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Fabrication of two-dimensional arrays of microlenses and their applications in photolithography

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Abstract
This paper describes several methods for the fabrication of microlenses, and demonstrates a lithographic technique that uses a microlens array to pattern the intensity of light incident on photoresist. Three different methods were used to fabricate microlenses: (i) self-assembly of transparent microspheres, (ii) melting and reflow of photoresist on glass substrates and (iii) self-assembly of liquid polymers on functionalized surfaces. These methods provide different advantages and convenience for the fabrication of microlenses. Microlens arrays produced by these techniques were used in photolithography to produce arrays of micropatterns in photoresist. The distribution of these micropatterns replicates the distribution of the microlenses in the array. Two types of illumination are used for exposure in this technique: collimated flood illumination and illumination through a mask. Depending on which type of exposure is used, a single microlens array can produce different patterns on its image plane: (i) an array of circular or noncircular microlenses under collimated illumination produces an array of optical micropatterns on an image plane positioned within micrometer distances from the lens array. The array of optical micropatterns corresponds to the distribution of spatial irradiance generated by simple lensing of the microlens array. The shapes of these micropatterns depend on the shapes and profiles of the microlenses. (ii) Under illumination patterned by a mask, each microlens approximately replicates the image of the patterned light source and produces a micro-scale image of this source on its image plane. The array of microlenses generates an array of repetitive micropatterns on the common image plane of the lens array. The shapes of the micropatterns depend on the patterns of the masks. Gray-scale masks can be used to produce repetitive microstructures with controlled profiles. Both techniques can generate microstructures with submicron resolution. We demonstrate that both methods produce arrays of uniform micropatterns over an area larger than 10 cm^2.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Arrays of microlenses have been used in many applications [1]: examples include as components of digital optical processors [2], imaging systems [3], optical communication [4] and confocal microscopy [5, 6]. In this paper, we demonstrate a simple photolithographic method that uses arrays of microlenses to generate arrays of micropatterns with submicron resolution. This technique includes two related but distinct methods: (i) microlens lithography using collimated

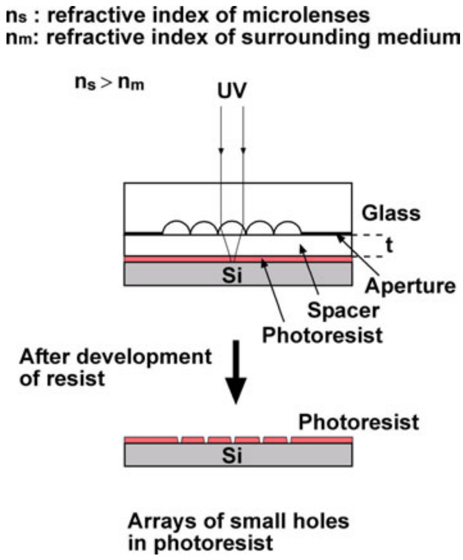

Figure 1. Collimated flood illumination for microlens photolithography. The shape and the size of the micropatterns depend on the image distance, which is equal to the thickness t of the spacer layer.

illumination and (ii) microlens lithography using patterned illumination. We have already demonstrated that both methods produce micropatterns with sub-500 nm resolution using the simplest optical elements—spherical lenses and plano-convex lenses [7, 8]. Both methods produce a variety of micropatterns; they control the shape of micropatterns by different principles. The first method uses the shapes and profiles of the microlenses to control the irradiance distribution of the optical micropatterns. The second method uses masks to pattern the illumination. An array of microlenses having simple shapes projects the patterned illumination and generates the micropatterns on its image plane.

Figure 1 sketches the optical system for the microlens lithography with collimated illumination. The micropatterns produced by this technique depend on three factors: (i) the size, shape and profile of the lenses, (ii) the image distance and (iii) the indices of refraction of the lenses, the lens support and the spacer. The patterns produced by this method are uniform over the whole illuminated area. We have generated arrays of uniform micropatterns over areas larger than 10 cm^2 in a single exposure using arrays of microlenses with sizes >1 μm. Figure 2 illustrates the optical system for microlens lithography using masked illumination. This simple method can produce arrays of repetitive micropatterns with shapes the same as the pattern on the mask. In this method, the target pattern to be replicated is printed on a transparency using a desktop printer. We place the transparency mask at a distance D_{mask} from the lens array ($D_{\text{mask}} \gg r_{\text{lens}}$, r_{lens} = radius of a lens). The layer of photoresist to be patterned is positioned at the image plane of the lens array. The array of microlenses images the bright pattern of the mask and projects an array of size-reduced micropatterns onto the resist layer.

Different technologies have been developed for the fabrication of microlens arrays [8–14]. In this paper, we used two types of microlens arrays: (i) 2D crystals of transparent microspheres as hexagonal arrays of ball microlenses [7] and (ii) arrays of plano-convex microlenses [8]. A 2D crystal of transparent microspheres acts as a dense array of ball microlenses and produces dense, hexagonal arrays of micropatterns. To produce micropatterns with specific patterns other than that of hexagonal arrays, we use a microlens array fabricated in the desired arrangement. In a previous paper [8], we demonstrated three different techniques to fabricate arrays of plano-convex microlenses with specific arrangements on different substrates: (i) melting and reflow of photoresist microstructures formed by conventional photolithography [10], (ii) self-assembly of liquid polymers on functionalized surfaces [11] and (iii) micro-molding [15]. Here, we modified the first two methods and used them to fabricate microlens arrays on glass substrates. Method (i) is commonly used in the micro-optics industry because it can produce refractive microlenses with a wide range of profiles and with high fill ratios. Method (ii) offers a simple and low-cost route for the fabrication of microlenses, although the lens arrays produced by this method have lower fill ratios and the elasticity used for contact printing allows the pitch of the lens array to vary slightly.

2. Experimental procedures

2.1. Preparation of microlens arrays

2.1.1. Self-assembly of transparent microspheres. We followed the procedure described before [7, 8] to prepare 2D crystals of microspheres. The crystals of microspheres were embedded in PDMS (poly(dimethylsiloxane), Sylgard 184, Dow Corning) membranes. This simple method generates dense arrays of microball lenses.

For low-fill-ratio lens arrays (fill ratio <50%), the transparent areas between neighboring lenses allow the transmission of incident illumination and cause fogging in the developed photoresist. To avoid this problem, an aperture stop should be placed on these areas to block the transmission of light. Here we describe two different methods for the fabrication of aperture stops self-aligned onto the arrays of plano-convex microlenses.

2.1.2. Fabrication of arrays of plano-convex microlenses. Melting and reflow of photoresist on glass substrates. We used conventional photolithography to fabricate a thin film of chromium patterned with an array of holes on the surface of a glass substrate (figure 3). This array of holes acts as an array of aperture stops for the microlenses which were then fabricated on top of them. For high-fill-ratio lens arrays, the spacing between the lenses is small (e.g. <2 μm) and the alignment required in this step could be difficult. Since most of the area on the substrate of a high-fill-ratio lens array is covered by the lenses, the improvement of image quality associated with the use of aperture stops is quite limited, and the fabrication of optical stops can be eliminated.

We fabricated an array of photoresist microstructures (Shipley Microposit S1800 photoresist) aligned onto the array of optical stops using conventional photolithography. To form an array of microlenses, we placed the glass substrate on a hot plate (T = 150 °C) for about 15 min to melt the photoresist

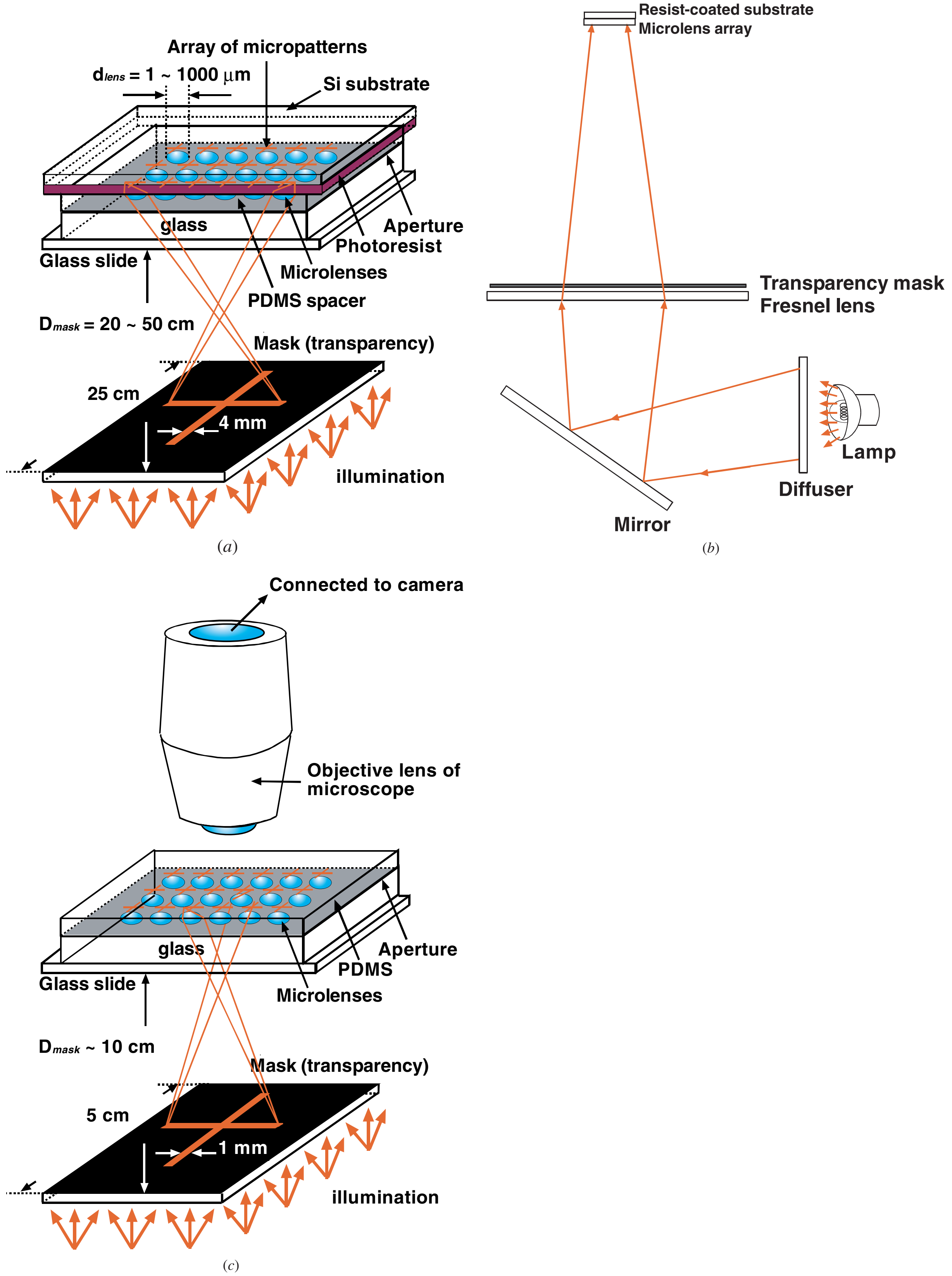

Figure 2. (*a*) Optical system for microlens projection lithography with masked illumination. (*b*) Overhead transparency projector for microlens lithography. (*c*) Setup for the characterization of optical micropatterns projected by microlenses.

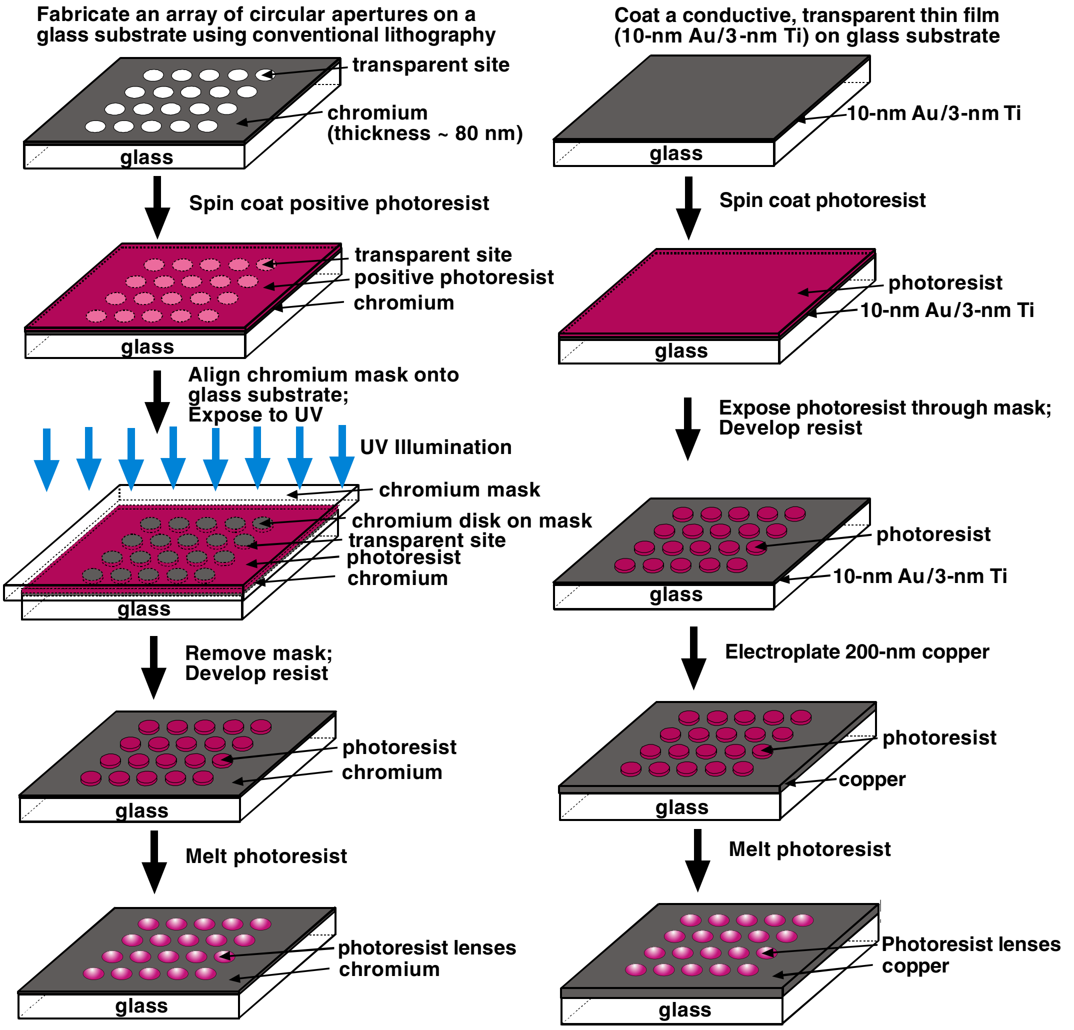

Figure 3. Fabrication of microlenses by melting and reflow of photoresist.

microstructures. Under the influence of surface tension, the melted photoresist formed a curved and smooth profile that could act as a lens. To allow the photoresist microlenses to harden, we gradually lowered the temperature of the hot plate (10 °C min^{-1}). This process is outlined on the left-hand side of figure 3.

Since the quality of images produced by an aperture-limited lens array is sensitive to the alignment between the aperture stops and the lenses, a high-precision alignment between these two elements is required for high-quality imaging. Although this method requires the use of expensive equipments such as an aligner, it provides the advantage of adjusting the numerical aperture of the lenses by changing the sizes of the aperture stops.

To avoid the difficulty of aligning the lens array manually to the array of aperture stops, we used an alternative approach for the fabrication of a microlens array that is self-aligned onto the optical stops. As shown on the right-hand side of figure 3, we coated a transparent metallic thin film (10 nm Au on 3 nm Ti) on a glass substrate, and fabricated an array of disks of photoresist on the substrate. We electroplated the metallic thin film with a layer of 200 nm thick copper using a solution for copper electroplating (Techni Copper U, Technic Inc.) The electroplated copper film formed an aperture stop that blocked the transmission of incident illumination on the areas between lenses. We followed the same procedure of melting and cooling the photoresist microstructures to produce an array of photoresist microlenses. This method generates arrays of high-quality lenses with sizes between 1 μm and 1 mm, and with either a circular or a noncircular profile in the plane of the support.

Self-assembly of liquid polymers on functionalized surfaces. Figure 4 illustrates the fabrication of self-assembled plano-convex microlenses. We deposited an opaque metallic film of 2 nm titanium and 80 nm gold on the surface of a glass substrate by evaporation. A PDMS stamp with a patterned surface was inked with mercaptohexadecanethiol in ethanol (HS(CH2)15COOH, 1 mM, Fluka) following published procedures [11]. We placed the membrane in conformal contact with a gold-coated substrate for 10 s to form a self-assembled monolayer (SAM) of HS(CH2)15COOH on the surface of the gold. We immersed the substrate in gold etchant (an aqueous solution of potassium ferrocyanide (0.01 M), potassium ferricyanide (0.001 M), sodium

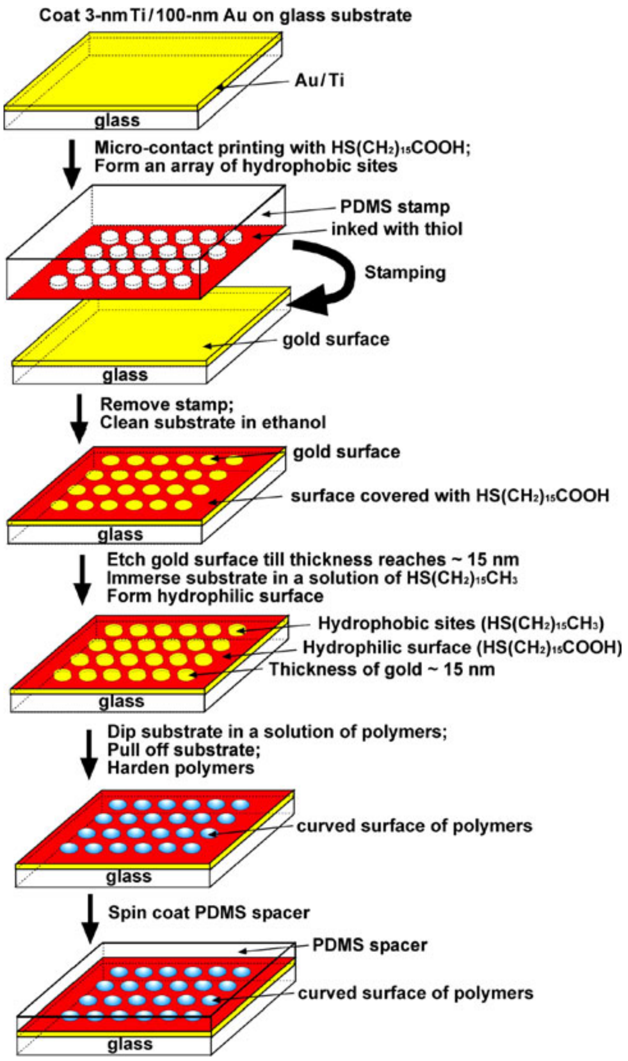

Figure 4. Fabrication of microlenses by self-assembly of liquid polymers on functionalized surfaces.

thiosulfate (0.1 M) and potassium hydroxide (1 M)) to etch the areas not covered by the SAM. The SAM acts as a resist and protects the surface of the gold that it covers from being etched. The unprotected area was etched for ∼70 s to yield a thinned transparent layer of gold with a thickness ∼15 nm. The etched substrate was then cleaned in water and dried under a stream of nitrogen. We immersed the substrate in an ethanoic solution of HDT (HS(CH2)15CH_3, 1 mM, Fluka) for 1 min to form a self-assembled monolayer of HDT on the thinned gold surface. Since the carboxylate group of HS(CH2)15COOH renders a surface hydrophilic, the SAM of HDT formed an array of hydrophobic sites on the gold surface. Thus, the surface consists of an array of transparent hydrophobic SAMs supported on transparent gold patterned in an otherwise opaque hydrophilic surface.

We cleaned the substrate in ethanol and dried it under a stream of nitrogen. To form an array of self-assembled microlenses, we dipped the substrate in a diluted solution of photoresist (Shipley 1800 photoresist diluted in polyglycol methyl ether acetate, PGMEA) and slowly (1 mm s^{-1}) pulled it out manually. Since photoresist adheres only to the hydrophobic sites of the surface, an array of drops of photoresist formed on the gold surface [11]. Surface tension assures that the photoresist on each hydrophobic site has a smooth, curved profile. This array of photoresist structures forms an array of plano-convex microlenses. We baked the photoresist on a hot plate ($T = 105$ °C) to harden the microlenses. We then spin-coated a layer of PDMS, with thickness equal to the focal length of the lens array onto the surface. This PDMS layer acts as a spacer between the lens array and the photoresist to be patterned. This procedure generates an array of plano-convex microlenses situated on transparent sites, with the microlenses embedded under a transparent spacer. The 80 nm thick opaque layer of gold surrounding the lenses acts as an aperture stop that blocks incident illumination other than that passing through the lenses.

We used three different methods to fabricate microlenses; each method has different advantages and disadvantages: (i) self-assembly of colloidal microspheres generates dense arrays of spherical microlenses that cannot be easily produced by conventional lithographic techniques. Due to the hexagonal arrangement of self-assembled colloidal microspheres, the micropatterns produced by these lenses are limited to hexagonal arrays. The defects in the assembly of microspheres also produce corresponding defects in the micropatterns. (ii) Reflow of melted photoresist serves as one of the most common methods of fabrication of microlenses in industry. Although this technique produces high-quality lenses, it requires the use of photolithographic equipment with uniform UV illumination. The fabrication also requires the use of cleanroom. (iii) Self-assembly of liquid polymers provides a convenient and low-cost route for the fabrication of plano-convex microlenses with a variety of shapes and arrangements. The sag of lenses produced by this method can be controlled by the concentration of the polymers, and composite lenses can be generated using multiple dip coating with different polymers. Although this method is convenient to use, it cannot easily generate lens arrays with 100% fill ratio. Narrow gaps between neighboring functionalized sites can result in connection of self-assembled polymers on the neighboring sites. The elasticity of PDMS stamps allows the variation of the functionalized sites on the substrates, and thus produces distortion and reduces uniformity of the lenses.

Figure 5 shows SEM micrographs of arrays of microlenses generated using these several methods. Figure 5(*a*) shows a square array of 1.5 μm circular photoresist lenses with a sag of ∼0.35 μm and a period of 3 μm. Figure 5(*b*) shows a square array of 10 μm circular photoresist lenses with a sag of ∼2.1 μm and a period of 15 μm. The lens arrays shown in figures 5(*a*) and (*b*) were produced by the reflow of melted photoresist. The lens array shown in figure 5(*c*) is a hexagonal array of hexagonal lenses generated by dip coating. The pitch of the lens array is 25 μm; the sag of the lenses is ∼2.4 μm. Figure 5(*d*) shows an array of hexagonal frame/circular dot microlenses. The diameter of the circular lenses is ∼11.2 μm; the sag of the lenses is ∼1.8 μm. The pitch of the lens array is 25 μm. The lens arrays shown in figures 5(*b*) and (*d*) were produced by heating and melting.

The shapes of the patterns produced by a lens array depend on the image distance between the lens array and

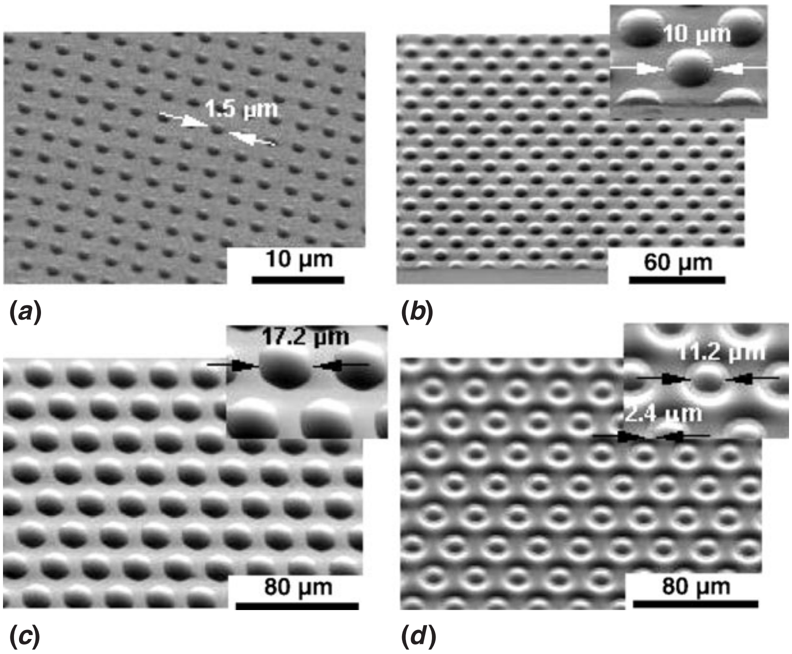

Figure 5. SEM micrographs of representative microlenses. (*a*) A square array of 1.5 μm circular photoresist lenses with a 3 μm pitch, produced by reflow of melted photoresist. (*b*) A square array of 10 μm circular photoresist lenses with a 15 μm pitch, produced by reflow of melted photoresist. (*c*) A hexagonal array of hexagonal lenses generated by dip coating. (*d*) An array of hexagonal frame/circular dot microlenses. This array was also generated by melted photoresist.

the photoresist. To obtain a uniform image distance, we fabricated a PDMS spacer on top of the microlens array with the thickness of the spacer equal to the image distance. PDMS membranes are commonly used in soft lithographic processes, and conformal contact between the membranes and the substrates to be patterned is required in many of these processes [16, 17]. Conformal contact eliminates air gaps between the lens array and the photoresist, and gives a uniform image distance for the lens array from the photoresist without vertical alignment.

To characterize the optical quality of the microlenses, we used an optical microscope (Leica DMRX, Kramer Scientific Corp) and a simple setup shown in figure 2(*c*) to measure the optical micropatterns projected by microlenses. Each microlens images the cm-size pattern on the transparency mask and projects a micro-scale image onto its focal plane. This image can be observed and characterized through the optical microscope. Since the optical microscope provides a resolution of $\sim$0.3 μm, this simple method can characterize the optical quality of microlenses also at a resolution of $\sim$0.3 μm. The photomicrograph shown in figure 6(*a*) illustrates an array of cross-shaped optical micropatterns projected by an array of 10 μm spherical lenses (polystyrene (PS) microspheres embedded in a PDMS membrane). This figure demonstrates the high uniformity and low distortion of the simple optical micropatterns generated by the lenses. Figure 6(*b*) shows the imaging of complicated patterns using the same lens array. The high off-axis aberration of spherical microlenses caused more distortion in the optical micropatterns. This figure demonstrates that spherical microlenses cannot easily produce undistorted, complicated micropatterns. Figure 6(*c*) shows an array of cross-shaped micropatterns in photoresist patterned by the same array of 10 μm spherical lenses. This simple method can be applied to characterize other types of microlenses such as plano-convex microlenses. Our measurement shows that the plano-convex lenses produced by reflow method or dip-coating technique also produce optical micropatterns with high uniformity.

2.2. *Photolithography*

2.2.1. Collimated flood illumination. To perform contact-mode photolithography, we placed a PDMS membrane containing embedded microlenses on a substrate spin-coated with positive-tone photoresist (Microposit S1800 photoresist, Shipley Inc., $n_{PR} = 1.7$); the membrane made conformal contact with the resist. To generate 2D micropatterns, we used resist with thickness ranging from 0.4 μm to 1.5 μm. We used a UV light source (Karl Suss Mask Aligner, Model MJB3 UV400) to expose the resist through the membrane. The aligner was equipped with a mercury lamp with emission peaks at 365, 405 and 436 nm. PDMS absorbs little of the incident UV intensity and is transparent to UV with wavelength ranging from 350 to 450 nm [7]. The incident UV light passes through the PDMS layer and is concentrated by each microlens into the photoresist layers. After exposure, we removed the PDMS membrane from the resist and developed the resist in a basic solution of sodium hydroxide (Microposit 351 developer, Shipley Inc., diluted 1:5 in 18 MΩ water).

2.2.2. Patterned illumination. Figure 2 illustrates the optical system for microlens projection photolithography. A light source such as an overhead transparency projector or a UV lamp is used for the exposure. The pattern to be used was

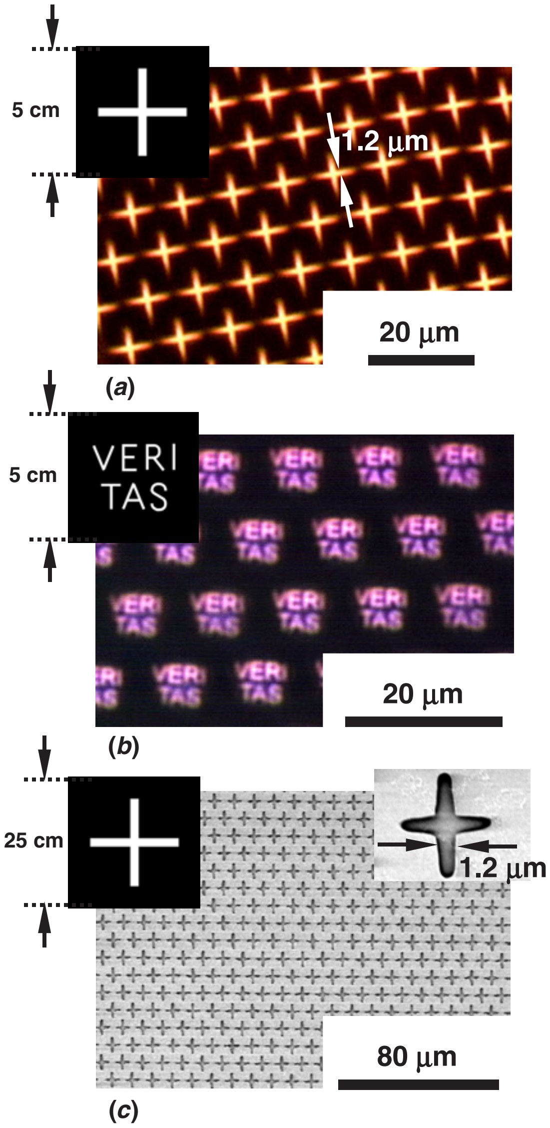

Figure 6. (*a*) An array of cross-shaped optical micropatterns projected by a hexagonal array of 10 μm spherical microlenses. (*b*) An array of complicated optical micropatterns projected by the same lens array. (*c*) An array of cross-shaped micropatterns in photoresist fabricated by the same lens array.

printed onto a transparency using a desktop printer. The transparency mask was placed in front of the light source. To make the illumination uniform, a diffuser such as a piece of ground glass is placed between the light source and the mask. The diffuser scatters the illumination from the light source and produces a uniform illumination. This illumination passes through the clear areas of the transparency mask. The microlenses receive the patterned illumination, and project an array of micropatterns onto their image plane.

For convenience in constructing the optical system, we used a commercially available overhead transparency projector as a light source. We placed an optical diffuser in front of the lamp in the projector to homogenize the illumination. The transparency mask was placed on top of the Fresnel lens of the projector. The Fresnel lens acts as a condenser lens that converges the illumination onto the image plane and generates a bright illuminated area on this plane. This image plane is about 40–60 cm from the Fresnel lens, depending on the design of the projector. We positioned the lens array on this plane to image the patterned illumination (figure 2(*b*)).

To perform photolithography, we placed the spacer in contact with a photoresist-coated substrate (photoresist: Microposit 1805, Shipley Inc.). The position of the substrate depends on the size of the mask and the numerical aperture (NA) of the lens array. For lens arrays with small NA, the substrates are placed at a larger distance from the mask. For a resist layer with a thickness of ~400 nm, the exposure took between 10 s and 5 min. The exposure time depended on the light source, the pattern on the mask and the mask distance between the lens array and the mask. With a fixed mask distance, the exposure time was determined by the minimum feature size on the mask: the smaller the minimum feature size, the longer the exposure. After exposure, the membrane was removed from the resist, and the resist was developed in a solution of sodium hydroxide.

The surface topology of the photoresist was examined with a scanning electron microscope (LEO 982 Digital scanning electron microscope) operating at 1 keV.

3. Results and discussion

3.1. Photolithography using flood illumination

Microlens arrays under flood illumination can generate arrays of uniform micropatterns over the entire illuminated area (>10 cm^2) [6]. Figure 7 shows representative micropatterns. The pattern shown in figure 7(*a*) was produced by the 1.5 μm lenses shown in figure 5(*a*). Figure 7(*b*) shows a hexagonal array of hexagonal rings/dots produced by the lens array shown in figure 5(*d*). The patterns shown in figures 7(*c*) and (*d*) were produced by the array of hexagonal lenses shown in figure 5(*c*) with different exposure time: 1.5 s for the pattern shown in figure 7(*c*) and 5 s for figure 7(*d*). The comparison of these two patterns demonstrates that the shapes of the micropatterns can be controlled by the exposure dose.

3.2. Photolithography using patterned illumination

3.2.1. Projection photolithography using arrays of microspheres. Figure 8 shows three representative micropatterns generated by a 2D crystal of 6 μm PS microspheres ($n_{PS} = 1.59$). The pattern shown in figure 8(*a*) was produced by a *negative* mask; this consists of a transparent pattern in a dark background. We call masks that consist of the reverse patterns—opaque figures in a transparent background—*positive* masks. Figure 8(*b*) shows a representative pattern generated by a negative mask. We have fabricated arrays of micropatterns with feature size less than 300 nm using this technique.

Since 2D crystals of transparent microspheres are dense-packed arrays of microlenses, they produce dense arrays of micropatterns. When the mask distance is decreased, the view angle of the mask spanned by each microlens is increased and the corresponding array of micropatterns becomes larger. With decreased mask distance (<10 cm for a mask with the size of the pattern ~10 cm) and appropriate orientation between the

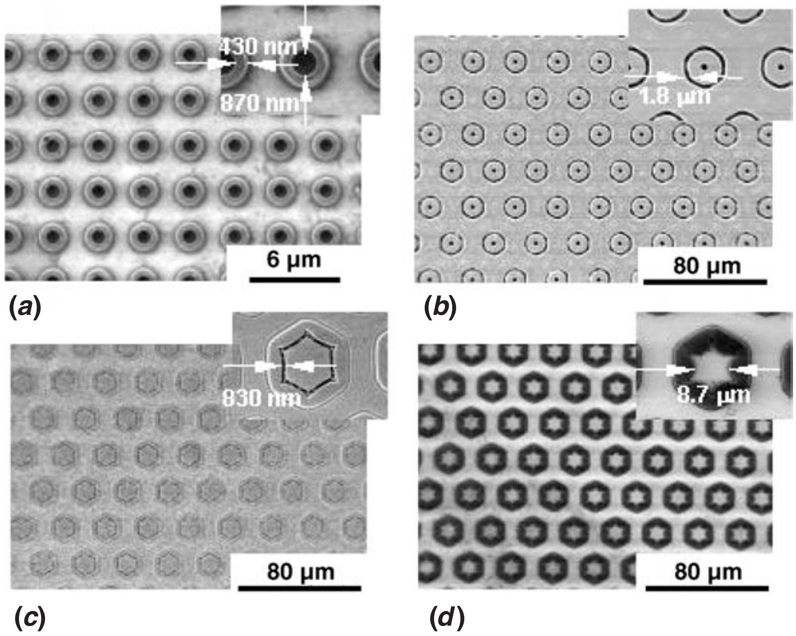

Figure 7. SEM micrographs of micropatterns produced by collimated flood illumination. (*a*) A square array of circular rings produced by the 1.5 μm lenses shown in figure 5(*a*). (*b*) A hexagonal array of hexagonal rings/dots produced by the lens array shown in figure 5(*d*). (*c*) and (*d*) Patterns produced by the array of hexagonal lenses shown in figure 5(*c*) with different exposure time: 1.5 s for the pattern shown in figure 6(*c*) and 5 s for figure 6(*d*).

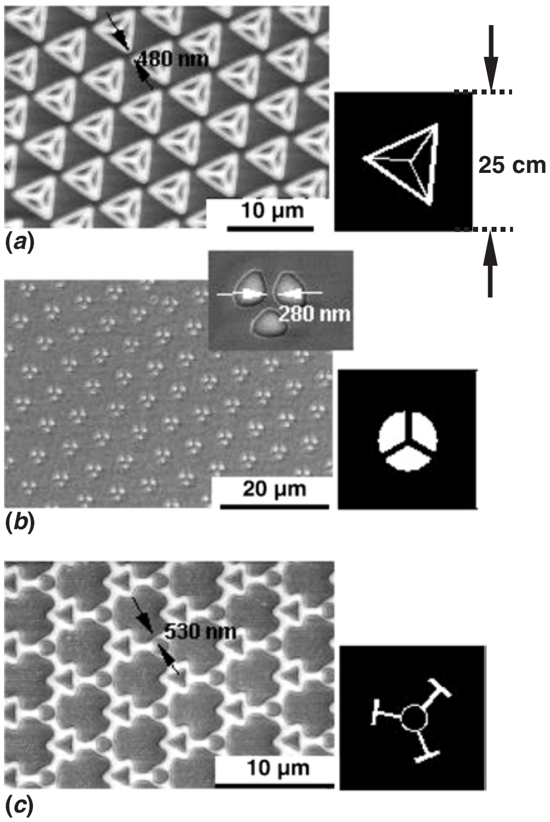

Figure 8. SEM micrographs of micropatterns generated by 6 μm PS microspheres under masked illumination: (*a*) by a positive mask, (*b*) by a negative mask and (*c*) an interconnected pattern. The masks are shown on the side of the SEM micrographs.

2D crystal and the mask, the microspheres can generate arrays of interconnected micropatterns. Figure 8(*c*) shows a typical interconnected pattern produced by 6 μm PS microspheres.

3.2.2. Projection photolithography with different orientation of microlens arrays. Figure 9 shows a comparison between two patterns produced by the same lens array and the same mask. Both patterns were produced by a 2D crystal of 6 μm PS spheres. The different orientation between the lens array and the mask resulted in the different micropatterns. This comparison demonstrates that substantially different micropatterns can be produced by adjusting the orientation of the lens array and the mask, and indicates a degree of flexibility for the method that is not available in conventional photolithography.

3.2.3. Projection photolithography using arrays of plano-convex microlenses. We used five arrays of plano-convex microlenses for the experiments: (i) a square array of 10 μm circular lenses (NA $\sim$ 0.25) with a 15 μm pitch, (ii) a square array of 40 μm circular lenses (NA $\sim$ 0.125) with a 100 μm pitch, (iii) a square array of 40 μm square lenses (NA $\sim$ 0.125) with a 50 μm pitch, (iv) a square array of 100 μm square lenses (NA $\sim$ 0.125) with a 150 μm pitch and (v) a square array of 100 μm circular lenses (NA $\sim$ 0.1) with a 110 μm pitch. The numerical apertures of the lenses were chosen experimentally to provide a useful compromise between resolution and aberration. Lower numerical apertures limit the resolution that can be obtained in the images, while higher numerical apertures cause aberrations such as field curvature in these images due to the off-axis imaging.

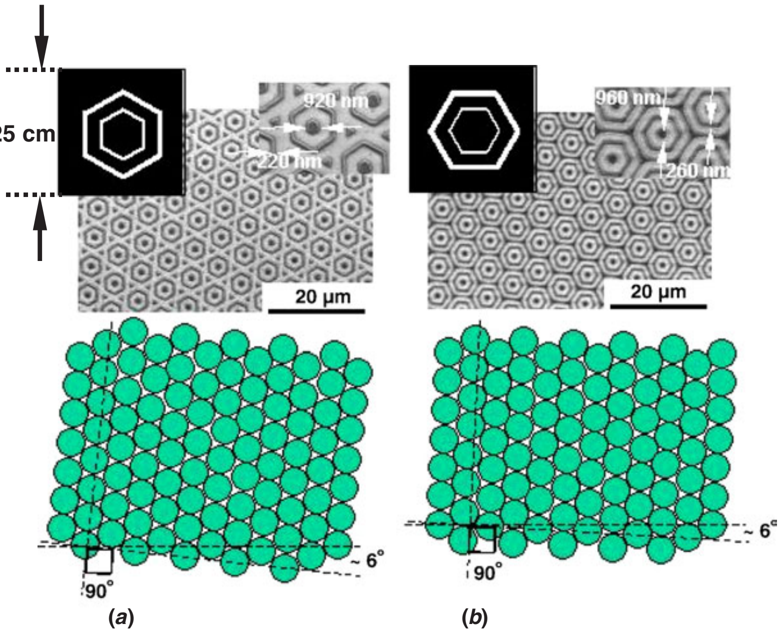

Figure 9. SEM micrographs of two patterns produced by the same lens array (6 μm PS spheres) and the same mask, but with a different orientation between the array and the mask. The orientation of each lens array is shown below the corresponding SEM micrograph. The different orientation between the lens array and the mask resulted in the different micropatterns.

Figures 10(*a*) and (*b*) show two micropatterns generated by the square array of 10 μm lenses. This figure demonstrates that micron and submicron scale patterns can be produced by arrays of plano-convex microlenses. The feature size can be controlled by the exposure dose, the pattern on the mask, the image distance and the object distance. We believe that these simple types of patterns will be useful in applications such as the fabrication of frequency-selective surfaces [18, 19].

Figure 10(*c*) shows a pattern of (approximately) a square grid, formed from interconnected 100 μm 6 × 6 grids. This pattern was generated using the array of 100 μm circular lenses with decreased mask distance. This pattern demonstrates that this technique can be used to fabricate optical elements such as gratings and beam splitters.

We can also use microlens arrays to generate arrays of complicated patterns (figure 11). The pattern in figure 11(*a*) was produced by the same array of 10 μm lenses as those used in figure 10. Microlenses with larger sizes can produce more complicated patterns. Figures 11(*b*) and (*c*) show the patterns generated by square arrays of 40 μm circular lenses and 100 μm square lenses, respectively. The high quality of the logo pattern 'VERITAS' shown in figure 11(*b*) suggests that this technique may be useful for micro-scale marking in a massively parallel way. Comparison between figures 11(*b*) and 6(*b*) also demonstrates that plano-convex microlenses produce micropatterns with less distortion. Transparent microspheres generate serious distortion in the micropatterns due to the larger off-axis aberration such as field curvature. The circuit-type pattern shown in figure 11(*c*) was produced using the square array of 100 μm square lenses. This pattern suggests that this method may be applicable to the fabrication of arrays of small ($<$1 mm) patterns appropriate for simple circuits and

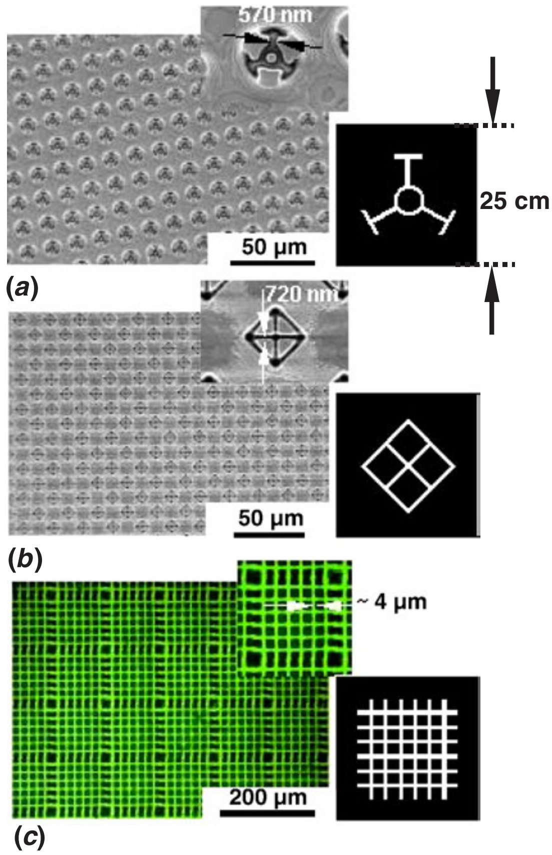

Figure 10. (*a*) and (*b*) SEM micrographs of three patterns produced by a square array of circular, 10 μm, plano-convex microlenses. (*c*) A pattern of square grid produced by a square array of 100 μm circular lenses. The irregularities in (*c*) reflect a slight misalignment between the pattern and the array of lenses.

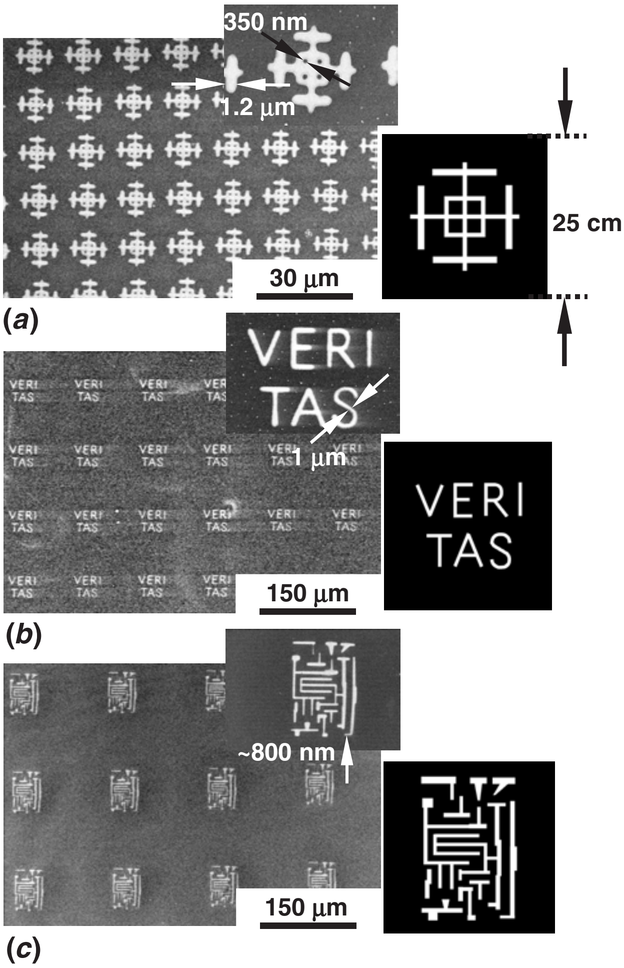

Figure 11. SEM micrographs of complicated patterns produced by different microlens arrays. (*a*) A pattern produced by a square array of 10 μm circular lenses. (*b*) A pattern produced by a square array of 40 μm circular lenses. (*c*) A pattern produced by a square array of 100 μm square lenses.

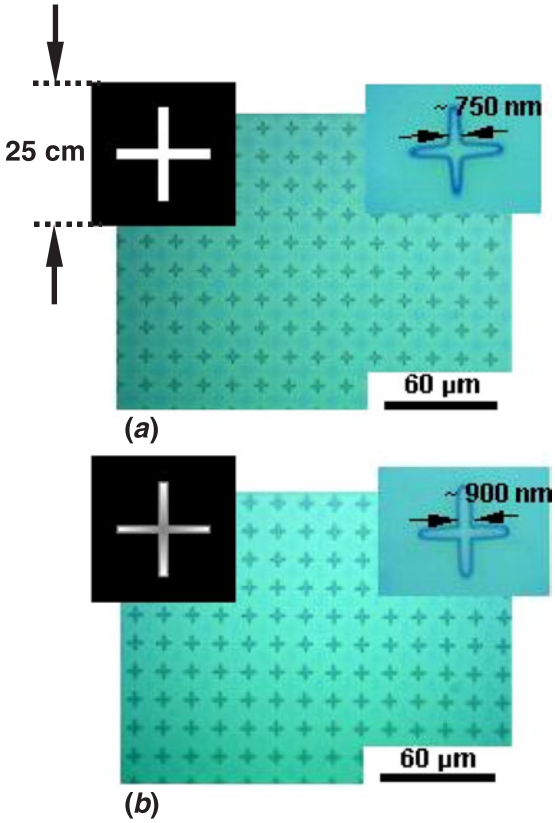

Figure 12. Photomicrographs of arrays of cross-shaped patterns produced using a square array of 10 μm lenses: (*a*) produced using a binary mask and (*b*) produced using a gray-scale mask with a compensated pattern.

microsystems such as simple microelectromechanical systems (MEMS).

3.2.4. Microlens lithography with gray-scale masks. This technique uses cm-size transparency masks with mm-size features. The patterns on the transparency masks can easily be printed with gray-scale opacity. Gray-scale masks are useful for fine adjustment of the transmitted intensity. They can be used for microlens lithography to adjust the spatial irradiance of the micro-images at submicron resolution. We use gray-scale masks for this technique for two purposes: (i) to compensate for the distortion of 2D micropatterns caused by diffraction and proximity effects [20, 21] and (ii) to generate 3D microstructures in a layer of photoresist.

Figures 12(*a*) and (*b*) show a comparison of two arrays of cross-shaped micropatterns generated using a binary mask and a compensated gray-scale mask. The linewidth of the crosses shown in figure 12(*a*) is broadened in the center and gradually tapered toward the end. This non-uniformity in linewidth is caused by two factors: (i) the aberration of the lenses, including spherical aberration and field curvature and (ii) proximity effects [20]. As shown in figure 12(*a*), the central area of each cross received exposure not only from the incident illumination but also from the four adjacent pattern elements on the four arms. Thus the central area of each cross received greater exposure than other pattern elements. This effect results in the broadened linewidth of each cross at its central area. To improve the uniformity of the linewidth, we used a mask with a gray-scale pattern to compensate the distortion [21]. Figure 12(*b*) shows that the compensated pattern produced an array of crosses with more uniform linewidth.

Figures 13(*a*) and (*b*) illustrate 3D microstructures fabricated using two types of gray-scale masks. The pattern shown in figure 13(*a*) was produced by a continuous-tone mask. The depth of the curved micropatterns is about 0.8 μm. The concave profiles of these microstructures can act as a square array of square micro-mirrors, if a thin film of metal is coated on the surface to enhance its reflectivity. The structure shown in figure 13(*b*) was generated by a multi-step gray-scale mask. The height of the pyramidal microstructures is about 1.8 μm. This array of microstructures may have potential applications for the fabrication of some devices such as micro-optical elements and pixel arrays.

Figure 13(*c*) shows an array of connected rectangular microstructures fabricated using an array of 40 μm microlenses. These microstructures were generated using

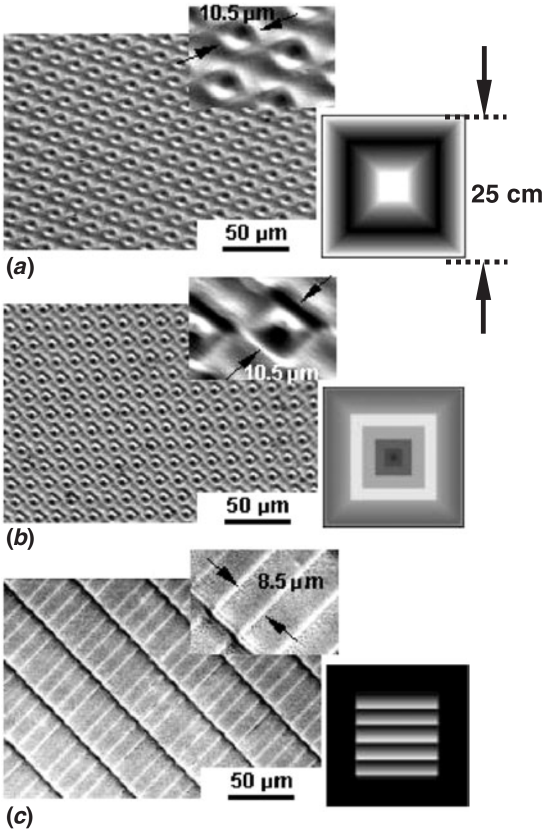

Figure 13. (*a*) and (*b*) SEM micrographs of 3D microstructures produced using a square array of 10 μm lenses and gray-scale masks. (*a*) An array of square microwells with smooth profiles. (*b*) An array of square-pyramidal microstructures. (*c*) SEM micrographs of an array of connected rectangular microstructures with linear slopes and blazed edges. These microstructures were generated using an array of 40 μm square lenses and a gray-scale mask.

a gray-scale mask that has a pattern of five rectangles with linear gradient. The mask is shown at the corner of the SEM micrograph. Each microstructure has a height of about 0.6–0.8 μm and a blazed edge. This figure demonstrates that microlens lithography can produce arrays of connected gray-scale microstructures with sharp edges. The blazed microstructures produced by this technique may be useful for the fabrication of diffractive optical elements.

3.2.5. Multiple exposures using multiple masks. Multiple exposures can be applied to microlens lithography to modify microstructures produced in photoresist. We used different masks for each exposure and left the lens array and the photoresist at the same position throughout the exposure processes. The developed resist shows a profile corresponding to a modified, combined pattern of all the masks. Figure 14(*a*) shows an array of hexagonal microstructures produced by a mask that has a gray-scale hexagonal pattern. Figure 14(*b*) shows an array of connected microstructures generated using two masks for double exposures: the first mask is the gray-scale mask as shown in figure 14(*a*); the second one is a binary mask that has a binary pattern of a tripole. Although the use of multiple exposures reduces the throughput in the form of

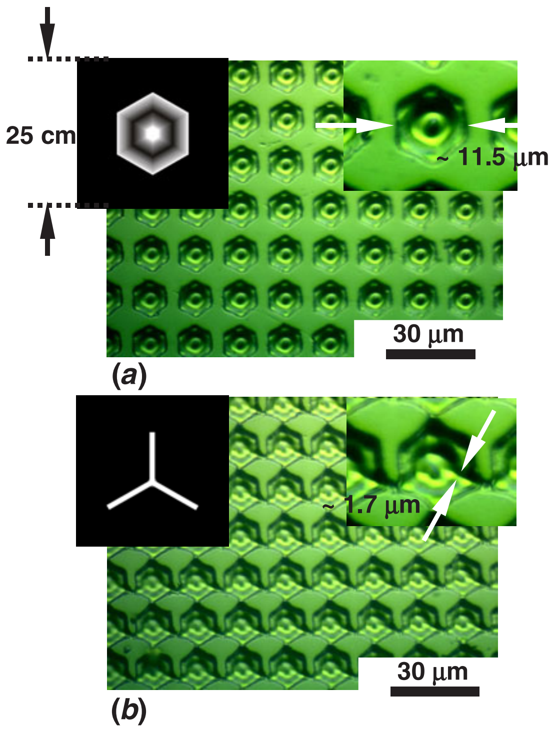

Figure 14. Photomicrographs of microstructures fabricated using two exposures with two masks. (*a*) An array of hexagonal microstructures produced using a gray-scale mask. (*b*) An array of connected microstructures generated after first exposure through the gray-scale mask as shown in (*a*) and the second exposure through a binary mask as shown at the corner. These photomicrographs were taken under an optical microscope with oblique illumination. The height of the microstructures is ~2.2 μm.

photolithography, it is convenient in fine modification of a microstructure at specific locations.

4. Conclusions

This paper demonstrates the use of 2D arrays of microlenses for photolithography to generate 2D arrays of micropatterns. We believe that these types of microfabrication will be useful for applications that require repetitive microstructures: e.g., frequency-selective surfaces [18, 19], flat-panel displays [22], information storage devices, sensor arrays [23] and array-based biosystems. We illustrate these methods with two procedures for generating micropatterns using two types of illumination. Using these methods, each type of illumination can generate uniform micropatterns on large areas ($>$10 cm^2).

The shapes of the patterns produced depend on four factors: the pattern of light used for illumination, the shape of the microlenses, the pattern of the microlenses, and the orientation of the mask (if any) used in illumination and the array of microlenses. If uniform (unpatterned) light is used, lenses with complicated profiles are required to produce dense, complicated micropatterns. Since it is not easy to fabricate complicated profiles on microlenses and it is difficult to simulate the optical correspondence between the lens profiles and the produced image, methods using unpatterned, uniform illumination are best suited for large-area fabrication of simple micropatterns (e.g., dots, bars, rings). To produce complicated micropatterns, it is more convenient to use microlens lithography with masked illumination.

Neither method is limited to periodic arrays of microlenses; both can be extended to arrays of microlenses produced in non-periodic geometry by photolithography: We can fabricate microlenses with different shapes, indices and arrangements on a transparent substrate. These microlenses, if positioned on the substrate in a complex arrangement, can produce non-periodic, complex optical patterns. We have recorded these complex patterns in photoresist, and transferred the patterns to thin films of chromium on quartz plates (for possible use as chrome photomasks).

Conventional photolithography is, of course, able to fabricate periodic arrays of micropatterns, but it requires the use of chrome masks, steppers and other expensive components. The technique we demonstrate here is simple and low-cost, and provides a route for the fabrication of large-area patterns with features having dimensions from $\sim$0.3 to >1 μm. Micropatterns or photomasks produced by this technique using multiple exposures have excellent registration with the original lens array. Different patterns or masks produced by the same lens array can be perfectly aligned to each other, and are free of positional errors of the types generated by step-and-repeat processes.

It may also provide a simple method for fabrication of chrome masks having repetitive features. The patterns produced by this technique can be applied to fabricate elements for soft lithography, such as stamps for micro-contact printing, or molds for micro-molding.

The quality of patterns produced by 2D arrays of microlenses depends on the quality and uniformity of the lenses. Thus, the process of fabrication of microlenses is a critical factor for the success of this technique. Moreover, since the patterns are produced by microlenses, they are subjected to the effects of diffraction and optical aberration. For lenses of the same size, the longer the focal length (lower NA), the more the diffraction and the lower the resolution of the micropatterns. On the other hand, the shorter the focal length (higher NA), the more the aberration caused by off-axis imaging and the smaller the field of high-definition images. There is a trade-off between the resolution of images and the size of image field; it is difficult to generate submicrometer features over the whole image field of a lens array. Due to this limitation, this technique is better suited for the fabrication of photomasks with dense arrays of micropatterns with micro-scale resolution. The use of these photomasks for a second-stage reduction photolithography can produce arrays of dense, submicrometer features. For particular applications in which repetitive patterns with submicrometer resolution are sparsely arranged, this technique might be useful for the direct fabrication of these low-density micropatterns.

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