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A robust and reliable stress-induced self-assembly supporting mechanism for optical devices

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Abstract The stress-induced supporting mechanism consisting of stress-induced bending beams and novel locking component used to assemble the micromachined optical devices has been realized. The tip deflection of the stress-induced bending beams has been exploited to lift up the micromachined devices. Based on the MUMPs platform, this study has successfully established an improved surface micromachining process (MUMPs-like process) to enhance the reliability of the stress-induced beams. According to the reliability test, the variation of the tip displacement is <<1% and the variation of curvature is <<<<1% after six months. Several tests relied on the BellCore standard is also achieved, the results reveal the reliability of dielectric film is much better than the metal film. Moreover, a novel locking component was also developed to accurately position the optical component and to prevent it from deviation as well. Experimental results elaborated the feasibility and stability of the novel locking component. With improved stress-induced beam and stronger locking component, the robust and reliable stress-induced self-assembly supporting mechanism for optical devices becomes available. To demonstrate the applications of the proposed mechanism, two optical devices were accomplished in this study as well.

1
Introduction

MUMPs (Multi-User MEMS process) is regarded as one of the most important fabrication platform for micromachined devices. Origins from the planar integrated circuit process, surface micro-machining technology can be much delicate in planar process than the bulk micro-machining or HARM (high-aspect ratio micromachining) technology. However, due to the nature of surface micro-machining process, a fundamental problem is its inability to produce highly 3D structures hence the applications are limited. To accomplish 3D devices after the process, residual stress of thin film, magnetic force [1], ultrasonic wave [2], photoresist [3], or solder reflow are widely adopted to be the self-assembly approaches. Shortcomings of many existing approaches are the requirements of additional fabrication processes and actuators, the complicated process and the consumption of wafer area are the major limitation. To avoid the additional processes or actuators, the residual stress inherent in the thin film materials during fabrication has been exploited in [4] to construct the 3D devices.

Moreover, the applications of the MUMPs devices are limited by the small gap between the surface micromachined structure and the substrate which is defined by the sacrificial layer. Presently, various assembly mechanisms have been exploited to extend the actuation range of optical surface micromachined devices. For instance, a cantilever bent by the residual stresses of Metal/Poly-Si films is employed in [5] to lift up the mirror of a 2D switch. The height of the mirror is determined by the length as well as the bending curvature of the cantilever. In addition, the bent cantilever is also acting as a spring during actuation. In [6], Lucent Technology has demonstrated a promising assembly mechanism to assemble a 3D optical switch. This mechanism contains not only the Metal/Poly-Si stress-induced beams but also a locking component. After the assistant of the locking component, the mirror plate could be precisely placed to a desired height. These beams are also used as the support of the mirror frame. This self-assembly mechanism has the potential to be applied in various optical MEMS devices. However, the stress relaxation of the metal film may influence the reliability of this mechanism [7]. Moreover, the deformation of the flexible stress-induced beams may lead to the offset of the mirror so as to affect the performance of the devices.

Based on the MUMPs platform, this study has established an improved surface micromachining process (MUMPs-like process). Through this process, the improved stress-induced self-assembly supporting mechanism has been realized. According to the result of reliability test, stress relaxation is significantly reduced using

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the dielectric film instead of the metal film. Furthermore, this study intends to present a novel locking component for surface micromachined devices. Relying on that, more robust and reliable self-assembly micromachined devices can be achieved, particularly for micro-optical applications.

2
Design and Analysis

The typical assembly schematic is composed of stress-induced beam and the locking component as shown in Fig. 1(a). Although the scheme is splendid, there still lies some paradox. The bimorph beam as a supporter may deform and the height of the mirror is deviated downward while the mirror is actuated by electrostatic force. To reduce the downward deviation, the folded torsional beam is adopted to decrease the driving voltage which is proportional to the electrostatic force. Unfortunately, the unwanted downward offset of the mirror due to the deformation of this flexible torsional bar occurs as well. Hence additional mechanical stopper is utilized to prevent such an offset. Not only the design becomes complicated but also leads reliability problem that comes with the wearing rotation.

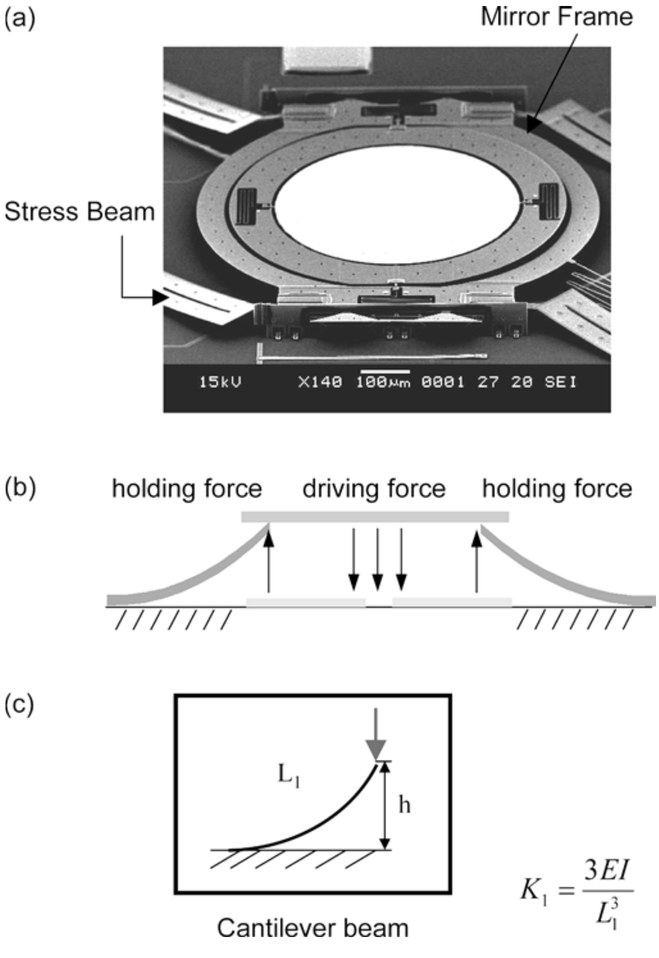

Fig. 1. (a) Typical assembly mechanism composed of stress-induced beam and the locking component. (b) Physical model of the typical supporting mechanism. (c) Bending stiffness K_1 of the defined cantilever beam

In general, stress-induced beam can act as either the lifter [1] or the actuator [2] for different applications. For the lifter purpose, maintaining the device to the desired height is the primary consideration. Hence the design should emphasis on the stiffness of the supporting structure and the accuracy of the locking component. On the other hand, the reliability of the stress-beam after repeated operation is the crucial issue for the actuator purpose. This study has established a modified process demonstrating reliable stress-induced cantilever beam for the actuator purpose. Moreover, a novel stress-induced self-assembly scheme consisting of the robust locking component and the stress-induced beam has been employed in this study as the lifter.

2.1
Novel locking component

The physical model of the existing stress-induced self-assembly mechanism is illustrated in Fig. 1(b). A transverse load applies on the bimorph beam when the mirror driven by the electrostatic force. Residual stress within the cantilever causing a radius of curvature to lift the device to a desired height, given known stress and height, the length of the cantilever can be obtained. For a typical height of 50µm, the cantilever should be at least 500 µm. As depicted in Fig. 1(c), the bending stiffness K_1 of the cantilever with length L_1 and moment of inertia I can be expressed as,

$$K_1 = \frac{3EI}{L_1^3} \tag{1}$$

where E is the elastic modulus of the thin film material. Hence, the stiffness of the stress beam may not large enough to support the structure. For instance, the measured frequency response of the typical structure shown in Fig. 1 is displayed in Fig. 2. While driving at the resonant frequency of the outer ring, the vibration amplitude of the stress beam is near 15% of that of the mirror center. It reveals that the unwanted wobble motion of the mirror due to the deflection of stress beam is remarkable. In addition, the mirror was pulled down to the substrate when the driving voltage reached 100 volts. This was due to the bending of the stress beams with 200 µm long and 40 µm tip deflection.

In this study, a straight beam as illustrated in Fig. 3(a) was exploited to increase the stiffness of the supporting structure. The axial stiffness K_2 of the straight supporting beam with length L_2 and cross section area A can be expressed as,

$$K_2 = \frac{3EA}{L_2} \tag{2}$$

According to Eqs. (1) and (2), the stiffness for a straight beam is much stronger than the cantilever because the ratio of K_1/K_2 is more than 10^6.

The novel stress-induced self-assembly mechanism proposed in this study consists of stress-induced beams and the positioning locking components. Similar with the typical mechanism as depicted in Fig. 1, these supporting frames are lifted up utilizing the stress-induced beams, and the final height of the mirror would be determined by

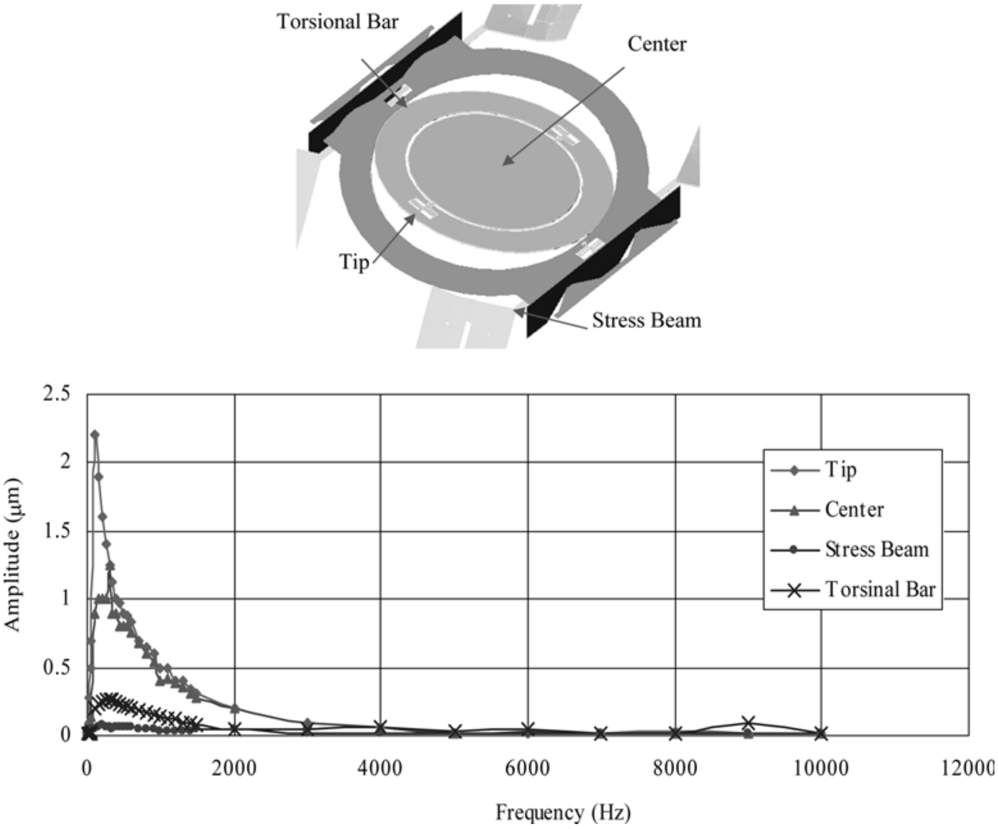

Fig. 2. Frequency response of the device shown in Fig. 1(a) while actuating at resonant frequency

the V-shape locking component. Characteristic of the locking component proposed in this study is the additional design of the position limit and the support limit demonstrated in Fig. 3(b). Figure 4 schematically illustrates the assembly flow of novel stress-induced self-assembly mechanism. The position limit and the support limit can constrain the upward and downward movement of the mirror frame respectively. Theoretically speaking, movement of mirror frame is restricted as rigid body with the support limit and the position limit hence the degree of freedom is zero in this structure. That means the structure is very robust and it's hard to affect the stability. Therefore, the locking component could be a strong supporter when the mirror is suffered from the downward electrostatic force.

2.2
Modified stress-induced beam

The gap between the surface micromachined structure and the substrate is near 2 μm since the limitation of the film thickness for sacrificial layer. In this regard, various methods have been proposed to lift and assemble microstructures, such as magnetic force, ultrasonic wave, photoresist, or solder reflow. However, many existing approaches require additional fabrication processes and actuators. The residual stresses that are inherent in thin films have been exploited to lift and assemble the micro-

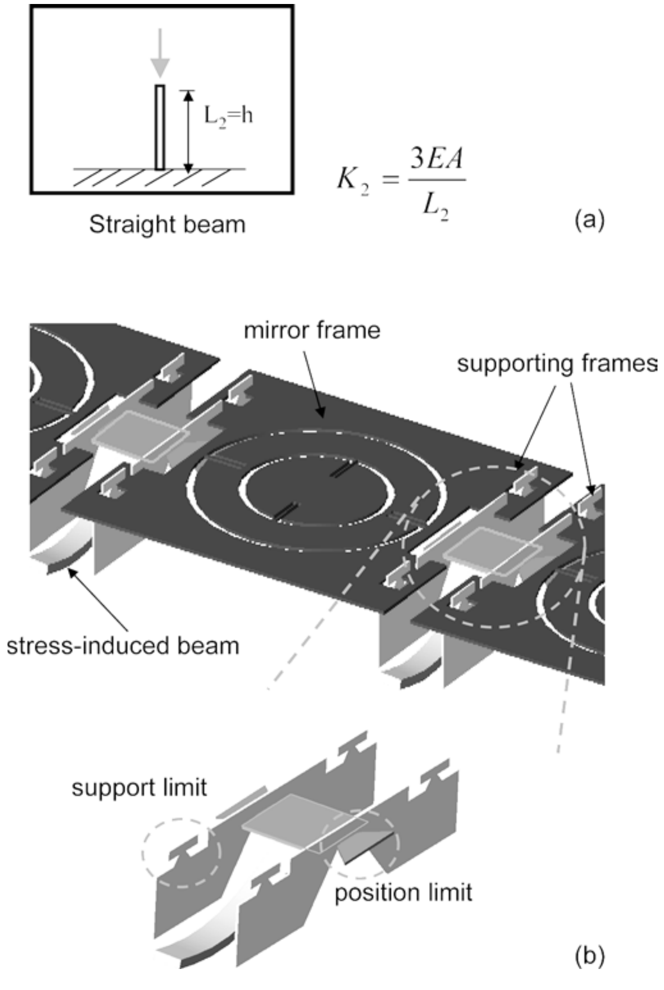

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Fig. 3. (a) Bending stiffness K_2 of the defined straight beam. (b) Novel locking component proposed in this study

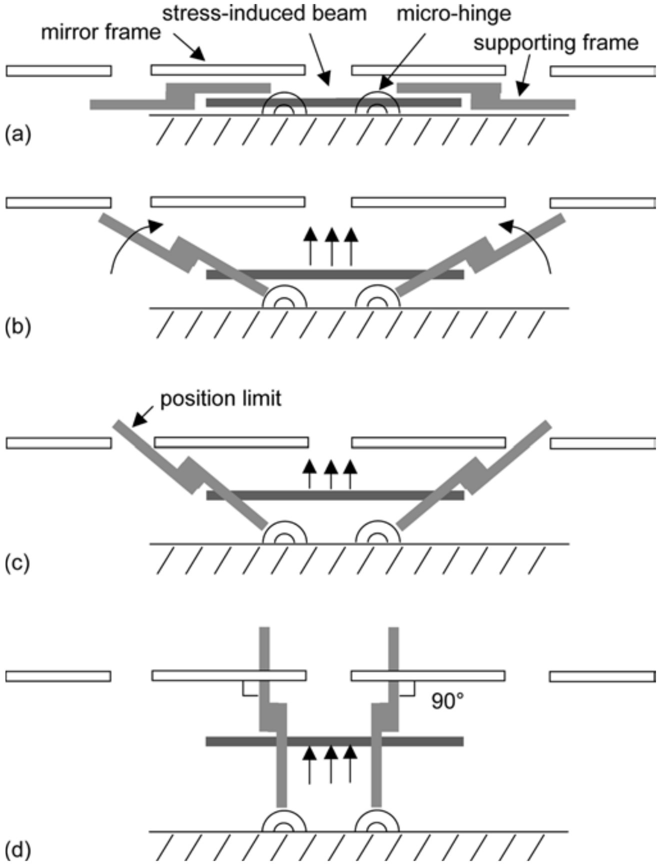

Fig. 4. The assembly flow of novel stress-induced self-assembly mechanism. (a) Before releasing. (b) Mirror frame was lifted by stress-induced beam. (c) Supporting frame entry the mirror frame. (d) Completing the self-assembly mechanism

Table 1. Layer description of the MUMPs-Like process proposed in this study

Level	Mask#	Purpose
SiO_2/SiN_x0	N/A	Isolation layer
Poly 0	#1 Poly 0	Ground layer
SiN_x1	#2 SiN 1	Isolation layer
PSG 1	#3 Dimple	Dimple or bushing for Poly 1
	#4 Anchor	Open holes for Poly 1 to SiN or Poly 0 connection
Poly 1	#5 Poly 1	1st structural layer
SiN_x2	#6 SiN 2	Stress assembly layer
PSG 2	#7 Via	Connection of Poly 1 and Poly 2
Poly 2	#8 Poly 2	2nd structural layer
Metal	#9 Metal	This metal for optical purpose

structures [6]. Presently, the bimorph structure consisted metal (Cr-Au) and Poly-Si films were used as the stress-induced beam for MUMPs processes. However, as reported in [7], the displacement of stress-induced beam would drop 70% after 6 months because of the metal relaxation. Consequently, the position of the lifted components is affected. As actuators, stress beam will be operated repetitively hence the reliability of the material is much more important. To eliminate the relaxation problem of metal film, the MUMPs-like process developed in this study employed low stress Si_xN_y together with Poly-Si to form a bimorph structure. According to the existing results, relaxation is much gentle for the dielectric film during long-term observation [8].

3
Experiment and results

In order to demonstrate the concept proposed in this study, surface micromachining processes were employed to realize the reliable self-assembly mechanism. The process developed in this study was similar with MUMPs process with additional stress layer for the assembly purpose. The process flow and the layer information are shown in Table 1. Characteristic of this MUMPs-like process is employing low stress Si_xN_y together with Poly-Si to form a bimorph structure. The stress of the Si_xN_y film can be adjusted by arranging the deposited conditions such as temperature, pressure and gas ratio [9]. Except the long-term stability as reported in [10], the performance of the Si_xN_y/poly-Si bimorph has been evaluated using various reliability tests.

The test Si_xN_y/Poly-Si bimorph cantilevers shown in Fig. 5(a) are some typical fabrication result. The variation of the tip displacement with time for these Si_xN_y/Poly-Si bimorph cantilevers was recorded first. In Fig. 5(b), the variation of the tip displacement is <1% and the variation of curvature is <<1% in all diagnostic beams without any additional humidity or temperature treatments during six months. Besides, several reliability tests relied on the BellCore 1209 standard is achieved and the data is recorded in Table 2. The monitored items based on the standard consist of long-term observation, vibration test, fatigue test, and the thermal cycling test. Deviations of the cantilever deformation are all smaller than 1%. Take only the long-term observation compared with the results demonstrated in [7], the Si_xN_y /Poly-Si bimorph is indeed much more reliable than the metal/Poly-Si bimorph. Needless to say the other experimental items displayed the stability of Si_xN_y film can even pass through the requirements of semiconductor standard. According to the testing conditions, the dielectric film is much more reliable than metal film, even under vibration or thermal variation. With the reliable stress-induce bimorph beam as the actuator, robust optical devices can be accomplished for sure [10].

The SEM photo of the 3D optical switch with the improved locking mechanism is shown in Fig. 6, an axial load instead of a transverse load applies on the supporting frame when the mirror driven by the electrostatic force, therefore, this supporting frame can sustain larger downward force. During the experiment, the vertical position of the supporting frame remained unchanged even when applied voltage is 200 V. Compared with the structure shown in Fig. 1, this novel supporting mechanism could be more robust, moreover, the offset of the mirror is remarkably reduced. Avoiding the drawbacks such as wearing and reliability, more rigid and reliable self-

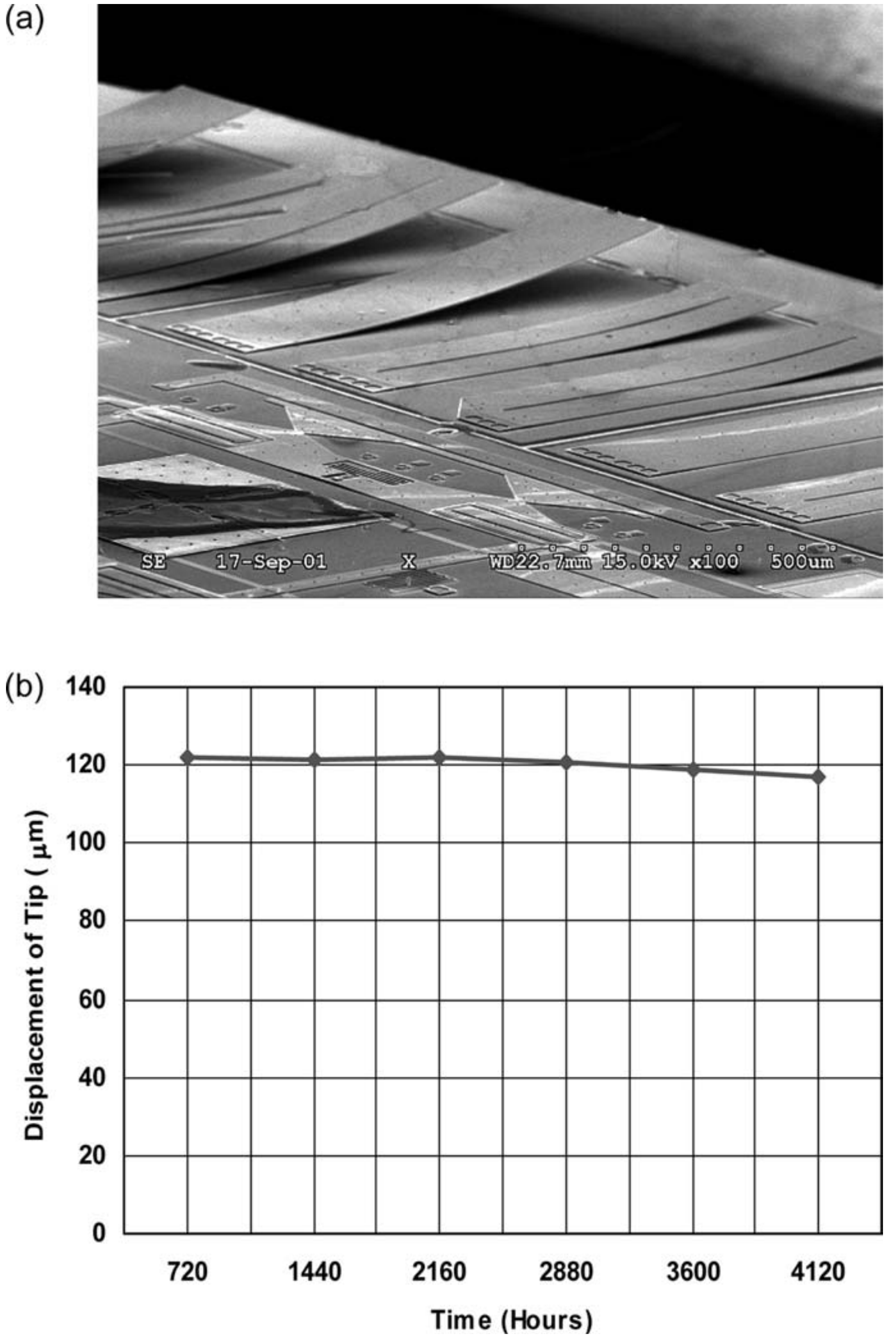

Fig. 5. (a) Typical fabrication results of the SixNy/Poly-Si bimorph stress-induced cantilevers. (b) Deviation of stress beam deflection during six months

Table 2. Experimental results of reliability test with the dielectric film

Monitored item	Long-term Observation	Vibration Test	Vibration Fatigue	Thermal Cycling
Testing Conditions	25 °C, 1 atm, without additional humidity treatment	300 Hz	Resonant frequency 55.39 KHz	−40 °C∼70 °C, Dwell time: 1 Hr Ramp Rate: 1 °C/min
Duration	4120 Hrs	48 Hrs	24 Hrs	80 Hrs
Deviation of Tip	Displacement	<1%	<1%	<1%

assembly mechanism is available. To demonstrate the feasibility of this mechanism, optical device such as 2D optical switch shown in Fig. 7 is fabricated as well.

4
Conclusion

In summary, utilizing the improved MUMPs-like process established by this study, stress relaxation is significantly

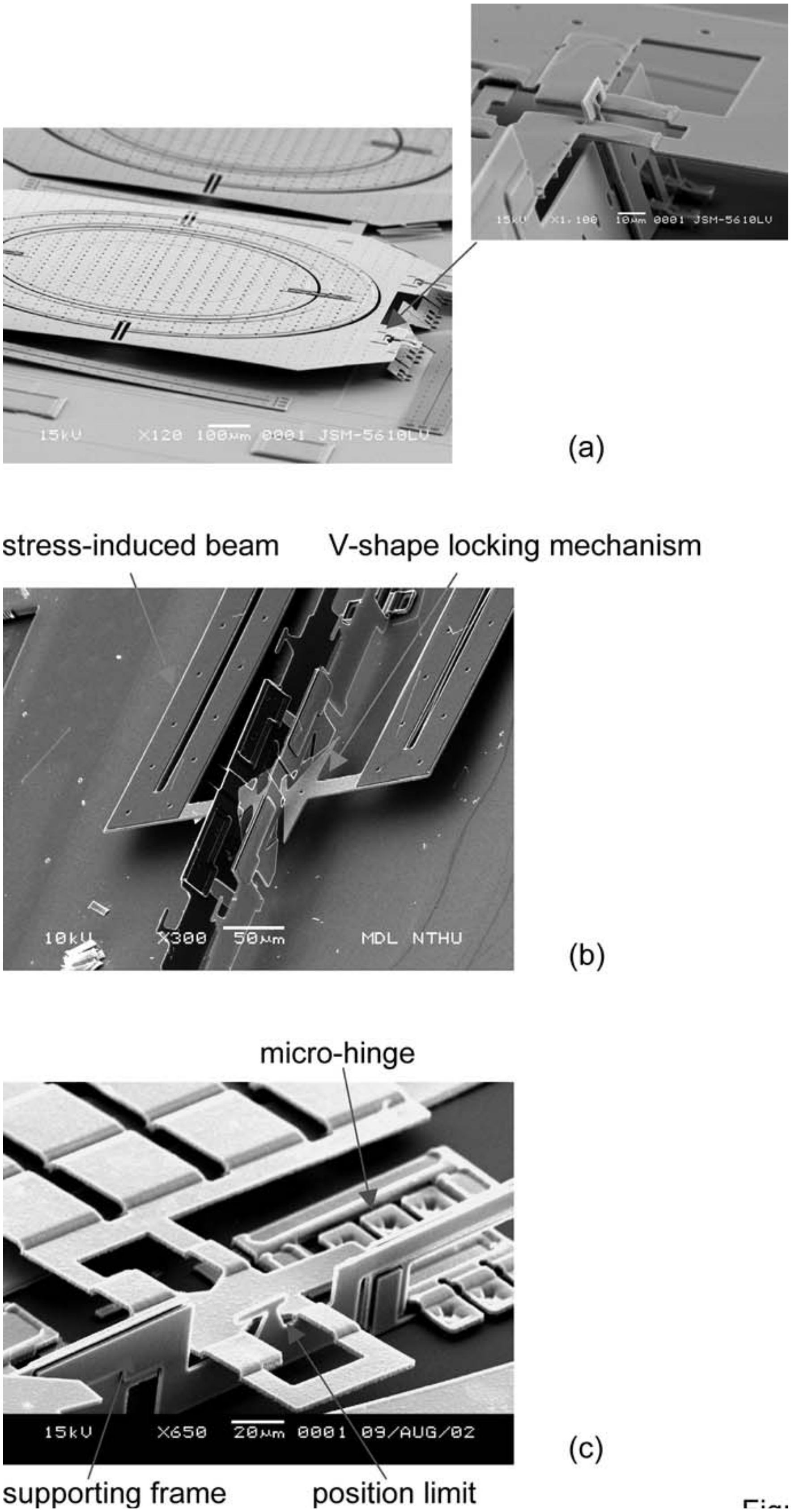

Fig. 6. (a) 3D optical switch accomplished with this novel mechanism. (b) The fabrication result of the V-shape locking component shown in Fig. 3(b). (c) The fabrication results of the position limit and supporting frame shown in Fig. 3(b)

reduced with adopting the dielectric film. Moreover, with the proposed novel locking component, more robust and reliable self-assembly stress-induced microstructure can be accomplished. The feasibility of the stress-induced self-assembly mechanism is also demonstrated. No matter for the applications of lifter or actuator, this study has pro-

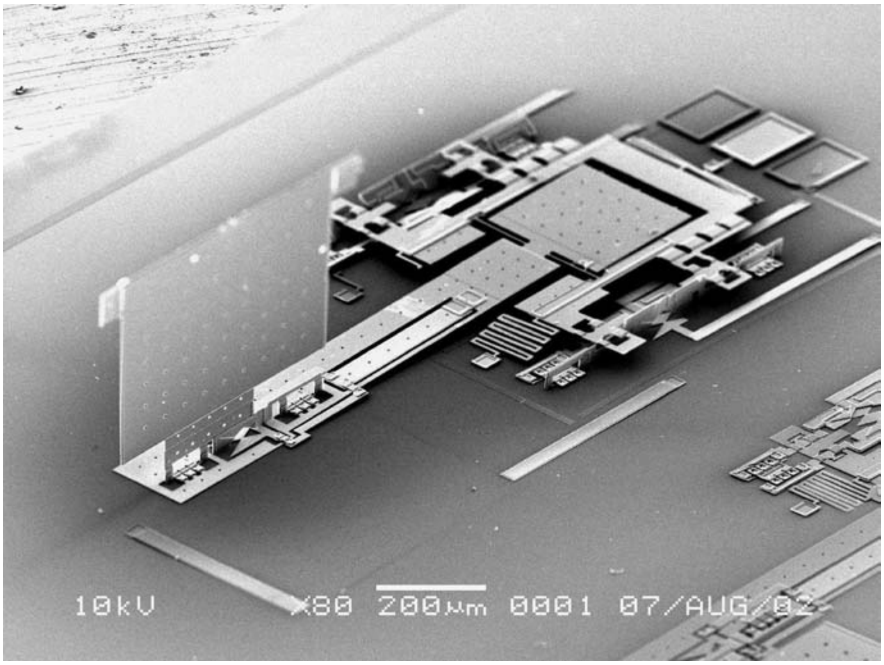

Fig. 7. Optical application demonstrates the feasibility of this supporting mechanism

vided both the solution of modified stress-induced beam and the novel locking component. Consequently, applications adopting the stress-induced self-assembly mechanism can be more extensive.

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