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Fabrication and analysis of the reflowed microlens arrays using JSR THB-130 N photoresist with different heat treatments

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Abstract This paper reports that the fabrication of the reflowed microlens by the negative tone JSR THB-130 N photoresist can be treated with different thermal treatments using hotplate and oven. The different disk or thin cylinder arrays with diameters of 40–70 μm and thickness of about 7.4 μm were patterned using photolithography technology, and baked at 220°C by two kinds of thermal treatments using hotplate and oven to form reflowed microlens arrays. The spot size of the refractive microlens was then measured by optical microscopy and the total focal length of refractive microlens was simulated by curve fitting the lens profiles. The resolution of the microlens arrays approaches to 400 dpi as coated with Hexamethyldisilazane material. The smallest spot size of about 2.72 μm at the nominal 40 μm microlens is obtained by the oven heat treatment, and the shortest total focal length of about 150 μm at the nominal 40 μm microlens is achieved by the hotplate heat treatment. The reduced spot size and total focal length of the microlens could improve the density and performance of optical devices and imaging systems.

1 Introduction

In recent years, the microlens arrays have been used for optical communications, interconnections, charge coupled device (CCD) imagers and thin film transistor-liquid crystal display (TFT-LCD) plate (Han et al. 2004). Different fabrication technologies have been proposed for the fabrication of microlens, including the reflowed

polymer by thermal process (Popovic et al. 1988), microdroplet of the polymer by microjetting technology (MacFarlane et al. 1994), patterning of the photoresist by gray-level mask method (Däschner et al. 1996), excimer laser machined polymer by contour scanning method (Lee et al. 2005) and so on. Popovic et al. (1988) reported that the profile and the curvature of microlens were related to the time of thermal treatment above the transition glass temperature of polymer (Popovic et al. 1988). MacFarlane et al. (1994) fabricated the microlens arrays by microjetting technology to effectively reduce the processing time. But, the diameter of the microlens would be limited to the viscosity of polymer properties and the size of nozzles, which could be clogged with polymer. Däschner et al. (1996) designed the gray-level mask to fabricate the profile of microlens arrays by controlling the different exposure doses for the photoresist. The cost of the gray-level mask is very expensive due to the use of high-energy beam sensitive glass (HEBS glass). Lee et al. (2005) developed the contour scanning method for fabricating the axially symmetric 3D microlens using the KrF excimer laser machining. It could control the microlens profile, but it was difficult to remove the scraps from laser ablation and fabricate the high-density microlens arrays due to the long pitch of lens with large unused area. The diameters of microlens finished by the above methods are in the range of several hundred micrometers. The higher the physical resolution of the microlens arrays, the smaller the size of the microlens (Nussbaum et al. 1997). Microfabrication technologies could be used to reduce the diameter for the high density of microlens arrays in batch process. The characteristics of microlens are related to the selection of photoresist and adhesion material together with the mask designed.

In this study, another photoresist of negative tone JSR THB-130 N with the adhesion material of Hexamethyldisilazane (HMDS) was utilized to fabricate the microlens arrays with disk arrays of diameters 40–70 μm . The resolution of microlens arrays could approach to 400 dpi (depth per inch). Different kinds of

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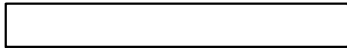
thermal treatment methods were used to change the profiles of microlens arrays. The optical properties of the JSR THB-130 N microlens were also analyzed by optical microscopy and curve fitting methodology.

2 Experimental procedures

Figure 1 shows the process flow of the reflowed microlens and described in the following:

1. Clean the pyrex 7740 glass of 500- μm thick by acetone and isopropanol.
2. Spin the HMDS to enhance the adhesion between glass substrate and photoresist. The spinning speed was controlled at about 3,000 rpm (rotate per minute).

1. Clean the glass



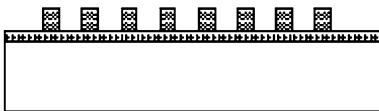
2. Spin coating the HMDS to enhance the adhesion between glass substrate and photoresist



3. Spin the negative tone JSR resist



4. Pattern and transfer the mask shape to photoresist, and develop the un-exposed structure of disk arrays



5. Reflow the photoresist at 220 °C on the hotplate and oven

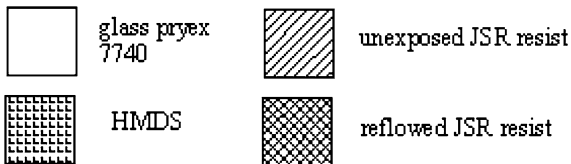


Fig. 1 The processing flow of reflowed JSR THB-130 N photoresist

3. Spin the negative tone photoresist JSR THB-130 N at 4,000 rpm, and the thickness was about 7.5 μm . Soft baking the photoresist is done with ramping rate of 1°C/min from 65 to 95°C. Keep the photoresist at 95°C for 20 min to increase the adhesion between glass and JSR THB-130 N. Cool down the pyrex glass to room temperature for photolithography.
4. UV exposure to pattern transfer the circle shape of mask to photoresist, and develop the un-exposed JSR photoresist to form the structure of disk arrays. The exposure energy density was about 200 mJ/cm^2 .
5. Reflow the JSR THB-130 N photoresist at 220°C for about 2 h by two kinds of heat treatment of the hotplate and oven.

The different thermal treatments by hotplate and oven were used to control the profiles of microlens arrays. The diameters of the different sizes of disk array were designed to be 40, 50, 60 and 70 μm . The different resolutions of microlens arrays were designed to be 100, 200, 300 and 400 dpi.

The 3D profiles and morphology of the reflowed JSR THB-130 N microlens were examined by 3D confocal microscopy (NanoFocus $\mu\text{Surf}^{\text{®}}$, Pentad scientific corporation) and Scanning Electron Microscopy (JEOL JXA-840A, Japan). The spot sizes of reflowed JSR THB-130 N microlens were measured by optical microscopy (Olympus BX-51, Japan).

3 Optical measurement and curve fitting methodology

The smaller spot sizes of the refractive microlens could be measured by optical microscopy, and the total focal length of microlens could be calculated with curve fitting using the data of the microlens. The data of microlens profile could be obtained by 3D confocal microscopy. The lens profile $z(r)$ of an axial symmetrical plano-convex lens could be expressed by:

$$z(r) = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum a_i r^{2i} \quad (1)$$

where $z(r)$ is the height of the lens, r is the distance from the center of curve surface, c is the curvature of lens, and k is the conic constant. Using the profile data and Eq. 1 above, the curve surfaces of reflowed-photoresist microlens can be plotted and fitted. According to the Lensmaker's Eq. 2 (Smith 2000) and the curve fitting results, the total focal length of reflowed microlens could then be calculated by Eqs. 2 and 3.

$$\frac{1}{\text{efl}} = (n - 1) \frac{1}{R} \quad (2)$$

$$\text{Total focal length} = \text{efl} + d \quad (3)$$

where efl means the effective focal length of a lens, n is the refractive index of material, R is the curvature radius of a lens, and d is the thickness of microlens which is the distance between top and bottom of the microlens in 3D

Table 1 The physical properties of JSR THB-130 N

Properties	Magnitude
Thermal conductivity (W/m °C)	0.7
Density (kg/m ³)	1,400
Specific heat (1,100 KJ/kg °C)	1,100

Table 2 The parameters of thermal distributions simulation of JSR THB-130 N by hotplate and oven heat treatment

	Hotplate conditions	Oven conditions
Environment temperature (°C)	20	220
Convection coefficient (W/m ² K)	1,000	0

measurements. The refractive index of JSR THB-130 N is about 1.64 (JSR Corporation 2006).

In order to understand the relationship between the profile of microlens and the thermal treatment method, we use simulate the thermal distributions of JSR THB-130 N under different thermal treatments of hotplate and oven by finite elements approach. The physical properties of JSR THB-130 N for simulation are listed in Table 1. The thermal conductivity is 0.7 W/m °C, the density is 1,400 kg/m³ and the specific heat is 1,100 KJ/kg °C. The parameters of simulating thermal distributions of JSR THB-130 N disk structures under both hotplate and oven equipments are listed in Table 2. The environment around the hotplate is cool air, so the environment temperature in clean room is assumed to be 20°C and convection coefficient is 1,000 W/m² K. On the contrary, the environment around the oven is hot air with steady state, so the environment temperature is assumed to be 220°C and convection coefficient is 0 i.e., very small.

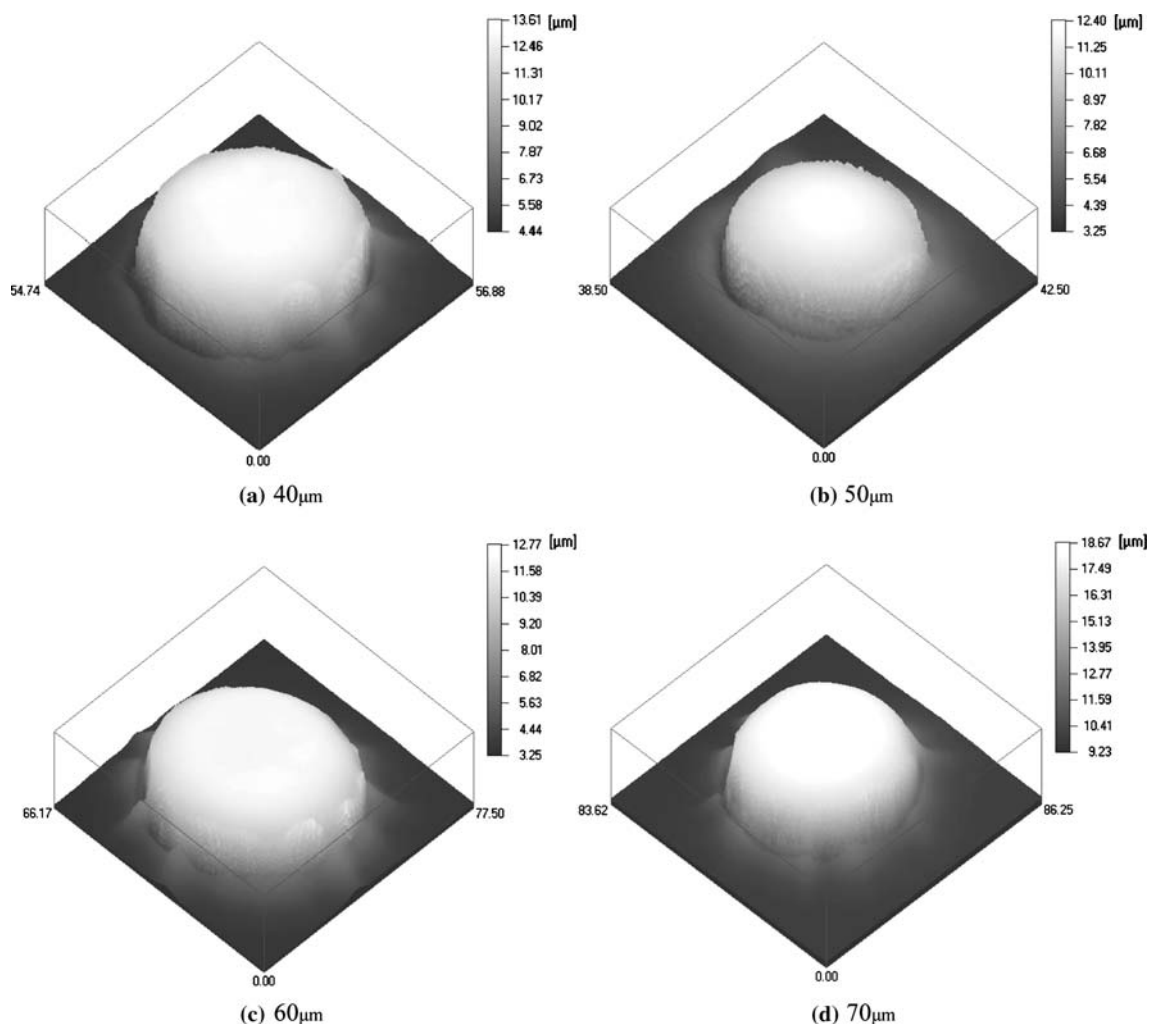


Fig. 2 a–d Three dimensional confocal images of different microlens with disk diameters of 40, 50, 60 and 70 μm , reflowed at 220°C for 2 h by the hotplate heat treatment, respectively

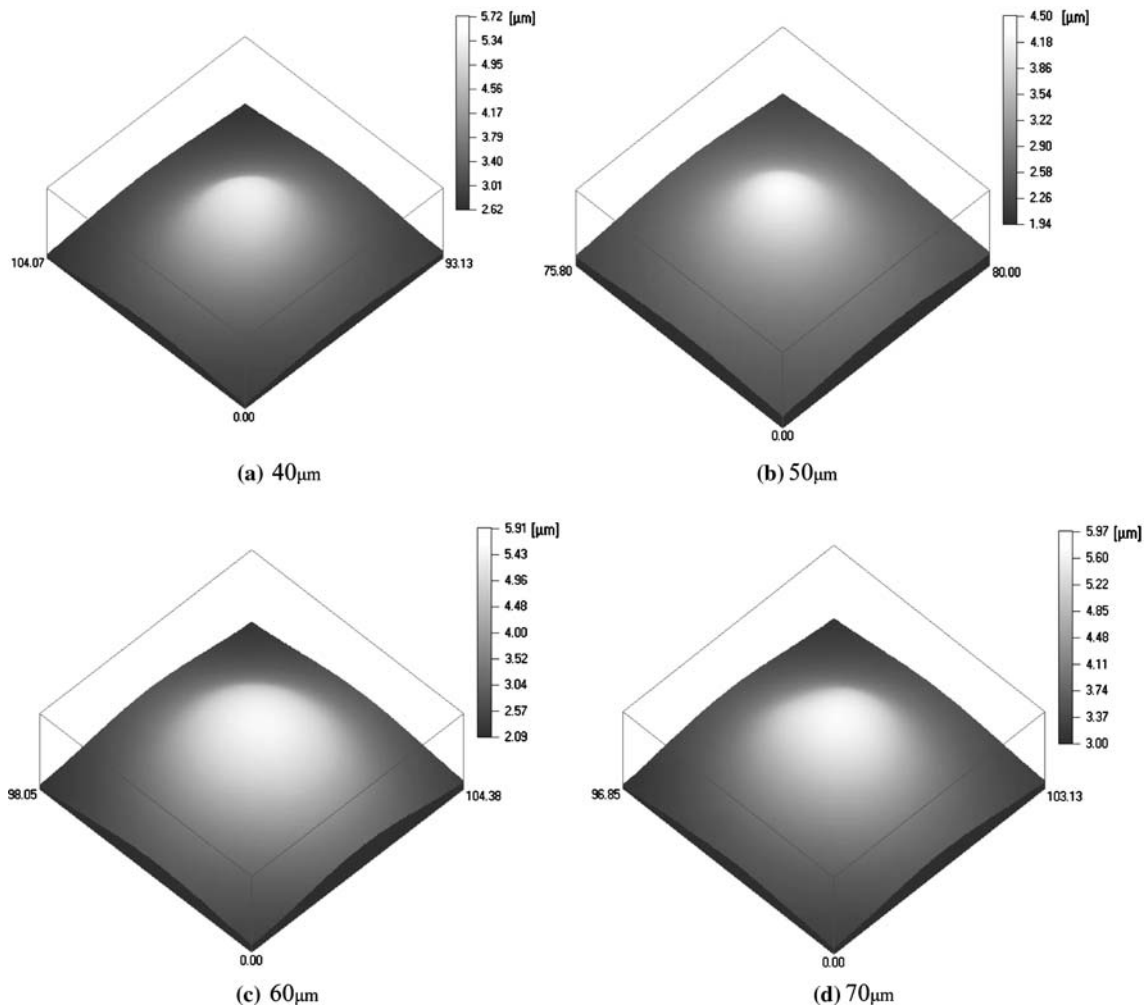


Fig. 3 a–d The 3D confocal images of different microlens with disk diameters of 40, 50, 60 and 70 μm , reflowed at 220°C for 2 h by the oven heat treatment, respectively

4 Results and discussion

Figure 2a–d shows the 3D confocal images of different microlens with disk diameters of 40, 50, 60, and 70 μm , reflowed at 220°C for 2 h on the hotplate, respectively. Figure 3a–d shows the 3D confocal images of different microlens with disk diameters of 40, 50, 60, and 70 μm , reflowed at 220°C for 2 h on the oven, respectively. In comparison with Figs. 2 and 3, the profiles of microlens by hotplate heat treatment are more prominent than that by oven heat treatment. It is because of the cold air around the photoresist on the glass wafer under the environment of hotplate. The surface of photoresist to air is constrained to reflow at low temperature of air while the interior to interface between the photoresist and hotplate tends to reflow at high temperature above glass transition temperature. The large temperature gradient leads to this prominent profile of microlens. On the other hand, the profiles of

microlens by oven heat treatment are more flat due to the hot air environment with very small temperature gradient. Figure 4a shows the overall 3D curve fitting profile of the reflowed JSR THB-130 N microlens arrays with disk diameters of 40–70 μm by hotplate treatment. Figure 4b shows the simulated thermal distribution of disk structures by hotplate treatment. As described previously, the large temperature gradient between the surface (cool air) and interior (high temperature) of photoresist leads to this prominent profile with little reflowed phenomenon of the photoresist. The final microlens diameter is close to the original disk diameter. Figure 5a shows the overall 3D curve fitting profile results of the reflowed JSR THB-130 N microlens arrays by oven heat treatment. Figure 5b shows the simulated thermal distribution of disk structures by oven treatment. There is nearly no temperature gradient in this disk structure; the temperature distribution was uniform. The final microlens

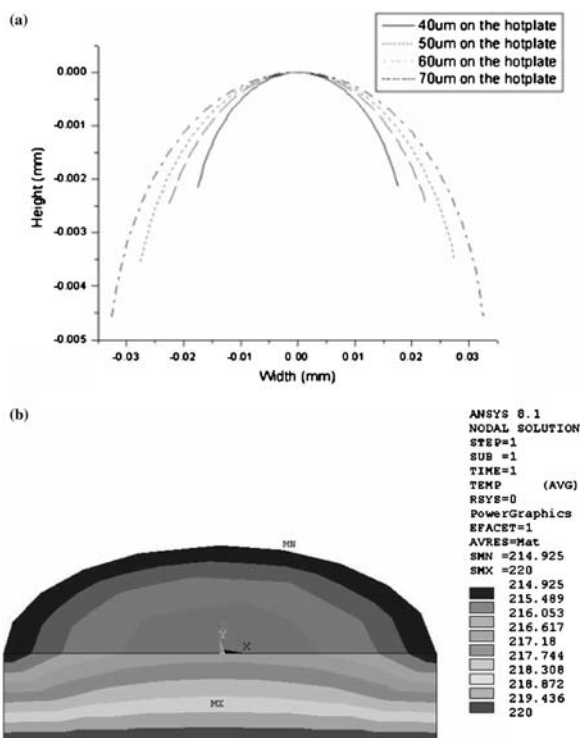


Fig. 4 The reflowed JSR THB-130 N microlens by hotplate thermal treatments: **a** overall 3D curve fitting profiles and **b** simulation of thermal distribution

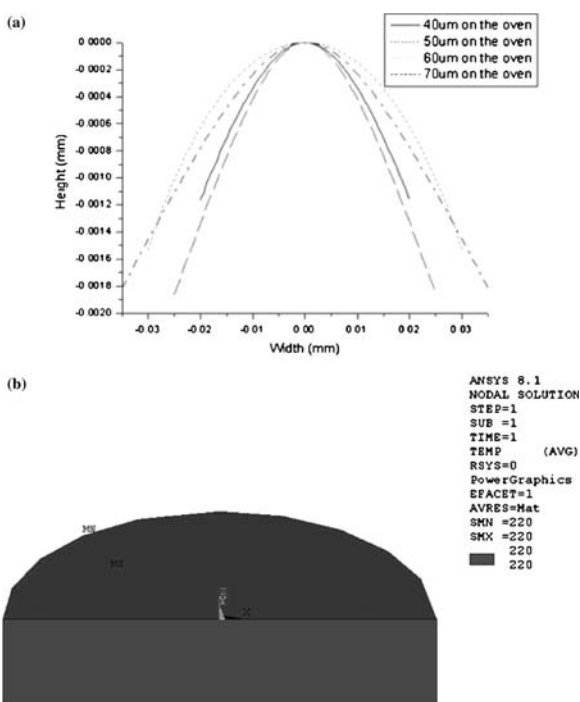


Fig. 5 The reflowed JSR THB-130 N microlens by oven thermal treatments: **a** overall 3D curve fitting profiles and **b** simulation of thermal distribution

diameter is less than the original disk diameter under oven heat treatment. Also, the profile difference of microlens can be compared in the curve fitting result. The conic constant of microlens by hotplate heat treatment is positive ($k > 0$, oblate ellipsoid) while that by oven heat treatment is negative ($k < -1$, hyperboloid). The profiles of microlens with oven heat treatment are more irregular (Fig. 5a) due to the whole hot air environment. Figure 6a, b shows the SEM micrographs of the one reflowed JSR THB-130 N microlens and one line of microlens array with a disk diameter of 40 μm by hotplate treatment, respectively. The symmetrical oblate ellipsoid profile can be seen which is in agreement with the curve fitting result ($k > 0$). Figure 7a, b shows the 3D confocal images of the reflowed microlens arrays with 400 dpi resolution and disk diameters of 40 and 70 μm, respectively, by oven. The hyperboloid-like profile can be seen which is in agreement with the curve fitting result ($k < -1$).

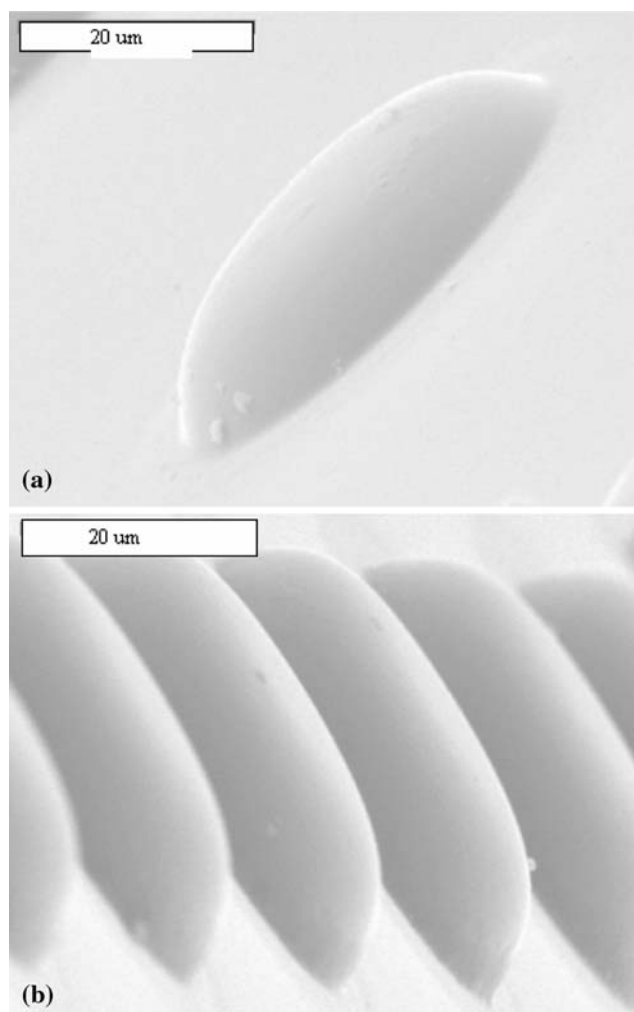


Fig. 6 SEM micrographs of reflowed JSR THB-130 N microlens with a disk diameter of 40 μm by hotplate: **a** one microlens, and **b** one line of microlens arrays

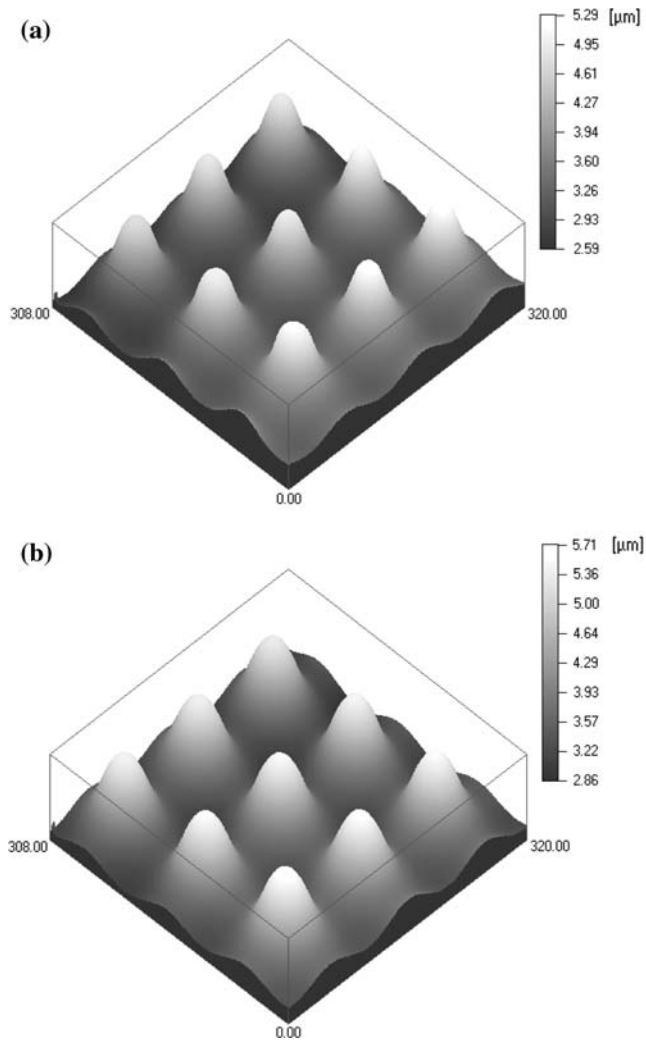


Fig. 7 **a** The 3D profile diagrams of 40 μm –400 dpi microlens arrays and **b** the diagrams of 70 μm –400 dpi microlens arrays by oven

Figure 8a, b shows the images of spot sizes of the microlens measured by optical microscopy for a disk diameter of 50 μm with 400 dpi by hotplate treatment and 50 μm with 200 dpi by oven treatment, respectively. The image of spot size of microlens obtained by hotplate treatment is larger than by oven treatment. It is in consistent with Figs. 2 and 3. According to the images of spot sizes of microlens, the optical focused beam profiles of the microlens can be measured. Figure 9a, b shows the optical focused beam profiles of reflowed JSR THB-130 N microlens with a disk diameter of 50 μm formed by hotplate and oven treatment, respectively. The optical focused beam diameter of reflowed microlens by hotplate treatment is larger than by oven treatment. Following the results of the focused beam, the real spot size of microlens can be estimated by the 13.5% normalized intensity of beam. Figure 10a shows the normalized intensity of the focused beam of the reflowed microlens with a disk

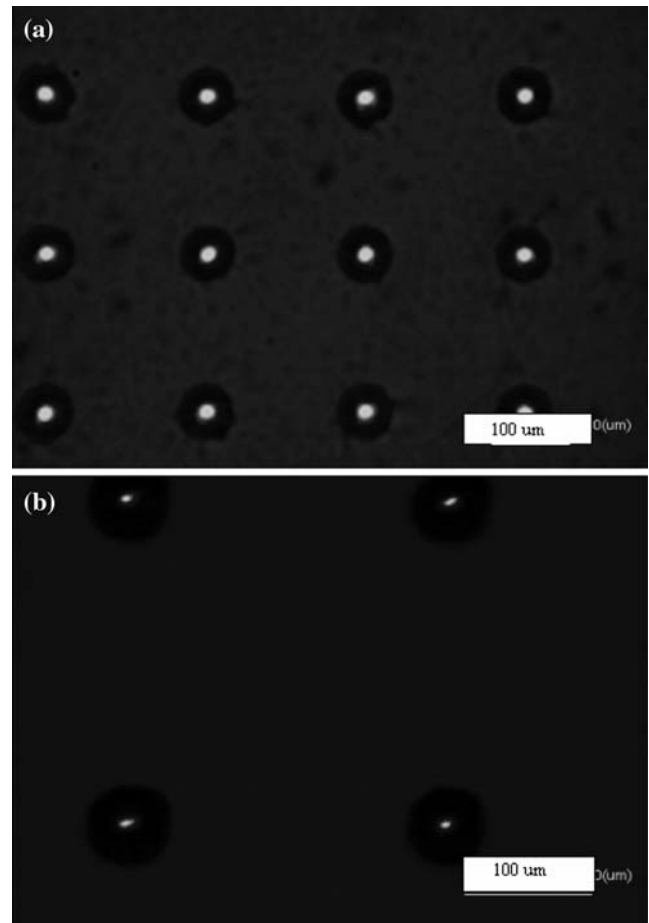


Fig. 8 The images of spot size of microlens measured by optical microscopy: **a** 50 μm , 400 dpi by hotplate and **b** 50 μm , 200 dpi by oven

diameter of 50 μm by oven heat treatment. The spot size can be estimated to be 3.02 μm . The whole spot sizes in this study by hotplate and oven heat treatment can be obtained in this approach as shown in Fig. 10b. The microlens by different heat treatments will lead to the different profile of reflowed-microlens, and the spot size of microlens by hotplate treatment is nearly four times larger than by oven treatment. The smallest spot size of the microlens is about 2.72 μm with a disk diameter of 40 μm by oven heat treatment. According to curve fitting Eq. 1, Figure 11 shows the curve fitting results of the 40 μm reflowed microlens by oven. P1 is the curvature of microlens (mm^{-1}), and P2 is the conic constant. The error of curve fitting profiles is below 10^{-10} . Figure 12 shows the diagram of the total focal length calculated by Eqs. 2 and 3 for this two heat treatment conditions. The total focal length of microlens by hotplate is shorter than that by oven. The smallest total focal length of the microlens is about 150 μm with a disk diameter of 40 μm by hotplate heat treatment. In comparison with the conventional reflowed microlens at more than 250°C using TMR-P7

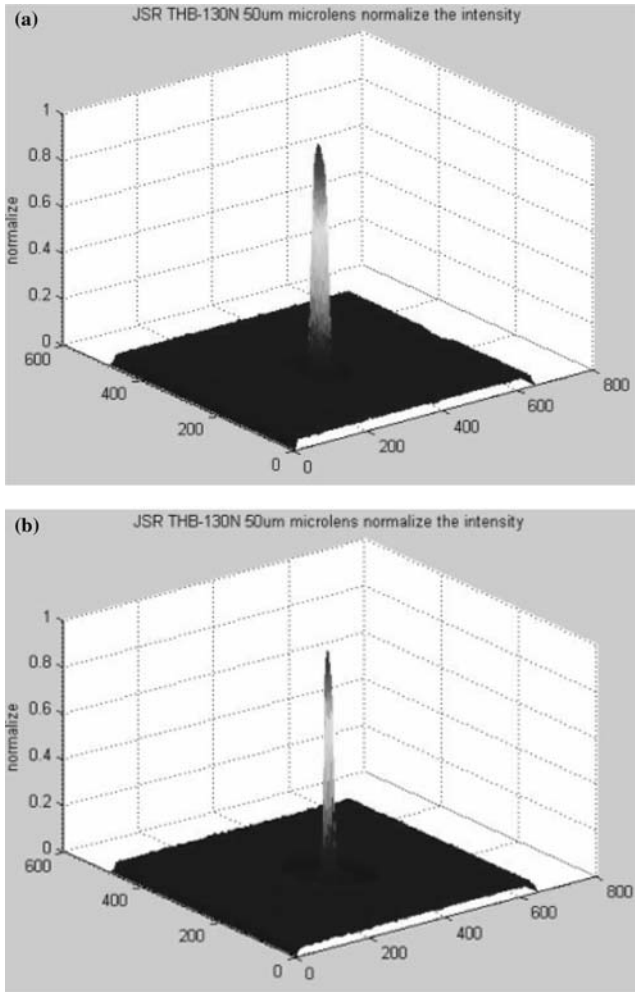


Fig. 9 Optical focused beam profiles of the reflowed microlens arrays **a** 50 μm by hotplate and **b** 50 μm by oven

photoresist (Han et al. 2004), our reflowed microlens arrays at 220°C using negative tone, JSR THB-130 N photoresist together with HMDS adhesion layer have the advantages of low process temperature, profile adjustment in wide range by different heat treatment for different application, and good thermal stability.

5 Conclusions

The reflowed-photoresist JSR THB-130 N microlens array with high resolution of 400 dpi has been demonstrated by different methods of hotplate and oven heat treatments for disk diameters of 40–70 μm . The microlens profile could be adjusted in wide range by different heat treatment. In this study, the shortest total focal length of microlens obtained by hotplate treatment is about 150 μm , and the smaller spot size of microlens by oven treatment is about 2.72 μm . The profiles of microlens by hotplate heat treatment are more prominent than that by oven heat treatment due to the cold air around the photoresist under the environment of

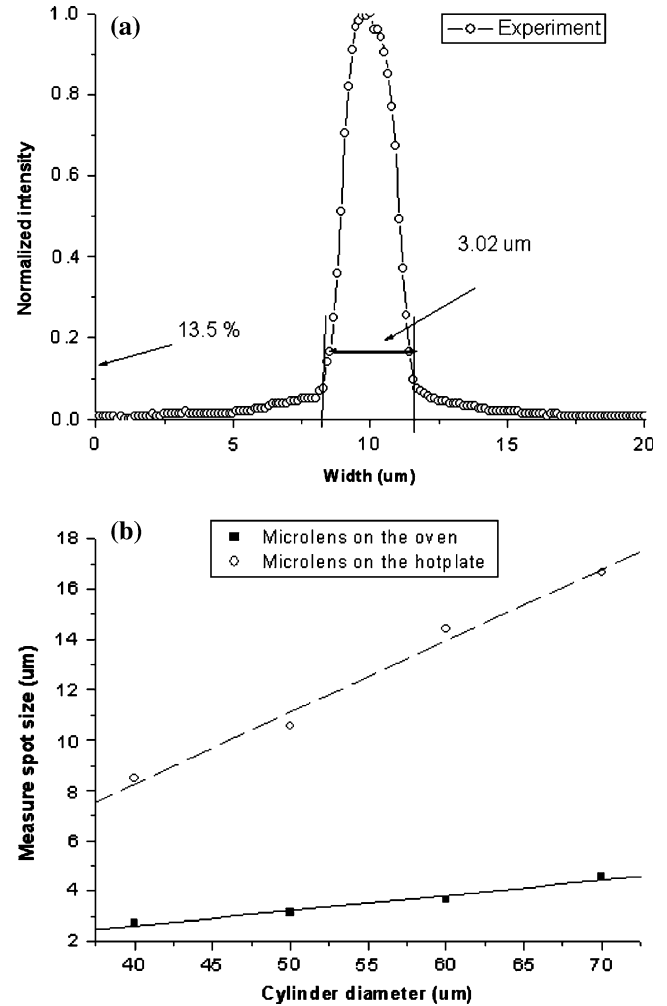


Fig. 10 a The normalized intensity of the focused beam of the reflowed microlens with a disk diameter of 50 μm by oven heat treatment. **b** The diagram of spot size by hotplate and oven heat treatments

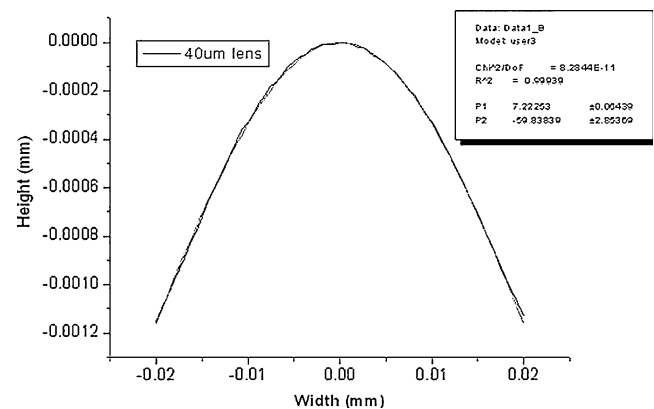


Fig. 11 The curve fitting result of the 40 μm reflowed-photoresist microlens by oven. P1 is the curvature of microlens (mm^{-1}), and P2 is the conic constant

hotplate with large temperature gradient. The symmetrical oblate ellipsoid profile by hotplate treatment can be seen by micrographs which is in agreement with the

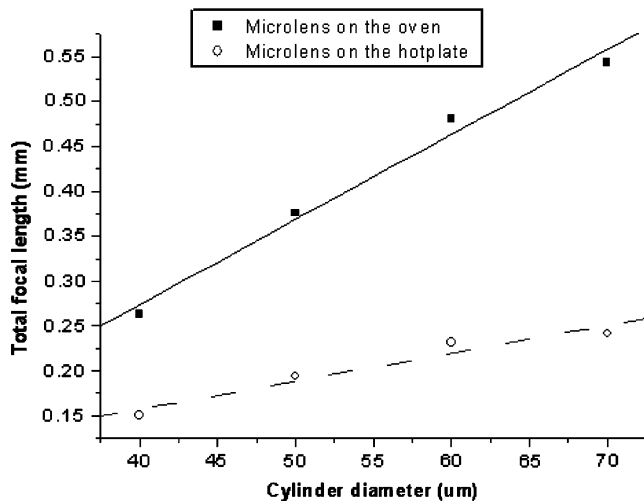


Fig. 12 The diagram of the total focal length by hotplate and oven heat treatments

curve fitting result ($k > 0$). In contrast, the profiles of microlens by oven heat treatment are more flat due to the hot air environment with very small temperature gradient. The hyperboloid-like profile can be seen by micrographs which is in agreement with the curve fitting result ($k < -1$). Our reflowed microlens arrays formed by negative tone, JSR THB-130 N photoresist have the advantages of low process temperature, profile adjustment in wide range and good thermal stability.

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