Environmentally responsive active optics based on hydrogel-actuated deformable mirror arrays

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ABSTRACT

We report hybrid polymer actuator arrays based on environmentally responsive hydrogel and actuatable optical microstructures that are designed to reversibly switch optical properties in response to the environment. Arrays of micrometer scale plates were patterned by deep reactive ion etching of silicon which served as master structures for replica molding in polydimethylsiloxane (PDMS). UV-curable epoxy was cast in a metal-sputtered PDMS mold to transfer a thin metal film onto each microplate to form a micromirror array. Polyelectrolyte hydrogel, such as poly(acrylamide-*co*-acrylic acid), was patterned on the micromirror array and acted as an artificial muscle, bending the micromirrors in response to the change in humidity or pH. Such hybrid systems showed reversible switching between high transmittance (low reflectivity) and low transmittance (high reflectivity) without the aid of external power. Our design of hybrid actuated optics opens a broad avenue for developing environmentally responsive adaptive and active optics.

Keywords: adaptive optics, reconfigurable structures, hydrogel, micromirror, transformable architecture

1. INTRODUCTION

Reconfigurable and transformable surfaces based on adaptive actuated structures are an emerging technology as dynamic materials[1] and systems that can enable new applications including microfluidic mixing,[2] particle propulsion and fluid transport,[3] capture and release systems,[4] and antifouling.[5] We have recently reported a novel bio-inspired actuation system in which flexible, polymeric high-aspect-ratio microbristle structures ("bones") are actuated by the swelling and contraction of a humidity-responsive acrylamide (AAm) hydrogel ("muscles").[6-7] The actuation directions and formation of reversible surface patterns could be controlled by modulation of hydrogel thickness. Combination of soft lithographic techniques and hydrogel patterning allowed for the fabrication of actuated polymeric nano/microstructures in a variety of sizes and shapes with a broad range of mechanical and chemical properties. The responsive materials acting as the actuator "muscle" can be further tailored for different responsiveness, such as pH or temperature, for a range of applications. We have also reported dynamic structures based on asymmetric nano/microstructures, such as microplates, in which the bending orientation is further biased due to reduced symmetry, thereby achieving a large area uni-directional bending actuation.[8]

Active optics is a concept first introduced by Horace W. Bobcock in 1953[9] in which the characteristics of optical components are actively controlled to sense and modify optical wavefronts in real-time to optimize the performance in the presence of external perturbation.[10-11] Typical applications include the maximization of the power density of a

laser beam onto a target, maximization of the angular resolution of a telescope operating through a turbulent atmosphere, lens testing, femtosecond pulse shaping, and since recently, measuring and correcting the high order aberrations of the human eyes in ophthalmology.[10] Current technologies to construct active optics comprise Bragg cells, segmented mirrors, deformable mirrors, monolithic mirrors, and membrane mirrors. Among these, deformable mirrors are the most commonly used platform with convenience and fast operating speed to sense and control the wavefronts.[12] However, deformable mirrors still need to overcome major drawbacks, such as limited stroke and high production cost.

Here we introduce a new concept that utilizes the adaptive function of responsive polymer gels to design reversibly reconfigurable, deformable mirror arrays. We fabricated an array of micromirrors embedded in a humidity or pH-responsive hydrogel layer, which adaptively deforms individual micromirrors according to the changes in the surrounding environment without requiring external input power. The response time of deformation is quite fast, typically on the order of tens to hundreds of milliseconds, and tunable deformations can be achieved according to the swelling ratio of the hydrogel used. Also of importance, the production cost of these adaptive systems is much lower than those utilizing existing methods, such as the fabrication of liquid crystal light modulators. Although there are still many remaining challenges to bring this concept to real applications, we envision that our new concept of using adaptive materials as the driving mechanism of the actuators will have a profound impact on the design and utilization of future generation, high-performance adaptive optics for astronomical imaging and vision research as well as for new optical applications operating in the presence of environmental stress.

2. **EXPERIMENTAL**

Figure 1 shows a schematic for fabrication of a hybrid actuator using an array of microplates and a pH-responsive polyelectrolyte hydrogel. The Si master of the microplate array was fabricated by patterning an array of microbars as etch masks and subsequently etching the Si by the Bosch etching process. The surfaces of Si masters were modified with a monolayer of a fluorinated silane, perfluorooctyltrichlorosilane, by vapor priming. PDMS (Dow Sylgard 184) molds were made from the Si masters as described previously.[13] The epoxy replicas of microplate arrays were fabricated by casting a prepolymer mixture (9:1 wt./wt. of Epotek UVO114 and glycidylmethacrylate) onto the PDMS mold followed by UV curing and peeling off the PDMS mold. A pre-polymer solution of a pH-responsive hydrogel was prepared by dissolving 200 mg of acrylamide (AAm), 200 mg of acrylic acid (AA), 20 mg of N,N-methylenebisacrylamide (BIS), and 20 mg of a phototoinitiator, 1-[4-(2-Hydroxyethoxy)-phenyl]-2-hydroxy-2-methyl-1-propane-1-one, in deionized water. The mixture was stored in the dark in a refrigerator until use. A drop of the pre-polymer solution (*ca.* 3 μL per cm^2 of sample surface area) was applied onto the microplate array replica then a coverslip was placed to cover the area. The assembly was exposed to UV light (Blakray, 100 mW/cm^2) for about 5 minutes to polymerize and crosslink the hydrogel. After the UV exposure, the assembly was immersed in deionized water for 30 minutes to swell the hydrogel, which allowed separation of the coverslip from the hybrid actuator assembly without damaging the hydrogel layer.

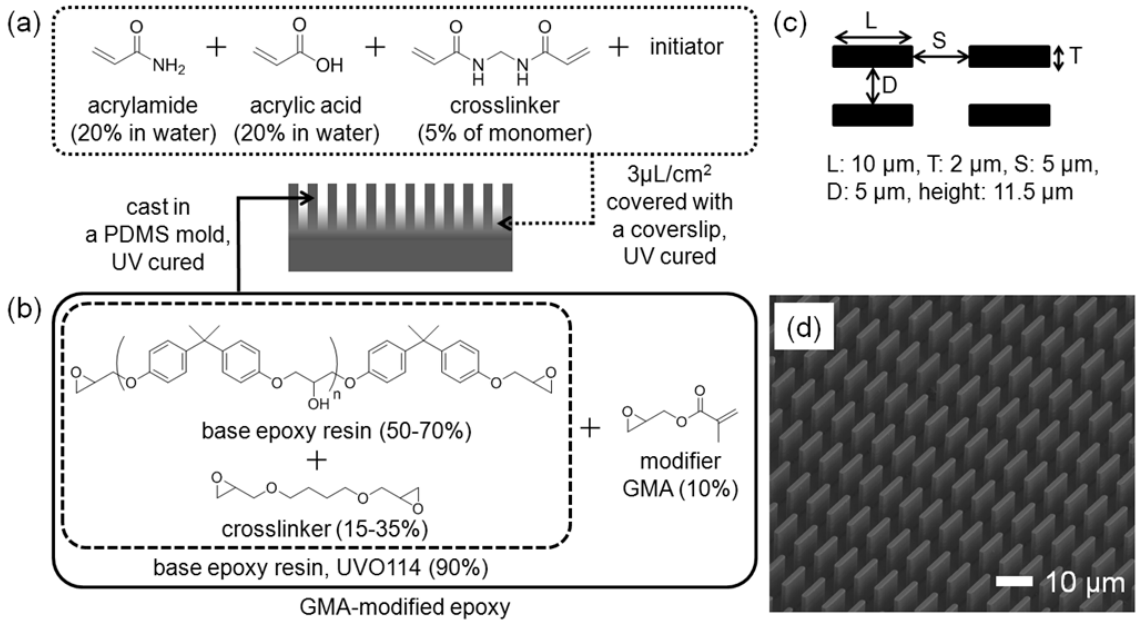

Figure 1. Schematics of hybrid actuator fabrication. (a) the components of the pH-responsive hydrogel, (b) the chemical structure of UV-curable epoxy modified with a bifunctional monomer, glycidylmethacrylate (GMA), to covalently attach hydrogel, (c) the dimensions of a microplate array, and (d) a scanning electron microscope (SEM) image of epoxy microplate array.

To turn the microplate structures into micromirrors, metal must be deposited on the surface and this was accomplished by two methods. Either a thin layer of metal (200 nm gold or silver with 10 nm of titanium as an adhesion layer) was shadow evaporated onto an epoxy microplate surface, or metal was sputter-coated on to the PDMS microplate mold to form a conformal coating before epoxy replication. As shown in Figure 2, micromirror arrays with a high on/off contrast were fabricated by this second method, where the metal film on the top surface of the PDMS mold was first removed by using scotch tape, and subsequent epoxy replication yielded near 100% transfer of the thin metal film from PDMS to the epoxy replica due to the difference in the adhesion of the metal to the two materials. In this way, no metal was deposited on the bottom substrate of the micromirror array and only the surfaces of each microplate were coated with reflective metal.

An inverted optical microscope with a CCD camera and a scanning electron microscope (JEOL JSM6390) were used to record optical and SEM images, respectively. Optical spectra were recorded using a fiber-optic spectrometer (Ocean Optics USB2000+, 300-800 nm range) coupled to a microscope in a transmission geometry.

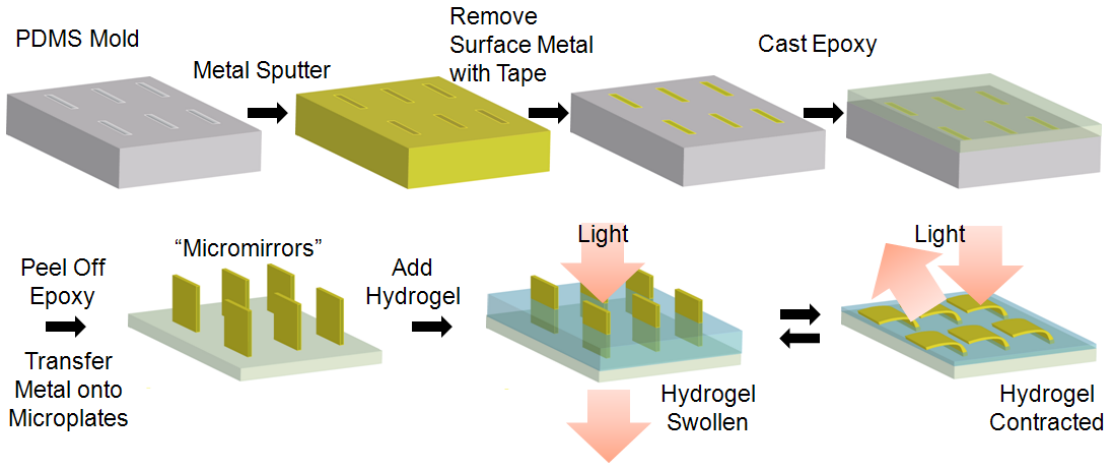

Figure 2. A schematic of micromirror array fabrication by metal deposition and transfer, hydrogel growth to form a hybrid actuator array, and the reversible switching of optical property of the hybrid actuator upon hydrogel swelling/deswelling.

3. RESULTS AND DISCUSSION

We fabricated a simple proof-of-concept adaptive and active optical surface: a micromirror array that adaptively changes reflectivity in response to humidity and pH change. Figure 3 shows the macroscopic change in transmittance and microscopic structural change of such a micromirror array. When the hydrogel expanded (*i.e.* when exposed to moisture, for the humidity-responsive gel or to pH > 4.25, for the pH-responsive gel), the micromirrors were in their normal upright configuration, maximizing the transmission of the incident light through the surface. When the hydrogel contracted (*i.e.* dried or exposed pH < 4.25) putting strain on the micromirrors, the mirrors were bent and the metal-coated side walls were facing the incident light reflecting it. This process was completely reversible and could be cycled many times by hydration/drying or by application of acid/base. The bending and unbending actuation response of the micromirrors was asymmetric and showed faster transition for bending than unbending, which is consistent with the general behavior of hydrogel swelling/deswelling kinetics.[14]

These hydrogel-driven micromirror arrays have rapid response to environmental stimuli and can change optical properties at a tunable rate, ranging from just fractions of a second to minutes or hours. The rate of hydrogel swelling and contraction is largely dependent on diffusion rates of water in and out of the gel, therefore for macro-scale structures this might be a slow process, but for a gel that is only a few microns thick, the process of diffusion occurs rapidly and fast response times (~10 ms) can be achieved. This means that the actuation rate is highly tunable, simply by changing the dimensions of the micromirror and accordingly the thickness of the deposited hydrogel layer. Even if the structures are entirely embedded in hydrogel, the transmittance at visible wavelengths remains largely unchanged due to the hydrogel being transparent to the visible light. Precise control of the composition and the thickness of the hydrogel may allow the control of the refractive index of the hydrogel layer during actuation for more sophisticated functions.

The direction of the deformation of the micromirrors is highly uniform over a large area as shown in Figure 3a; this figure shows several square centimeters of actuation, and the size is limited only by the size of the sample itself. This uniformity/unidirectionality is due to the large difference (~70 times) in the bending stiffness of the micromirrors perpendicular to the long axis and along the long axis, meaning that it takes substantially less energy for the mirrors to deform along a single direction. The degree of hydrogel swelling, as a function of environmental stress, can be controlled by carefully designing the composition of the hydrogel precursor solutions. They can be formulated to show a

sharp transition or to show a smooth transition in response to environmental stress. Moreover, this threshold of environmental stress can be precisely tuned by choosing different monomers for the hydrogel synthesis. This tunability will allow us to design systems with either abrupt switching of optical properties or continuous deformation and tilting of the structures to generate a gradual optical response in a pre-determined way. The examples shown in this paper may be useful as a low cost switchable transreflective mirror, a variable diffuser, a switchable optical polarizer, or can be further developed as a variable phase reflector.

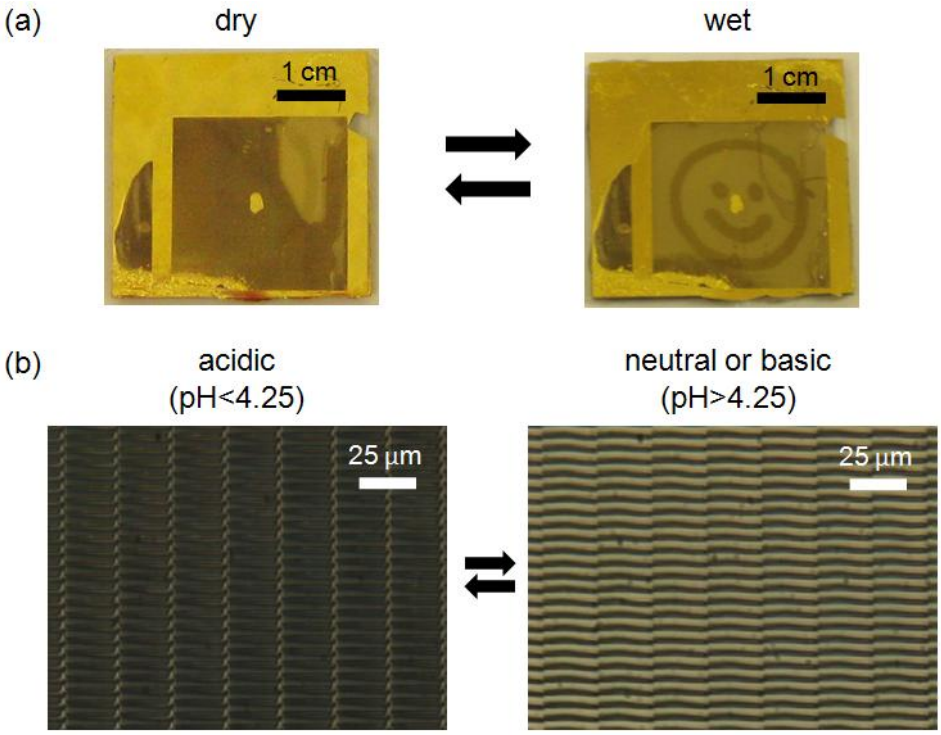

Figure 3. (a) Digital photographs of a large area (*ca.* 2cm x 2cm) hydrogel-actuated micromirror array switching between opaque and transparent states by humidity change. (b) Optical microscope images of a portion of a pH-responsive hydrogel-actuated micromirror array. The two images represent the lowest light transmission (left, contracted hydrogel) and the highest light transmission (right, swollen hydrogel). See Optional Multimedia File for a movie showing the actuation (http://dx.doi.org/doi.number.goes.here).

Figure 4 shows the transmission spectra of the pH-responsive hydrogel-actuated micromirror array shown in Figure 3b. Red corresponds to the low transmittance state (in an acidic environment) and blue corresponds to a high transmittance state (in a basic environment). It should be noted that the contrast between the two states is not optimally high due to the low ratio of the height of each micromirror to the spacing between each, as easily seen in Figure 3b. The contrast ratio can be increased either by using a thin and tall but narrowly spaced micromirror array or by using a micromirror array with staggered geometry to cover the entire surface when the mirrors are bent. The arrangement of the micromirrors can be designed to cover desired fractions of the surface area upon actuation.

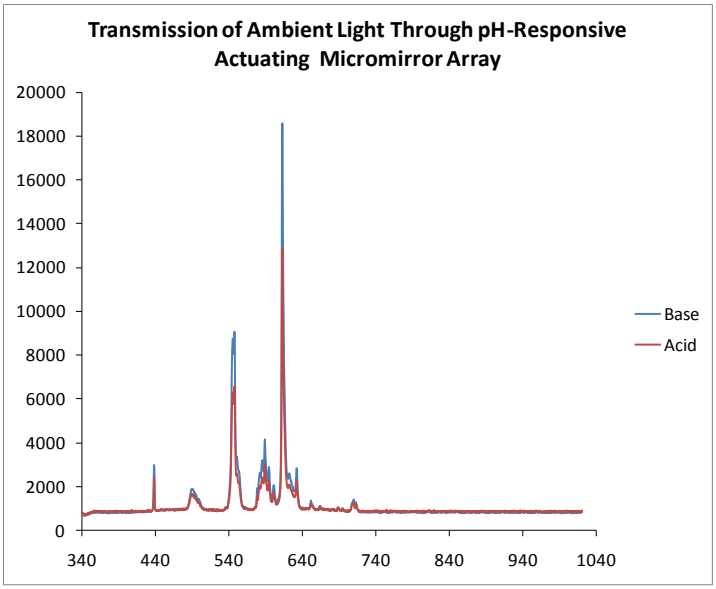

Figure 4. Transmission spectra of a pH-responsive hydrogel-actuated micromirror array for low transmittance (acid, red) and for high transmittance states (base, blue).

The development of particular applications of the adaptive optics based on temperature-responsive hydrogels and light-responsive hydrogels is currently under way. Furthermore, we are exploring approaches to multi-responsive active optics via combining modular hydrogels responsive to different stimuli.

4. CONCLUSIONS

We have demonstrated a new design concept for active optics by using deformable mirrors based on an actuatable micromirror array and a layer of environmentally responsive hydrogel. As our approach can be applicable to various microstructures with well-established responsive artificial muscles, when combined with various existing designs of active optics, the range and scope of the development of next generation active optics components using this platform are exceptionally wide.

5. ACKNOWLEDGEMENT

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