light. The average angular deviation is $1.2 \pm 0.4°$. The large deviation is mainly caused by mirror 2, which was only latched on one side in current design. This problem can be solved by adding locking

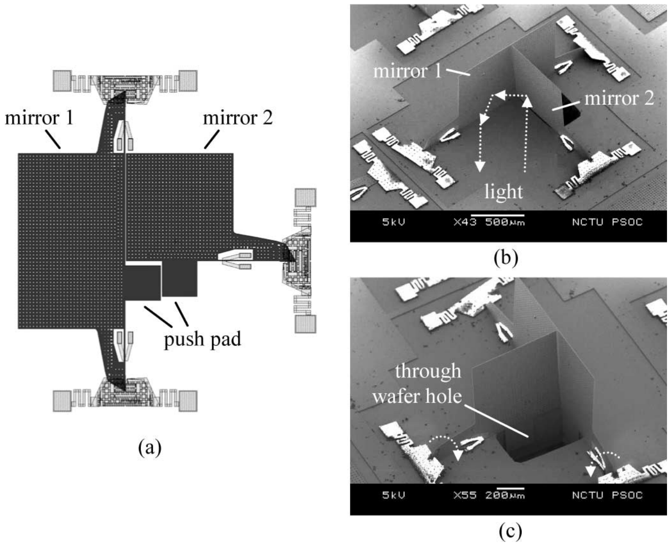

Fig. 10. Corner cube reflector. (a) Layout. (b) Reflection of light. (c) Assembly of device.

mechanisms between mirror 1 and mirror 2 to lock the mirror 2 on two sides.

V. Conclusion

A novel vertical one-push method was proposed and demonstrated for the assembly of 3-D MEMS components. The advantages of the method include simple operation and large tolerance of probe positioning. The devices were fabricated in SOI wafers with SU-8 as the second structure layer. Batch assembly of multiple component was demonstrated by using a row of probes to push a row of mirrors. Vertical and 45° mirrors were fabricated and assembled with 89.8 ± 0.3° and 45.9 ± 0.2° angles, respectively. A corner cube reflector was also demonstrated. The reflected light had a 1.2 ± 0.4° angular deviation. Though some improvement of the structure and mechanism design is needed for more accurate angles, the concept of the new assembly method is successfully proved.

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Wei-Zhi Huang, photograph and biography not available at the time of publication.

Jhong-Wei Wu, photograph and biography not available at the time of publication.