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# Synthesis of photoacid crosslinkable hydrogels for the fabrication of soft, biomimetic microlens arrays

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**Soft, biomimetic microlens arrays were fabricated by interference lithography from the copolymers of poly(2-hydroxyethyl methacrylate), whose hydroxyl groups were crosslinked by photoacids and external crosslinkers.**

Clear vision is an important adaptation to biological organisms. Million of years of evolution have perfected many of their optical features that adjust their properties in response to external stimuli.[1] For example, the human eyes have bending lenses that dynamically change focus and gains, while the muscles in the octopus eyes move the lens backwards and forwards within the shell, resulting in much stronger focus than human eyes.[1] Brittlestars cover their body with solid microlens arrays (Fig. 1) that function as an adaptive optical device with the "transition sunglasses" capability: the lenses guide and concentrate light onto photosensitive tissue, and the intensity of light reaching the receptors is regulated by the movement of pigment in the porous network.[2,3] The unique capability in bio-optics makes it attractive for researchers to mimic the biological design and functions for multi-faceted roles because most technological microlenses only have simple functions, and therefore the attainable range of their tunability and complexity is rather limited. We recently synthesized rigid biomimetic microlens arrays with integrated pores from epoxy (SU8), whose appearance and function are markedly similar to their biological prototype.[4] The complex microstructure was created directly by three-beam interference lithography in a single, few seconds exposure over an area of several $mm^2$. These synthetic microlenses can be used as (i) an adjustable lithographic mask,[5] and (ii) tunable optical device transporting liquids in and out of the porous channels.[4] The shape and position of rigid microlenses are fixed once fabricated. To provide further tunability of optical properties, it will be highly desirable to replace rigid microlenses with *soft* structures, which could change the geometry and refractive index continuously in response to external stimuli.

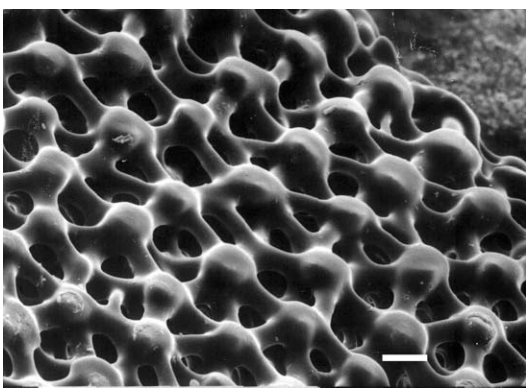

**Fig. 1** Scanning electron micrograph (SEM) of brittlestar microlens arrays. Scale bar 50 μm.

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Responsive hydrogels are such intelligent materials, whose volume and shape can change up to several hundred percent in response to external stimuli, such as pH, temperature, light, electric potential, chemicals, and biological agents. They have been used in drug delivery and as tissue scaffolds,[6,7] actuators and sensors.[8,9] The biocompatibility, flexibility, high transparency, high oxygen permeability and diffusivity in poly(2-hydroxyethyl methacrylate) (PHEMA) have made it the primary ingredient in soft contact lenses.[10] Other materials, such as poly(acrylate), poly(methacrylate), and poly(vinyl alcohol),[11,12] and self-assembled colloidal particles from poly(*N*-isopropylacrylamide-*co*-acrylic acid)[13] have also been studied.

Most reported hydrogels lenses are, however, prepared from their corresponding liquid monomers by free radical polymerization, which makes them inappropriate for multi-beam interference lithography. Photocrosslinking during exposure will disturb the original interference pattern due to the change of refractive index. The inhomogeneity of the radical formation and the lack of control over the radical diffusion in hydrogels has limited the resolution to 5 μm. In addition, radical polymerization from liquids is often accompanied by a large volume change, which causes swelling and collapsing that are detrimental to the formation of complex structured gels. A photosensitive hydrogel precursor that has a high glass transition temperature ($T_g$) and can be crosslinked by photogenerated acids clearly will be advantageous. In general, the generation of photoacids is much better controlled compared to that of radicals. The use of high $T_g$ polymers will improve the lens mechanical strength, minimize film roughness, and prevent unnecessary acid diffusion prior to post-exposure bake to achieve better resolution.

In this communication, we report the fabrication of soft, biomimetic lens arrays (see Fig. 2) from a photoacid crosslinkable hydrogel system, including hydrogel precursors, poly(2-hydroxyethyl methacrylate-*co*-methyl methacrylate, PHEMA-*co*-PMMA, 80 : 20, 70 : 30, 50 : 50 mol : mol), photoacid generators (PAG) and external crosslinkers, in a single exposure step for a few seconds using three-beam interference lithography. The well-controlled

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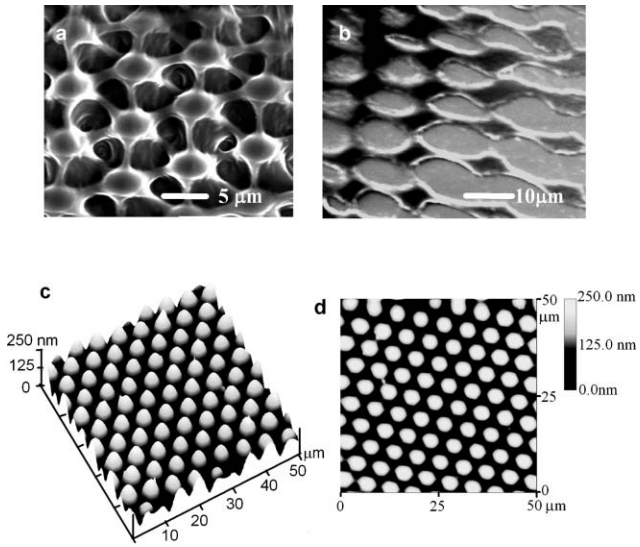
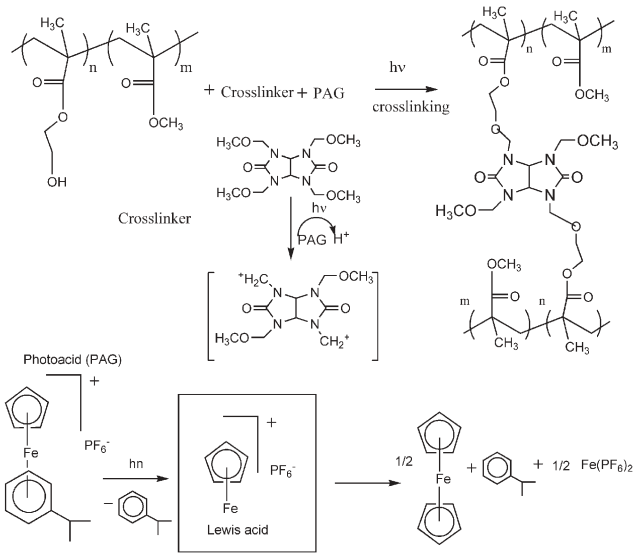



**Fig. 2** Hydrogel microlen arrays formed from poly(2-hydroxyethyl methacrylate-*co*-methyl methacrylate) by interference lithography. (a,b) SEM images of (a) non-deformed and (b) highly deformed microlens arrays. (c,d) Atomic force micrographs (AFM) of the topography of hydrogel lens arrays shown in (a) side (c) and top (d) views.




**Scheme 1** Schematic illustration of photoacid generation and crosslinking reaction in poly(2-hydroxyethyl methacrylate-*co*-methyl methacrylate).

photoacid generation and its diffusion in such system provides much improved resolution (minimum feature size up to ~600 nm).

We choose PHEMA and PMMA due to their relatively high $T_g$s, 108 and 100 °C, respectively. PMMA is copolymerized with PHEMA to control the content of hydroxyl groups and avoid physical gelation of PHEMA by itself. The copolymers were synthesized using 2,2′-azobis(2-methylpropionitrile) (AIBN) as the radical initiator. As an example, 14.0 mL of HEMA (15.0 g, 0.115 mol) and 5.3 mL MMA (4.9 g, 0.049 mol) were added to a 500 mL three-necked round bottom flask fitted with a thermometer, a condenser, and a septum, and dissolved in 200 mL of tetrahydrofuran (THF) under $N_2$. 0.2995 g of AIBN (1.5 wt%) were added to the solution after 20 minutes of stirring, and the reaction temperature was raised to 60 °C overnight. The excess THF was rotovapped off and the product was precipitated in diethyl ether. After another two cycles of dissolution in methanol and precipitation in diethyl ether, the resulting precipitate was dried under vacuum at room temperature, with an overall yield of 12.93 g (65.0%). The chemical compositions in polymers were calculated using $^1$H NMR ($\delta$, ppm in $CD_3OD$) from the hydroxy ethyl protons in HEMA ($HOCH_2CH_2$, 4.08, 2H and 3.82, 2H respectively) and the terminal methoxy protons in MMA ($OCH_3$, 3.66, 3H). The normalized molar ratio of HEMA : MMA is 72.6 : 27.4, close to the 70 : 30 mol : mol feed ratio. Since the copolymers are partially soluble in THF, their molecular weight and polydispersity were not measured by gel permeation chromatography (GPC).

The hydroxyl groups in the copolymers were crosslinked by photoacid generators and external crosslinkers (see Scheme 1). To ensure uniform generation of photoacids in interference lithography, we used a one-component photoinitiating system, ($\eta^6$-naphthalene)($\eta^5$-cyclopentadienyl)iron(II) hexafluorophosphate (Irgacure 261 from Ciba Specialty Chemicals), which has weak absorption in the visible regions as a visible photoacid generator, instead of the previously reported combination of visible photosensitizer and iodonium salt as photoacid generator.[14] Upon irradiation, the iron arene complex defragments to a coordinatively unsaturated, iron containing intermediate, which has the characteristics of a Lewis acid.[15] During post-exposure bake in the presence of a strong acid, tetramethoxymethyl glycoluril (TMMGU, from CYTEC Industries, Inc.) induces crosslinking through O-alkylation of both polyester and acrylic polymers that have hydroxyl functionality.[16,17] Since TMMGU has a high melting point (90–110 °C), it can dramatically increase the photoresist viscosity, which is especially desirable to achieve the maximum feature resolution with minimum flow or distortion during post-exposure bake at a temperature slightly above $T_g$ of the resist. It has been applied to negative tone photoresist systems, such as novolac resins and poly(*p*-hydroxystyrene).[16–18]

We performed three-beam interference lithography of the hydrogel precursors at visible wavelength ($\lambda$ = 532 nm) utilizing the same optics setup that we used for photopatterning of SU8.[4] The photoresist that consisted of poly(HEMA-*co*-MMA), 2 wt% Irgacure 261, and 10 wt% TMMGU, was dissolved in cyclopentanone. The solution was then spin coated on a precleaned glass substrate followed by soft bake at 90 °C to completely remove solvent, and exposed to a laser beam (output of 2 W) for 1–10 s. The exposed film was post-exposure baked at 120 °C for 20 min., followed by development in methanol to remove the unexposed region. The selective generation of photoacids occurred in regions that corresponded to the periodic variation in the interference pattern. The acid diffusion took place during post-exposure bake above the $T_g$. After development in alcohol, a contour of a lens is introduced in the highly exposed regions where the intensity exceeds a certain threshold, while the unexposed or very weakly exposed regions form pores.

Fig. 2 shows hydrogel microlens arrays that we synthesized using the above procedure. They are periodic and defect-free in a large area (diameter of 3–4 mm). It is worth noting the low shrinkage (<10%) in the lattice size of the soft microlens arrays compared to that of the rigid ones from epoxy (SU8),[4] in contrast

to the large shrinkage typically observed in radical-polymerized hydrogels. A minimum feature size of 600 nm was resolvable, demonstrating the strongly nonlinear threshold relationship between exposure dose and solubility in the interference lithography. The hydrogel lenses are highly deformable due to their soft nature. At the edge of the film where the hydrogel lenses were less crosslinked and not well-connected, they were often found stretched and deformed by the capillary force of alcohol during drying (Fig. 2b).

The use of PHEMA as a hydrogel precusor offers numerous synthetic and functional advantages. It can be copolymerized with various comonomers to realize different 3D hydrogel structures with tailored architectures, tunability and functionalities. For example, using responsive hydrogels as microlens materials, we could dynamically tune the lens shape, size, focal length, and/or refractive index,[19] to enhance the dynamic range of tunability beyond the rigid structures. Our initial results suggested successful photopatterning of microstructures from poly(2-hydroxyethyl methacrylate-*co*-acrylic acid) (HEMA-*co*-AA). Copolymerization with acrylic acid (up to 40 mol%) did not interfere with the crosslinking process, while making the hydrogel pH sensitive.[8,20,21] We have observed the change of focus in response to pH in shape tunable poly(HEMA-*co*-AA) hydrogel lens arrays.[22]

In addition, we test the incorporation of inorganic materials (*e.g.* $TiO_2$), which will strengthen the hydrogel lens mechanical properties without sacrificing its deformability, as well as increase the overall refractive index. It will be particular beneficial to use the above synthesized hydrogel precursors as matrix since the solvents (alcohol and water) used in hydrogel lens preparation and fabrication are compatible to the sol–gel chemistry. We have photopatterned poly(HEMA-*co*-MMA-*co*-AA) mixed with titanate pursor, Tyzor® AA-75 (from DuPont), using the same photochemistry. We found the latter system has a faster photospeed compared to that in the absence of TMMGU. The detailed results will be reported elsewhere.

In summary, we have successfully fabricated *soft*, biomimetic microlens arrays from various hydrogels, which potentially may provide much wider range of tunability of the optical properties due to the ability to change the geometry in response to external stimuli. We have demonstrated that photocrosslinking by photoacid generation mechanism results in a significant improvement of the film mechanical strength and allows one to achieve submicron resolution of the patterned features. Although it was demonstrated in poly(HEMA) copolymers, the chemistry and fabrication process can be conveniently extended to other hydrogel systems since the hydroxyl groups are readily available in biological and biocompatible polymers. We believe that the chemistry and process described in this communication is applicable to micropatterning of a variety of hydrogel systems with tailored architectures, functionalities and tunability

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