Microfabrication of hybrid structure composed of rigid silicon and flexible PI membranes

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The authors have designed and microfabricated millimetre-scale wing-shaped hybrid microstructures composed of rigid structures of single crystal silicon (SCS) substrates and flexible polyimide (PI) membranes. The wing-shaped microstructures mimicking insect flapping flight have been newly designed using a fluid-structure interaction analysis, and the hybrid microstructures based on the design method have been successfully microfabricated using a simple process flow with SCS substrates coated with PI membranes. Shape of the SCS parts in the hybrid microstructures have been successfully fabricated using deep reactive ion etching of the SCS substrate with small etching rate, and the wing plates of PI membranes have been prepared with the photolithography and the curing processes. The flexibility of the PI membranes of the fabricated hybrid microstructures was also confirmed using the bending test of the PI membranes.

1. Introduction: Three-dimensional (3D) microstructures of single crystal silicon (SCS) have received much attention as the key structures of bulky movable micromechanical components, and have been already used in the technical applications such as the micromechanical resonators and microcantilevers [1, 2]. The SCS offers advantages as the structural material of the movable microstructure because of the high mechanical stiffness and the low internal loss. The SCS is also convenient to create microstructure using microfabrication technologies including deep reactive ion etching (D-RIE) process of silicon. Recently, the hybrid microstructures including rigid silicon components and some flexible organic polymers also have shown much potential for some applications such as microrobots [3] and sensing devices on a flexible substrate [4]. In the fabrication of the hybrid structures, polyimide (PI) is one of the organic polymers widely used for many electrical applications as the flexible substances [5], which is known for high thermal stability, chemical resistance, and insulation performance.

In this Letter, we have designed and fabricated millimetre-scale wing-shaped hybrid microstructures composed of the rigid silicon structures and the flexible PI membranes. In the microfabrication, we have proposed a fabrication process with SCS substrates and photosensitive PI, and have successfully fabricated the hybrid microstructures using D-RIE of the SCS substrates with small etching rate. Flexibility of the PI membrane part of the fabricated hybrid microstructures could be achieved using curing process under low-oxygen condition and was also confirmed using the bending test of the PI membrane.

2. Deign of the hybrid microstructures: In this Letter, we have newly designed and fabricated a millimetre-scale wing-shaped hybrid microstructure, which is schematically shown in Fig. 1. This structure demonstrates the microflexible wing mimicking insect flapping flight proposed in our previous studies [6, 7]. The present design is briefly summarised as follows.

Fig. 2 shows the concept of the microflexible wing mimicking insect flapping flight. As shown in this figure, the so-called 2.5D structure was adopted for the microflexible wing. In this structure, the elastic membrane is used for the wing membrane, and the stiff beam at the leading edge is used to support the elastic membrane. This wing flaps and its pitching motion is caused by the interaction with the surrounding air to create the sufficient lift [8–11]. The small input from the microactuator is amplified to flap the wing with the large stroke angle using the resonance due to the plate spring placed at the wing base.

In this Letter, the substrates of SCS and PI membrane were used, respectively, for the stiff parts such as the leading edge (beam structure) and the wing base, and the flexible parts such as the wing membrane and the plate spring. Therefore, the hybrid microstructure is the fundamental structure of the microflexible wing. The dimensions of each part of the hybrid microstructure have been determined using a fluid-structure interaction analysis [6, 7], where the equilibrium equation for the elastic body, the incompressible Navier–Stokes equations, and their interface conditions were monolithically solved using the finite element method [12, 13].

For the millimetre-scale wing length, we found the area of the satisfactory design solutions or the design window (DW) [14] in the vicinity of the resonance frequency, where each satisfactory design solution can generate enough lift to support the weight of the actual small fly. Fig. 3 shows an example of DW in the case, where the wing length was set as 2.5 mm. Finally, the hybrid microstructure for the fabrication was determined based on this DW.

3. Microfabrication of the hybrid microstructures: For the microfabrication of the millimetre-scale wing-shaped hybrid microstructures as shown in Fig. 1, we need to propose the methods to combine the flexible parts of thin PI membrane with the rigid SCS parts of the wing (leading edge and wing base). In this Letter, we employed spin coating of photosensitive PI solution to prepare the thin PI membrane on the SCS substrate and to combine those two materials. We used a 100 µm thick SCS substrate to fabricate the rigid SCS parts. Moreover, we controlled the final thickness of the thin PI membrane to be about 1 µm by selecting the proper rotation speed in the spin coating of the photosensitive PI solution.

In detail, the wing-shaped microstructures composed of SCS and PI have been microfabricated using the process flow as shown in Fig. 4. At first, the photosensitive PI spin coated on the SCS substrate (Fig. 4*a*) was patterned using photolithography process. After that, the SCS substrate with the patterned PI membranes was heated in an electric furnace to cure the PI membranes for 1 h at about 200°C under low-oxygen condition (Fig. 4*b*). Then, a support substrate of SCS (thickness: about 525 µm) was temporarily bound to the upside (the side with the patterned PI membranes)

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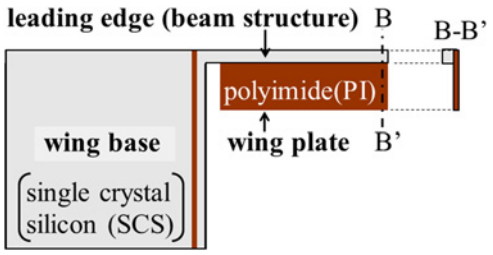


Fig. 1 *Schematic diagram of wing-shaped hybrid microstructure composed of rigid SCS and PI membranes*

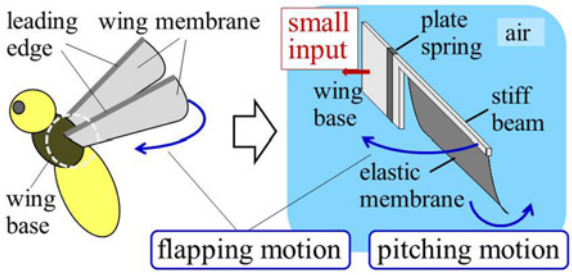


Fig. 2 *Concept for the design of microflexible wings mimicking insect flapping flight*

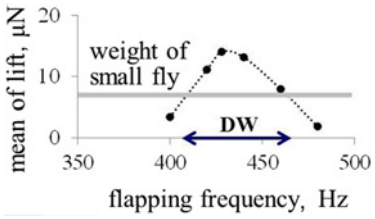


Fig. 3 *Example of the DW in the case where the wing length was set as 2.5 mm*

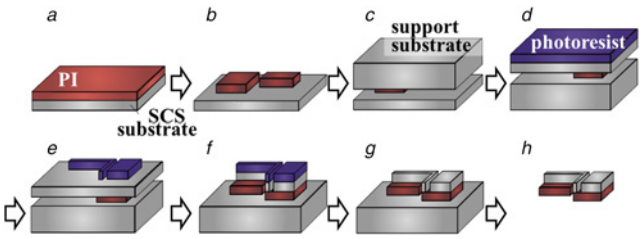


Fig. 4 *Process flow of the wing-shaped hybrid microstructure*
a Spin coating of photosensitive PI on an SCS substrate
b Photolithography and curing of patterned PI membranes
c Bonding of a supporting substrate to the side with the patterned PI membranes of the SCS substrate
d Spin coating of photoresist on the backside of the SCS substrate
e Photolithography of photoresist
f D-RIE through the SCS substrate with photoresist mask patterns from the backside
g Removal of residue of the photoresist patterns
h Release of wing-shaped hybrid microstructure from the supporting substrate

of the SCS substrate with commercially available thermal release sheets for electronic component processing (Fig. 4*c*). The support substrate was used to prevent the warp and break of the PI membranes and the SCS substrate during the subsequent processes in the microfabrication. It was also useful to protect the surface of

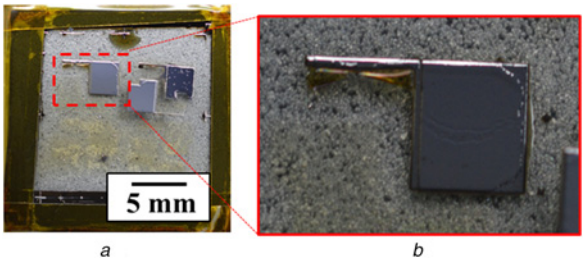


Fig. 5 *Photographs of wing-shaped hybrid microstructures fabricated on the support substrate after the D-RIE process*
a Three microstructures on the support substrate
b Magnified image of one of the microstructure

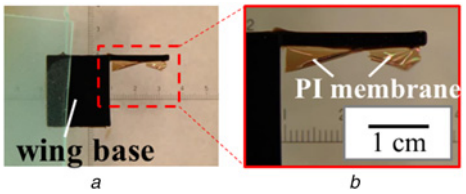


Fig. 6 *Photographs of a released wing-shaped hybrid microstructure*
a Whole structures of the hybrid microstructure
b Magnified image around the PI membrane

the cured PI membrane and to promote the convenience in the treatment of the sample in the microfabrication. Moreover, photosensitive resist (photoresist) spin coated on the backside of the SCS substrate was patterned using photolithography process to prepare the protection mask pattern for the D-RIE process of the SCS substrate (Figs. 4*d* and *e*). After the D-RIE process through the SCS substrate (Fig. 4*f*), the residual photoresist pattern was removed (Fig. 4*g*). Moreover finally, the wing-shaped hybrid microstructures were released with the aids of the heated thermal release sheet from the support substrate which had been temporarily bonded in step *c* (Fig. 4*h*). In the release, we could softly release the fabricated microstructure without loading of the large peeling force onto the microstructure because the adhesive strength of the thermal release sheets was dramatically decreased when the sample with the release sheet was heated.

In the microfabrication of the hybrid microstructures, the precise control of the condition in the curing process of PI membranes (Fig. 4*b*) is strongly required to prepare the flexible PI membranes. Therefore, in the preliminary experiments, we had attempted to find the enough flow rate of nitrogen gas through the electric furnace in curing to prepare flexible PI membranes. When the flow rate of nitrogen gas was not enough, the cured PI membranes were so brittle, and they broke into pieces so easily when we touched the PI membrane with tweezers. However, when we set the gas flow rate of nitrogen to be large enough in the curing process, the fabricated PI membranes kept the flexibility as described in the next section. In the microfabrication process, the D-RIE process of the SCS substrate was also so important step to fabricate the rigid SCS microstructures combined with the thin flexible PI membranes. Therefore, we also had investigated proper process conditions in the D-RIE process (Fig. 4*f*), and used the controlled D-RIE process condition with so small etching rate of SCS (about 1.1 μm/min) to prevent the break of the PI membranes.

Fig. 5 shows photographs of the wing-shaped hybrid microstructures fabricated on the support substrate by the controlled D-RIE process condition. After that, we have successfully released the hybrid microstructures from the support substrate as shown in Fig. 6. Those experimental results indicate that the millimetre-scale hybrid microstructures which unify the rigid silicon parts and the

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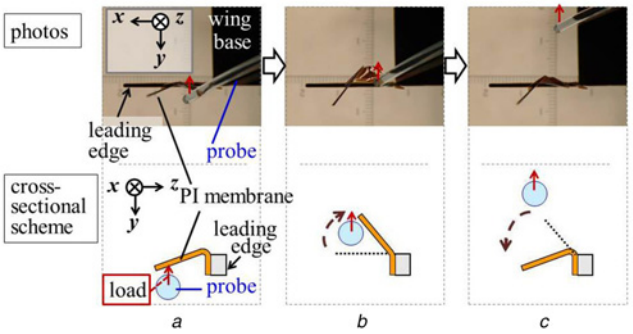


Fig. 7 *Flexibility measurement of PI membrane of the fabricated wing-shaped hybrid microstructure*
a Step-1: load was added to PI membrane from the probe
b Step-2: PI membrane deformed by added load
c Step-3: PI membrane returned to the original shape when the load had been removed

flexible PI membranes can be successfully fabricated using the simple microfabrication method we have proposed in this Letter though the patterned PI membrane has been partly broken. It is likely that the PI membrane has been broken because the mechanical strength of the thin PI membrane (thickness: about 1 μm) was not enough to prevent the break in the microfabrication. Therefore, it is probable that the increase of the thickness of the PI membrane is favourable to prevent the break of the membrane.

4. Flexibility measurement of the fabricated PI membrane: In the fabrication of the hybrid microstructure of this Letter, it is also required to prepare the wing plate of flexible PI membranes. Therefore, we also have investigated the flexibility of the PI membrane of the fabricated microstructures. In detail, we have added load to the PI membrane (wing plate) of a fabricated hybrid microstructure to confirm the flexibility of the PI membrane. Fig. 7 shows the results of an experiment, in which a PI membrane was deformed by adding load with the moving probe (bending test). The PI membrane was deformed when the load was added to the membrane by the probe (Fig. 7*a*), and the PI membrane kept the deformed condition while the load was added (Fig. 7*b*). However, the PI membrane returned to the original shape when the added load had been removed (Fig. 7*c*). The flexibility of the PI membranes of the fabricated microstructure was confirmed using the bending test of the PI membrane.

5. Conclusion: In conclusion, we have designed and microfabricated millimetre-scale wing-shaped hybrid microstructures composed of rigid SCS structures and flexible PI membranes. In microfabrication, we have proposed a simple process flow with SCS substrates coated with PI membranes. Moreover, the flexibility of the PI membranes of the fabricated hybrid microstructures was also confirmed using the bending test of the PI membranes.

From the experimental results we showed in this Letter, we can also demonstrate the potential of the proposed microfabrication method for the adaptable and practical microfabrication of the millimetre-scale hybrid microstructures with the wide range of shapes and sizes. First, we can independently fabricate each part of the SCS and PI in separate processes. In details, shapes of the SCS parts in the hybrid microstructures have been successfully fabricated using D-RIE of the SCS substrate with small etching rate, and the wing plates of PI membranes have been prepared with the photolithography and the curing processes under low-oxygen condition. Secondly, the thicknesses of the PI membranes can be easily controlled by the rotation speed in the spin coating of the photosensitive PI solution (Fig. 4*a*) because we had employed the conventional spin-coating method to prepare the PI membranes.

Moreover furthermore, the proposed microfabrication method can be applied for fabrications of the wide range of hybrid microstructures such as the array of micromachined sensor elements with flexible sheet substrates [15] in addition to the hybrid microstructure for part of the microrobot systems.

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