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Rolling origami with smart materials

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Three-dimensional (3D) functional devices have become an interesting topic meeting the challenge of device miniaturization and high integration in electron devices and microelectromechanical systems. Based on this exciting situation, origami in micro/nanoscale combining art and advanced science was widely utilized to transform two-dimensional (2D) sheets into 3D microstructures for various applications, such as micro-grippers [1] (Fig. 1a), 3D photodetectors [2], ultrasensitive sensors [3], robots [4], and energy devices [5]. Gradually, researchers explored classes of origami methods in micro/nanoscale originated from different principles as buckling, folding and bending [6,7]. Among various methods, rolling origami is a tantalizing technique which rolls 2D patterns up by internal stress to transform into 3D microstructures. Rolling origami provides a convenient way to in situ convert ultra-thin nanomembranes into rolled-up 3D structures. Moreover, rolled-up microstructures not only contain different geometries as tubes, and helices, but also permit all kinds of materials ranging from polymers to metals and oxides [8,9]. Recently, 3D functional devices based on rolled-up microstructures with smart materials were added into the functional device family. Smart materials are a large group of materials which have responsive behavior with external stimuli. Benefiting from the high energy density, strain sensitive and soft properties of curly nanomembranes, rolled-up microstructures with smart materials perform quick response ability and large deformation amplitude, which pave the way towards responsive 3D micro/nanostructures. Herein, we introduced two works [10,11] to give a glimpse into the great potential of 3D functional micro/nanostructures based on rolling origami combined with smart materials.

Researchers reported a rolled-up structure as visual hydrogen detector established on the stimuli-responsive behavior of palladium (Pd) in hydrogen milieu [10]. Some excellent properties, such as high integration, sensitive detection and enhanced macroscopic visual could be realized in this rolled-up structure. Authors claimed that nanomembranes were deposited layer by layer on the patterned photoresist layer to construct prestress. After etching the photoresist layer, a high integrated array was then realized on chip attributed to internal strain. With hydrogen stimuli, the whole array of rolled-up structures would uniformly change from tubular structures to planar status due to volume expansion of Pd after hydrogen absorption (Fig. 1b). This high integration and orderliness features profit from using rolling origami in the size of micro and nano, as well as could make rolled-up structures be an integrated system. Furthermore, the rolled-up structure with the small-thin nanomembrane is highly sensitive to strain, which enables quick stimuli-responsive behavior in the system. Here, authors demonstrated that the array had a response time of several seconds, which would be a quick stimuli-responsive behavior for the hydrogen detection without electrical contact and energy supply. Meanwhile the properties could be improved with optimal structure design or electrical readout for optical changes. Combining high-density array of detector and short stimuli-responsive time, applications of enhanced macroscopic visual based on this device were illustrated. With hydrogen stimuli, the visual change of FUDAN characters and FUDAN logo would occur as depicted in Fig. 1c and d, which could be a meaningful technique in the integration design. Hence, rolling origami with smart materials would be reliable to fabricate rolled-up structures as 3D functional devices for detection.

Not only for hydrogen detection, researchers also reported a microactuator based on rolled-up structures with vanadium dioxide (VO_2) [11]. VO_2 has a metal–insulator transition (MIT) at 68 °C which is widely applied as actuator. Compared with conventional actuators, rolled-up structures with ultra-thin VO_2 nanomembranes would have large deformation with small strain. Moreover, microstructure with tubular shape is a novel structural form as VO_2 microactuator, which could have great potential for functionalized devices. In this work, authors fabricated a rolled-up structure consisting of Cr/VO_2 biomorph. With different thickness of Cr layer, the internal strain in the nanomembranes would be different, which influences the curvature of the rolled-up structure. After releasing internal stress, the nanomembranes were transformed to tubular microstructures with different diameters, as shown in Fig. 1e. Interestingly, benefiting from controllable internal strain of nanomembrane, different phase transition temperature of VO_2 was realized in the rolled-up structure, which was observed in the tests of curvature and resistance during heating and cooling. Furthermore, the microactuator was transformed from the tubular structure to a planar nanomembrane under stimuli as increasing temperature, and when temperature decreased to room temperature, the planar nanomembrane was rolled into the tubular structure, as shown in Fig. 1f. The deformation from tubular status to

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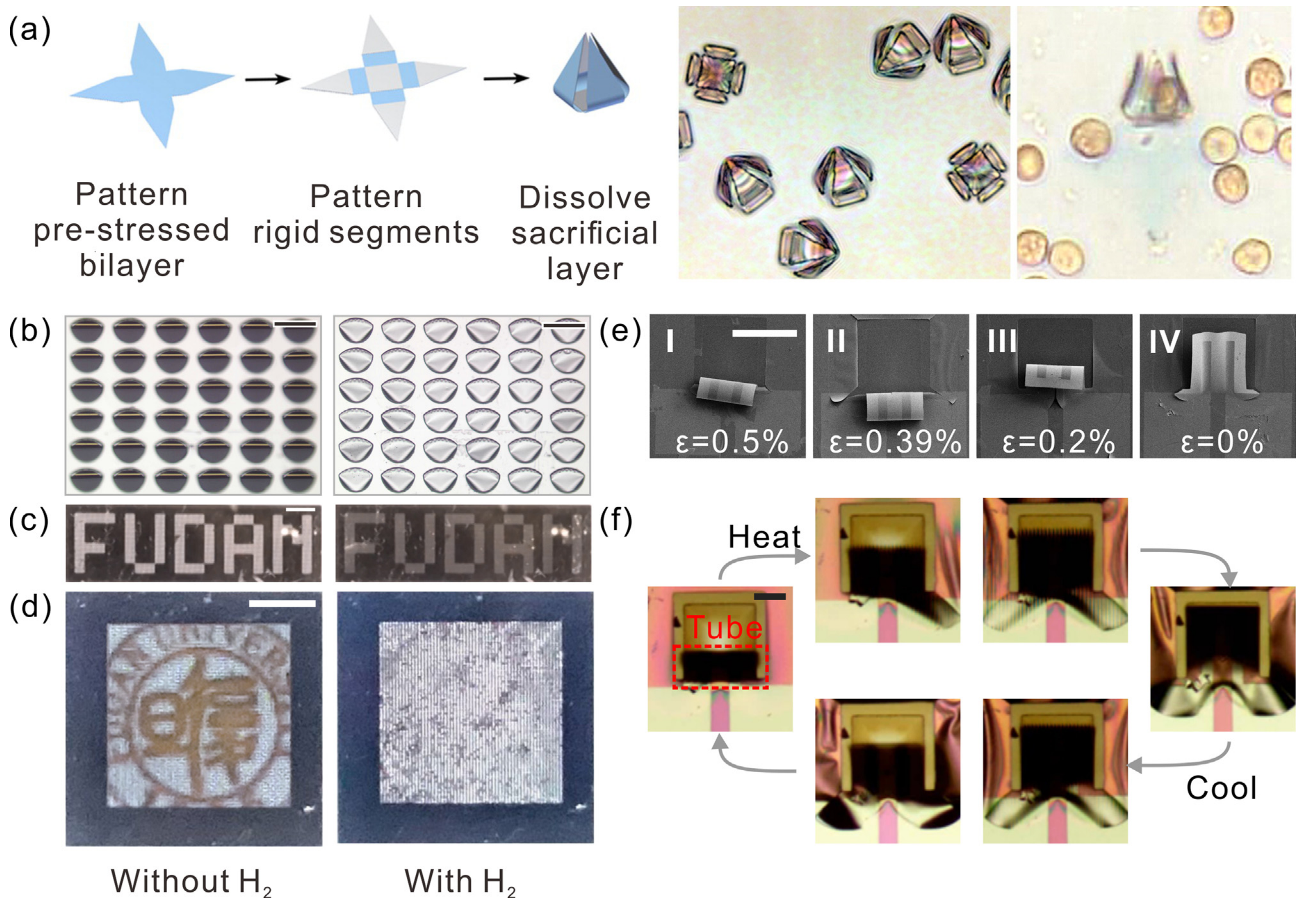

Fig. 1. (Color online) Origami structures as grippers [1] and rolled-up microstructures with smart materials as detectors and actuators [10,11]. (a) Model and mechanism for micro-grippers by origami. The grippers are 30-50 μm in diameter and the red blood cells are 6-8 μm in diameter. (b) Scheme of hydrogen detection and high integration devices based on rolled-up microstructures. Scale bars, 500 μm. (c) Enhanced macroscopic visual hydrogen detection with "FUDAN" character. Scale bar, 2 mm. (d) Enhanced macroscopic visual hydrogen detection with "FUDAN" logo. Scale bar, 2 mm. (e) Scheme of temperature-dependent microactuators and controllable rolled-up structures with different curvatures. Scale bar, 100 μm. (f) The curvature changes of rolled-up microactuators during heating and cooling. Scale bar, 50 μm. Reprinted with permission from Ref. [1,10,11], Copyright 2014 American Chemical Society, 2018 Science publishing group, and 2018 American Chemical Society.

planar status is large with such small strain (less than 1%), attributed to the ultra-thin nanomembrane. Based on these exciting results and previous work, the rolled-up structures would have capacity applied in tunable and functional devices. Moreover, as established on origami induced programmable morphing in robotics [12], the rolling origami would also show great potential in the applications of micro and nano robotics.

In conclusion, rolled-up microstructures with smart materials show nontrivial properties utilized in 3D functional devices. Rolling origami could make 2D ultra-thin nanomembranes be programmable transformed into 3D rolled-up microstructures by design. Owing to high integrated, strain sensitive and soft properties, rolled-up structures with ultra-thin nanomembranes have evident advantages in stimuli-responsive devices ranging from 3D detectors, electric switches, antennas to actuators and artificial muscles. Due to these inspiring results, we believe that rolling origami with smart materials would become an important method in the 3D functional devices, such as energy storage devices, electric devices, wearable devices and robots.

Conflict of interest

The authors declare that they have no conflict of interest.

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