Fabrication of Arrays of Microlenses with Controlled Profiles Using Gray-Scale Microlens Projection Photolithography

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This paper demonstrates the use of microlens projection lithography using gray-scale masks to fabricate arrays of microstructures in photoresist. In microlens projection lithography, an array of microlenses (diameter $d = 1-1000$ μm) reduces a common, centimeter-scale pattern in an illuminated mask to a corresponding pattern of micrometer-scale images in its image plane. The pattern of intensity projected by the array of microlenses depends on the shape and gray-level distribution of the pattern on the illuminated mask and on the shape and pattern of the lenses. The distribution of intensity in the microimages could be adjusted using gray-scale masks. After the recording of this intensity distribution in layers of photoresist and developing, the developed resist showed arrays of 3D microstructures over areas larger than 10 cm^2. We used these arrays of 3D microstructures as masters and cast transparent elastomer onto them to generate complementary replicas. For a specific microlens array and a fixed light source, the profile of the 3D microstructures generated by this method depended on the pattern on the illuminated mask and on the distance of the mask from the lens array. An appropriate mask with noncircular, gray-level patterns generated arrays of 3D microstructures that acted as lenses. This technique generates arrays of noncircular microlenses over areas larger than 10 cm^2 in a single exposure.

Introduction

This paper describes a simple method for fabrication of arrays of microlenses with controlled profiles, using microlens projection lithography (μLPL) and gray-scale masks. Array-based microstructures with controlled topographies can be produced by lithographic techniques such as laser pattern writing,[1] holographic lithography,[2] and conventional photolithography using gray-scale masks.[3–6] These technologies have different advantages for the fabrication of microstructures. For example, laser pattern writing and conventional gray-scale photolithography can generate microstructures not limited to repetitive patterns. Holographic lithography produces arrays of uniform, high-resolution microstructures over large areas (>100 cm^2)[2] without the use of a stepper. These technologies also have disadvantages: they require the use of expensive optical equipment (e.g. high-precision optical stages and aligners). Laser pattern writing is a serial technique, and therefore time-consuming and low-throughput. Conventional gray-scale photolithography requires expensive masks with high-resolution gray-level patterns. Holographic lithography produces only periodic or quasi-periodic microstructures.

We have previously demonstrated the use of μLPL for fabricating arrays of micropatterns.[7–11] This technique is a form of photolithography in which a common image is projected onto a layer of photoresist using an array of microlenses positioned close to the photoresist. This technique provides a size reduction in the patterns of greater than 10^3 and makes it possible to generate features with ~300 nm size in a single exposure, starting with millimeter-scale patterns. We have also demonstrated that μLPL can produce both arrays of small (<30 μm), simple patterns (e.g., arrays of 10-μm crosses) and arrays of large (>30 μm), complicated patterns (e.g., arrays of 300-μm patterns of the complexity needed for simple circuits). We believe that for certain applications that require only a single layer of pattern formation and are relative tolerant of lateral distributions—for example, certain patterns for photomasks for photolithography, elastomeric stamps or molds for soft lithography,[12–14] arrays of pixels, optical gratings, and frequency-selective surfaces[10,15,16]—μLPL may provide an alternative to conventional projection lithography using a stepper.

In this paper, we demonstrate the fabrication of arrays of microstructures with a controlled, 3D topography using gray-scale masks and μLPL. Figure 1a illustrates the optical system in this work. We used transparencies with a size ~20 × 20 cm^2 as the masks. The patterns on

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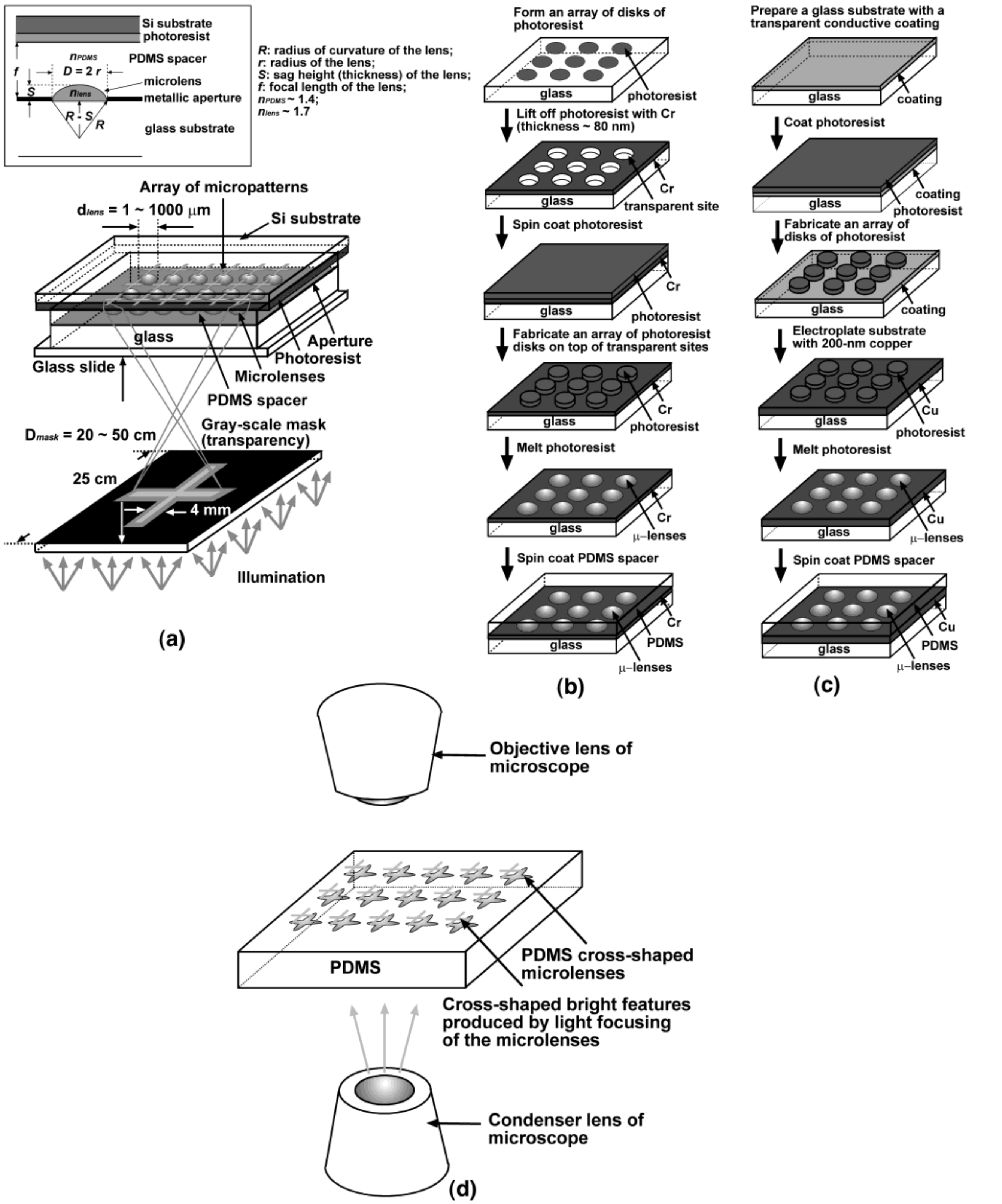

Figure 1. (a) Optical system for microlens projection photolithography. A layer of photoresist coated on a substrate was placed at the image distance from the microlens array. (b, c) Fabrication of microlens arrays with aperture stops using reflow of melted photoresist. (b) Fabrication of aperture stops using alignment. (c) Fabrication of aperture stops using electroplating. (d) Lensing of noncircular microlenses under white-light illumination.

transparency masks were printed using a desktop printer with a 3840-dpi resolution (Pageworks, Cambridge, MA). We used a CAD (computer aided design) software, Freehand (Freehand 10, Macromedia Inc., San Francisco, CA), to design the patterns on the masks. The software provides 100 Gy levels, from 0% of full transmission to 100% of full opacity. These gray-scale patterns have lateral dimensions of ~10 cm and sub-20 μm resolution in the gray-scale levels.

The depth of features produced in photoresist by gray-scale μLPL is nonlinearly proportional to the gray level of the pattern on the transparency mask. This nonlinearity is caused by two factors: (i) The opacity of a transparency film is linearly proportional to the designed gray levels under white light illumination. This linear relation is not, however, followed for either UV or other nonwhite-light illumination: since photoresist absorbs UV radiation more effectively than it does white light, the absorption of incident illumination in the UV by photoresist is not proportional to the opacity of the transparency film in the visible. (ii) The depth of features in an exposed and developed photoresist is also not linearly proportional to the exposure dose.[17] Thus, the depth of features produced by μLPL is not linearly proportional to the opacity of transparency films. To minimize this nonlinearity, the gray-scale intensities on transparency masks can be used to control profiles of exposed and developed photoresist. This compensation is similar to that used in contact-mode gray-scale photolithography.[4]

The intensity of the microimages produced by each microlens depends on the shape and gray-level distribution of the pattern on the mask, the distance of the mask from the lens array, the numerical aperture (NA) and the aberration of the lens, and the irradiance distribution of the light source. For a fixed light source and a constant distance of the mask from the lens array, we can adjust the distribution of intensity in the projected, focused microimages by adjusting the gray-level transmittance of the pattern on the transparency. Using this procedure, we can also control the profile of the microstructures generated in photoresist after exposure and development. Mask patterns with appropriate gray-level distribution generate arrays of microstructures with curved profiles.

We used these microstructures in photoresist as masters and cast transparent elastomeric slabs of PDMS (poly(dimethysiloxane), Sylgard 184, Dow Corning) against them. Removal of the PDMS membranes from the surface of photoresist produces an array of microstructures with topography complementary to the patterned photoresist. This method can also generate noncircular microstructures if a transparency mask with noncircular patterns is used for exposure.

Experimental Section

Preparation of Microlens Arrays. We used two types of microlens arrays for these experiments: (i) 2D crystals of self-assembled transparent microspheres embedded in PDMS (these spheres act as micrometer-scale ball lenses[7]); (ii) arrays of plano-convex microlenses fabricated on glass substrates. The fabrication of both systems has been described previously.[7−11] We fabricated microlens preforms in photoresist, heated the photoresist, and allowed surface tension to produce plano-convex microlenses. The areas between neighboring microlenses can be covered with an opaque layer of metals to block the transmission of stray light.[9] This layer of metals acts as an aperture stop that avoids the formation of features in the area of photoresist not covered by the lenses.

Figure 1b,c illustrates the process for the fabrication of microlenses and two types of methods for the fabrication of aperture stops: (i) One method involves decreasing the thickness of an opaque metal film on the areas where microlenses will be fabricated at a later step. This type of method includes etching and lift-off of photoresist with metal films. (ii) A second method involves increasing the thickness of a transparent metal film on the areas between neighboring lenses. This type of process uses electroplating, although other methods (e.g. electroless deposition) should also work. Figure 1b,c schematically shows the formation of aperture stops by lift-off of photoresist with metals and the production of aperture stops using electroplating, respectively. The first method requires the use of an aligner to fabricate microlenses on top of the aperture stops. Although this method requires alignment between lens arrays and aperture stops with a positional error less than 500 nm, it has the advantage of controlling the numerical aperture of the lenses by changing the size of the apertures. To avoid the difficulty of alignment, we used an alternative approach to fabricate the aperture stops (Figure 1c). These methods in Figure 1b,c produce aperture stops about the same size as the lenses.

In these methods, we fabricated a thin film of PDMS as a spacer on the lens array. PDMS is a transparent elastomer that allows nondamaging conformal contact with photoresist. It has been widely used in soft lithography for near-field contact-mode photolithography.[18,19] The spacer on a lens array is fabricated to have a uniform thickness equal to the image distance of the lens array. Since the distance of the mask from the lens array is much larger than the focal length of the lenses in the array, the image distance is about the same as the focal length. The use of PDMS spacers for μLPL has several advantages: (i) The conformal contact between PDMS spacers and photoresist makes the distance between the lens arrays and the photoresist uniform. No high-precision alignment equipment for vertical alignment between the lens array and the photoresist is required. (ii) PDMS spacers also protect the lens arrays from physical contact with external objects and avoid possible damages to the lens arrays from physical contact.

Figure 1a schematically shows the cross section of a lens and PDMS spacer in contact with a layer of photoresist. Since the reflow technique forms spherical profiles of photoresist lenses, the optical parameters of the lenses can be expressed as follows:

$$R = \frac{S^2 + r^2}{2S} \tag{1}$$

$$f = \frac{R}{\frac{n_{\text{lens}}}{n_{\text{PDMS}}} - 1} \tag{2}$$

Here R = radius of curvature of the spherical lens,
S = sag height (thickness) of the lens,
f = focal length of the lens,
n_{lens} = refractive index of the photoresist lens (~1.73),
and n_{PDMS} = refractive index of PDMS (~1.4).

These formulas are useful for the estimating both the focal length of a lens array and the thickness of a PDMS spacer. They also provides the information useful for the design of numerical aperture of a lens array.

We used Shipley 1818 photoresist to fabricate arrays of 10-μm circular lenses. The sag height of the lenses is about 3.5 μm. On the basis of the above equations, the focal length of the lenses is about 22.6 μm. In our experiments, we found empirically that the optimal thickness of PDMS spacer for these lenses is about 20 μm, which is close to the theoretical value of the focal length. The numerical aperture (NA) of these lenses is about 0.25.

Microlens Photolithography. The optical element with a microlens array was placed in contact with a layer (1−10 μm) of photoresist supported on a silicon substrate (Figure 1a). The optical element is an array of lenses separated from the resist by a PDMS spacer. Depending on the NA of lenses, the distance of the mask from the lens array, the intensity of the illumination, and the minimum size of features on the mask, exposure required tens of seconds to several minutes.

To use an overhead transparency projector as a light source for μLPL, we place the transparency film on top of the Fresnel lens of the projector. A diffuser such as a piece of ground glass is placed in front of the light source to produce uniform illumination.[7] To increase the efficiency of exposure, we placed the diffuser in front of the lamp of the projector rather than on top of the Fresnel lens. The lens array was positioned on the image plane of the diffuse light source. The distance between the transparency and the lens array is about 40−60 cm, depending on the design of the projector. The typical exposure time also

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ranges from tens of seconds to several minutes, depending on the lamp of the projector.

After exposure, we separated the substrate from the optical element and developed the resist in a solution of sodium hydroxide. Since we used positive resist for the experiments, a transparent slit on the mask produced a groove in the exposed and developed resist. The profile of the groove depends on the gray-level distribution of the slit on the mask.

Fabrication of Elastomeric Microlens Arrays Using Replica Molding.[20] We silanized (using tridecafluoro-1,1,2,2-tetrahydrooctyltrichlorosilane, United Chemical Technologies, Inc., Bristol, PA) the array of microstructures fabricated in photoresist to passivate its surface. This resist layer was used as a master for molding microlenses. We cast PDMS (thickness ~5 mm) on this topographically patterned photoresist and cured it in an oven at 60 °C for ~1 h. We used an atomic force microscope (AFM, Nanoscope IV, Digital Instrument) in tapping mode to characterize the surface images and profiles of the samples. We used an optical microscope (Leica DMRX, Kramer Scientific Corp.) to characterize the lensing of the noncircular microlenses under white-light illumination. The optical patterns were recorded using a CCD camera (Sony DXC-960MD). The optical system for characterizing the microlensing is illustrated in Figure 1d.

Results and Discussion

Microstructures Generated Using Gray-Scale Masks and Microlens Array. We used replica molding described above to fabricate microstructures on PDMS membranes. Since we used positive photoresist to produce microstructures, the darker the pattern on the mask, the higher the microstructures produced in photoresist and the lower the complementary microstructures on PDMS replica. Figure 2a,b shows the optical micrographs of two PDMS microstructures produced using two different gray-scale transparency masks. The masks are shown at the corners of the corresponding micrographs. The mask shown in Figure 2a has a pattern that consists of two lines with the same widths and with different linear gradients. The peak opacities of the two gradient lines are 100% and 50%, respectively. The AFM image shown in the inset shows a difference in the profiles of the two gradient lines due to the difference of gray-level distribution. The two peak opacities produced two wavy microstructures in photoresist with amplitudes of 710 and 290 nm, respectively. This figure also demonstrates the nonlinear relationship between the opacities on the masks and the amplitudes of microstructures produced in photoresist.

The pattern of the mask shown in Figure 2b consists of two concentric circular rings with 100% peak opacities. Figure 2b shows the photomicrographs of the microstructures in PDMS produced by the mask; the profile of the microstructures is similar to the design on the mask. Although the peak opacities and the widths of the two rings are the same, the AFM image shown in the inset indicates a significant difference between the amplitudes of the two concentric rings: the inner ring has an amplitude of ~550 nm; the outer ring, an applitude of ~180 nm. The bottom of the central hole is ~410 nm higher than the flat area outside of the microstructure, while the circular trench is ~300 nm higher than the same reference plane. Due to the off-axis aberration of the lenses, incident illumination is more and more out-of-focus toward the peripheral region of the image fields. The spread of the incident intensity in the peripheral regions reduces the depth and resolution of the features on these regions. The photoresist on the central area of the image field of the individual lens receives more exposure and produces features with larger depth or amplitude than those on the outer region.

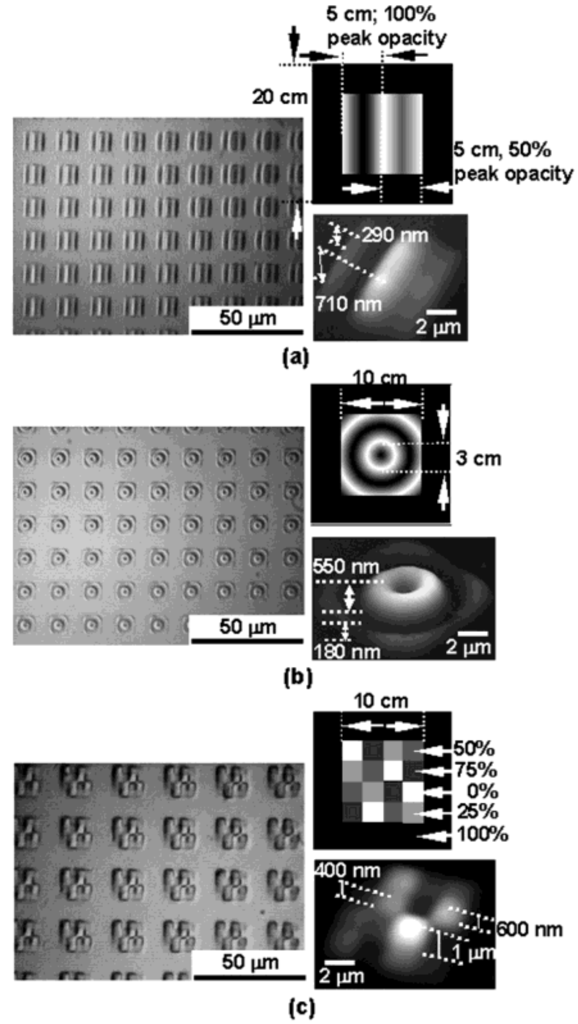

Figure 2. Photomicrographs and atomic force microscopy (AFM) micrographs showing three representative microstructures in photoresist produced by gray-scale microlens photolithography. (a) The mask has a pattern consisting of two linearly gradient lines: one with 100% peak opacity and the other with 50% peak opacity. (b) The mask has a pattern consisting of two concentric rings with linear gradient. The peak opacities of both lines are 100%. (c) The mask has a pattern of a 4 × 4 pixel array with four different gray levels: 0%; 25%; 50%; 75%.

The resolution of the microstructures produced by this technique is limited by the numerical aperture (NA) and aberration of the lens array: (i) Arrays of high-NA microlenses produce high-resolution microstructures on the paraxial image field. The microstructures produced by off-axis imaging have lower resolution, due to aberration such as field curvature. High-NA lens arrays also have smaller depth of focus (DOF) than lenses with low NA; this characteristic reduces the depth of high-quality features in patterned photoresist. (ii) Arrays of low-NA microlenses provide larger DOF and lower curvature of field. These advantages allow the formation of deeper, more uniform features in photoresist, although the resolution of the microstructures is reduced.

Figure 2c shows an array of PDMS microstructures produced using a mask with a 4 × 4 Gy-scale pixel array. Each PDMS microstructure consists of a multistep 4 × 4 pixel array. Each row or column in the pixel array was produced by four different gray-level pixels on the mask:

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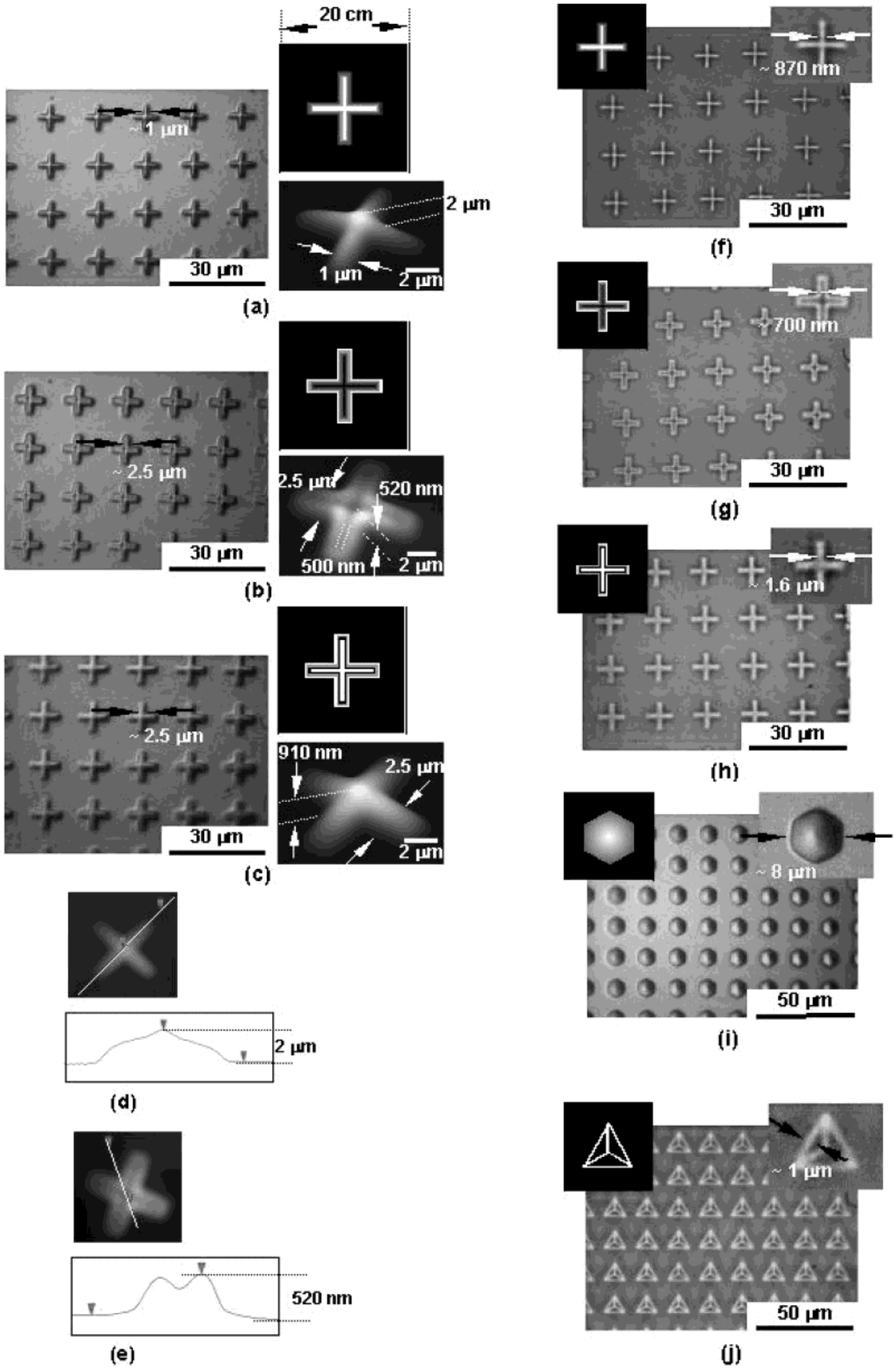

Figure 3. (a−c) Photomicrographs showing three cross-shaped PDMS microlenses produced using replica molding. These lenses were fabricated with different profiles using three different gray-scale masks for μLPL. The AFM images show the details of the profiles of these lenses. (d, e) Lateral profiles of the cross-shaped lenses shown in Figure 3a,b, respectively. (f−h) Photomicrographs showing the focused images of the noncircular microlenses shown in Figure 3a−c under white-light illumination. The optical setup is shown in Figure 1d. (i) Square array of hexagonal microlenses produced using a square array of 10-μm circular microlenses. (j) Array of images of a transparency mask projected by the array of hexagonal microlenses. The mask that produced the images is shown at the corner.

0%, 25%, 50%, and 75% opacities. The background has 100% opacity. The AFM image shows that the depth of each step is nonlinearly proportional to the opacity of the corresponding pixel on the mask. Pixels with the same opacity on the mask may produce microstructures with different depths and shapes. This difference is generated by two factors: (i) the aberration of the lenses; (ii) the proximity of optical elements. For factor i, the steps on the peripheral areas are distorted and receive off-focus illumination, due to the off-axis aberration of the lenses.

This factor results in the reduced height of the steps on these areas. For factor ii, an exposed pattern element receives exposure not only from the incident illumination but also from light spreading from adjacent pattern elements, due to diffraction. Thus, pixels with the same opacity produce different depth in photoresist when the surrounding pixels have different arrangements of gray-level distribution. A pixel surrounded by lower gray-level pixels generates larger depth in photoresist; the spreading of the light from the neighboring pixels increases the exposure dose and enlarges both the depth and size of the feature in photoresist produced by the pixel. Proximity effects are common in all kinds of projection lithography.[21,22] The distortion of patterns caused by this effect can be minimized by compensation of the pattern on the mask.[23]

Microlenses Produced Using Gray-Scale Microlens Lithography. Figure 3a–c shows three arrays of cross-shaped microlenses produced using masks with cross-shaped patterns. We also used replica molding to fabricate these cross-shaped PDMS microlenses. The masks are shown at the upper left corners of the photomicrographs. These cross-shaped patterns have the same size but different gray-level distribution. Each cross-shape pattern consists of five cross-shaped frames with different gray steps. The mask shown in Figure 3a has a gray distribution of 80%, 60%, 40%, 20%, and 0% from the outermost frame to the innermost one. This gray distribution generates microlenses with a sharp profile in the center. The masks shown in Figure 3b,c also have five gray steps. The gray distribution of the mask shown in Figure 3b is 0%, 20%, 40%, 60%, and 80%, while the gray distribution of the third mask is 80%, 60%, 100%, 40%, and 20%. As shown in the AFM images included in Figure 3a,b, the central bright frame in the first mask enhanced the height of the lenses and the central dark frames in the second mask generated a U-shaped dip in the profile of PMDS lenses. The gray distribution of the first mask (brightest in the center of the cross pattern) produced lenses with reduced line width (~1 μm) and larger height (~2 μm), while the gray distribution of the second one (darkest in the center of the cross pattern) generated lenses with larger line width (~2.5 μm) and lower height (~520 nm). The details of the surface profiles of the first two types of cross-shaped lenses are given in Figure 3d,e.

The masks shown in Figure 3b,c generate lenses with the same widths of 2.5 μm but different profiles. The AFM images show the difference of the profiles in these PDMS cross-shaped lenses due to the different distribution of gray levels. These figures demonstrate that the use of gray-scale masks can be used to fabricate and modify microlenses with controlled profiles at submicrometer resolution.

Imaging by Noncircular Microlenses. Figure 3f–h shows the focused images produced by the cross-shaped microlenses corresponding to Figure 3a–c, using the optical setup shown in Figure 1d. The sizes of the features in these images are in the range of 300 nm–2 μm. These images demonstrate that the microlenses produced by masks with different gray-level distribution generate different optical patterns on their focal planes. Figure 3g particularly shows an array of optical micropatterns with cross-shaped frames produced by the cross-shaped lenses shown in Figure 3b. These figures demonstrate that the intensity distribution of the optical patterns corresponds to the gray-level distribution on the masks and that it can be adjusted using modified gray-scale masks.

Hexagonal Microlenses Fabricated Using Circular Microlenses for Gray Scale μLPL. Figure 3i shows a square array of 8-μm hexagonal plano-convex microlenses fabricated using a square array of circular 10-μm lenses and a mask with a hexagonal gray-scale pattern. The focal length of these lenses is about 15 μm. They perform high-quality imaging under a white light illumination through a mask (Figure 3j). This figure demonstrates that gray-scale μLPL can produce refractive microlenses with controlled profiles and shapes. The optical properties—for example, focal length and numerical aperture of the lenses produced by this technique—can be adjusted using masks with a different gray-level distribution.

Conclusions

Microlens projection lithography (μLPL) using gray-scale masks can produce arrays of microstructures with controlled profiles; replica molding produced microstructures with complementary topographies. These microstructures can act as lenses and generate submicrometer bright features under white-light illumination. This technique has a number of advantages for the fabrication of simple microstructures. (1) The centimeter-size patterns used in the masks are printed using desktop printers; these masks can be easily prepared and quickly modified at very low cost. The ease with which these transparency-based masks can be made makes it possible to prototype arrays of microstructures easily. (2) Since this technique offers a size reduction in the patterns by a factor more than 1000 in a single step, a centimeter-sized pattern is reduced to an array of micrometer-sized microstructures and a millimeter-scale modification on the centimeter-sized pattern results in a change in the distribution of intensity at the submicrometer scale. (3) Modification of the topography of the microstructures in photoresist can be accomplished by changing the gray-level distribution of the patterns on the transparency mask at the submicrometer scale. (4) The pattern formed is quite insensitive to the lateral position of the mask. For example, a 10-μm-scale lens can project a 10-cm-scale pattern on a mask onto a 10-μm-scale image field. Thus a millimeter-scale lateral shift of the mask results in only a submicrometer-scale lateral shift of the micropattern on the image field. The scale of this lateral shift of the micropattern is about 1% of the image field.

This technique also has some disadvantages: (i) The image field of a microlens is limited by its numerical aperture and off-axis aberration. Resolution of microstructures on the peripheral areas of images fields is reduced; high-definition microstructures form only on the central areas of the image fields. Only a portion of the illuminated area on photoresist can produce high-quality patterns. (ii) The microstructures produced outside the paraxial image areas are generated by oblique illumination. The focal spots due to oblique illumination are distorted to noncircular shapes. The microstructures formed on these areas are distorted due to off-axis imaging.

The profiles of the microstructures depend on several parameters, such as the numerical aperture or depth of focus (DOF) of the microlenses, the aberrations of the lenses, the gray-scale pattern on the mask, the spectrum of the light source, the exposure dose, and the photoresist materials. Each parameter has its limitation on the control of the profiles of the microstructures. Although modifica-

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tion or compensation of gray-scale patterns on masks can modify the microstructures or minimize the distortions at submicrometer scale, there are still limitations on the adjustment of the microstructures. For example, microstructures with a depth or height larger than the DOF of the lens array cannot be easily produced using this technique; i.e., the DOF of a lens array imposes an upper limit on the depth of microstructures that the lens array can generate. Similarly, this technique cannot directly generate microstructures with sizes smaller than the resolution limit of the lens array. Therefore, this technique cannot produce all types of complex microstructures simply by adjusting all the parameters. Although this technique has this limitation, it can still produce a wide range of microstructures and provide the advantage of convenient, micrometer-scale modification of the profiles by millimeter-scale adjustment of the gray-scale pattern on the mask.

This technique offers a simple, low-cost route for generating arrays of microstructures with submicrometer feature size. These patterned microstructures have characteristics appropriate for a number of applications. We have demonstrated the fabrication of noncircular microlenses; others include diffraction gratings, beam splitters, photonic crystals, information storage devices, and flat panel displays. We believe this technique will be useful for rapid prototyping of functional devices consisting of repetitive microstructures.

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